

Exploration des solutions de reconfiguration dynamique pour améliorer la fiabilité des micro-réseaux à courant continu

Francesco Di Gregorio

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THÈSE POUR OBTENIR LE GRADE DE DOCTEUR DE L'UNIVERSITÉ DE MONTPELLIER

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Exploration of Dynamic Reconfiguration Solutions for Improved Reliability in DC Microgrids

Présentée par Francesco Di Gregorio Le 19 Novembre 2021

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Dedicato alla mia famiglia ...

Abstract

Critical systems such as distributed computing systems require high reliability and resilience to ensure the quality of service. Moreover, 90% of all service interruptions experienced by customers derive from the power supply and distribution system. This is because existing distribution systems are centralized and rely primarily on the utility grid. On the other hand, DC microgrid technology is becoming more and more common in buildings, ships, and data centers. It promises a change of orientation from centralized to distributed and greener co-generation. However, existing DC microgrid architectures are static, meaning they cannot change their topology after installation. This aspect limits the flexibility and adaptability of the power network to such a heterogeneous and variable scenario.

This thesis proposes a novel DC microgrid architecture that enables the concept of "Software-Defined Power Domains". In fact, by using the conceived power crossbar network, the topology can be changed by software dynamically. This aspect improves the flexibility of the power distribution system, which can reconfigure itself to best adapt to loads and sources condition. Moreover, the system's availability is widely enhanced because of the bus redundancy and segmentation provided by the crossbar. Finally, the resilience increases thanks to the dynamic operations able to instantaneously isolate a fault, reconfigure the topology and restore the system's functioning.

In this thesis, all the details about this architecture are provided. Then, the control and some dynamic operations are explored and tested by the PSIM simulator to validate the assumptions mentioned above. Moreover, the system's reliability and availability are widely analyzed through Markov chains or Monte Carlo methods when considering components with constant or non-constant failure rates, respectively. Finally, the case study of a DC-powered data center is taken to validate the advantages of the proposed architecture. Several transformations are applied to the basic architecture that gradually improves the availability and MTBF of the system. For instance, the crossbar-based architectures. Then, a proposal of an availability-aware power distribution system for data centers based on power crossbars is provided in the perspective, including renewable energy sources combined with batteries able to temporarily supply the data center even in case of failure on the main distribution line.

Résumé

La transition énergétique nécessite des changements substantiels dans la manière dont l'électricité est acheminée du fournisseur aux clients. En effet, la demande d'électricité toujours croissante des systèmes énergivores tels que les centres de données et les véhicules électriques met au défi le système actuel d'approvisionnement et de distribution d'électricité. Le paradigme de la production centralisée, où l'électricité est produite dans une installation centralisée puis transmise par des lignes de transmission à haute tension, ne peut plus résister à cette demande croissante.

Le paradigme de la production distribuée est ensuite introduit dans lequel le réseau électrique est aidé par plusieurs resources d'énergie distribué (DERs) placés à proximité du côté de la charge. De cette façon, la demande d'électricité peut être satisfaite localement, en particulier pendant les heures de pointe. Toutefois, l'introduction de nouvelles sources d'énergie telles que les sources d'énergie renouvelable (RES), les systemes de stockage d'énergie (ESS) de différentes natures pose plusieurs problèmes de contrôle et de stabilité du système de distribution électrique. De plus, la pénétration des énergies renouvelables devient de plus en plus critique et pourrait avoir un impact sur la stabilité du réseau électrique si le rapport entre l'énergie renouvelable et l'énergie du service public approche de l'unité.

Par conséquent, les systèmes de distribution d'électricité existants doivent être entièrement repensés pour répondre à ces besoins sans compromettre leur stabilité et leur sécurité. Nous pensons que l'architecture du système de distribution joue un rôle clé dans la résolution du casse-tête mentionné ci-dessus. En effet, dans un scénario où les acteurs de l'énergie sont hétérogènes et où leur production et leur consommation d'énergie varient, la flexibilité et le contrôle intelligent du réseau électrique deviennent fondamentaux pour coordonner ce trafic énergétique massif.

Dans ce contexte, le micro-réseau est un bon compromis qui permet d'intégrer de plus en plus de sources renouvelables et de consommation d'énergie et n'est pas affecté par le dimensionnement du système de distribution. En effet, dans les micro-réseaux, le contrôle est confié à plusieurs contrôleurs locaux de sorte que la complexité est divisée. En outre, le micro-réseau peut être connecté au réseau électrique ou fonctionner indépendamment avec ses ressources énergétiques locales, ce qui améliore la fiabilité et la disponibilité du système d'alimentation électrique. Enfin, les micro-réseaux peuvent partager leur énergie indépendamment du réseau public si une connexion est établie entre eux. Cela renforce la résilience du système de distribution d'électricité et réduit les contraintes sur le réseau public. En effet, en cas de défaillance d'un micro-réseau, le micro-réseau adjacent peut aider à alimenter au moins les charges les plus critiques.

En raison de la nature en courant continu de la plupart des charges que nous utilisons aujourd'hui, le micro-réseau en courant continu devient la tendance pour les futurs réseaux électriques. Bien que la transmission de l'énergie en courant continu soit déjà utilisée pour les lignes de transmission à haute tension en raison des pertes plus faibles, il manque encore certains composants dans les gammes de basse et moyenne tension pour passer complètement à un système de distribution d'énergie en courant continu. Par exemple, l'efficacité des convertisseurs de puissance dans la gamme de moyenne tension n'est toujours pas comparable à celle des transformateurs de courant alternatif. En outre, la sécurité des systèmes à courant continu est plus difficile à assurer que celle des systèmes à courant alternatif en raison de l'absence de passage par zéro dans les systèmes à courant continu. Cependant, les progrès réalisés dans les systèmes de contrôle numérique permettent aux algorithmes de contrôle complexes de détecter rapidement un défaut et de prévenir les dommages aux personnes et/ou aux équipements.

Cette thèse explore une nouvelle architecture de micro-réseau DC qui permet le concept de "Software-defined Power Domains". En effet, l'introduction de crossbars de puissance dans le système de distribution électrique permet d'installer plusieurs topologies electriques sur la meme implementation physique. De cette façon, le système de distribution d'énergie peut s'adapter dynamiquement aux conditions des sources et des charges. De plus, la reconfiguration dynamique de la topologie permet l'isolation et la récupération instantanées des défauts. En outre, la redondance des chemins offerte par le système crossbar assure une haute disponibilité par rapport aux architectures précédentes. Par conséquent, cette architecture est un bon candidat pour les systèmes critiques qui demandent un niveau plus élevé de flexibilité, de fiabilité et de résilience.

Un benchmark d'architectures de micro-réseaux à courant continu est utilisé comme comparaison avec l'architecture proposée. Par exemple, les architectures "ring" et "ladder" ont été identifiées comme référence pour déterminer les gains en fiabilité, flexibilité et résilience de l'architecture proposée. En particulier, quelques premières analyses statiques sont effectuées sur ce benchmark. Premièrement, une analyse de flexibilité compare le nombre de chemins redondants que chaque architecture offre pour connecter une source à une charge. Ensuite, l'analyse de fiabilité statique est effectuée pour retrouver les fonctions

de fiabilité des trois architectures considérées dans trois cas d'utilisation. Dans les trois cas d'utilisation, l'architecture à base de crossbars présente un MTBF plus élevé par rapport aux autres architectures du benchmark.

La théorie classique de la fiabilité est utilisée pour cette analyse. Dans le premier cas d'utilisation, le système crossbar présente un gain de MTBF de 2x par rapport à la ladder et de 4x par rapport à l'anneau. Ceci est dû à la redondance de la connexion terminale offerte par le système crossbar. En fait, d'autres cas d'utilisation ont été analysés qui insèrent la redondance des commutateurs terminaux pour l'architecture en anneau et en échelle également. Même si la fonction de fiabilité de l'architecture en anneau et en échelle se rapproche de celle de l'architecture à barres croisées avec ces modifications, le MTBF de l'architecture à barres croisées est toujours plus élevé. Enfin, une analyse d'efficacité basée sur les pertes de puissance dans les commutateurs de puissance est effectuée. D'après cette analyse, l'architecture crossbar, en raison de la redondance et du parallélisme des bus, présente une efficacité énergétique supérieure à celle des autres architectures.

Un prototype physique représentant une architecture basée sur des barres transversales a été realisé pendant ma thèse dans le cadre d'un projet régional financé par la région Occitanie. Par conséquent, toutes les simulations et validations effectuées au cours de ma thèse ont été calibrées à l'aide du matériel dont nous disposons au laboratoire.

Par exemple, les opérations dynamiques sont explorées dans le Chapitre 4. En effet, la flexibilité offerte par le système crossbar est mieux exploitée s'il existe des opérations dynamiques qui permettent de changer de topologie sans affecter le fonctionnement du système. Dans ce but, l'opération de handover et les opérations de reprise sur panne sont présentées. La première est l'opération qui permet le changement dynamique de topologie. En fait, une commutation de topologie transparente est obtenue en synchronisant le fonctionnement des commutateurs crossbar et des convertisseurs de puissance. Le simulateur PSim est utilisé pour valider cette opération dans un scénario d'exemple.

La seconde est nécessaire dans le cas d'une condition de défaut. En effet, lorsqu'un défaut survient sur un composant, l'architecture doit être capable de détecter le dispositif défectueux, de l'isoler et de trouver un moyen de rétablir le fonctionnement du système. Par conséquent, un protocole de récupération de fautes est présenté au chapitre 4 et simulé à l'aide du simulateur PSim.

En particulier, deux exemples de défaut sont examinés : un défaut sur une source d'énergie et un défaut sur un bus. Dans les deux cas, l'architecture et le système de contrôle associé permettent d'isoler le défaut et de rétablir le fonctionnement complet en quelques millisecondes, sans interrompre l'alimentation de la charge.

De plus, une analyse de fiabilité dynamique du benchmark DCMG est réalisée dans le chapitre 5. Cette analyse diffère de la première du chapitre 3 car elle considère la réparation des composants. En effet, une défaillance critique d'un système se présente généralement comme une combinaison de plusieurs défaillances élémentaires. Ensuite, en supposant que la flexibilité et la redondance de l'architecture permettent de récupérer cette défaillance en reconfigurant la topologie, comme le montre le chapitre 4. Dans ce cas, le fonctionnement du système n'est pas compromis pendant cette période. Ensuite, dans ce scénario, une défaillance critique se produit lorsque des fautes consécutives sur tous les chemins redondants fournis par l'architecture se produisent avant que le processus de réparation ne soit terminé. Puisque le système est réparable, nous ne sommes plus intéressés par la fonction de fiabilité mais par la fréquence à laquelle une défaillance critique se produit, représentée par la disponibilité et le MTBF.

L'analyse est effectuée en considérant d'abord les composants à taux de défaillance constant, puis ceux à taux de défaillance non constant. En effet, si les composants sont remplacés avant d'arriver à leur fin de vie, leur taux de défaillance peut être considéré comme constant. Dans ce cas, des chaînes de Markov homogènes dans le temps sont utilisées pour évaluer la disponibilité et le MTBF. Les modèles de Markov du benchmark DCMG sont décrits dans le chapitre 5, et les résultats montrent les gains élevés en disponibilité obtenus par le système de barres transversales. En effet, en considérant la réparation des composants, les gains de la redondance s'amplifient. Par exemple, l'architecture crossbar présente un MTBF supérieur d'un ordre de grandeur aux architectures ladder et ring grâce à la redondance des dispositifs terminaux fournie par le système crossbar.

D'autre part, lorsque des politiques de maintenance moins strictes sont utilisées, les modèles de Markov ne sont pas plus adaptés. En effet, dans ce cas, il faut prendre en compte le vieillissement des composants qui fait que le taux de défaillance augmente après sa durée de vie utile. Par conséquent, la simulation de Monte Carlo est utilisée pour analyser le cas des composants avec des taux de défaillance non constants. Les résultats confirment la haute disponibilité de l'architecture basée sur les barres transversales même en considérant le vieillissement des composants.

Enfin, l'architecture à base de barres transversales a été appliquée à une étude de cas plus réaliste : un centre de données alimenté en courant continu. Plusieurs modifications ont été apportées aux architectures standard afin d'améliorer la disponibilité de ces systèmes. Par exemple, l'architecture à base de barres croisées est appliquée au bus 48V afin de fournir une redondance du bus et une reconfiguration de la topologie. Étant donné qu'un taux de défaillance non constant est considéré pour le convertisseur de puissance, la simulation Monte Carlo est utilisée pour évaluer la disponibilité de ces architectures. De plus, deux

stratégies de maintenance sont évaluées afin d'estimer les coûts de maintenance. La première consiste à remplacer le composant lorsqu'une défaillance survient sur celui-ci. La seconde consiste à remplacer le composant lorsqu'il atteint sa phase de fin de vie.

Les résultats montrent que l'architecture à base de barres croisées double presque le MTBF d'un centre de données lorsqu'elle est utilisée en mode isolé. En revanche, si les barres transversales sont interconnectées entre elles en mode linéaire ou matrice, le MTBF atteint quatre fois la valeur de l'architecture standard.

En outre, l'utilisation d'une stratégie de maintenance stricte n'affecte pas l'architecture à base de barres transversales en termes de disponibilité. En effet, chaque composant présente une redondance et peut être réparé/remplacé. Par conséquent, en adoptant cette architecture, on peut utiliser une stratégie de maintenance moins stricte qui réduit de moitié les coûts de maintenance et rend ces systèmes plus durables.

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Chapter 1

Introduction

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1.1 Background on Power Distribution Systems

A power distribution system is an interconnection of power electronic circuits, busses, transmission lines that bring the energy from the producers to the consumers. In this thesis, we use the term Energy Player (EP) to refer to any device able to produce, consume or store energy.

Figure 1.1 shows the four main classes of EPs. In particular, conventional energy sources refer to all sources commonly present in traditional power distribution systems such as the AC grid or the Fuel cell. Second, DC or AC loads refers to any load normally supplied by the utility grid. Third, Energy Storage Systems (ESS) refers to any EP that can store energy. Examples of ESS are batteries and super-capacitors. Finally, Renewable Energy Sources (RES) refers to any EP able to harvest energy from external sources and transform it into electricity, such as Photo-Voltaic (PV) panels and wind turbines.



Fig. 1.1 Example of Energy Players divided into categories: a) Conventional energy sources, b) loads c) Energy storage systems (EES) and d) Renewable Energy Sources (RES).

This section presents different paradigms of power distribution. Moreover, it discusses the motivation that brought researchers to investigate DC microgrid implementations.

1.1.1 Distributed Generation

Distributed generation (DG) is electrical generation and storage performed by various small, grid-connected or distribution system-connected devices referred to as distributed energy resources (DER). Figure 1.3 shows a diagram of the distributed generation scheme. It differs from the conventional centralized generation (CG), where the energy is produced in a centralized facility (such as a coal-fired power plant) and then transmitted over high voltage transmission lines, as shown in Figure 1.2. DG is not replacing traditional CG, but it gives a reliable, high efficiency and economical way to provide sufficient power to loads. In fact, by building DG close to the load side, power demand can be fulfilled locally, thus helping providing energy, especially during peak hours.

About two decades ago, the centralized generation was indubitable. The principal reason for this was that the economies gained by building larger power plants outweighed the additional costs of transporting the electricity to consumers. Therefore DG was almost nonexistent in the 1990s. However, thanks to the deregulation of the power industry and the encouragement of the low carbon energy policy aimed at reducing the emissions linked to climate change by governments, DG is receiving increasing attention.

Indeed, the inherent advantage of low transportation costs and a combination of renewable energy can minimize the dependency on fossil fuels and their price.



Fig. 1.2 Schematic diagram of centralized generation.

In addition, co-generation or combined heat and power plants generate electricity and heat in a single process. The waste heat from the generation process can be used beneficially in industrial processes or to provide heat to local communities, rather than being rejected by the environment. Such applications can double the overall system efficiency.



Fig. 1.3 Schematic diagram of distributed generation.

DG Limitations. DGs need power converters to interface to the utility grid. RES such as wind turbines, PV panels provide electricity in different shapes that need synchronization in order to adapt to the Alternate Current (AC) of the utility grid. Even though some energy devices such as wind turbines and hydro microturbines naturally provide an AC output, it has to be transformed in DC and then back to AC to synchronize to the phase and frequency of the utility grid. These conversion steps translate into less efficiency and reliability. Moreover, an increasing number of DG connected to the utility grid could affect its power quality because of the non-perfect synchronization of these sources and the variability in the energy generation of RES.

1.1.2 Microgrids

To overcome the above-mentioned limitations, DG started to be integrated with proximity to loads in order to directly supply local loads, without passing through the AC grid, thus forming a microgrid. In fact, a microgrid is defined as a group of interconnected loads, DER and Energy Storage Systems (ESS) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the AC grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or islanded mode[75][61].

Moreover, depending on the type of the common DCB, micro-grids can be classified into DC or AC micro-grids. In the past, the lack of efficient power electronic devices and control circuits brought the choice to the AC micro-grids[13]. AC power was easier to transfer for the ready-technology of transformers, increasing the voltage on the transmission line and thereby reducing transmission losses. Today, the advancements in Power Electronics and Digital control circuits permit increasing the voltage in DC in a very efficient and safe manner. Indeed, actual boost converters allow increasing the transmission voltage with high gain and high efficiency. Therefore, energy can be transmitted on through High Voltage DC (HVDC) transmission lines[37][6].

1.1.3 DC Microgrids

Figure 1.4 shows the fundamental building blocks that constitute a DC micro-grid. In particular, it consists of:

- EPs as shown in Figure 1.1;
- a common DC Bus that permits the energy sharing between all the EPs;
- at least one interface to the utility grid;
- power converters to adapt the voltage of the EPs to the common DC Bus;
- eventually one or more gateways that permit sharing energy with other adjacent DC microgrids.

There are several advantages to transmit energy in DC[43]. First of all, transmission losses are smaller in DC lines with respect to an equivalent AC line. Moreover, the core electronics of 80% of the electrical and electronic devices used in the home is powered in DC [77]. Electric Vehicles (EVs) that starts to be widely used worldwide and have a big role in the energy transition is powered in DC. This means that for 80% devices we use, there is at least an additional conversion step that decreases the overall efficiency of the distribution

system [13]. Finally, DC systems are compliant with renewable energy sources such as PV panels, wind turbines that are starting to be integrated massively in cities and rural places.



Fig. 1.4 Building blocks of a DCMG.

A disadvantage of the DC power lines is that fault conditions have to be managed very carefully to avoid accidents to people or equipment. In fact, the DC current has not zerocrossing point as its counterpart AC current. Fortunately, thanks to the System on Chip (SoC) technology advancements, real-time sensing and actuation permit the implementation of complex and distributed control algorithms that can solve the safety problem at low costs. For the reasons mentioned above, this thesis focuses on DC micro-grids (DCMG), but the proposed concepts can be applied to AC Microgrids.

On the other hand, the addition of communication and automation to a DCMG enable intelligent energy management strategies. This is what is commonly called a smart grid [26]. In smart grids, decisions are taken by the EPs themselves in a distributed way or by a single central entity. Several advantages can be observed in data-connected DCMGs. First, measurements on producer and consumer sides permit adaptation of the power flows on the power network in real-time. In the same way, the intermittent nature of RES is better managed. Finally, monitoring and communication permits to apply real-time strategies and optimization algorithms in order to achieve objectives such as energy price minimization, energy efficiency, Quality of Service (QoS) or reliability[27][84][54][59].

1.2 Treated Problems

Non-dispatchable sources are generators whose output power can not be controlled, but it depends on external conditions such as climatic conditions, sun irradiation, the quantity of

energy stored, etc. Examples of non-dispatchable sources are PV panels, wind turbines and hydropower plants. The variability of non-dispatchable sources and loads in DC microgrids is challenging in terms of control and stability. In fact, the more non-dispatchable sources and loads are connected to the same bus, the higher the complexity in its control. Usually, one or more suited energy storage with their associate two-way controllers are introduced to have an energy reserve that can be used to guarantee the stability of the microgrid. However, the strict real-time operation of these controllers needed to absorb the variability of all non-dispatchable generators and loads leads to high complexity and implementation costs, especially for large implementations.

Moreover, the reliability of a system is linked to the number of devices electrically connected. As the size of the microgrid increases, its reliability decreases. Therefore, increasing the availability often translates into using strict maintenance policies that replace devices even when they are still working. In fact, for physical reasons, every device is subject to ageing. Then, replacing them before they arrive at their end-of-life phase increases the system's reliability, despite increasing the maintenance costs.

On the other hand, from the point of view of sustainability, using the devices for their entire lifetime regardless of their reliability characteristics is definitely an added value. However, actual static architectures need strict maintenance policies to guarantee reliability and Quality of Service, especially for critical systems such as data centers, electric mobility, etc.

1.3 Thesis Contributions

This thesis proposes a novel DCMG architecture based on power crossbars that add bus redundancy together with dynamic topology reconfiguration functionality to overcome the issues mentioned above. The bus redundancy and the dynamic path creation provided by the power crossbar gives another degree of freedom in the power distribution system that can be used to isolate and instantaneously restore fault conditions. Moreover, the ability to dynamically create, divide and re-organize the power distribution network improves the stability and scalability of the DC microgrid. Finally, the redundancy of almost all components in the system provided by this architecture permits less strict maintenance policies without compromising the availability and Mean Time Between Failures (MTBF). Therefore, maintenance costs are reduced and makes critical systems such as data centers greener due to less frequent replacements.

The contributions of this thesis are listed below.

- A novel DCMG architecture based on power crossbars is proposed that enable the concept of Software-Defined Power Domains. Moreover, a power crossbar is conceived that best fit this concept.
- A protocol to manage dynamic operations such as the handover operation and the fault recovery operation are presented and simulated by using PSIM simulator.
- Reliability analysis is performed on a benchmark of DCMG architectures to compare the proposed architecture with the ones present in the literature. Markov Chains and Monte Carlo simulations are used to evaluate the reliability and availability when considering constant and non-constant failure rates, respectively. Moreover, the repair of components is considered in the models.
- The case study of a DC powered data center is evaluated in terms of availability. Some modifications to existing architecture are applied in order to improve reliability. Then, the crossbar-based architecture is applied that further improve the availability of the power distribution system. Moreover, several configurations of crossbar-based architecture are analyzed.

1.4 Thesis Organization

The remainder of this thesis is organized as follows:

- Chapter 2 gives an overview of microgrid architectures, control techniques, together with methods to assess the reliability and resilience of power distribution systems.
- **Chapter 3** presents the proposed DCMG architecture and some static analyses that compare this architecture to the others present in a selected DCMG benchmark.
- Chapter 4 gives some example of control techniques can be used in the proposed architecture. Moreover, dynamic operations such as the handover and fault recovery are simulated in some example scenarios.
- Chapter 5 is dedicated to the reliability and availability analysis of the DCMG benchmark presented in Chapter 3. In particular, Monte Carlo simulation and Markov chains are used to evaluating the availability when considering or not the ageing of components, respectively. Furthermore, the repair of components is considered in these models.

- **Chapter 6** applies all the exposed concepts to a more realistic case study: a DCpowered data center. In particular, some transformations are introduced to the basic architecture to gradually improve the system's availability. Finally, the crossbar-based architecture is applied and its availability is compared with classical architectures.
- **Chapter 7** provides a general discussion about the presented results and gives future research directions.

Chapter 2

DCMG State of the Art

Contents

2.1	Micro	grid Topologies
2.2	Cross	bar Architectures
2.3	Contr	ol Strategies
	2.3.1	Basic control strategies
	2.3.2	Multi-level control techniques
2.4	Reliat	oility Analysis
	2.4.1	Analytical methods
	2.4.2	Simulation-based methods
	2.4.3	Hybrid methods
2.5	Resili	ence Analysis
2.6	Summ	nary

This chapter presents the state of the art of DCMG and crossbar architectures. Moreover, the control techniques in DCMG are surveyed. Finally, an overview of reliability and resilience assessment methods for power distribution systems is provided.

2.1 Microgrid Topologies

The choice of the topology is very important in the design of DCMG systems [13] [49] [56] [50]. It influences many factors such as cost, resiliency, controllability, reliability, availability, resource utilization, and flexibility. DCMG architectures have been surveyed according to the number of available paths between loads and the AC grid in [49]. In this survey, it

is shown that system reliability heavily depends on path diversity: in radial and ring (see Figure 2.1.a) configurations, for example, there is a single AC feeder. The architecture topology then exhibits more or fewer paths to the AC grid interface. The limitation of these architectures is that if a fault occurs on the AC feeder, the whole micro-grid functionality will be compromised because of the impossibility of accessing this secure and stable energy resource, thereby decreasing reliability.

To overcome these limitations, interconnected architectures such as ladder-type [50] (see Figure 2.1.c) and zonal-type DCMG [74] (see Figure 2.1.b) can be used. These two architectures solve the reliability issue by adding AC feeders and additional redundant paths to the power network. However, this addition increases the architecture implementation costs and decreases the resource utilization because of the rather static [36] [50] nature of most current architectures. Other redundant paths are usually added to the system to connect a point A with a distant point B, i.e. a load with the AC feeder to enhance the architecture flexibility as in the mesh-type configuration [49][24]. This aspect adds complexity and costs to the whole system. Even though the concept of energy routing already exists in literature [10] [4], there is no, to the best of our knowledge, physical implementation of a device that enables to proactively connect groups of EPs.



Fig. 2.1 State of the art of DCMG architectures: a) Ring, b) Zonal, and c) Ladder architectures.

The proposed power crossbar-based architecture aims to tackle these issues by adding the possibility to dynamically and electrically reconfigure the power network by software. This

greatly enhances the flexibility of the system compared to the existing static architectures. Moreover, power crossbars increase the number of redundant paths between loads and the AC feeder, improving reliability without compromising resource utilization.

2.2 Crossbar Architectures

The architecture of an energy router is proposed in [55] which interfaces 2 AC Microgrids (ACMG) to the electrical grid, as shown in Figure 2.2 b). This energy router controls the power flow between the three ports using power converters. The limitation of this configuration is that it is static and not scalable. The greater the number of ports, the higher the complexity in its control. Moreover, this architecture has a single point of failure. Therefore, a fault on the DC Bus (DCB) determines the inability of the three ports to interconnect.



Fig. 2.2 State of the art of crossbar architectures: a) data-domain crossbar, b) energy router.

As found in telecommunication networks, data crossbars are on their side specifically designed to create independent point to point connections between a set of inputs and a set of outputs. In a crossbar architecture, each input is connected to a dedicated bus connected to any output bus by using one of the switches present at every X-Y cross-point. This allows to dynamically create a data path where information flow from the input to the output. This technique is well known in computer science as circuit switching [11]. The advantage of this architecture is that a bus failure does not compromise the functioning of the full crossbar but only of the connected units. Such crossbars are however oriented, therefore limiting the applicability should one draw inspiration from such communication crossbars towards a power switching architecture where input and output concepts are irrelevant (see Figure 2.2 a)). Indeed a connection between two "outputs" is possible at the cost of allocating an input bus, thereby limiting the architecture's flexibility.
Architecture	Cost	Flexibility	Reliability
Energy Router in [55]	Low	Low	Low
Crossbar (communication network)	High	Medium	Medium

Table 2.1 Comparison of crossbar architectures.

Table 2.1 qualitatively compares the two architectures in terms of cost, flexibility and reliability.

2.3 Control Strategies

Another essential aspect to consider in a DCMG is the control strategy. DCMG control strategies can be categorized into two sections [23][70]: Basic control strategies and multilevel control strategies. Basic control strategies can be implemented through centralized, decentralized and distributed control. Multilevel control is implemented through different levels of control in the hierarchy. Each level of control uses one of the basic control strategies.

2.3.1 Basic control strategies

Communication is the main element of control. Based on it, three control strategies can be distinguished: centralized control, decentralized control and distributed control.

Centralized control

In a centralized control strategy, each unit is controlled by a central controller. Figure 2.3 shows a schematic diagram of the centralized scheme. Data from distributed units are collected, processed and commands are sent back to them through a Digital Communication Link (DCL).



Fig. 2.3 Schematic diagram of a centralized control scheme.

Communication is the heart of the central control scheme. The advantages of this scheme include strong observability and controllability of the whole system. It also suffers from many disadvantages such as single-point failure of the system, reduced reliability, flexibility

and scalability. Therefore, this control scheme is suitable for small size DCMG systems where the information to be collected is limited and control can be performed with Low Bandwidth Communication structure [76].

The Master-Slave control strategy is a typical example of a centralized control strategy. In fact, in this control strategy, a converter is appointed as a Master, and the others work as Slaves. The Master controller operates in Constant Voltage (CV) mode and is responsible for the DC Bus voltage regulation. In contrast, the others converters work in Constant Current (CC) mode, following the pattern of the Master converter. Figure 2.4 shows a schematic diagram of the Master-Slave control technique. This control strategy relies on the High Bandwidth Communication (HBC) [78]. This control strategy's drawbacks include the possibility of single-point failure due to the system reliability mainly depends on the master converter, and requirement of supervisory control, poor scalability, responsible for shorter battery life.



Fig. 2.4 Schematic diagram of the Master-Slave control technique.

Decentralized Control

Figure 2.5 shows a schematic diagram of the decentralized scheme. There is no communication link in this control. Independent controllers control the distributed units through their local variables. Although this control scheme has some performance limitations because of insufficient information about other units of the systems, it is considered the most reliable control scheme due to not requirement of communication links between different units of the system [69].



Fig. 2.5 Schematic diagram of a decentralized control scheme.

A popular decentralized control strategy is the droop control strategy, where the converters are connected in parallel with the DCMG [23], as shown in Figure 2.6. This strategy is usually adopted to avoid circulating currents between the converters without the use of DCLs. Output power or output current is selected as the droop feedback in the droop control strategy.



Fig. 2.6 Schematic diagram of the Droop control technique.

Distributed Control

Figure 2.7 shows a schematic diagram of the distributed scheme. This scheme includes advantages of both centralized and decentralized schemes. The controller of each unit exchanges data with only its neighbour's units via available limited DCLs. So, objectives such as proportional load power-sharing, voltage restoration, current sharing, SoC balancing can easily be performed [83] [5]. Sometimes it is tough to implement a centralized control scheme due to the significant increase in DG units. In that case, the distributed control scheme is a good option. This strategy is immune to single point failure because the system

can keep full functionary even with some DCLs. The main drawbacks of distributed control schemes are bus voltage deviation, power tracking error and complexity of the analytical performance. Consensus-based control strategies and agent-based control strategies are typical examples of a distributed control scheme.



Fig. 2.7 Schematic diagram of a distributed control scheme.

2.3.2 Multi-level control techniques

Power systems require higher intelligence control systems to realize several basic objectives such as voltage control, current control and power control as well as advance objectives such as power-sharing between DGs, Power Quality control, Provision for ancillary services, participation in energy markets, minimization of operating cost etc. It is not easy to realize these objectives through a single level control such as centralized or distributed control. Even basic control such that droop control for load sharing can better realize by multi-layer control. In fact, in droop control, its known drawback of load-dependent voltage deviation and propagation of voltage error along resistive transmission lines leads to deterioration of current sharing. Therefore, a secondary controller must be employed to restore the voltage and a tertiary controller to ensure accurate current flow among different power system buses. Consequently, a multilevel control system is needed for modern power systems such as DCMG where simple functions can be executed through local controllers to the surety of a basic operation of the system and advance functions can be executed through central controller [80].

Figure 2.8 shows a diagram of a three-levels control scheme. Recent developments in communication technologies made multilevel control configuration a preferred choice for large scale DCMGs structures. Multilevel control introduces a certain degree of independence among control levels. Moreover, it is more reliable because even in the failure of upper-level controls, system operation continues due to lower levels of controllers.



Fig. 2.8 Schematic diagram of a three-levels control scheme.

2.4 Reliability Analysis

The term reliability has a broad meaning. Reliability is a summary term meaning stability, proper efficiency and dependability. Entirely, reliability distinguishes the capability of the power network to carry out its determined function, where past experience can perform advanced estimation for future implementations. A description that demonstrates the different dimensions of the reliability meaning is the following [25]:

"Reliability is the probability of a device or system performing its function adequately, for the period of time intended, under the operating conditions intended."

From a power distribution system's point of view, its function is to supply electrical energy to final customers without interruptions, and within accepted tolerance margins (i.e. acceptable values for voltage and frequency) [12].

Power distribution systems are responsible for approximately 90% of all service interruptions experienced by customers [12]. Therefore, it is essential to understand how the distribution system behaves and the weight that each element has to determine the system reliability; an accurate evaluation of power distribution reliability is essential to identify design weaknesses and areas within the system that require special attention. A distribution system is composed of many elements; a failure in one of these elements will affect the continuity of service provided to customers. The impact of element failure will depend on the element's statistical parameters, and system design [47]. The most important statistical parameters are the failure rate and the repair time. A failure rate is defined as the number of expected failures per element in a given time interval. In contrast, repair time is required to restore service, whether by repairing or replacing the failed element.

Another important metric in reliability analysis is the Mean Time To Failure (MTTF). It indicates the mean time needed for that system to have a failure. For instance, assuming a set of 1000 identical components that work at the same operating conditions, the MTTF indicates the average time these components will fail. In a system, the same reasoning can be applied, letting 1000 or more equal systems work in the same operating conditions and tracking the Time To Failure (TTF) of each system. However, this is not feasible in reality for obvious reasons. Therefore, analytical methods and simulation methods help designers to evaluate the reliability characteristics of a system having the reliability characteristics of its components.

Furthermore, when the repair of components is considered in the reliability model, another metric is introduced: Mean Time Between Failures (MTBF). It indicates the mean time between two consecutive failures as in [79]. In fact, a fault can be recovered in repairable systems either by replacing the faulty component or by re-configuring the power network. Then, in these systems, we are more interested in the frequency at which failures occur, given by the MTBF. Furthermore, another important metric in such systems is the percentage of time over long periods the system is running correctly, that is, the availability *A* of the system. Also, the Mean Time To Repair is introduced in such systems as the mean time needed to repair the system subjected to a critical fault. Finally, the Mean Time To Detection (MTTD) is defined as the mean time needed to detect a fault. The latter is neglected in this work because we assume the detection time is much shorter than the MTTR and MTBF. Figure 2.9 shows a schematic diagram explaining the relationships between these metrics.



Fig. 2.9 Schematic diagram of MTTF, MTTR, MTTD and MTBF metrics.

In mathematical terms, we have:

$$MTBF = MTTF + MTTD + MTTR$$
(2.1)

That for the reasons explained above becomes:

$$MTBF = MTTF + MTTR \tag{2.2}$$

Then, availability A and unavailability U of a system can be expressed to as:

$$A = \frac{MTTF}{MTTF + MTTR}$$
(2.3)

$$U = 1 - A \tag{2.4}$$

The analysis of a power distribution system reliability is performed either with analytical or simulation-based approaches. These two approaches are not mutually exclusive. They both have different purposes and are carried out at different stages but are equally relevant to the reliability evaluation of a power distribution system.

In this thesis, static reliability analysis refers to evaluating the reliability when the repair of components is not considered. In fact, from this analysis, the reliability function and the MTTF are retrieved by combining each element's reliability functions. Analytical methods can be used for this analysis.

On the other hand, dynamic reliability analysis refers to studying the reliability of a system when dynamic restoration operation and the repair of components are considered. In this case, the availability and MTBF of the system are obtained. Moreover, some typical reliability indices such as System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI) and Customer Average Interruption Duration Index (CAIDI) can be retrieved. The following relationships define the latter:

$$SAIFI = \sum_{i=1}^{n} \frac{N_i}{N_T}$$
(2.5)

$$SAIDI = \sum_{i=1}^{n} \frac{N_i H_i}{N_T}$$
(2.6)

$$CAIDI = \frac{\sum_{i=1}^{n} \frac{N_i H_i}{N_T}}{\sum_{i=1}^{n} \frac{N_i}{N_T}} = \frac{SAIDI}{SAIFI}$$
(2.7)

where k is the number of interruptions, N_i is the number of customers interrupted by a fault, N_T is the total number of customers in the system, and H_i is the duration of interruption to customers interrupted by a fault.

The latter can be calculated statistically by using actual data from energy distributor companies or calculated by simulation-based methods such as Monte Carlo simulation [7].

2.4.1 Analytical methods

In analytical methods, all system elements are represented through mathematical models. These methods use analytical equations to estimate system reliability indices; due to the complexity of real distribution systems, analytical methods generally rely on assumptions and simplification techniques. The evaluation of the analytical equations is relatively straightforward, and results can be found quickly. However, developing the equations that model system behaviour can be complex, especially when considering reconfiguration processes and distributed generation.

For instance, Reliability Block Diagram (RBD), Markov Chains (MC) belong to this category. Reliability Block Diagram (RBD) is a method of modelling how components and sub-system failures combine to cause a system failure. Moreover, it can be used to determine the critical components from a reliability viewpoint. However, one major drawback of RBD is its inability to take repair and maintenance into account. On the other hand, Markov chains can be used to evaluate the reliability of a system when considering the repair of components. Moreover, the Markov model can be applied to any random system that may vary continuously or discretely with respect to time and space. However, Markov models predominantly suffer from state-space explosion problems, and it requires exponential probability distribution functions (pdf), which means constant failure rates.

2.4.2 Simulation-based methods

As the name implies, simulation-based methods rely on system simulation to analyze the system's reliability under evaluation. The Monte Carlo method has been extensively used in power system reliability evaluation due to the random behaviour presented by system failure. This approach can be used in either a sequential or non-sequential manner. In applying the Monte Carlo method, random variables are generated to represent the state of system elements and times related to fault duration and service restoration. For instance, in [71] [72] the availability of a Tier IV power distribution system for data center is analyzed by Monte Carlo simulation. Simulation-based methods present the main disadvantage: they require large computational efforts and long simulation times to obtain accurate results.

2.4.3 Hybrid methods

On the other hand, hybrid approaches can be used that combine analytical and simulationbased methods. Since we are interested in finding the probability of failure of a system, the

	Non-constant		Computational		
Method	failure rate	Repair	burden	Hybrid	Modular
Algebraic	No	No	Low	No	No
Markov chain	No	Yes	Low	No	No
Monte Carlo	Yes	Yes	High	No	No
Method in [44]	Yes	Yes	Medium	Yes	Yes

Table 2.2 Methods for Reliability Analysis.

Dynamic Fault Tree is used as an intermediate step [86]. Then, several approaches can be found in the literature to solve DFT.

For instance, in [44] a hybrid approach that uses all the methods mentioned above contemporaneously is presented. It consists of modularising the system DFT into several independent sub-trees that can be divided into independent sub-sub-trees. Then, these sub-trees are recursively solved to retrieve the probability of the top event, which corresponds to the probability of having a system failure.

The resolution of the sub-trees is performed by using one of the methods explained before. For instance, if the sub-tree is static, algebraic formulas can be used. On the other hand, if the sub-tree is dynamic, it can be solved either by Markov chains or Monte Carlo simulation depending on the nature of the failure rate of the basic components. In particular, if the sub-tree contains components having constant-failure rates, it is solved by Markov chains. Instead, if the sub-tree contains some component with non-constant failure rates, it is solved by Monte Carlo simulation.

Table 2.2 shows a comparison of the state of the art methods used for reliability and availability assessment.

Others methods used to solve DFT are Petri net-based approaches [15][60], Bayesian Network-based approaches [9][57], sequential binary decision diagrams (SBDD) [81], [32], Boolean logic Driven Markov Process [46] [67], Dynamic Reliability Block Diagrams [21] [22] and stochastic methods [85].

2.5 Resilience Analysis

Several definitions of system resilience are present in the literature depending on the discipline and application. For instance, in ecological systems resilience is "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables" [38].

In engineering application, the first publications about reliability Engineering began in the early 21st century [68], and is presented as a new approach to complex socio-technical

systems safety management. [68] says that resilience is a proactive view of system safety as "something a system or organization does, rather than something or an organization has" [68]. In this sense, a resilient system must be capable of anticipating, perceive and respond to changes or threats caused by internal and external factors.

As the focus of this study is DCMG Resilience, it is adopted the definition of the US National Academy of Sciences, Engineering, and Medicine [3]:

"Resilience is the ability to prepare and plan for, absorb, recover from or more successfully adapt to actual or potential adverse events".

Based on such definition, resilience can be divided into short and long-term. The former accounts for the system resistance to stressing events, i.e. vulnerability, lack of redundancy or resources to accommodate damages, and recovery capability to restore performance after damages. The latter is about future improvements or adaptations to handle future hazards considering lessons from past events.

Many studies in the context of resilience have proposed one or more metrics for resilience using different methods that can be generally categorized into qualitative and quantitative approaches [39] [30].

Qualitative approaches for evaluating resilience include conceptual frameworks and semi-quantitative indices [39]. Conceptual frameworks are usually based on fundamental elements of the resilience concept such as absorption capacity, adaptive capacity, and recovery capacity.

Semi-quantitative indices are based on assessing specific resilience attributes (e.g., adaptability, resourcefulness, robustness) usually within a range of 0-100 (percentage scale) and their integration achieves a unified index [39].

In order to have a clear comparison between the pre-event and post-event resilience levels of a power system, a quantitative assessment is preferred, and more attention is paid to it in the related literature. Quantitative methods for resilience assessment can be mainly classified into statistical methods [53], risk-based methods [35], system fragility-based methods [62], graph theory-based methods [14], simulation-based methods, and fuzzy logic models [39] and they involve both operational and infrastructure mathematical formulations of resilience metrics.

Generally, the model presented in [52] is used for a quantitative evaluation of resilience. Here, resilience pertaining to a specific extreme event is essentially portrayed by changes in system performance after such an event unfolds. System performance can be converted into a quantifiable non-negative value by considering a particular aspect of operations (e.g., generation adequacy, operation security, and power quality). In principle, a higher level of system performance is more desirable.



Fig. 2.10 Evolution curve of System performance under fault condition.

Figure 2.10 depicts a typical evolution curve of system performance in the wake of an extreme event, where the level of system performance Q(t) is denoted as a function of time t. After the occurrence of an extreme event at time t_0 , the system performance remains at the normal level Q_0 due to the resistance to initial disruptions. Then it witnesses a rapid decline from time t_1 when disruptions become severer. At the time t_2 , the system performance bottoms out at the lowest level Q_{min} and starts to bounce back starting from time t_3 , which is due to ongoing restoration efforts. The system performance is below the normal level until time t_4 when the restoration is completed.

The system resilience concerning this extreme event can then be quantified as the reciprocal of the system's loss of performance as follows:

$$resilience = \frac{1}{loss}$$
(2.8)

The quantification of the performance loss can be achieved by various means. In this work, we use the following definition of loss. In particular, the performance loss is calculated by integrating the relative deviation throughout performance degradation, i.e. from time t_1 when the extreme event occurs to time t_4 when the normal level performance is restored. That is

$$loss = \int_{t_1}^{t_4} \left[\frac{Q_0 - Q(t)}{Q(t)}\right] dt$$
(2.9)

Therefore, the degree of resilience can be quantified, which theoretically ranges from 0 to infinity. Specifically, infinity, in this case, refers to the perfect resilience (i.e., no performance degradation will be caused by the extreme event) and 0 means no resilience (i.e. immediate collapse after the extreme event occurs).

2.6 Summary

This chapter presented an overview of the main DCMG architectures found in the literature. In particular, the more the interfaces to the utility grid, the higher the reliability. Since the main component of the proposed DCMG architecture is the power crossbar, a review of crossbar architectures and energy routers is provided both in data and energy domains.

On the other hand, control techniques are reviewed. Centralized, decentralized and distributed control methods are used for small implementations. However, as the size of the DCMG increases, multilevel control is more suited.

Moreover, this thesis aims to explore novel DCMG architectures that are more flexible, reliable and resilient with respect to the ones present in literature. Therefore, an overview of methods for the reliability and resilience assessment of power electronic systems is provided. In particular, RBD and Markov chains are used in this thesis for the reliability and availability assessment of DCMG interconnections when considering components with constant failure rates. On the other hand, Monte Carlo methods and hybrid methods are used in the case of non-exponential distributions. The latter permits to evaluate and also to compare several maintenance strategies.

Finally, the resilience is evaluated by dynamic simulation of failure conditions in DCMG. In fact, depending on the nature of the failure and how the DCMG responds to that failure, a performance loss is obtained, which can be easily transformed in resilience by inverting the equation (2.8).

Chapter 3

Generic crossbar architecture for Software-Defined Power Domains

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This chapter describes the novel crossbar-based DCMG architecture. Moreover, it proposes a power crossbar architecture suited for the energy domain, taking inspiration from previous crossbars and routers topologies. Then, a benchmark of DCMG architectures is introduced, which will constitute a reference to evaluate gains of the proposed architecture in the analysis performed during this thesis. In particular, this chapter presents some static analysis as follows:

1. Flexibility analysis based on the number of redundant paths connecting pairs of sources and loads.

- 2. **Implementation cost** is evaluated and compared to previous DCMG architectures present in the benchmark.
- 3. **Static reliability analysis** of the presented DCMG architectures is performed by using algebraic formulas.
- 4. Efficiency analysis based on the number of components (i.e. switches) between sources and loads.

3.1 Crossbar-based DCMG Architecture

Actual DCMG architectures are static, which means that the topology can not be changed after installation. In such architectures, the reliability is enhanced by adding further AC feeders and additional redundant paths to the power network. However, this addition increases the architecture implementation costs and decreases resource utilization.

To tackle these issues, we present, here, the crossbar-based architecture able to reconfigure its topology by software by using the power crossbar network.



Fig. 3.1 Crossbar-based DC Microgrid architecture.

An example of implementation of the proposed crossbar-based DCMG architecture is shown in Figure 3.1. It consists of a set of DER (i.e. solar panel, wind turbine), loads (i.e. servers, Electric Vehicles), and ESS's (i.e. batteries or supercapacitors) interconnected together by using power crossbars [20]. In order to let this heterogeneous set of energy sources and loads interact together, power converters are used. As will be explained in the next section, the power crossbar guarantees security for each EP. Then, it allows the dynamic reconfiguration of the DCMG by software. Indeed, it permits to dynamically create, decompose or even connect independent clusters of EPs, here referred to as Power Domains (PDs). It allows resource sharing between sources and loads connected to different crossbars. Finally, it acts as a bridge to connect any two adjacent power crossbars without involving the local EPs. These EPs can still share their local resources by using an alternative bus provided by the crossbar to which they are physically connected, as will be explained later.

The control of the whole system and its associated crossbar is assigned to one or more SoCs integrated on each crossbar. In particular, the Master-Slave control [61] [50] is used for the local power management. PI or PID controllers, which drive power converters in CC or CV mode, are implemented directly in the software by exploiting the peripherals of the SoCs. Furthermore, diagnostic and fault recovery functionality are handled by using local sensors and control. Finally, the addition of a communication interface allows different power crossbars to communicate, enabling the application of global and smart energy management strategies [36].

Generic Crossbar Proposal

The power crossbar is the device that serves to defines PDs in software. It consists of a set of power switches (i.e. relays, MOSFET switches) controlled by software to physically define electrical paths on the Power Network for energy transfer between two or more EPs. Power crossbars have an arbitrary number of external ports and independent busses. Depending on this number, some connection combinations between external ports are achieved. The bigger the number of ports and independent busses, the greater the flexibility, at the expense of more complexity in the crossbar topology and control.



Fig. 3.2 N-ports, M-busses crossbar: a) Top and b) Side view.

Figure 3.2 shows the architecture of an N-ports, M-busses power crossbar. Figure 3.2 a) represents a top view, outlining the number of ports, while Figure 3.2 b) shows a side view, where the busses with their power switches are highlighted. The number of ports defines the maximum number of external connections of the crossbar. The number of busses defines both the maximum number of independent paths that can be created on a crossbar and the maximum power capacity the crossbar can support.

The maximum transmission power can be dynamically adjusted by connecting more busses in parallel. For instance, Figure 3.3 shows the electrical schematic of a 6-ports 2-busses crossbar, which is the one selected for the experiments along with this thesis.

Another critical aspect to consider in the architecture is the implementation cost, notably in relation to the number of power switches. Here, we use the number of switches normalized to the number of EPs, denoted by $N_{sw_{EP}}$, as a metric to estimate the implementation cost and compare different DCMG architectures.



Fig. 3.3 Electrical schematic of a 6-ports, 2-busses crossbar.

For instance, in Ring and Ladder ones (see Figures 2.1 a) and 2.1 c) respectively), N_{sw_EP} is always equal to 3. In the proposed DCMG architecture, assuming identical crossbar instances, N_{sw_EP} is calculated with the following formula:

$$N_{sw_{EP}} = M * (1 + N_{CR_{INT}} / N_{EP})$$
(3.1)

where M is the number of independent busses of the crossbar, $N_{CR_{INT}}$ is the total number of crossbar ports used for interconnections, N_{EP} is the total number of EPs in the DCMG. For instance, in Figure 3.1 $N_{CR_{INT}}$ = 6 and N_{EP} = 12. From Equation (3.1), using 2-busses crossbars (M = 2), one obtains an implementation cost of 3 switches per EP, which is equal to that of Ring and Ladder architectures. However, for the crossbar-based architecture, the cost can be reduced by reducing the ratio $N_{CR_{INT}}/N_{EP}$, which is obtained by adding more EPs per crossbar.

Physical Realization. This thesis has been prepared as part of the ICARE project funded by Occitanie region. In this project, a demonstrator of crossbar-based DCMG architecture has been realized, as shown in Figure 3.4.



Fig. 3.4 Schematic of the demonstrator of a crossbar-based DCMG architecture realized at the LIRMM laboratories.

In particular, it represents a node of a multi-node architecture where energy is shared through power crossbar interconnections. The node is composed of a battery, a solar panel, a load, and an AC grid interface that are interconnected together by using power converters. Then, the power crossbar allows these local EPs to share their energy with other remote nodes connected to the the power crossbar network.

The control of the whole system is assigned to several System on Chips (SoCs) installed onboard. In particular STM32 microcontrollers are used to implement functionalities such as power converter control, communication, security checks. Moreover, the Real-Time Operating System (RTOS) FreeRTOS has been used on the node controller.

Figure 3.5 shows a picture of the first two prototypes of this demonstrator, whose final system is currently installed on the roof of the Polytech Montpellier. Therefore, the analysis and simulations that will be presented in the following part of the thesis are calibrated by using the hardware and tests performed on these boards.



Fig. 3.5 Pictures of the a) first and b) second prototypes of crossbar-based DCMG architecture realized at LIRMM laboratory.

3.2 DCMG benchmark

A benchmark of DCMG architectures is identified to have a mean of comparison for the proposed architecture. It is composed of ring, ladder and the proposed crossbar-based DCMG architecture. Figure 2.1 a), c) and Figure 3.1 show an example of implementation for these architectures. In particular, they contain four RES (two PV and two wind turbines), three ESS (two batteries and one supercapacitor), three loads (two DC and one AC) and two conventional energy sources (AC grid and Fuel Cell).

Ring architecture

Figure 2.1 a) shows a schematic of the ring architecture. Here, EPs are connected to busses creating a geometrical loop or ring shape. Moreover, it presents a single AC grid interface that two redundant paths can reach. Fast DC switches are placed at both ends of each DC Bus to allow isolation in case of fault. For instance, when a fault occurs on a bus, the DCMG controller detects and isolates the fault by using these switches. Once the fault is isolated, the DCMG controller provides another path to any EP.

The ring network is known to be the most structured one since it forms a closed loop by joining nodes to each other. Due to this, several zones of protection within the ring network can be implemented. This network structure has a better performance compared to radial ones with higher reliability. In case one feeder is under fault or maintenance, the ring Bus is still energized by other feeders connected to it whilst saving in cabling/copper compared to parallel feeders [40].

However, the major disadvantage of this structure is that the network is highly dependent on the cables that connect other components to the network. In terms of complexity, a loop feeder system is only slightly more complicated than a radial system. However, it has a major drawback of catering for the capacity and cost of the loop system.

Overall, the ring architecture is more reliable compared with a radial architecture. However, if two consecutive faults occur on the ring, the connectivity of the EPs is extremely reduced.

Ladder architecture

Figure 2.1 c) shows a schematic of the ladder architecture. Ladder configuration further increases redundancy by offering multiple alternative connections to all network nodes. It provides great flexibility but also makes the operation and protection of the DCMG challenging.

Ladder architecture is efficient for short-distance transmissions and can incorporate existing network structures such as radial configurations. Other advantages are a relatively balanced voltage profile and high reliability through redundancy. However, the more complicated configuration with respect to radial and ring configuration makes the control and protection of the distributed power network challenging [73].

Figure 3.6 shows a schematic diagram of the DCMG benchmark considered for the following analysis. In particular, the ring architecture is represented in Figure 3.6 a). Depending on the position of the source and the load, the reliability calculation changes. However, in this thesis, all combinations of source-load are considered, and the reliability function is derived for each. The ladder architecture presents two main use cases as shown in Figure 3.6 d) and e), respectively. The first refers to a connection source-load behaving to the same step of the ladder. The second refers to a source-load pair behaving to different steps of the ladder. Finally, two use cases are identified for the crossbar-based architecture as shown in Figure 3.6 b) and c). The first refers to a connection source-load behaving to the same crossbar. Instead, the second refers to a connection source-load behaving to different crossbars.

The following sections perform static comparative studies on this DCMG benchmark. The scope of this analysis is to quantitatively evaluate the static reliability, flexibility and



Fig. 3.6 Analyzed connections source-loads of the DCMG benchmark: a) Ring, b) Ladder case 1, c) Ladder case 2, d) Crossbar case 1, e) Crossbar case 2.

efficiency of these architectures when the reparation of components and dynamic operations are not considered.

3.3 Flexibility Analysis

Flexibility is defined as the ability to change easily according to the situation. More specifically, in DCMG domain, it refers to the ability of the architecture to serve loads by one or more sources using the available paths created statically or dynamically. The former refers to paths created offline, i.e. when the power network is not in operation, and permits to physically define paths on the power network by using power switches (relays or solid-state switches). The latter refers to paths created online, i.e. acting simultaneously on switches and DC/DC converters to reconfigure the power network without interrupting the functioning of the other loads.

In order to quantify the flexibility of a DCMG architecture, we introduce a new metric N_{redu} as the number of redundant paths which the architecture permits to have between a pair source-load. Ring DCMG, for instance, always presents two paths to connect a source to a load which correspond to the two semi-arcs of the ring as we can see in Figure 3.6 a). If two consecutive faults occur on the two semi-arcs, the connection is lost. Therefore, for ring architecture, $N_{redu} = 2$. On the other hand, ladder architecture presents higher flexibility because it uses its common buses L1 and L2 to connect all the branches. This allows a load

to be reached by each branch of the ladder independently. In the hypothesis of having a source per branch, there are two connection types: 1) source and load are on the same branch (see Figure 3.6 d)) and 2) source and load are on different branches (see Figure 3.6 e)).

In the first case, the connection is made directly on the branch or by using one of the b-1 external branches, then $N_{redu} = 1 + (b-1) = b$ where b is the number of branches of the ladder. In the second case, the load can be reached directly by two paths or indirectly by using the external paths in both directions, then $N_{redu} = 2 + 2 * (b-2)$. Despite the ladder architecture having two busses, the crossbar-based architecture presents M available busses on each crossbar. The calculation of the redundant paths is more complicated because it depends on the number of busses per crossbar (M), the number of ports per crossbar used for interconnections (N_{CR_INT}) and how crossbars are interconnected.

To quantify and compare the flexibility the example in Figure 3.1 is considered. As for the ladder, the crossbar-based architecture has two connection types: 1) source and load are connected to the same crossbar (see Figure 3.1 b)) and 2) source and load are connected to different crossbars (see Figure 3.1 c)). In the first case, the number of redundant paths is calculated as:

$$N_{redu} = M + 2(N - 2) \tag{3.2}$$

where the first term accounts for the direct connections made exploiting the local crossbar and the second term includes all the indirect connections that involve the others N - 2 ports of the local crossbar. In the second case, the number of redundant paths can be calculated using the following relationship:

$$N_{redu} = M^2 + M^3 \tag{3.3}$$

where the first terms account for the paths involving two crossbars and the second one involves the use of the three crossbars (see Figure 3.1).

Table 3.1 collects the values of flexibility obtained with the above relationships for the examples in Figure 2.1 a), c) and Figure 3.1. The crossbars used in the analysis are 2-buses 6-ports crossbars. We can see that the crossbar-based DCMG architecture presents higher flexibility compared to the other architectures. Moreover, we expect an exponential increase of this flexibility for larger implementations due to the increase in crossbar number, which allows creating further paths through the crossbar network.

Architecture	N _{redu}
Ring	2
Ladder1	6
Ladder2	10
Crossbar1	10
Crossbar2	12

Table 3.1 Flexibility Analysis of the DCMG benchmark.

3.4 Static Reliability Analysis

Reliability is the probability that a system will carry out its function satisfactorily for the stated period of time when used according to the specified conditions. In this work, the correct operation of a DCMG architecture refers to its ability to serve all loads. For this reason, the reliability of power switches and their interconnection is examined. First, the reliability of a connection source-load is analyzed by using the general reliability theory. Then, reliability analysis of a DCMG consists in finding the probability that a load keeps at least a connection to any dispatchable source present in the microgrid. We call this analysis static reliability analysis because it does not consider the repair of components and the dynamic operations. In fact, the latter will be discussed in Chapter 4 and 5.

The static reliability analysis permits obtaining the reliability function and the Mean Time To Failure (MTTF) of a DCMG architecture from the point of view of a load. Then, this process can be repeated for each load present in the DC microgrid to obtain the reliability characteristics of the whole DC microgrid.

3.4.1 Reliability Analysis of DCMG architectures

In this section, the static reliability analysis of the DCMG architectures benchmark presented above is carried out. The reliability function of each architecture is calculated, and a comparison between the presented architectures is made.

The system's reliability is calculated as a combination of the reliability function of each component (see Appendix A for further details on electronic components in DCMG and their reliability characteristics). In this thesis, DCMG reliability is evaluated as the ability to serve every load in a given interval of time. Supposing the capacity of the source is always enough to supply the loads in the microgrid, reliability becomes the probability that each load is connected to at least a dispatchable source in that microgrid. Even though a fault occurs on the primary connection of that pair source-load, this analysis will also consider the possibility of the architecture using another available path to keep that connection.

Important Hypothesis - Moreover, the hypothesis of independent components is used in this analysis. This means that a failure on a component does not cause any issue to adjacent parts. This hypothesis is especially true when protection devices are fast enough to stop the propagation of failures over the power network.

Then, the reliability of the ring, ladder and crossbar-based architectures are evaluated by calculating the reliability function of the interconnection system defined by each architecture.



Fig. 3.7 Schematic of the reliability analysis of Load x.

Figure 3.7 shows a block diagram of the reliability analysis performed in this section. For instance, the reliability function of a connection source-load between load Lx and source S1 can be expressed as follows:

$$R_{Lx_{1}}(T) = R_{T_{Lx}}(T) * R_{archi_eq}(T) * R_{T_{S1}}$$
(3.4)

where $R_{Lx_1}(T)$ is the reliability function of the connection S1 -> Lx, $R_{T_Lx}(T)$ is the reliability function of the terminal switch connected to Lx, $R_{archi_eq}(T)$ is the equivalent reliability function of the considered architecture whose calculation will be explained later and R_{T_S1} is the reliability function of the terminal switch connected to the source S1.

Since the microgrid presents four dispatchable sources S1, S2, S3 and S4 (see Figure 3.7), the reliability function of the load Lx is expressed as follows:

$$R_{Lx}(T) = R_{T_Lx}(T) * R_{archi_eq}(T) * [1 - (1 - R_{T_S1})(1 - R_{T_S2})(1 - R_{T_S3})(1 - R_{T_S4})]$$
(3.5)

where $R_{Lx_1}(T)$ is the reliability function of the load Lx and R_{T_2} , R_{T_2} , R_{T_3} and R_{T_3} are the reliability functions of the terminal switches connected to S2, S3 and S4, respectively.

As we can see, the DCMG architecture is modelled as a black box in this analysis. Then, once this function is retrieved for the ring, ladder and crossbar architecture, it is easy to calculate the overall reliability of each load by using equations 3.4 and 3.5.

Finally, the reliability of the whole architecture is defined as the probability that, after a certain time interval T, all loads are supplied. In mathematical terms, this leads to the following relationship:

$$R_{SYS}(T) = \prod_{k=1}^{N} R_{T_L_k}(T) * R_{archi_eq}(T) * [1 - (1 - R_{T_S1})(1 - R_{T_S2})(1 - R_{T_S3})(1 - R_{T_S4})]$$
(3.6)

where $R_{Lk}(T)$ is the reliability function of the load L_k and N is the number of loads present in the microgrid.

Then, once the reliability function of the system is obtained, the MTTF can be retrieved by its definition, as follows:

$$MTTF = \int_0^\infty R_{SYS}(t)dt \tag{3.7}$$

The reliability of all the connections source-load is calculated for each architecture. Therefore, each architecture's worst-case and best-case reliability functions are retrieved that define the reliability characteristics.

In the following part of this section, the reliability of the ring, ladder and crossbar architecture will be calculated for a randomly chosen disposition of sources and loads onto the architecture. The three considered architectures consist of five dispatchable sources (AC grid, fuel cell, two batteries and a supercapacitor), three loads (one AC and two DC) and four non-dispatchable sources (two PV panels and two wind turbines). Moreover, these analyses will consider switches, power converters and busses.

Experiments summary

The reliability of each DCMG architecture is, here, evaluated. In particular, three use cases are identified, which are represented in Figure 3.8. The first use case considers just switches. Then, the analysis is extended in the second use case by including busses and power converters. Finally, since the power converters are the weakest components, a third use case is studied, which introduces redundancy on the power converters.

The failure rate of switch devices, power converter and busses is retrieved from the IEEE Gold Book [2] and reported in Table 3.2.



Fig. 3.8 Use cases for the static reliability analysis: a) only switches, b) complete and c) complete with redundancy on terminal devices.

Component	MTTF [hours]	Failure rate [failures/yr]
Switch	$1 \ge 10^{6}$	0.0088
Bus Bars/ Switch Board	4.38 x 10 ⁶	0.002
DC-DC Converter	50000	0.175

Table 3.2 Components reliability data in [2].

3.4.2 Use Case 1: Only Switches

In this experiment, the reliability function of the DCMG benchmark presented above is calculated by considering just the switches/circuit breakers present in the architecture. These devices are used to protect devices and decouple busses.

3.4.2.1 Ring Architecture

As shown in Figure 2.1 a), the ring architecture uses three switches per EP: one to decouple the EP from the ring bus and two others to connect each side of the ring (i.e. left and right side). Then, a connection source-load has two possible redundant paths corresponding to the two semi-arcs of the ring (see Figure 3.6 a)). For instance, the connection between battery B2 and load DL2 in Figure 2.1 a) is obtained by passing from the PV1–>B1–>SC (PATH1) path or by flowing in the other path DL1–>W2–>FC–>W1–>ACG–>AL–>PV2 (PATH2). We define the length of a path as the number of EPs crossed, which multiplied by two gives the number of relays crossed. Then, in the example, PATH1 has length 4 while PATH2 has length 8. Assuming relays with similar characteristics and a constant fault rate λ , we obtain the following relationship for the reliability of the connection B2–>DL2:

$$R_{archi,ring}(T) = [1 - (1 - R^{2*n_1})(1 - R^{2*n_2})]$$
(3.8)

where n_1 is the length of the shortest path, n_2 is the length of the longest path, and n_R is the ring length. Given a specific configuration of sources and loads along the ring, this

relationship permits calculating the reliability of each connection source-load. Then, by using equations (3.5) and (3.6), one can estimate the reliability of the whole architecture.

3.4.2.2 Ladder Architecture

Figure 2.1 c) shows the ladder architecture, which consists of EPs connected in pairs to 2 busses L1 and L2. Those busses allow connecting different branches. As for the ring architecture, each EP needs three relays: a relay for decoupling and two others for the bus segmentation. As seen in the last section, ladder architecture presents a higher number of redundant paths than ring architecture. Depending on the position of the source and the load, reliability calculation changes. In particular, for ladder architecture, there are two connection types: 1) source and load belong at the same branch (see Figure 3.6 d)) and 2) source and load belong to different branches (see Figure 3.6 e)). In the first case, the reliability of the connection is calculated by using the following relationship:

$$R_{archi,ladder1}(T) = 1 - [1 - R^2] * [1 - R^2 * \{1 - [1 - R^4]^{b-1}\}]$$
(3.9)

where *b* is the number of branches of the ladder. On the other hand, in the second case, the reliability of one connection source-load can be calculated by the following relationship:

$$R_{archi,ladder2}(T) = 1 - [1 - R^4]^2 * [1 - R^6]^{b-2}$$
(3.10)

Note that as the number of branches b increases, the second term tends to 1. Then the reliability of the connection tends to R^2 , which corresponds to the reliability of the two terminal switches. This was expected because a fault on a terminal relay leads directly to a connection fault. In fact, terminal relays are the most critical components of the architecture in terms of reliability.

3.4.2.3 Crossbar-based Architecture

Finally, the reliability of the proposed crossbar-based DCMG is evaluated. Due to the redundancy of terminal switches, the crossbar-based DCMG architecture is intrinsically more reliable. Two connection types have been considered: a) source and load on the same crossbar (see Figure 3.6 b)) and b) source and load on different crossbars (see Figure 3.6 c)).

In the first case, considering crossbars with M buses, the reliability can be determined by the following relationship:

$$R_{archi,cross1}(T) = 1 - [1 - R^2]^M = R_t$$
(3.11)

In the second case, the reliability can be expressed as:

$$R_{archi,cross2}(T) = R_t * \left[1 - (1 - R_t)^p * (1 - R_t^2)^q \dots (1 - R_t^n)^i\right]$$
(3.12)

where the exponents 1, 2,...,n are the number of crossbars crossed and p, q,...,i are the number of redundant paths with the corresponding number of crossbar crossed.

Figure 3.9 a) shows a comparison of the three considered architectures in terms of reliability. We can see that crossbar-based architecture has its reliability function shifted to the right with respect to the other architectures, translating into a greater MTTF.

3.4.3 Use Case 2: Complete

In this experiment, the reliability of the DCMG benchmark is analyzed, also considering the other devices present in the interconnection system, such as busses and DC/DC converters. The reliability data of these devices is found in Table 3.2.

3.4.3.1 Ring Architecture

The ring architecture is evaluated, then, by using the same method as explained before, by including just the busses and power converters as shown in Figure 3.8 b). In particular, power converters are placed on the terminal segments attached to each EP. On the other hand, a bus is a segment between two or more switches, depicted in blue in Figure 2.1. For instance, ring architecture contains 12 busses and 12 power converters as shown in Figure 2.1 a) and c).

So, the reliability of the terminal segments connected to loads and sources ($R_{T_L}(T)$) and $R_{T_s}(T)$, respectively) of each EP can be calculated as follows:

$$R_{T_{L}}(T) = R_{T_{S}}(T) = R_{CB} * R_{DCDC}$$
(3.13)

where R_{CB} is the reliability function of switches and R_{DCDC} is the reliability function of DC/DC or AC/DC converters. In this work, the reliability of the latter is considered equal.

Therefore, the reliability of the ring architecture $R_{archi,ring}(T)$ becomes:

$$R_{archi,ring}(T) = R_{Bus_L} * R_{Bus_S} * [1 - (1 - R_{CB}^{2n_1} * R_{Bus}^{n_1})(1 - R_{CB}^{2n_2} * R_{Bus}^{n_2})]$$
(3.14)

where R_{Bus_L} and R_{Bus_S} are the reliability functions of the terminal busses of the load and source, respectively.

3.4.3.2 Ladder Architecture

The ladder architecture is then analyzed by considering busses and power converters. The process is the same as described for the ring architecture. Power converters are inserted in the terminal segment of each EP. Moreover, in the considered implementation, each step of the ladder presents three busses. Finally, the two busses L1 and L2 permitting the connection between steps are considered as well.

First, the reliability function of the terminal segments connected to sources and loads $(R_{T_L}(T) \text{ and } R_{T_S}(T), \text{ respectively})$ is calculated with Equation (3.13) as for the ring architecture.

Then, the reliability of the ladder architecture when the considered source and load behave to the same step of the ladder (see Figure 3.6 d)) is calculated with the following relationship:

$$R_{archi,ladder1}(T) = R_{Bus_L}R_{Bus_S} \{ 1 - [1 - R_{CB}^2 * R_{Bus}] * [1 - R_{CB}^2 * R_{Bus}^2 \{ 1 - [1 - R_{CB}^4 * R_{Bus}^3]^{b-1} \}] \}$$
(3.15)

where b is the number of branches in the considered implementation.

On the other hand, when the source and load behave to different steps of the ladder (see Figure 3.6 e)), the reliability becomes:

$$R_{archi,ladder2}(T) = R_{Bus_L}R_{Bus_S}\{1 - [1 - R_{CB}^4 * R_{Bus}^3]^2 * [1 - R_{CB}^6 * R_{Bus}^5]^{b-2}\}$$
(3.16)

3.4.3.3 Crossbar-based Architecture

Finally, crossbar-based architecture is considered. In particular, power converters are attached to each terminal segment of the EPs. Furthermore, the analysis considers the M busses contained in each crossbar and the external busses used for crossbar interconnection (depicted in blue in Figure 3.1).

First, the reliability of the terminal segments connected to loads and sources $(R_{T_L}(T))$ and $R_{T_S}(T)$, respectively) of each EP is calculated as follows:

$$R_{T_L}(T) = R_{T_S}(T) = R_{DCDC}$$
 (3.17)

Then, the reliability of the crossbar-based architecture $R_{archi,cross1}(T)$ in the case of source and load connected to the same crossbar (see Figure 3.6 b)) is calculated by the following relationship:

$$R_{archi,cross1}(T) = 1 - [1 - R_{CB}^2 * R_{Bus}]^M = R_{CR}$$
(3.18)

which we define here as the reliability of a crossbar R_{CR} .

On the other hand, the reliability of the crossbar-based architecture $R_{archi,cross2}(T)$ in the case of connection source-load behaving to different crossbars (see Figure 3.6 c)) is calculated as follows:

$$R_{archi,cross2}(T) = R_{CR} * \left[1 - (1 - R_{CR})^p * (1 - R_{CR}^2)^q * \dots * (1 - R_{CR}^n)^i\right]$$
(3.19)

where the exponents 1, 2,...,n are the number of crossbars crossed and p, q,...,i are the number of redundant paths with the corresponding number of crossbar crossed.

3.4.4 Use Case 3: Complete with Redundancy on Terminal Devices

Finally, the third use case is considered where a redundancy on the terminal segment is inserted, as shown in Figure 3.8 c). In fact, being the power converter and, in general, the terminal segment is the most critical in terms of reliability, the calculation depends mainly on this device. Then, redundancy is placed on the terminal segment to see better the advantages of having a crossbar component in the system. In particular, a switch and a power converter in redundant mode are inserted in the ring and ladder architectures. On the other hand, the crossbar-based architecture already provides redundancy on the switch. Then, just a redundant power converter is inserted.

Then, the reliability of the three architectures can be calculated with Equation (3.4) where the reliability of the terminal segmented ($R_{T_L}(T)$ and $R_{T_S}(T)$, respectively) are calculated as follows for the three architectures:

3.4.4.1 Ring Architecture

$$R_{T_L,ring}(T) = R_{T_S,ring}(T) = 1 - (1 - R_{CB} * R_{DCDC})^2$$
(3.20)

0

3.4.4.2 Ladder Architecture

$$R_{T_L,ladder}(T) = R_{T_S,ladder}(T) = 1 - (1 - R_{CB} * R_{DCDC})^2$$
(3.21)

3.4.4.3 Crossbar-based Architecture

$$R_{T_L,cross}(T) = R_{T_S,cross}(T) = 1 - (1 - R_{CB} * R_{DCDC})^{M}$$
(3.22)



where M is the number of busses of the crossbar.

Fig. 3.9 Static reliability analysis results of the DCMG benchmark in the three considered use cases: only-switches, complete, complete with redundancy on terminal devices.

To summarize, the reliability function of the DCMG benchmark presented in this Chapter has been calculated for three use cases: only switches, complete and complete with redundancy on terminal devices. Figure 3.9 shows the results comparing the ring, ladder, and crossbar-based architectures in the three considered use cases.

Notice that the system's reliability drastically decreases in use cases 2 and 3 with respect to use case 1 because of the addition of power converters that represent the most critical devices in terms of reliability. In fact, the overall reliability in use case 2 depends mostly on them. For this reason, in use case 3, a redundant power converter is placed on each terminal segment to increase the system's reliability. However, even though there are improvements in the reliability and MTTF, the static scenarios considered do not allow retrieving the best from redundancy. In fact, the reliability still heavily depends on the power converters.

Nevertheless, the crossbar-based architecture presents higher MTTF with respect to the other architectures of the benchmark in all three considered use cases as shown in Table 3.3.

Table 3.3 MTTF results of the DCMG benchmark for the three use cases.

Architecture	Use Case 1 MTTF [hours]	Use Case 2 MTTF [hours]	Use Case 3 MTTF [hours]
Ring	176 520	22 122	46 457
Ladder	295 250 (+67%)	23 489 (+6,2%)	51 774 (+11,4%)
Crossbar-based	558 760 (+217%)	24 864 (+12,4 %)	53 028 (+14,1%)

3.5 Efficiency Analysis

We analyze and compare the energy efficiency of the three architectures shown in Figures 2.1 a), 2.1 c) and 3.1. In order to estimate the energy transport efficiency, the number of crossed switches is considered. For this analysis, power relays are considered as switching devices. We assume that cable losses can be neglected due to short distances and only account for the contribution to the transmission losses given by the static power loss needed to activate a relay and the power losses contact resistance. Unit loss figures are extracted from a commercial power relay to ensure realistic assessment even though relative units such as the number of relays crossed would yield similar conclusions. The chosen relay [29] has a static power consumption of 1.7W, a maximum DC current of 50A and uses AgSnO2 as contact material that presents an average contact resistance of $2m\Omega$ [48]. The comparison is made by analyzing the shortest paths allowing the connection of a source-load pair. Then, depending on the number of relays found on that path, transmission efficiency is estimated.

Shortest Path	Path Ring	Path Ladder	Path Crossbar-based
1st	$B1 \rightarrow PV1 \rightarrow B2 \rightarrow DL1$	$B1 \rightarrow L2 \rightarrow DL1$	$B1 \rightarrow C1(1) \rightarrow C2(1) \rightarrow DL1$
2nd	$\begin{array}{c} B1 \rightarrow SC \rightarrow DL2 \rightarrow PV2 \\ \rightarrow AL \rightarrow ACG \rightarrow W1 \rightarrow FC \\ \rightarrow W2 \rightarrow DL1 \end{array}$	$\begin{array}{c} B1 \rightarrow PV1 \rightarrow L1 \rightarrow B2 \rightarrow \\ DL1 \end{array}$	$B1 \rightarrow C1(2) \rightarrow C2(1) \rightarrow DL1$
3rd	Does not exist.	$\begin{array}{c} B1 \rightarrow L2 \rightarrow W2 \rightarrow AL \rightarrow \\ L1 \rightarrow B2 \rightarrow DL1 \end{array}$	$B1 \rightarrow C1(1) \rightarrow C2(2) \rightarrow DL1$

Table 3.4 Shortest paths ranking for the source-load pair $B1 \rightarrow DL1$.

In Table 3.4, an example of a comparison between the three architectures is made by considering the pair battery B1 with the DC load DL1 (see Figures 2.1 a), 2.1 c) and 3.1). In particular, the table presents the three shortest paths allowing to connect B1 with DL1. Note that the ring architecture always has two paths to connect a source with a load whose sum equals the number of serial relays on the ring. Ladder architecture has a better organization of its resources thanks to its two common busses L1 and L2, which overall provide higher efficiency and path redundancy. Crossbar-based architecture, thanks to the bus segmentation and reconfigurability, makes for a higher number of redundant paths with higher efficiency.



Fig. 3.10 Transport efficiency comparison between Ring, Ladder and Crossbar-based architectures for several source-load pairs: a) 1^{st} , b) 2^{nd} and c) 3^{rd} shortest paths.

Figure 3.10 shows an estimation of transmission efficiency obtained in the three architectures. In particular, four samples of source-load pairs were selected and represented, next to the average on all possible pairs, represented in the fifth column. Results show that the crossbar-based architecture has a higher energy efficiency compared to Ring and Ladder. The transmission power of 1051W is used for the simulation, corresponding to the optimal transmission power calculated from the relay characteristics: static power losses in the coil and contact resistance.

3.6 Summary

This chapter presents a novel DCMG architecture that relies on a power crossbar component, which would enable the "Software-Defined Power Domains" concept. The solution makes it possible to set up arbitrary electrical topologies onto densely connected physical micro-grids. Flexibility is analyzed as the number of redundant paths permitting a connection of a pair source-load. Then, static reliability analysis is performed using the reliability theory to determine the MTTF of DCMG architectures. Finally, performance losses and efficiency of the proposed architecture are calculated and compared to the other architectures present in the DCMG benchmark. Crossbar-based DCMG architecture demonstrates improving flexibility, reliability and efficiency compared to the others present in the DCMG benchmark.

Chapter 4

Dynamic Reconfiguration in the SDPD

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The last chapter presented the general description of the proposed crossbar-based DCMG architecture. Moreover, some first static analyses are performed to compare it with other architectures of the DCMG benchmark. This chapter, then, presents the dynamic operations that can be performed on this architecture.

First, a multi-level control strategy is described that guarantees the PD stability and manages their interaction. In particular, a two-level control strategy is presented that uses the Master-Slave control technique as the first level of control and a higher level control that manages the topology reconfiguration and the interaction between PDs.

Furthermore, some dynamic operations are presented. First, the handover operation enables the dynamic reconfiguration of the power network without affecting the functioning
of the loads. Second, the fault recovery operation is presented that permits dynamically recovering from a fault condition. It consists of isolating the fault and re-configuring the power network to let the system continue operating. PSIM simulator is used to validate these operations on two examples of scenarios.

4.1 Software-Defined Power Domains

A new paradigm has entered the lexicon of Information Technology since the last decade: software-defined. It describes how, using reconfigurable architectures, it is possible to introduce a new level of 'plasticity' to a network, or a pool of computing resources, remaking and un-making connections, or re-allocating compute resources, on the fly.

In the IT domain, the impact of software-defined has been immediate, significant and disruptive. While the application of more intelligence and automation is helpful in almost all markets, the opportunities for innovation in power distribution are still not so clear. The data center is a stand-out example: extensive facilities present a great opportunity for suppliers because of the size and growth of the market, vast over-provisioning, high costs, and inflexibility in power distribution and use.



Fig. 4.1 Software-Defined Power Domains representation.

The most obvious connection of this architecture in the energy domain is the SDP as defined in [51]. The key of this concept is to reduce the need for spare capacity and divert or reserve power for applications, racks or rows that most need it and away from those that need least. Some already existing solutions use distributed lithium-ion batteries in the racks of the data center to provide a "virtual" distributed pool of power that can be used and managed when needed or to provide backup [51]. In this sense, it is analogous to the homogeneous pool of computing resources in a software-defined data center.

By using a power crossbar-based DCMG architecture, a novel concept related to the term software-defined is introduced as an extension of the SDP: SDPD. While SDP increases the redundancy of the power supply system, which uses distributed energy sources to provide a "virtual" backup to all the data center [51], SDPD adds the possibility to reconfigure the whole topology of the power distribution network by software. The significant advantage of this architecture is that it permits the creation of separate and independent Power Domains (PDs) that can be reconfigured at run-time by software. Figure 4.1 shows an example of independent PD creation onto a crossbar-based architecture. This aspect helps manage huge power distribution systems because the complexity of the control can be divided into smaller, independent and easily controllable PDs. This architecture not only provides better controllability, reliability, resiliency and scalability, but it also allows distributed energy sources to be easily integrated into the power distribution pool.

Critical systems such as data centers start to be integrated with RES, ESS and conventional energy sources. The crossbar-based DCMG architecture helps this transition because it adds flexibility to the grid topology needed when involving this heterogeneous set of sources and loads. In fact, grid topology can be reconfigured accordingly to the loads and sources conditions. Redundancy and reliability of critical loads can be adjusted at run-time by varying the topology of the power distribution network. Finally, the reconfiguration improves resiliency, which permits isolating a fault and restoring the system's functioning.

4.2 Control Strategy

The control strategy of a DCMG plays an essential role in the security of the power distribution system. In the crossbar-based DCMG, each crossbar has its controller that manages the crossbar connections, communicates with other crossbar controllers and with a central controller in order to synchronize their operations in the topology reconfiguration and energy sharing. In particular, a central controller sends commands to the crossbar controllers to organize the topology configuration. Then, several independent PDs are created that are controlled by the local crossbar controllers. Master-Slave technique is chosen in this thesis to control each PD. Therefore, the central controller assigns the Master role to a controller attached to a dispatchable source, which keeps the DC Bus voltage of the PD constant. Then, the others controllers work in Slave mode.

In this scenario, the role of the power crossbar is to communicate with the central controller to define power domains and keep the security of all attached EPs. To this scope, the power crossbar needs sensors on its ports and to communicate with the power converter controllers. So, the power crossbar has its internal busses at a constant voltage, and each EP is connected to the crossbar using power converters. Then, the power crossbar controller commands the crossbar switches together with the power converters and can read data from inputs and outputs of the power converters. In this way, it can make decisions in the local power domain and can treat fault conditions.

When a fault occurs, power crossbars connected to the faulty domain are in charge to localize the fault and isolate it, restoring in the fastest possible way the functioning of the power domain by using another available bus.

Many control techniques for microgrids can be found in the literature [50][8][34]. A two-level hierarchical control has been chosen for the proposed crossbar-based DCMG. In particular, the first level of control manages the power balance between EPs connected to the same PD. Master-Slave technique is used to reach this objective for its simplicity and effectiveness in small and medium-sized power networks. Then, the second level of control defines PDs, assigns the Master role to a power converter in each PD and manages the dynamic topology switching operation.

4.2.1 First Level of Control

The Master-Slave technique is used for the local power management of each PD because of its simplicity and effectiveness in small and medium-sized power networks. In this technique, a power converter is assigned as Master of the PD, and the others work as Slaves. The Master controller ensures a stable and constant voltage on the common DCB. On the other hand, Slave controllers work in constant current mode, injecting or taking current from the DCB. The Master controller can be either a dispatchable source or an ESS or even a controllable load as in [41]. Its objective is to guarantee the power balance between the EPs of that PD, keeping a constant voltage on the DCB.

Figure 4.2 shows the schematic of the DC/DC converter used in this work. This configuration is very flexible. In fact, depending on how the MOSFET is controlled, it works in Buck or Boost mode in both directions. Moreover, specific protocols can be applied to the MOSFET to help the domain change, as we will see in the following sections.



Fig. 4.2 Electrical schematic of the used DC/DC converter.

4.2.2 Second Level of Control

The second level of control is centralized. It is in charge of defining PDs, assigning the Master role to a dispatchable EP controller, and commanding the handover and fault recovery operations. In this thesis, these functionalities are implemented manually for each simulated scenario. Future works could include the realization of an algorithm that automatically decides the topology configuration depending on the sources and loads condition. For instance, machine learning techniques could be used for this purpose.

4.3 Handover for Dynamic Optimization

One of the advantages of the proposed architecture is flexibility. The power network can adapt to different conditions to best satisfy the load and guarantee the Quality of Service. We refer to topology reconfiguration as handover operation. The handover operation is a dynamic (online) operation that permits reconfiguring the topology without service interruption.



Fig. 4.3 Handover operation analogy: a) wireless communication system and b) crossbarbased DCMG.

Handover operation firstly was introduced for wireless communication systems. In fact, this operation allows to dynamically change the base station of a connected mobile device without interrupting the ongoing call, as shown in Figure 4.3 a). This can happen for several reasons, such as a better signal from another base station or high data traffic in the actual base station. Moreover, the user does not notice this change as it takes place within milliseconds.

In the same way, the handover operation in a crossbar-based DCMG allows an EP to dynamically change the power domain without interruption of the power supply of the load as shown in Figure 4.3 b). Moreover, it guarantees that there is always a Master controller per PD. For instance, if EP1, the Master controller of PD1, has to switch the domain to PD2, the handover algorithm first assigns the Master control of PD1 to another dispatchable source and then perform the domain change of EP1 to PD2. While the software reconfiguration presented in Chapter 3 is a static operation performed when the system is OFF, the handover operation is a dynamic (online) operation that acts simultaneously on both switches and power converters.

4.3.1 Handover Operation

Here, we will explain reliable techniques for handover operation. The techniques do not alter the power quality that we here define as maximum acceptable voltage ripple, arbitrarily set to 6%. The methods are simulated with the PSIM simulator. This scenario, depicted in Figure 4.4, involves two generic voltage sources of 20V, represented by a battery B1 and a fuel cell FC that reach a DC load DL1 by using the power crossbar network.



Fig. 4.4 Dynamic topology switching protocol: a) Init, b) handover and c) domain change.

In the beginning, the B1 converter (DD3) is the Master of PD1, guarantying a constant voltage of 36V on the DC-bus, and the FC converter (DD7) is in slave mode, helping feeding DL1. On the other domain, PD2, B2 converter (DD6) is the Master, keeping a constant voltage of 30V while receiving the maximum power the solar panel PV, which is in Slave mode, provides. Then, the handover protocol permits changing the Master control of PD1

between the two sources and lets B1 change domain, switching from discharging mode to charging mode.



Fig. 4.5 PSIM simulation of handover and domain change.

The following steps are applied in order to set up this domain change without compromising the power quality of both DC-busses (see Figure 4.5):

- 1. t=50ms > the DCMG controller gradually changes the current set point of the FC converter in order to reach the initial contribution of the B1 converter;
- t=55ms -> the handover operation takes place by reversing the control of the Master DD3 and the Slave DD7. DD3 current is set according to the last measurement of its current sensor in order to reduce perturbations on the DC-bus. Then, the reconfiguration process starts by setting relays (note that chosen relays need 25ms to operate[29]);
- 3. $t=60ms \rightarrow B1$ set point is gradually brought to 0A;

4. t=80ms -> Power relays close, and the reconfiguration is complete. B2 disconnects from the PD2 domain and is turned OFF in order to let B1 charge and take all of the power coming from the solar panel. Master control of PD2 pass to B1.

A ramp function with a slope of 2.6A/ms is used in the simulation to change the setpoints to the PI controllers gradually. As shown in Figure 4.5 the handover operation does not affect the voltage of the PD1 DC-bus, which undergoes a slight voltage oscillation of 1V corresponding to 2,78% of its nominal value. A greater voltage peak of 2V corresponds to the activation of relays due to DD3 capacitance already charged from the previous operation.

4.3.2 Handover optimization: Case Studies

The scenario examined in the last section presents acceptable oscillations under the handover operation. In reality, these oscillations are not fixed to these values, but they will change their amplitude and frequency according to the examined scenario, voltages difference between the PDs, DC Bus capacity of the PDs. For these reasons, methods to avoid oscillations during the handover operation are presented in this section. They use the DC/DC converters connected to the crossbar to precharge capacitance before performing the handover operation. For example, considering the scenario described in Figure 4.4, a more significant difference between the DCB voltages of PD1 and PD2 would have given bigger oscillations due to the capacities involved in the circuit. Moreover, when new EPs are connected to the DCMG, an inrush current is produced by charging the power converter capacitances. This causes a voltage drop in the DC Bus that should be considered to avoid service interruption for the other loads connected to the DCMG.

We consider, here, two handover categories depending on the nature of the EP involved and its role. They are as follows:

- 1. handover of an energy source with associated power controller working in Slave mode
- 2. handover of an energy source with associated power controller working in Master mode

In the following sections, an example scenario of each category is examined. Moreover, a protocol is proposed in order to smooth the transition, avoiding oscillations.

4.3.2.1 Handover of a Source working in Master mode

The first examined scenario considers the handover of an energy source that is working in Master mode. The scenario depicted in Figure 4.4 falls in this category. In fact, the battery

B1, which is the Master of PD1, is performing a handover operation to connect to PD2. In this case, the first operation is to assign the Master role of PD1 to another dispatchable source connected to that domain. This is because each PD need at least a Master controller, as discussed above. Then, the handover operation takes place.



Fig. 4.6 Capacitor precharge protocol during handover operation.

Figure 4.6 shows the main steps of the handover protocol in this use case. In particular, Figure 4.6 a) is the initial scene where the battery - here denoted as EP1 - is connected to the Bus 1 of the crossbar that corresponds to the PD1. Then, in the second step (see Figure 4.6 b)), the crossbar relay connected to PD1 has to open, and the relay connected to PD2 starts to close. Usually, the operation time of a relay is longer than the release time. In this work, we consider relays to present an operating time of 25ms and release time of 5ms. Then, even though the command of opening and closing is given at the same time t_{action} , the closing action is finished about 20ms earlier than the opening act. In these 20ms, the power converter is completely disconnected from the DCMG.

Then, we use this dead-time in order to prepare the output capacitor of the power converter to match the voltage level of PD2. Figure 4.7 shows a diagram that summarizes the steps of the described protocol.

A particular focus on the fourth step of the protocol is made in this paragraph. In fact, the preparation for the connection to PD2 is the most critical part of the whole protocol. This

connection can produce a high inrush current and cause instability into the PD if it is not well managed. Several variables are involved in this process, such as the capacity and voltage level of the DCB of PD2, the voltage level and capacity of the output capacitance of the DC/DC converter connected to EP1. Here, a method to handle this particular operation is proposed.

It consists in using the EP1 DC/DC converter to precharge the output capacitor *Cout* at the same level of the voltage of PD2. The scenario is depicted in Figure 4.6. In particular, the inductance and the MOSFETs M1 and M3 of the DC/DC Converter are used to precharge the capacitance. A PWM signal is applied to these MOSFETs for a defined number of periods. Then, depending on this number, the capacitor is charged more or less. In order to calculate the number of periods needed to charge the capacitor from a voltage level, V_{ini} to a voltage level V_{fin} , the following relationship can be used.



Fig. 4.7 Handover optimization steps in the first case: Source working in Master mode.

First of all, we can calculate the initial energy stored in the capacitor and the energy needed to the capacitor in order to reach a voltage level of V_{fin} as follow:

$$E_{C_{out},ini} = \frac{1}{2}C_{out}V_{C_{out},ini}^2$$
$$E_{C_{out},fin} = \frac{1}{2}C_{out}V_{C_{out},fin}^2$$

Then, we can calculate the difference of energy needed to the capacitor C_{out} to reach the desired voltage level V_{fin} as the difference between the two energies:

$$\Delta E_{C_{out}} = E_{C_{out},fin} - E_{C_{out},ini}$$

This is the energy we have to provide to the capacitor C_{out} in order to reach the voltage level V_{fin} . Since the battery has a lower voltage with respect to the DC Bus voltage, the DC/DC converter works in Boost mode. In this operation mode, there are two main phases:

inductance charge and inductance discharge. The equivalent circuits in these two phases are shown in figure 4.8 a) and b), respectively.



Fig. 4.8 Equivalent circuit of the DC/DC converter during the a) charging and b) discharging phase.

In ideal conditions, the energy stored in the inductance in the first PWM semi-period will be transmitted to the capacitor in the second part of the period. As the resistances and current levels are very low in the circuit, this approximation is valid. In order to calculate the energy stored in the inductance in each cycle, we consider the circuit in Figure 4.8a). It is an RL circuit in which the current in the inductance can be calculated as:

$$i_L(t) = \frac{V_{BATT}}{r_{ON}} * (1 - e^{-\frac{r_{ON}}{L} * t})$$

where r_{ON} is the ON resistance of the MOSFETs plus the parasitic resistance of the inductance.

Considering a duty cycle of 50%, we can substitute $t = T_{sw}/2$, which correspond to the half period of the PWM. Then, the current flowing in the inductance after the first half of the PWM is calculated with the following relationship:

$$I_{L}(t) = \frac{V_{BATT}}{r_{ON}} * (1 - e^{-\frac{r_{ON}}{2*L*f_{SW}}})$$

where f_{sw} is the frequency of the PWM signal. This permits to calculate of the energy stored in the inductance during half period T_{sw} as:

$$E_L = \frac{1}{2} * L * I_L^2$$

Assuming that in the remaining half of the PWM, the inductor is able to fully discharge into the capacity - which is the case because we are controlling both M1 and M3 MOSFETs with the PWM signal – the number of cycles needed to the DC/DC converter to reach V_{fin} is calculated as:

Name	Value	Description
r _{ON}	$5,2m\Omega$	ON resistance of the MOSFETs
L	136µ <i>H</i>	Inductance of the DC/DC converter
\mathbf{r}_L	$42 \mathrm{m}\Omega$	parasitic resistance of the inductance L
V_{BATT}	18V	Battery voltage
f_{sw}	31,76kHz	Switching frequency of the PWM signal
Cout	$150 \mu F$	Output capacitance of the DC/DC converter
V _{ini}	20V	Initial voltage on the capacitor C _{out}
V_{fin}	36V	Desired voltage corresponding to the voltage on the DCB of PD2

 $N_{cycles} = \frac{\Delta E_{C_{out}}}{E_I}$

Table 4.1 Simulation parameters



Fig. 4.9 PSIM results of the capacitance pre-charge during the handover operation.

This method has been simulated in PSIM. The device parameters used in the simulation are reported in Table 4.1. Using the parameters in the table, the number of PWM cycles needed to charge the capacitor from 20V to 36V is 233. Figure 4.9 shows the simulation results.

The obtained voltage on C_{out} after 233 cycles of charging is 35,35V, which is very close to the desired one. The mismatch is due to the energy dissipated into the parasitic resistance during the whole process, neglected for simplicity. A more accurate calculation could take into account the power dissipated into the parasitic resistors.

4.3.2.2 Handover of a Source working in Slave mode

The second examined scenario considers the handover of a source working in Slave mode. This use case is very similar to the first one. The only difference is that the first step is not necessary because the controller is already in Slave mode. Figure 4.10 shows the diagram of the handover steps for this use case.



Fig. 4.10 Handover optimization steps in the second case: EP working in Slave mode.

In particular, the method used in the first case to precharge the capacitance to a defined voltage level can be used in the same way in this case.

4.4 **Resilience Analysis**

In this section, the crossbar-based architecture is analyzed in terms of resilience. In particular, two fault conditions are examined and simulated by PSIM simulator. The first one considers a fault on the Master controller of a power domain. In this case, the topology reconfiguration is used to connect another dispatchable source to the faulty PD, restoring the correct functioning. The second one considers a fault on a crossbar bus. Since the crossbar presents more than one bus, this case is solved by simply connecting the affected EPs to another crossbar bus.

These two case studies demonstrate the advantages of having a crossbar-based interconnection system to isolate faults and dynamically recover the correct functioning of the whole microgrid. In fact, a fault on a bus of ring and ladder architectures limits the connectivity of sources and loads attached to that bus.

On the other hand, in the crossbar-based architecture, faults could happen on an internal bus of the crossbar or an external bus. The former are the busses that allow connection between EPs of the same crossbar. The latter are busses that permit connections between crossbars. In the first case, the connectivity of EPs is not compromised at all because EPs can use the other available bus of the crossbar to interconnect. In the second case, the connectivity of the two crossbars is limited, but EPs connected to the same crossbar are still able to exchange energy locally. Moreover, in large implementations, each crossbar is expected to have more than one connection to other crossbars (as in the linear and matrix configuration shown in Chapter 6). Therefore, even if a fault occurs on an external bus, one other port in the linear configuration and three other ports in the matrix configuration allow that crossbar to continue making inter-crossbar connections.

4.4.1 Fault recovery operation: Use Case 1

An example scenario of the first case study is shown in Figure 4.11. The cloud represents the fact that we are considering just a small portion of a more extensive implementation in which other PDs may function simultaneously by using other independent busses.



Fig. 4.11 Fault recovery protocol in the first fault condition: Fault on the Master controller.

In the considered PD, a 400W load is initially supplied by the parallel of two energy sources SRC1 and SRC2, using the crossbar network. In particular, SRC1 works in Slave mode, providing a constant power of 180W, while SRC2 works in Master mode, providing the remaining part to the load.

At a certain point, a fault occurs on SRC2. Then, the DC Bus controller senses the drop of the DC Bus voltage and detects the fault on SRC2. The fault detection method is not part of the objectives of this thesis, so a simple voltage drop detection method is used for this experiment. At this moment, the crossbar network starts to reconfigure the topology in order to connect another dispatchable source to that PD to replace the damaged one. The re-configuration protocol is then acted as depicted in Figure 4.11.

The crossbar controller alerts the SRC1 controller to temporarily switch in CV mode to react to the DC Bus voltage drop caused by the damaged SRC2. At the same time, it finds another dispatchable source in the microgrid (in this case, SRC3) and starts the reconfiguration process. Usually, the first operation is faster than the second one. Indeed, the first operation needs just a message exchange between the crossbar controller and the power converter controller, which is resolved in hundreds of μs . On the other hand, the second operation needs the opening and closing of relays that takes 25 ms. Then, once the network is reconfigured, the SRC3 converter starts to work in CC mode. Finally, a Handover operation let the SRC1 return in its initial mode (CC) and SRC3 switch in master mode (CV).



Fig. 4.12 PSIM simulation of the fault recovery protocol in the first fault condition.

Figure 4.12 shows the results of the presented method simulated with PSIM simulator. The first chart shows the currents of SRC1, SRC2 and SRC3 in blue, red and heavenly, respectively. Moreover, the current set point of the controller working in slave mode is also depicted in the same chart by a black dotted line. On the other hand, the second chart

represents the voltage of the common DC Bus during the whole process. Furthermore, a black dotted line represents the voltage set point of the Master controller of this power domain.

In the beginning, the SRC1 controller works in CC mode following the current set-point depicted by the black dotted line in the first chart of Figure 4.12. SRC2 works in Master mode, guarantying a constant voltage of 36V on the common DC Bus. At t=50ms, a fault occurs on SRC2. Then, after $200\mu s$, the fault is detected, and the SRC1 passes in Master mode. At the same time, SRC2 is disconnected from the PD, and the reconfiguration process starts in order to connect SRC3 to that power domain. At t=75ms, the relays are closed, and the reconfiguration process is completed. Then, the SRC3 controller starts to work in CC mode following the black dotted line in the first chart of Figure 4.12. Finally, at t=95ms, the handover operation is performed in order to let SRC1 return working in CC mode, and the SRC3 controller is set as Master of the PD.

4.4.2 Fault recovery operation: Use Case 2

The second use case analyzes the fault recovery operation in case of fault of the internal bus of the crossbar connected to the load. Even though fully redundant architectures add redundancy in power supply and power converters, the terminal bus remains without redundancy and thus becomes the most critical component. In fact, a fault on this component compromises the functioning of the attached loads until the bus is repaired.

The crossbar-based architecture tackles this issue by allowing the dynamic restoration of a bus failure. Figure 4.13 shows the reconfiguration protocol applied to a crossbar-based architecture in the second fault condition.

The initial scenario is similar to the one described in the first fault condition. Moreover, the load need 12V. Then, a power converter is inserted to adapt the 30V of the DC Bus to the 12V required by the load. Furthermore, all EPs use the Bus1 of the load-side crossbar in order to share their energy. Then, at t=80ms, a short-circuit occurs on Bus1 of this crossbar. Once the fault is detected, the power converters of SRC1 and SRC2 are turned OFF to electrically disconnect from the faulty bus and avoid damage to the sources. Then, the reconfiguration operation starts by setting the relays of the crossbar attached to the load to use the second available bus (Bus2). The relay closing operation takes 25ms to execute. Once the relays are closed, the reconfiguration process is completed, and the power converters restart their function in the same configuration they had before the fault.

Figure 4.14 shows the simulation results of this fault recovery operation in this second case.

In particular, the first graph represents the voltages on Bus1 and Bus2 of the crossbar in blue and black, respectively. Moreover, the voltage on the load is depicted in red. On the



Fig. 4.13 Fault recovery protocol in the second fault condition: Fault on a bus of the load crossbar.

other hand, on the second graph, currents of the photovoltaic panel (PV), the battery (BATT) and the load (LOAD) are represented in blue, black and red, respectively.

Therefore, the reconfiguration process provided by the crossbar permits restoring a fault on a bus in 25ms. However, this time is sufficient to bring the voltage to 0V and shut down the load. This behaviour is unacceptable, especially in critical systems such as data center, where few ms of black-out are sufficient to shut down the servers with loss of data and interruption of service.

There are two main causes of this black-out of 25 ms. The first is the use of electromechanical relays in the crossbar that present an operating time of 25ms, making the reconfiguration process slow. The second is the value of the capacitor on the load side that is not big enough to contain the energy needed to keep the voltage stable during the reconfiguration process.

Therefore, two solutions are investigated to the issues mentioned above. The first consists of replacing the electromechanical relays with Solid-State Relays (SSR). In fact, SSR (made by power MOSFETs) presents an operation time of a few μs , which makes the reconfiguration process way faster. The second solution consists of increasing the capacitance value on the load side. Indeed, the load could continue working using the energy stored in the capacitor

during the reconfiguration process. For instance, supercapacitor technology could be used that presents capacitance in the order of hundreds of Farads, able to supply a load for a few ms. However, capacitors of such capacitance value are costly, large and heavy.



Fig. 4.14 PSIM simulation of the fault recovery operation in the second fault condition: Fault on a bus of a crossbar.

A hybrid solution is then applied in this thesis that uses SSR as switching devices and a larger capacitance on the load in order to reduce the voltage drop speed.

Figure 4.15 shows the simulation results when replacing SSR in place of electromechanical relays and using an output capacitance of the load power converter of 1,5mF instead of 150uF.

The recovery time is then reduced from 25ms to 1,13ms. Moreover, the load voltage drops to a minimum of 7,2V without reaching 0V during the whole reconfiguration process.

4.5 Summary

This chapter presents and demonstrates more in detail the concept of Software-Defined Power Domains. The ability to divide a DCMG architecture into several independent PDs simplify the control and improve the power distribution network's scalability and resilience.

First, a multi-level control technique is proposed for this architecture. The first level is a Master-Slave control technique applied to each PD. The second level is in charge of



Fig. 4.15 PSIM simulation of the fault recovery operation in the second fault condition using SSR: Fault on a bus of a crossbar.

defining PDs, assigning Master control to a dispatchable source, and managing the topology switching operations.

Moreover, two essential dynamic operations are described and tested. The first is the handover operation that performs a topology reconfiguration. The second is the fault recovery operation that permits isolating a faulty device and reconfiguring the power network to continue supply all loads. PSIM simulator is used in order to validate these operations in some example scenarios.

Finally, optimization techniques have been presented that use capacitors pre-charge and SSR technology to smooth oscillations, reduce reconfiguration time, and make these operations transparent to loads. However, SSR technology must be used carefully. Indeed, because of the loss of galvanic insulation, a closed switch does not guarantee complete independence between the connected PD. Therefore, a more complex control system is needed that avoid a fault condition to propagate and damage adjacent units.

Therefore, the Software-defined Power Domains concept with such dynamic operations promises a high level of resilience in DC microgrids. However, the control of such processes in larger implementations remains a challenge.

Chapter 5

Dynamic Reliability Analysis

Contents

5.1	Dynamic Reliability Approaches			
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In this chapter, the dynamic reliability metrics will be evaluated on the DCMG benchmark. Moreover, the repair of components and the dynamic operations explained in the last chapter are considered in this analysis. Then, the latter is performed first with the assumption of components having constant failure rates. This first analysis is performed by using the Markov chains method. Then, a second analysis evaluates the reliability of the presented DCMG benchmark when considering the ageing of components (non-constant failure rates) by using Monte Carlo simulations. Finally, observations on the obtained results are discussed at the end of the chapter.

5.1 Dynamic Reliability Approaches

"Dynamic" reliability refers to the study of reliability when the repair of components and the dynamic operations presented in Chapter 4 are considered. It differs from the "static" reliability analysis performed in Chapter 3. In fact, the latter aims to calculate the reliability function of the system without considering the repair of components. On the other hand, the "dynamic" reliability analysis aims to obtain the system's availability, MTBF and MTTR when the repair or replacement of components is considered in the model.

Several approaches can be found in the literature to evaluate the availability of a repairable system. They are classified depending on the nature of the failure rate of the components. For instance, for components with constant failure rates, Continuous Markov Process (CMP) can be used [42]. This method is computationally efficient. In fact, once the model is created, an associate system of equations can be retrieved whose resolution provides the steady-state probabilities of being in each model state. Then, the availability and unavailability of the system are calculated by summing up the probabilities of being in healthy states and faulty states, respectively. The drawback of Markov chains is the state-space explosion when the number of components grows up.

Another approach to evaluate the reliability metrics of a repairable system is to use Monte Carlo simulations. In fact, a Monte Carlo simulation can be set up by knowing the reliability characteristics of the system's components such as switches, power converters, and busses. In this simulation, the state of components is computed each time step, and the system's state can be retrieved depending on the components states. The advantage of this technique is that it permits evaluating the reliability metrics even in the case of non-constant failure rates. The drawback of the Monte Carlo technique is the computational burden required to perform these simulations.

Other techniques can be found in the literature that uses the advantages of both Markov chains and Monte Carlo methods. These hybrid techniques have been widely surveyed in [45]. For instance, a method to study the reliability of a system in a modular way is presented. This method solves the Dynamic Fault Tree (DFT) of a system in a modular and hierarchical manner. In fact, starting from the Top Event (TE), which indicates the system fault, several independent sub-tree can be identified that permits decomposing of a DFT in several smaller sub-trees. Then, the identified sub-trees can be solved by using either algebraic formulas, Markov models or Monte Carlo simulation depending on the type of the sub-tree. For instance, if the sub-tree is static, the algebraic method is used. On the other hand, in the case of dynamic sub-tree, the Markov approach is used for exponentially distributed failures and Monte Carlo simulation for non-exponentially distributed failures.

5.2 Constant-failure rates

The Markov models of ring, ladder and crossbar-based DC microgrid architectures are extracted in this section. Since the ladder and crossbar-based architectures have two different types of source-load connections, they are modelled by two different Markov models. Then, in total, there are five Markov models corresponding to the five use cases represented in Figure 3.6 that are named as follows: ring, ladder1, ladder2, crossbar1, crossbar2.

5.2.1 Experiments Hypothesis and Assumptions

For this first analysis, just the switches are considered. Moreover, the assumption of independent components explained in Chapter 3 for the static reliability analysis is used. The failure rate λ and repair rate μ of power switches is chosen arbitrary to 1/15 failures/years and 1,14 repairs/years, respectively.

So, these data will be used in the Markov models to retrieve the availability and MTBF of the DCMG benchmark.

The considered interconnection system presents two types of faults: restorable faults and critical faults. The former are faults that cannot be restored by online operations and need human intervention. The latter are faults that can be restored by re-configuring the topology by software with the online operations explained in the previous chapter. This work assumes that online operations restore the correct functioning instantaneously in case of restorable faults. On the other hand, critical faults result in service interruption, which can be restored only with human intervention. The latter depends on the repair rate of the faulty component.

5.2.2 Markov chains

One property that makes the study of a random process much more accessible is the "Markov property". In a very informal way, the Markov property says, for a random process, that if we know the value taken by the process at a given time, we will not get any additional information about the future behaviour of the process by gathering more knowledge about the past. Stated in slightly more mathematical terms, for any given time, the conditional distribution of future states of the process given present and past states depends only on the present state and not at all on the past states (memoryless property). A random process with the Markov property is called Markov process.

Based on the previous definition, we can now define "homogeneous discrete-time Markov chains" (that will be denoted "Markov chains" for simplicity in this thesis). A Markov chain is a Markov process with discrete time and discrete state space. So, a Markov chain is a

discrete sequence of states, each drawn from a discrete state space (finite or not), following the Markov property.



Fig. 5.1 Typical bathtub curve characteristic of an electronic component failure rate.

System of switches can be treated as Markov processes if the probability of failure of a switch is constant in time. This is the case in the middle part of the bathtub curve shown in Figure 5.1. In fact, if we consider that components are replaced when they reach their wear-out phase, we can study the reliability of a DCMG architecture by Markov models. The resolution of a Markov model consists in achieving the steady-state probability of each state of the model. Then, summing up the steady-state probability of faulty states gives the Unavailability U of the architecture. On the other hand, by summing up the steady-state probability of states in which the system is correctly functioning, we obtain the Availability A of the system. Then, knowing the MTTR of switches, it is possible to retrieve the MTBF of the system by inverting the equation 2.4.

Markov Chain of a connection source-load

To illustrate the resolution of a Markov model, the example of a connection source-load with a single switch in between is analyzed as shown in Figure 5.2.

The Markov model of this connection is represented in Figure 5.2 b). Here, states 1 and 2 denote the state of the switch SW1. When we are in state 1, the switch is working, and the connection can be made. On the other hand, when we are in state 2, the switch is in a failure condition, and then it cannot be used to create this connection. The arrows represent the transition probabilities. For instance, the probability to transit from state 1 to state 2 is given by $\lambda \Delta t$ where λ is the failure rate of the switch SW1, and Δt is the considered interval of time. Then, if the model is evaluated each hour, the failure rate in [failures/hours] directly gives the transition probability.



Fig. 5.2 Markov Model of a connection between a Source and a Load by using 1 switching device.

Moreover, another property of a Markov model is that the sum of steady-state probabilities of each state has to be equal to the unity as follows:

$$\sum_{i=1}^{N} P_{Si} = 1 \tag{5.1}$$

where P_{Si} is the steady-state probability of being in state i and N is the number of states of the Markov model. This equation is referred in literature to as the normalization equation. From this diagram, the following equation in matrix form can be derived.

$$\begin{bmatrix} -\lambda & \mu \\ \lambda & -\mu \end{bmatrix} X \begin{bmatrix} P_{S1} \\ P_{S2} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$
(5.2)

where P_{S1} is the steady-state probability of being in state 1 and P_{S2} is the steady-state probability of being in state 2. From (5.2), and using the normalization equation in (5.1), one can calculate the steady-state probabilities of each state. If we divide the set of states into *S* safe states and *F* faulty states, we obtain the availability and unavailability of the system to as:

$$U = \sum_{i=1}^{F} P_{FSi} \tag{5.3}$$

$$A = \sum_{n=1}^{S} P_{SSn} \tag{5.4}$$

where P_{FSi} is the steady-state probability of the faulty state i and P_{SSi} is the steady-state probability of the safe state n.

5.2.3 Markov model of DCMG Architectures

This section describes the calculation of the reliability of a DCMG architecture when considering the repair of components. Compared to the analysis performed in Chapter 3, it adds the possibility to model the repair of a switch in a fault condition. The obtained model is closer to reality because it considers that a fault on a switch can be detected and replaced within a specific time interval. Markov chains are used as a mathematical tool to model the DCMG architecture and to determine the MTBF of the system. The model considers all the cases which lead to a connection fault. A connection fault is a condition where a source cannot supply a load because all available paths are faulty. The repair rate μ is defined as the rate at which faulty components are replaced.

States of the Markov models, in our application, represents different fault stages of the system. In fact, starting from the state where all components are OK, the system could transit in states where some non-critical components fail without compromising the system functioning. Finally, the chains terminate when a state representing a critical system fault is reached. In these states, the system is considered down, and only a repair operation could let the system works again.

Then, solving the Markov model, it is possible to determine the steady-state probability of faulting a connection source-load related to the connection's availability. Finally, by using equations (3.5) and (3.6), the availability of the architecture can be retrieved.

5.2.3.1 Ring Architecture

The ring architecture is evaluated here, using Markov chains when considering just switching components. Figure 5.3 a) shows the ring architecture highlighting an example of connection source-load between Battery 2 (B2) and DC Load 2 (DL2).



Fig. 5.3 Markov model of the Ring architecture: in blue the operating states and in red the fault states.

Since we are interested in the probability of failure, just the chains of events that bring to a critical failure are considered. This permits a reduction in the number of states of the Markov chain.

In fact, each state of a Markov model usually represents a particular combination of the component states. For instance, a system with four components has $2^4 = 16$ states in the respective Markov model. Therefore, in the considered system with 36 switches, the number of states should be 2^{36} that become very complex to treat.

On the other hand, pre-analyzing the conditions that lead to a critical failure, one can focus just on these causes, thus reducing the state space. This process is well known in the literature as Dynamic Fault Tree (DFT) analysis [86]. In fact, in the case of the ring configuration, the main causes that bring to a connection failure are two. The first is a fault on one of the terminal switches. In this case, one of the EPs has no access to the architecture, and therefore the connection cannot be dynamically recovered. The second consists in having a consecutive fault on both the semi-arcs of the ring. This means having at least a failure on the first semi-arc and at least a failure on the second semi-arc. For instance, the connection Battery 2 (B2) \rightarrow DC Load 2 presents $2 * n_1$ switches on the shortest semi-arc of the ring and $2 * n_2$ switches on the longest semi-arc of the ring.

Since the components are independent, the two main causes of fault are independent as well, and then a modular approach can be used as explained in [44]. In fact, if the DFT consists of many independent sub-trees, they can be modelled and solved separately, and algebraic formulas or further models could aggregate the results [44].

From the above considerations, two sub-modules are found in the ring architecture that corresponds to the two leading causes of connection fault explained above as shown in Figure 5.3 b) and c).

Moreover, another approximation on the Markov model can be made. In fact, from the reliability theory, the probability of success $R_S(T)$ of a series of two identical devices having a constant failure rate λ over an interval of time *T* is given by

$$R_{S}(T) = R_{1}(T) * R_{2}(T) = e^{-\lambda T} * e^{-\lambda T} = e^{-2\lambda T}$$
(5.5)

where $R_1(T)$ and $R_2(T)$ are the reliability functions of the two components evaluated in T. Then, the series of two identical components can be modelled as a single component having a double failure rate.

The same reasoning can be applied to a series of n switches. For instance, in Figure 5.3 b) the Markov model of the two semi-arc of the ring is presented where $2 * n_1$ switches of the first branch are grouped under a single state S2 and $2 * n_2$ switches of the second branch are grouped under the state S3. Finally, the transition probability for these states is given by the

number of switches times the failure rate of a single switch λ . Notice that passing from the DFT of the system has enormously reduced the number of states from $2^{2n_1+2n_2}$ to just three states.

Figure 5.3 c) shows the Markov model of the terminal switches whose failure is modelled by a single state S2 for the same reasons as before.

Once the two Markov models are solved, the availability and unavailability of the two sub-modules are retrieved. Then, the probability of having a critical connection fault is determined by the following algebraic formula:

$$U_{ring} = 1 - A_{sub1} * A_{sub2} \tag{5.6}$$

where U_{ring} is the overall unavailability of the connection Battery 2 -> DC Load 2, A_{sub1} is the availability of the Markov model in Figure 5.3 b) and A_{sub2} is the availability of the Markov model in Figure 5.3 c). For instance, for the considered failure rates and repair rates, availability of 0,711 and MTBF of 24 567 hours are obtained.

5.2.3.2 Ladder Architecture

The ladder architecture is then analyzed. In particular, the availability calculation changes depending on the source-load pair position. In this work, two cases of source-load connection are evaluated, as depicted in Figure 5.4 a) and 5.5 a). The first considers a source-load pair belonging to the same step of the ladder. The second considers a source-load pair belonging to different steps of the ladder.

1° case

Figure 5.4 a) shows a schematic of the ladder architecture in the first case. We can distinguish three types of switches: terminal switches as for the ring architecture that permit the connection of the EP to the DCMG and IN/OUT switches that allow connection to the internal part of the branch or the external bus, respectively. Then, from the DFT of the architecture, three main causes of connection fault are identified:

- 1. a fault on a terminal switch;
- 2. a fault on a IN switch && OUT switch of source or load;
- 3. a fault on a IN switch && all the external branches (EXT1 && EXT2 && EXT3 && EXT4 && EXT5).

Based on these assumptions, two independent sub-modules are identified in the DFT. The first relates to the terminal switches, and the corresponding Markov model is depicted



Fig. 5.4 Markov model of the Ladder architecture: source and load are on the same branch

in Figure 5.4 c). The second relates to the other two fault causes, and the corresponding sub-module is depicted in Figure 5.4 b). Since the external branches are independent with respect to the IN and OUT switches, they can be treated separately in a sub-sub-module as depicted in Figure 5.4 d).

The resolution of this DFT is made hierarchically. First, the sub-sub-module representing the external branches is solved. Availability and unavailability of the latter are retrieved and used to obtain the equivalent failure rate λ_{eq} shown in red in Figure 5.4 b). Then, the Markov model of the sub-module in Figure 5.4 b) can be solved. On the other hand, the sub-module related to the terminal switches are solved separately.

Finally, the unavailability of the ladder architecture is obtained by the following relationship:

$$U_{ladder1} = 1 - A_{sub1} * A_{sub2} \tag{5.7}$$

where A_{sub1} is the availability obtained solving the Markov model in Figure 5.4 c) and the A_{sub2} is the availability obtained solving the Markov model in Figure 5.4 b) and d).

For instance, for the considered failure rates and repair rates, availability of 0,851 and MTBF of 56 931 hours is obtained, which is slightly higher than the ring architecture.

2° case

Figure 5.5 a) shows an example of a connection of a ladder architecture in the second case where source and load belong to different steps of the ladder.

In particular, in this case, a connection fault occurs in the following conditions:



Fig. 5.5 Markov model of the Ladder architecture in the second case: source and load behave to different steps of the ladder.

- 1. a fault on a terminal switch of source or load;
- 2. a fault on both IN and OUT switches of the source or the load
- 3. a fault on IN-IN or OUT-OUT relays together with all the external branches

Based on these assumptions, two independent sub-modules are identified in the DFT of this connection. The first relates to the terminal switches. The corresponding Markov model is depicted in Figure 5.5 c). The second relates to the other two fault causes. The corresponding sub-module is depicted in Figure 5.5 b). Since the external branches are independent of the IN and OUT switches, they can be treated separately in a sub-sub-module as depicted in Figure 5.5 d).

Then, the model is solved recursively. First, the sub-sub-MC related to the External branches is solved, and an equivalent failure rate λ_{eq} is calculated. Then, the sub-MC in Figure 5.5 b) is solved by using the retrieved λ_{eq} and the unavailability U_{sub2} of the sub-MC is obtained.

On the other hand, the terminal relay MC in Figure 5.5 c) is solved independently retrieving its unavailability U_{sub1} .

$$U_{ladder2} = 1 - \left[(1 - U_{sub1})(1 - U_{sub2}) \right]$$
(5.8)

By solving this model, availability of 0,8397 and MTBF of 52 400 hours is obtained, very close to the first connection case.

5.2.3.3 Crossbar-based Architecture

Finally, the reliability of the proposed crossbar-based DCMG architecture, including the repair of components and online operations, is evaluated. As for the ladder architecture, we examine two different connection cases: 1) source-load connected to the same crossbar and 2) source-load connected to different crossbars. For instance, the connection between Battery 1 (B1) and DC Load 2 (DL2) is considered for the first case, as shown in Figure 5.6 a) and the connection between Battery 2 (B2) and DC Load 2 (B2) is considered for the second case, as shown in Figure 5.7 a).

 1° case

In the crossbar-based architecture, we can distinguish two types of switches: terminal switches that permit the connection EP -> DCMG and interconnection switches that are used to connect the crossbars. On the other hand, Internal busses are used for the energy sharing between EPs connected to the same crossbar and External busses are used to create inter crossbar connections.





In this use case, a connection fault occurs in the following conditions:

- 1. A fault on all terminal switch of source or load. Notice that the crossbar-based architecture has more than one terminal switch per EP. This improves the reliability of the connection because of the redundancy of the most critical component.
- 2. if each bus presents at least a terminal relay in fault && all the other crossbar ports present at least a fault each.

Based on these assumptions, the Markov model of the crossbar-based architecture is retrieved as shown in Figure 5.6 b). As for the case of the ladder architecture, the crossbar also presents an independent sub-MC representing the state of the other ports of the crossbar as shown in Figure 5.6 d). In this work, other ports refer to the ports of the crossbar not directly involved in the source-load connection.

Then, the obtained Markov model is solved hierarchically. First, the sub-MC related to the other ports of the crossbar is solved, and its equivalent failure rate λ_{eq} is retrieved. Second, by using the λ_{eq} , the overall MC in Figure 5.6 b) is solved and the availability $A_{crossbar1}$ of the connection is retrieved.

For instance, for the considered failure rates and repair rates, availability of 0,9873 and MTTF of 774 319 hours is obtained, which is several orders of magnitude higher than the ring and ladder architecture.

2° case

Figure 5.7 a) shows a schematic of the second connection case. Here, the Markov model depends on how the crossbars are interconnected. Then, a connection fault occurs in the following conditions:

- 1. a fault on a terminal port (both terminal switches of source or load);
- 2. interconnection ports of the crossbars of source and load are in fault;
- 3. interconnection ports of intermediate crossbars (if any) allowing the crossbars of the source and load to connect are at fault.

This case is more complicated to solve because there is a lot of dependency between modules, and the number of operating scenarios increases.

The Markov model of the crossbar-based architecture in case 2 is retrieved, as shown in Figure 5.7 c). The crossbar2 architecture presents an independent sub-MC representing the state of a crossbar port, as shown in Figure 5.7 b)

Then, the obtained Markov model is solved hierarchically. First, the sub-MC related to a port of the crossbar is solved, and its equivalent failure rate λ_{eq_P} is retrieved. Second, by



Fig. 5.7 Markov model of the Crossbar-based DCMG architecture: source and load are connected to different crossbars.

using the λ_{eq_P} , the overall MC in Figure 5.7 b) is solved and the availability $A_{crossbar2}$ of the connection is retrieved.

For instance, for the considered failure rates and repair rates, availability of 0,989 and MTBF of 919 209 hours is obtained, which is several orders of magnitude higher than the ring and ladder architecture.

Table 5.1 reports the availability and MTBF results of the architectures of the DCMG benchmark.

Architecture	Availability [%]	MTBF [hours]	MTBF Gain [%]
Ring	71,1	24 567	
Ladder1	85,1	56 931	+132%
Ladder2	83,97	52 400	+113%
Crossbar1	98,73	774 319	+3052%
Crossbar2	98,9	919 209	+3642%

Table 5.1 Availability and MTBF comparison of the DCMG benchmark architectures when considering constant-failure rates.

5.3 Non-constant Failure Rates

In the last section, we analyzed the dynamic reliability of the DCMG benchmark presented in Chapter 3, considering components with constant failure rates. This hypothesis is valid when components are regularly replaced before they reach their wear-out phase. However, when a lighter maintenance policy is used, a more accurate model of the device reliability is needed. In fact, the failure rate of devices increases once they reach their wear-out phase, as depicted in Figure 5.1.

Therefore, in this section, we are going to study the availability of the three architectures of the DCMG benchmark considering the ageing of components. Several methods are found in the literature in order to retrieve the availability with non-constant failure rates. First, the Time-Inhomogeneous Markov Process can be used. In this case, the transition matrix is calculated each time step in order to obtain the transient behaviour of the availability of a system. The limitation of this method is that it is not possible to consider all possible scenarios because possible scenarios are infinite as detailed in [17]. Then, an approximation is needed. For instance, in [17] just two scenarios are considered: the case of no fault in the time interval considered and the case in which just one fault occurs in the considered time interval. In fact, if the probability of having one or zero faults in that time interval is high compared to the sum of probability of all the other scenarios, the obtained model represents a good approximation that permits to determine the transient behaviour of the availability of a system.

Another approach to retrieve the availability of a system with non-constant failure rates is the Monte Carlo simulation [1]. In fact, knowing the reliability function of each component, one can sample this function by random draft in order to retrieve the Time To Fault (TTF) of that particular instance. The same process is applied to retrieve the Time To Repair (TTR) when a fault occurs on a component. Then, once the TTF and TTR of each component are retrieved for the overall simulation time, the system's state in each time step can be retrieved. Another advantage of the Monte Carlo simulation is that it can simulate any reliability function. However, the drawback of this method is the computational burden it takes to obtain the reliability metrics such as availability, MTBF and MTTR.

In this thesis, Monte Carlo simulation is used to evaluate the case of non-constant failure rates. Moreover, when a large pool of availability results is obtained from these simulations, statistical inference can be performed to retrieve the statistics. For instance, using a simple mean and variance estimator, a Gaussian function of each reliability metric is obtained, thoroughly describing the system's availability.

In this particular analysis, just switching devices are considered, but the study can be extended when also including busses and power converters.

5.3.1 Monte Carlo simulation

As said above, the failure rate of an electronic component follows the bathtub curve as shown in Figure 5.1. In particular, in the third phase - the wear-out phase - the failure rate increases due to the ageing of the devices. For instance, in the case of electronic components, the mathematical function that best models the probability density function $(f_W(t))$ in this phase is the Weibull function defined as:

$$f_W(t) = rac{eta}{\eta} \left(rac{t}{\eta}
ight)^{eta - 1} e^{-} \left(rac{t}{\eta}
ight)^{eta}$$

where β is the shape parameter, and η is the scale parameter. Then, the corresponding reliability function can be retrieved by applying the definition as follows:

$$R_W(t) = 1 - \int_0^t f_W(\tau) d\tau = e^{-} \left(\frac{t}{\eta}\right)^{\beta}$$

Finally, the non-constant failure rate during the wear-out phase can be derived as:

$$\lambda_W(t) = rac{f_W(t)}{R_W(t)} = rac{eta}{\eta} \left(rac{t}{\eta}
ight)^{eta-1}$$

Figure 5.8 a), b) and c) show the $f_W(t)$, $R_W(t)$ and $\lambda_W(t)$ of a Weibull distribution function with parameters $\beta = 5$ and $\eta = 10$.



Fig. 5.8 Wear-out phase characteristics: a) probability distribution function, b) reliability, c) failure rate.

5.3.1.1 Series connection

As an example, the series connection of power converters that links a source-load pair in a microgrid system is considered, as shown in Figure 5.9 a). In particular, a connection between a battery and a DC load is analyzed. Converter 1 adapts the voltage and current

levels of battery 1 to the DC Bus voltage. On the other hand, Converter 2 adapts the DC Bus voltage level to the load voltage requirements.



Fig. 5.9 Example of series connection source-load in a microgrid system and its corresponding Markov model.

The reliability of components in series is calculated as follow:

$$R_S(t) = R_{Conv1}(t) * R_{Conv2}(t)$$
(5.9)

where R_{Conv1} and R_{Conv2} are the reliability of Converter 1 and Converter 2, respectively. If constant failure rates are assumed for Converter 1 and 2, the failure rate of the series connection λ_S can be calculated as follow:

$$\lambda_S = \lambda_{Conv1} + \lambda_{Conv2}$$

where λ_{Conv1} is the failure rate of the Converter 1 and λ_{Conv2} is the failure rate of the Converter 2. Then, considering a constant repair rate μ , the connection can be modelled by a CMP as shown in Figure 5.9 b). Then, steady-state probabilities of each state can be calculated, which bring to availability *A* and unavailability *U* of the series connection. Finally, the MTBF of the connection can be calculated, as seen in the last section.

On the other hand, when non-constant failure rates are considered, the last model cannot be used. In fact, in this case, the failure rate of each converter varies in time according to equation 5.3.1. In the case of a single component, steady-state availability and unavailability can be calculated with the following equations.

$$A = \frac{\eta \Gamma(1 + 1/\beta)}{\eta \Gamma(1 + 1/\beta) + 1/\mu}$$
(5.10)

$$U = \frac{1/\mu}{\eta \Gamma(1 + 1/\beta) + 1/\mu}$$
(5.11)

With the chosen parameters, it gives A = 88,9% and U = 11,1% for a single converter. Even if the two converters are equal, when the first failure and repair occurs, the two converters become different in terms of reliability. Therefore, the calculation of the availability must consider the ageing of each component of the series individually. Figure 5.10 represents this scenario. In fact, at $t = t_F$ a fault occurs on converter 2 and then it is replaced. Then, for $t > t_F$, the converter 1 continues his history, and converter 2 (that has been replaced) start a new history.



Fig. 5.10 Reliability of a series connection of two converter in case of non-constant failure rate.

A method to retrieve the reliability indexes in this scenario is shown in Figure 5.11



Fig. 5.11 Monte Carlo model for the availability evaluation of a series connection considering the wear-out phase.

The model starts in state 1 where the series connection of the two converters shown in Figure 5.9 is a safe state. A time step of 1 hour is considered for the Monte Carlo simulation.

Then, every simulated hour, the new failure rate is calculated as the sum of the failure rates of each converter. When a fault occurs, the system goes in State 2 that corresponds to the faulty state of the series connection. If there are no redundant paths that can be used to make the connection between the battery and the load, then the system goes in Connection Fault as shown in Figure 5.11.

Then, the faulty converter enters the repairing process that replaces the faulty component with a constant repair rate μ . Once the component is replaced (see Figure 5.11 at $t = t_F$), the failure rate of the repaired converter returns to $\lambda(0)$ following the Weibull characteristic while the other converter continues its history from $\lambda(t_F)$.
Figure 5.12 shows the Monte Carlo simulation results of a series of 2, 6 and 12 components, respectively. Components have the same characteristics in terms of failure rate and repair rate. Moreover, the availability is evaluated at incremental time steps of 1 year over a range of 76 years.



Fig. 5.12 Availability calculation of a series connection of a) 2, b) 6, and c) 12 components.

Results show that the availability of a repairable system reaches a steady-state value after a settling time. In fact, in the beginning, the availability is high because all components are new. Then, once components start to reach their wear-out phase and fail, the availability stabilizes to a value that indicates an equilibrium between failures and repairs in the system.

5.3.1.2 Redundant Connection

The other necessary connection type to analyze in a distribution system is the redundant connection. In fact, redundancy acquires a critical added value in repairable systems. Then, we examine, here, the redundant connection of two converters with non-constant failure rate, as depicted in Figure 5.13. In particular, a converter is used at a time, and the other is in cold standby redundancy configuration [16]. Cold standby redundancy means that the converter wakes up only when a fault occurs on the first converter; otherwise, it remains in standby mode. In this scenario, the connection source-load is modelled by the Markov model shown in Figure 5.13.

In this model, only one converter is active at a time. Moreover, we consider the converter in standby as if it is not ageing because it is not functioning. On the other hand, the active



Fig. 5.13 Cold standby redundant connection - Markov model and failure rate.

converter is functioning and then subjected to the ageing process modelled by the Weibull function. Furthermore, the model considers that a fault can occur just on the active converter. Finally, when a fault occurs on a converter, we consider that the control system can activate the other converter in a short time that permits the load to continue working properly, without interruptions. In fact, the fault recovery operation described in Chapter 4 is used for this purpose.

In this scenario, when a fault occurs, the faulty converter is replaced by the standby converter that starts its history following the Weibull function as shown in Figure 5.13. In the meanwhile, the faulty converter can be repaired with a constant repair rate μ . If the repair rate is much larger than the failure rate of the converter, very high levels of availability are obtained.



Fig. 5.14 Monte Carlo simulation results of a redundant connection vs steady state-value from from algebraic formulas.

For instance, if the converters are identical, with availability A and unavailability U, the total availability of the cold redundant connection A_{TOT} is calculated as the probability of

success of the first converter plus the probability of fault of the first converter multiplied by the probability of success of the second converter during the reparation time described by MTTR. The latter corresponds to the reliability of the converter calculated in MTTR $R_2(MTTR)$. In mathematical terms, we have:

$$A_{TOT} = A_1 + U_1 * R_2(MTTR)$$

This result is significant because it says that in reparable systems where components have a cold standby redundancy, we can adjust the availability of the connection by acting on the mean time to repair MTTR or repair rate. The lower the MTTR, the higher the availability of the connection. Figure 5.14 shows the results of a Monte Carlo simulation on a redundant connection. As expected, the redundant connection increases the availability of the connection that here passes from 88.9% to 99.4%.

Moreover, the steady-state value of the availability is evaluated by algebraic formulas, which give a close value of 99.2% as shown in red dotted line in Figure 5.14.

5.3.2 Monte Carlo simulation of the DCMG architectures

The method presented is then applied to evaluate the availability of the DCMG benchmark considering the repair of components and non-constant failure rate. A repair rate of 1/10000 repairs/hours is used in the following simulations.

5.3.2.1 Simulation Results

The wear-out phase of switches is modeled by a Weibull function with parameters $\beta = 5$ and $\eta = 10$. Figure 5.8 shows the probability density function, reliability and failure rate of the switches.

Moreover, a time step of 1 hour is considered such that the failure rate in [failures/hour] becomes the failure probability over 1 hour. Then, each time step, the algorithm calculates the failure rates of each component (or group of components). Afterwards, a random draft is compared to this probability, which gives the component's state (or group of components). For instance, if the generated random number is higher than the calculated failure rate, the component (or group of components) is OK. On the other hand, if the random number is lower than the calculated failure rate, then a failure occurs on that component (or a group of components).

Once a fault occurs, the repair process starts. Therefore, the random draft is now compared to that component's repair rate to determine whether it will be repaired or not. Then, this process is repeated for each component (or group of components) in the model.

Finally, once the state of each component (or group of components) is determined, the connection state is retrieved by combining the elementary component states, following the DFT of that connection.

Ring

The ring architecture considering the aging of components is considered here. Figure 5.15 b) shows the obtained Monte Carlo model.



Fig. 5.15 Monte Carlo model of the ring architecture.

In particular, three independent groups of components are identified in this architecture, corresponding to the three basic elements simulated by Monte Carlo simulation. The first (1° branch) represents the series of $2n_1$ switches belonging to the shortest semi-arc of the ring as shown in Figure 5.15 a). The second (2° branch) represents the series of $2n_2$ switches forming the longest semi-arc of the ring. The third (Term. relays) represents the two terminal switches connected to the source and the load.

Then, by using Monte Carlo simulation, these groups are tested each hour by a random draft. Depending on their state, the overall connection state can be retrieved. For instance, in this case, if the two semi-arcs of the ring are at fault, this brings to a connection fault, as shown in Figure 5.15 b). Furthermore, to consider the ageing of components, their failure rate is updated each hour, following the Weibull function of the device.

In order to have a consistent result, the simulation is repeated 100 times for each considered interval of time. Figure 5.16 shows the results of the Monte Carlo simulation of the ring architecture. In particular, the graph on the top-left represents a 3-D histogram of the availability varying the simulation time between 5 years and 75 years. Then, using these raw data, an inference is performed using the Gaussian function as a model, which gives the graph on the top-right. The third graph on the bottom represents a 2-D (x-y axis) view of the



Fig. 5.16 Results of the Monte Carlo simulation on a ring DCMG architecture with nonconstant failure rates.

second graph. The ring architecture presents an availability of 36.88% and an MTBF of 5 842 hours from these simulations and with the considered parameters.

Ladder1

The ladder architecture in the first connection case is evaluated here, considering the ageing of components. In this connection case, the source-load pair belongs to the same step of the ladder, as shown in Figure 5.4 a). Figure 5.17 shows the Monte Carlo model of this architecture.

In particular, there are eight independent groups of switches that are simulated at different levels of redundancy. The level of redundancy is represented by the black dotted lines in Figure 5.17. For instance, the IN1, OUT2, and Terminal switches are the first simulated groups, corresponding to the first shortest path between the source-load pair. In case of fault on the Terminal relays, the model does not present another redundant path for these devices, and then a connection fault occurs. On the other hand, in case of fault on the IN1 Branch, the first redundant level starts to be simulated, represented by the IN2 and OUT1 branches



Fig. 5.17 Monte Carlo model of the ladder architecture in the connection case 1.

groups of switches. This is repeated until the last level of redundancy is consumed, which brings to a connection fault.

The red and yellow lines correspond to the paths to a critical fault. Then, a critical fault occurs if all the conditions crossed by these lines are true. For instance, in Figure 5.17, the first red line brings to a fault if the IN1 and OUT1 branches are Not OK (NOK).

Figure 5.18 shows the simulation results of this model.

As before, the simulation is repeated 100 times for each simulation period in order to increase the accuracy of the results. The top-left graph represents a 3-D histogram of the availability varying the simulation time from 5 to 75 years. Then, the top-right and bottom graphs represent the inference of the Monte Carlo simulations for each simulation period in 3-D and 2-D view, respectively. These graphs show the transient behavior of the availability before reaching a steady-state value.

From these simulations and with the considered parameters, the ladder architecture in the first connection case presents an availability of 67.19% and an MTBF of 20 479 hours.

Ladder2

The ladder architecture in the second connection case is analyzed here, considering the aging of components. In this connection case, the source and load belong to different steps of the ladder, as shown in Figure 5.4 a). Then, the Monte Carlo model becomes the one depicted in Figure 5.19.

In this model, nine independent groups of switches are simulated. Then, depending on the state of each group, the system state is retrieved. For instance, in Figure 5.19, the paths that bring to a critical fault are highlighted with red and yellow lines. The difference in colour serves to distinguish between the several fault conditions that involve the same devices. In fact, depending on the combination of fault on the four IN and OUT groups of switches, the



Fig. 5.18 Monte Carlo simulation results of a ladder architecture in the first case with non-constant failure rates.



Fig. 5.19 Monte Carlo model of the ladder architecture in the connection case 2.

level of redundancy changes. For example, the first red line that involves a consecutive fault of IN1 and OUT1 has redundancy level 1. On the other hand, the yellow line that involves a consecutive fault on IN1, IN2, EXT1, EXT2, EXT3 and EXT4 has a redundancy level of 5.

The Monte Carlo simulation of this model is performed 100 times per time interval, and results are represented in Figure 5.20.



Fig. 5.20 Results of the Monte Carlo simulation on a ladder DCMG architecture in the connection case 2 with non-constant failure rates.

As before, the top-left graph represents the histogram of the availability for the 100 simulations per time interval. More specifically, for each time interval (represented by the Simulated time in Figure 5.20), a histogram of the 100 simulations performed on this model is retrieved, which represents the availability result over the 100 simulations.

Then, the inference of these results is made for each simulated time by using a Gaussian function as a model. The top-right graph represents the obtained result. Finally, the graph on the bottom of Figure 5.20 represents a 2-D view on the x-y axis of the second graph that shows the evolution of the availability in time. A steady-state availability of 60,71% is obtained from these results corresponding to an MTBF of 15 451 hours.

Crossbar-based 1

The crossbar-based architecture in connection case 1 is evaluated here, considering the ageing of components. Figure 5.21 shows the Monte Carlo model used for these simulations.



Fig. 5.21 Monte Carlo model of the crossbar-based architecture in the connection case 1.

In particular, eight independent groups of switches are simulated. The first four represents the terminal switches of the source and load named as R_{TS1} , R_{TS2} , R_{TL1} and R_{TL2} . The combination of fault on these devices can bring to a critical fault as in the case of the couples $(R_{TL1} - R_{TL2})$ and $(R_{TS1} - R_{TS2})$ identified by the red lines. Otherwise, the other combinations have redundancy level 5 and need more consecutive elementary faults to bring to a critical fault, as depicted by the orange lines in Figure 5.21.



Fig. 5.22 Results of the Monte Carlo simulation on a crossbar-based DCMG architecture in the first case considering non-constant failure rates.

Figure 5.22 shows the results of the Monte Carlo simulation. In particular, 100 simulations per time interval are performed in order to have quite good accuracy of the availability result.

Therefore, the histogram of the 100 simulations for each time interval is depicted in the 3-D graph in Figure 5.22 top-left. Moreover, the inference is performed on these results by using a Gaussian function and results are shown in the other two graphs in Figure 5.22 in a 3-D and 2-D view, respectively.

Finally, a steady-state availability of 95,53% is obtained that corresponds to an MTBF of 213 714 hours.

Crossbar-based 2

The crossbar-based architecture in the connection case 2 is evaluated here, considering the ageing of components. Figure 5.25 shows the Monte Carlo model used for these simulations.



Fig. 5.23 Schematic of the crossbar-based architecture in the connection case 2.

In particular, 16 groups of independent switches are simulated. The first four represents the switches of the terminal ports of source and load, as shown in Figure 5.23. If a fault occurs of one of these ports, the system goes directly in connection fault.

On the other hand, the other twelve groups represent the switches of the interconnection ports between crossbars. In fact, there are two interconnection paths named *INT*1 and *INT*2 that permit the interconnection of the source's crossbar to the load's crossbar, as shown in Figure 5.23. The first is accessed by the ports *INT*1_*L* and *INT*1_*S*. The second is accessed by the ports *INT*2_*L*, *INT*2_*L*_*M*, *INT*2_*S*_*M* and *INT*2_*S*. Then, the Monte Carlo model represents the state of the switches of these ports.

Figure 5.24 shows the results of the Monte Carlo simulation. In particular, 100 simulations per time interval are performed in order to have quite good accuracy of the availability result.

Therefore, the histogram of the 100 simulations for each time interval are depicted in the top-left graph of Figure 5.24. Moreover, the inference is performed on these results by using



Fig. 5.24 Results of the Monte Carlo simulation on a crossbar-based DCMG architecture in the second case with non-constant failure rates.

a Gaussian function and results are shown in the other two graphs in Figure 5.24 in a 3-D and 2-D view.

Finally, a steady-state availability of 96,57% is obtained that corresponds to an MTBF of 281 545 hours.

Table 5.2 summarizes the obtained results of availability and MTBF for the three DCMG architectures of the benchmark when considering the ageing of components.

Table 5.2 Availability and MTBF results of the DCMG benchmark when considering nonconstant failure rates.

Architecture	Availability [%]	MTBF [hours]	MTBF Gain [%]
Ring	36.88	5 842	
Ladder1	67.19	20 479	+250%
Ladder2	60.71	15 451	+164%
Crossbar1	95.53	213 714	+3558%
Crossbar2	96.57	281 545	+4719%



Fig. 5.25 Monte Carlo model of the crossbar-based architecture in the connection case 2.

As we can see, when considering the repair of components, the advantages of the cold redundancy amplify. In fact, the crossbar-based architecture that presents redundancy in any of its devices has gains ranging from +3558% to +4719% with respect to the ring architecture, here considered as a reference.

5.4 Discussion

In this section, the availability of the DCMG benchmark is evaluated in two hypotheses: components with constant failure rates and components with non-constant failure rates. The

former is evaluated by using Markov chains, while the latter is evaluated using Monte Carlo simulation. In both cases, the crossbar-based architecture presents a gain of at least +3000% in MTBF with respect to the ring architecture. This is due to the fully redundant configuration and to the fact that the repair of components is considered in these models.

Chapter 6

Case Study: DC Powered Data Center

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Chapter 3, 4 and 5 have demonstrated the advantages of the proposed crossbar-based DCMG architecture with respect to the ones presented in the DCMG benchmark. In fact, the crossbar network's dynamic reconfiguration and bus redundancy result in higher flexibility, reliability, and resilience. Moreover, some technical solutions are presented in Chapter 4 regarding the control and some dynamic operations.

This chapter applies the crossbar-based architecture to a more realistic case study: a DC-powered data center. In fact, a data center needs continuous maintenance in order to guarantee the required availability. By exploiting the flexibility of the crossbar network, the availability and MTBF of actual implementations can be improved.

We then apply the crossbar-based architecture to this application, and we analyze the reliability metrics of the obtained power distribution system. Due to the complexity of these systems, Monte Carlo simulation is used to assess the reliability analysis.

6.1 Data Center Power Supply and Distribution System

The Global Data Center Authority "Uptime Institute" has defined a standard to classify data centers in terms of availability. Tier I, II, III and IV are defined in this standard, where Tier IV represents the highest availability. The classification levels of data centers represent a certification of design. A tier is another way of saying "level of service". Some of the metrics used to define Tiers are redundant electrical path for power, up-time guarantee, and concurrent maintainability, to name a few.

For instance, a Tier IV data center implementation uses redundancy in the whole power supply and distribution chain to obtain the required availability and Quality of Service.

On the other hand, the energy consumption in a data center, such as servers, lighting, cooling systems, are in some way controllable. In fact, typically, distributed computing system operations such as workload migration permit moving the workload from a server to another in the network. Consequently, the energy consumed by each server can be controlled at runtime. However, workload migration needs hundreds of TB of data transfer through the network, which is an energy and time-consuming task.

The power supply and distribution system play an essential role in determining the availability of a data center. In fact, most of the failures in a data center are related to issues in the power supply and distribution system. Therefore, backup energy sources such as Diesel generators and Uninterruptible Power Supply (UPS) are used to overcome these issues and increase the data centre's uptime.

Even though the latter improve the availability of the energy sources ready to supply the data center, the power distribution system remains centralized. This means that the power of these sources conveys into a common point (i.e. ATS) and, from there, it is distributed to the loads. Then, the advantages of having a set of potentially distributed sources are partially lost because of the classic tree-like power distribution system.

In this scenario, we believe that a re-configurable power distribution system in which sources are spatially distributed around the data center increases the system's availability, allows for ease of renewable sources integration, and improves the scalability of the data center.

We then explore, here, the availability of a classic DC-powered data center and compare this basic architecture with a data center powered by a crossbar-based DCMG.

First, the basic architecture of a DC-powered data center is analyzed in terms of reliability. Then, a first re-design is performed to improve the system's availability by introducing redundancy on critical components, which is equivalent to a Tier IV data center.

Then, the crossbar system and the dynamic reconfiguration is applied to the basic architecture, and the availability of the obtained system is calculated. In particular, three use cases are studied: the isolated crossbar architecture, the linear crossbar architecture and the matrix crossbar architecture. The advantages and limitations of these architectures compared to the basic ones are then highlighted.

Finally, two maintenance strategies are applied to the obtained architectures in order to obtain maintenance costs.

6.2 DC-powered Datacenter Architectures

In this section, the benchmark of power supply and distribution architectures is presented. Then, reliability analysis is performed on this benchmark and results are reported.

6.2.1 Basic Architecture

The architecture of a DC-powered datacenter is presented in [58] and reported in Figure 6.1.



Fig. 6.1 Topology of a DC-powered datacenter.

The architecture of a DC powered datacenter is presented in Figure 6.1 complies with a Tier IV standard. In fact, two independent power supply paths bring energy to the data center racks. Each independent path has a utility powering the UPS and a backup Diesel Generator. Both UPSs have their battery bank. Then, the two independent paths bring the energy to two busses at 400V DC that can be connected by using the Normally Opened Circuit Breaker (N/O CB) as shown in Figure 6.1. Here, redundant, isolated DC/DC converters bring the energy to a 48V DC bus. Finally, terminal DC/DC converters transform the 48V DC into the needed voltage of all IT devices (from 1V to 12V DC).

Furthermore, additional battery banks are placed at this level to provide another temporary backup energy source in case of fault on the above mentioned DC/DC converters. In fact, if a fault occurs on the 400V-48V DC/DC converters or the 400V Bus, these battery banks could keep the system up for a few hours. This permits to quietly shut down non-critical servers, keeping ON the more critical ones for a longer time. However, a fault on the 48V DC Bus or the terminal DC/DC converters forces all attached servers down instantaneously, with consequent loss of data and reduction of quality of service.

Therefore, further redundancy and crossbar-based architecture are applied to the 48V level to overcome the aforementioned issues.

In order to do that, a first qualitative analysis of the basic architecture is done. It results that the most critical component in this architecture is the terminal DC/DC converter that converts the 48V level to the 1V/...12V, as shown in Figure 6.1. In fact, a fault on this converter cannot be restored by any of the presented online operations. Moreover, in this case, the attached rack is forced to go down with consequent damage and data loss.

6.2.2 Modified Architecture

Then, the first action to improve the availability of the system is the addition of a redundant power converter on each load point. This has been done in the "modified architecture" as shown in Figure 6.2.

Then, the modified architecture is used in this work as a reference to estimate the real gains of having a crossbar system. This architecture is a needed intermediate step before arriving at the crossbar-based architecture. In fact, the crossbar-based architecture already presents redundancy on the terminal devices (i.e. switches and power converters) that connects to several busses of the crossbar.

Although the redundancy of the terminal DC/DC converter improves the availability of the data center, another critical point is found that limits the availability of the system, which is the 48V DC Bus. In fact, a fault on the latter directly brings down all the connected racks.



Fig. 6.2 Topology of a DC-powered data center modified with a redundancy on the terminal DC/DC converters.

6.2.3 Crossbar-based Architecture

Therefore, the crossbar-based architecture is applied at the 48V DC bus level to avoid the above-mentioned issue. In this use case, the bus at 48V is replaced by a crossbar system to provide bus redundancy and segmentation. In this way, a bus fault is no longer critical because of the presence of more busses per crossbar. Moreover, the topology reconfiguration provided by the crossbar system permits isolating a faulty bus or device and let the rest of the system work properly.

Three crossbar-based architectures are identified depending on how crossbars are interconnected: isolated, linear and matrix architectures.

6.2.3.1 Isolated crossbars

The first is the isolated crossbar-based architecture. In this case, a crossbar is inserted in the place of the 48V DC bus in order to interconnect the rack, a battery backup system and the main power distribution line (AC grid, Diesel Generator). Moreover, no connection is provided between crossbars.

Figure 6.3 shows a schematic of the obtained architecture.

The redundancy on the 48V bus provided by the crossbar improves the availability of the system. However, the potential of the crossbar is not fully exploited because of the missing



Fig. 6.3 Topology of a data center powered by a crossbar-based DCMG in isolated configuration.

connections between crossbars. Moreover, in this architecture, each crossbar needs a battery backup source. Therefore, the implementation costs are high for this architecture.

6.2.3.2 String of crossbars

The second proposal is the crossbar string architecture. In this case, crossbars of different racks are connected to form a string of crossbars, as shown in Figure 6.4.



Fig. 6.4 Topology of a data center powered by a crossbar-based DCMG in linear configuration.

In particular, two ports for each crossbar are dedicated to crossbar interconnection. Thanks to this interconnection between crossbars, the number of battery backup sources can be reduced. In fact, by using the power crossbar network, a battery backup source can reach any rack connected to the crossbar string.

This architecture improves the availability compared to the isolated crossbar architecture. Compared to the isolated crossbar-based architecture, implementation costs are also reduced due to the reduced number of battery backup systems. However, the flexibility of the interconnection system provided by the crossbar network is still limited by the fact of having just two ports dedicated to crossbar interconnections.

6.2.3.3 Matrix of crossbars

The third crossbar-based architecture interconnects the rack's crossbars to form a matrix. In this case, four ports of each crossbar are used for crossbar interconnections. Moreover, the battery backup sources of energy can still be reduced because of the flexibility of the power distribution network that enables energy sharing at the 48V level. Figure 6.5 shows a schematic of this architecture where four battery backup sources are placed to supply 12 racks in case of fault of the main supply line.



Fig. 6.5 Topology of a data center powered by a crossbar-based DCMG in matrix configuration.

Then, if a fault occurs on the 400V DC Bus or a 400V/48V DC/DC converter, the four battery banks route their energy through the crossbar network to reach the racks that need energy. Compared to the other architectures, the flexibility of the crossbar network can be

exploited to reduce the number of battery backup sources. This modular approach permits to easily scale up the data center and the power distribution system by simply adding other racks and sources to the crossbar network by using other crossbars.

Moreover, renewable energy sources can be easily integrated into such systems in conjunction with batteries by simply adding them to the crossbar network, in the same way, it happens in a microgrid.

6.3 Reliability Analysis

In this section, the reliability of the presented architectures is evaluated by means of Monte Carlo simulation. Since we consider repairable systems, the availability and MTBF metrics are extracted from these simulations. All components present in the architecture are simulated. For instance, components such as busses, circuit breakers, power converters, utility grids, diesel generators, battery are modelled in terms of reliability. Moreover, reliability data of these components are retrieved from the IEEE Gold Book [2] and reported in Table 6.1.

Component	Inherent Availability [%]	MTBF [hours]	MTTR [hours]
Utility grid	99.9705	8030	2
Diesel Generator	99.8	2000	4
Circuit Breaker	99.9998	1 x 10 ⁶	2
Bus Bars/ Switch Board	99.99979	4.38×10^6	9
3-phase Rectifier	99.99	20000	2
DC-DC Converter	99.996	50000	2
Lead Acid Battery	99.9967	240×10^3	8

Table 6.1 Component reliability data in [2].

The Monte Carlo simulation is performed with the same method as explained in Chapter 5. To summarize, each time step (of 1 hour) random drafts determines the state of the components of the system by comparing them with the failure rate of each component. Once the state of each component is computed, the system state is obtained as a combination of component states. This process is repeated for the whole simulation time. In particular, a simulated time of 5 million hours is chosen for the following simulations. Furthermore, 100 simulations per architecture are performed to retrieve an accurate result with a certain level of confidence.

Another aspect to consider in the Monte Carlo model is the limited amount of energy contained in a battery backup source. In fact, when a fault occurs on the main supply line, a

battery backup system takes over continuing supply the racks. However, the energy present in the batteries is not infinite. Therefore, it is assumed that the energy present in a battery backup source is sufficient to supply the system for two hours after a fault condition. After two hours, if the connection with the main supply line is not restored, a system connection fault occurs.

6.3.1 Crossbar controller

Furthermore, crossbars need a digital controller in order to work correctly. In fact, if a distributed control method is chosen, each crossbar has its controller. Locally, the crossbar controller commands the crossbar switches and communicates with the connected power converter controllers to manage the energy sharing between EPs. Globally, the crossbar controller communicates with the adjacent crossbar controller and with the central controller to manage the PDs creation and guarantee the security of the power distribution system.

Even though this aspect improves flexibility and adds smart functionalities to the power network, controllers can fail, compromising the security of the power network. Therefore, the crossbar controllers are accounted for in the Monte Carlo model to have more realistic results.

In particular, it is assumed that if the controller is not working, crossbar switches return to their initial states. In this sense, the initial state of the crossbar should be able to guarantee minimal functionality to the power network. Therefore, the crossbar switches connected to Bus 1 are Normally Closed (N/C), while all the other switches are Normally Opened (N/O). In this way, if the controller fails, the EPs can still use the Bus 1 of the crossbar and share their energy on this bus. On the other hand, when the crossbar controller is functioning, the EPs can use the other available busses of the crossbar to make their connections.

6.3.2 Aging of Power Converters

Several methods can be found in literature to calculate the reliability of power converters [17][63]. For instance, in [66], the failure rate of electrolytic capacitor and switching devices (SDs) in their useful life and wear-out phase is used to estimate the reliability of a power converter. Indeed, from field data, these are the most critical components in the power converter operation in terms of reliability. The following relationship then calculates the reliability of a power converter:

$$R(t) = exp(-\int_0^t \lambda_C(\tau) d\tau)$$

where R(t) is the converter reliability at instant t and λ_C is the failure rate of the converter which is calculated as:

$$\lambda_C = \lambda_{C-useful} + \lambda_{C-wear}$$

where $\lambda_{C-useful}$ and λ_{C-wear} are the failure rates of the converter in the useful life and the wear-out phase and are calculated as:

$$\lambda_{C-useful} = \sum \lambda_{Caps-useful} + \sum \lambda_{SD-useful}$$

 $\lambda_{C-wear} = \sum \lambda_{Caps-wear} + \sum \lambda_{SD-wear}$

where $\lambda_{Caps-useful}$ and $\lambda_{Caps-wear}$ are the failure rates of an electrolytic capacitor in the useful life and wear-out phase, respectively and $\lambda_{SD-useful}$ and $\lambda_{SD-wear}$ are the failure rates of an SD in the useful life and wear-out phase, respectively. Several models permit the calculation of the failure rates of electronic components by considering the environmental variables, the operating conditions, and the mission profile. The FIDES approach [28], for example, provides a straightforward method for estimating the constant failure rate of electronic components. Moreover, it considers the statistics of possible failure causes according to the physics of failure analysis. In particular, the failure rate of SD can be obtained by the following formula:

$$\lambda = \prod_{PM} \prod_{Process} \lambda_{Phy}$$

where λ_{Phy} is calculated by the following relationships for SD and capacitors:

$$\lambda_{Phy-SD} = \sum_{i}^{Phases} \left(\frac{t_{annual}}{8760}\right)_{i} x \begin{pmatrix} \lambda_{0TH} \Pi_{Thermal} \\ +\lambda_{0TCyCase} \Pi_{TCyCase} \\ +\lambda_{0TCySolder joints} \Pi_{TCySolder joints} \\ +\lambda_{0RH} \Pi_{RH} \\ +\lambda_{0Mech} \Pi_{Mech} \end{pmatrix} x (\Pi_{Induced})_{i} x \left(\prod_{i=1}^{N} \frac{1}{2} \prod_{$$

$$\lambda_{Phy-Caps} = \lambda_{0Cap} \sum_{i}^{Phases} \left(\frac{t_{annual}}{8760}\right)_{i} x \begin{pmatrix} \Pi_{Thermo-electrical} \\ +\Pi_{TCy} \\ +\Pi_{Mechanical} \end{pmatrix} x (\Pi_{Induced})_{i}$$

where the failure rates λ_{0X} and the corresponding Π_X are provided in [28, p. 120] and [28, p. 138] for SDs and Caps, respectively. Moreover, t_{annual} is the time associated with

each phase over a year, Π_{PM} is the component manufacturing factor defined in [28, p. 104] and $\Pi_{Process}$ is a quality factor of the integrated circuit design and production process defined in [28, p. 117]. Finally, $\Pi_{Induced}$ is the induced factor, and *i* is the considered phase.



Fig. 6.6 DC-DC converter reliability characteristics: a) pdf, b) reliability function and c) failure rate.

In particular, in [17] the reliability function of a power converter for a DC Microgrid system is modelled by the above-explained method. A Weibull function with parameters $\beta = 3$ and $\eta = 8.5$ is retrieved for these power converters. Figure 6.6 shows the reliability characteristics of the modelled power converter.

In the following Monte Carlo simulations, power converters are modelled according to these functions.

6.3.3 Maintenance Strategies and Maintenance Costs

Finally, another factor that influences the availability and costs is the maintenance strategy. In fact, critical systems such as data center use strict maintenance strategies to increase the system's availability. These strategies lie in replacing components before they arrive at their wear-out phase. This facilitates the reliability analysis because, in this case, components can be modelled with constant-failure rates. On the other hand, this permits keeping the system always young, reducing the probability of a critical fault. However, strict maintenance policies translate into higher maintenance costs because more components are replaced over time.

Therefore, two maintenance strategies are evaluated in the Monte Carlo simulations to observe their effect on the system availability.

The first is a corrective maintenance policy. It consists in replacing components on fault, as shown in Figure 6.7 a). In particular, replacements are not scheduled, but they are performed randomly depending on component states. Therefore, this maintenance strategy leads to the worst-case scenario in terms of availability because nothing is done to prevent or

avoid components failures, which, occasionally, could bring the system down for a certain interval of time.



Fig. 6.7 Maintenance strategies used in the Monte Carlo simulations: a) corrective and b) preventive.

On the other hand, a preventive maintenance strategy consists in trying to replace a component before it is subjected to a fault condition, as shown in Figure 6.7 b). Usually, preventive maintenance strategies replace a component in correspondence with a pre-defined point on its reliability curve. In fact, the reliability curve of a component describes statistically how many devices over an initial population work after a certain interval of time. The BX (or "Bearing Life") is introduced in the research and industry field to identify the point on the reliability curve at which X% of devices over a population will fail. For instance, if we accept that just 10% of components may fail in our system, then the components must be replaced after a time on the reliability curve corresponding to 100% - 10% = 90%. Therefore, the availability of a system that applies a preventive maintenance strategy is improved with respect to a corrective one.

Usually, in critical systems such as a data center, the B10 point is used as a reference point to determine the useful life of a component. Then, in this thesis, the preventive maintenance strategy consists in replacing components when they reach the B10 point on their reliability characteristics. For instance, in the power converters described above, the B10 point corresponds to 35168 hours or four years. Then, a preventive maintenance strategy applied on these converters consists in replacing these components after four years of operation.

6.3.4 Simulation Results

The availability of the five presented architectures is evaluated here by using Monte Carlo simulation. In particular, the wear-out of power converters is considered, which is the weakest component in terms of reliability. The reliability characteristics of the power converter are represented in Figure 6.6. The other components are modelled by the data provided by the IEEE Gold book [2], reported in Table 6.1. Furthermore, the corrective and preventive maintenance strategies are evaluated in these simulations.

Table 6.2 reports the results of the Monte Carlo simulation on the five presented architectures when applying a corrective maintenance strategy.

In particular, the modified architecture presents a 4x gain in MTBF with respect to the basic architecture due to the redundancy on the terminal power converter. Then, the latter is considered as a reference to calculate gains of the crossbar-based architectures. For instance, the crossbar-based architecture presents an MTBF gain of 58,2% with respect to the modified architecture due to the redundancy on the 48V bus provided by the crossbar. Furthermore, the crossbar-based architecture in linear configuration increases by more than three times the MTBF. Finally, the interconnection of the crossbars in matrix configuration leads to an MTBF 4 times higher than the modified architecture, as shown in Table 6.2.

	Availability	MTTR	MTBF	Used	Relative
Architecture	[%]	[hours]	[hours]	DCDC	Gains
Basic					
Architecture	99,9963	2,18	59 294	227	
Modified Architecture	99,9996	10,04	2 511 107	226	Ref.
Crossbar-based Architecture (Isolated)	99,999836	8,66	3 972 300	226	+58,2%
Crossbar-based Architecture (Linear)	99,99991	7,37	8 204 911	303	+227%
Crossbar-based Architecture (Matrix)	99,99992	9,18	11 610 037	452	+362%

Table 6.2 Results of the Monte Carlo simulation using a corrective maintenance strategy

Notice that the number of power converters used along with the whole simulation increases in the case of the crossbar-based architecture linear and matrix. This is because the battery converter is included in this count. In fact, the model considers two battery backup systems for the linear crossbar-based architecture and four battery backup systems for the matrix crossbar-based architecture. Then, increasing the number of battery backup systems increases the number of power converters. On the other hand, all racks connected to the crossbar network (linear or matrix) use these battery backup systems. In the Isolated crossbar-based architecture, the battery backup system is used by just a rack. Instead, the number of racks connected to the crossbar network is higher in the linear and matrix crossbar-based architecture. Then, a more precise calculation would consider the resource sharing and divide the cost of the battery backup systems by the number of racks present in the crossbar network. For instance, if there are four batteries in a crossbar network containing 12 racks (as in the case of Figure 6.5), the cost related to the battery power converters is divided by 12, which gives a lower cost with respect to the isolated crossbar architecture.

Table 6.3 reports the results of the Monte Carlo simulation on the five presented architectures when applying a preventive maintenance strategy.

	Availability	MTTR	MTBF	Used	Relative
Architecture	[%]	[hours]	[hours]	DCDC	Gains
Basic	00 0088	2.68	221 181	137	
Alcintecture	<i>99,99</i> 00	2,00	221 101	437	
Modified Architecture	99,999685	8,5	2 700 404	475	Ref.
Crossbar-based Architecture					
(Isolated)	99,99983	9,6	5 690 662	435	+110%
Crossbar-based Architecture					
(Linear)	99,9999	8,24	8 499 196	588	+215%
Crossbar-based					
Architecture (Matrix)	99,999919	9,16	11 269 558	870	+317%

Table 6.3 Results of the Monte Carlo simulation using a preventive maintenance strategy

The preventive maintenance policy is used to obtain higher availability and MTBF with respect to the corrective maintenance policy due to the increased reliability of the components. This is especially true for the basic architecture because of the missing redundancy on the terminal power converter. In fact, in this case, the MTBF of the system applying a preventive maintenance policy is four times higher with respect to the same architecture when applying a corrective maintenance policy, as shown in Tables 6.2 and 6.3. This is because a fault on the terminal power converter leads directly to a connection fault. Therefore, if we increase the reliability of this component by applying a more strict maintenance policy, the MTBF greatly increases. However, the number of power converters used during the whole simulation has doubled, and consequently, the maintenance costs.

On the other hand, for the other architectures, due to the redundancy in all power converters, the use of a preventive maintenance strategy does not bring to great advantage in terms of availability with respect to a corrective strategy. This means that in repairable systems where all components have redundancy, a corrective maintenance strategy is sufficient to guarantee a good level of availability. Therefore, in such systems, maintenance costs can be reduced without affecting the availability of the system, as shown in Tables 6.2 and 6.3, comparing the number of used power converters.

Figure 6.8 shows the results of the Monte Carlo simulation on the five presented architectures when considering a corrective or a preventive maintenance strategy.



MTBF [hours]

Fig. 6.8 MTBF results of the five analyzed architectures using a corrective or preventive maintenance strategy.

6.4 Discussion

The outcomes of these simulations are, here, summarized. Despite the higher maintenance costs, a preventive strategy generally increases the availability of a system. However, when the repair is considered, and all components present cold redundancy, the gains of using a preventive maintenance strategy are negligible with respect to a simple corrective policy. The crossbar-based architecture helps to reach the fully redundant system by adding busses redundancy and reconfiguration to the power network. This leads to an MTBF 4x higher than a classical architecture.

Since a strict maintenance strategy such as the preventive one has no more effect on the availability results, a corrective maintenance strategy can be used. This has two important consequences. First, the use of a less strict maintenance strategy reduces the maintenance costs because a lower number of components are used over time. Second, the system becomes

more sustainable. In fact, a strict maintenance policy obliges to replace a component even if it can potentially live a more extended time. This increases the waste of electronic materials.

Furthermore, using the crossbar-based architecture in a data center power distribution system permits reducing the battery backup units. In fact, the flexibility offered by the crossbar network permits the route of the energy where needed.

Moreover, failures on a bus are no more critical in the crossbar-based architecture. In fact, the bus segmentation and bus redundancy offered by the crossbars permits, in case of fault, to isolate it and re-configure the power network to use another available bus. This greatly enhances the availability of the system, seen in Figure 6.8.

Finally, the use of the crossbar-based architecture permits easily scaling up the system by adding crossbars and other energy sources. Furthermore, the integration of RES in conjunction with ESS is facilitated in such architectures due to the topology reconfiguration. In fact, the topology reconfiguration permits the route of the RES energy to charge the most discharged ESS in the system while others stable sources supply the racks.

Chapter 7

Conclusions and Perspectives

Contents

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7.1 Conclusions

Energy Transition needs substantial changes in the way electricity is delivered from the producers to the customers. In fact, the ever-growing electricity demand of energy-hungry systems such as data centers, EVs is challenging the actual power supply and distribution system. The centralized generation paradigm where electricity is produced in a centralized facility and then transmitted over high voltage transmission lines could no longer withstand these growing demands.

On the other hand, the integration of an increasing number of renewable energy sources in the grid adds further variability that could impact the electrical grid's stability if the ratio of renewable and utility power approaches unity.

Therefore, existing power distribution systems need a complete redesign to face these needs without compromising the system's stability and security. We believe that the architecture of the power distribution system plays a key role in the resolution of the brainteaser mentioned above. In fact, in a scenario with all this heterogeneity in the energy players and variability in their energy production and consumption, the power grid's flexibility and smart control become fundamental to coordinate this massive energy traffic.

In this context, microgrids are a good compromise that permits the integration of more and more renewable sources and energy consumption and is not affected by the scaling of the distribution system. In fact, in microgrids, energy is produced and consumed locally, and the control is assigned to several controllers such that the complexity is divided. Moreover, because of the DC nature of most of the loads we use today, the DC microgrid is becoming the trend for future power grids. However, the static nature of most current architectures limits their flexibility in such heterogeneous and intermittent scenarios.

This thesis explores a novel approach referred to as "Software-Defined Power Domains" that relies on a power crossbar component. The solution makes it possible to set up arbitrary electrical topologies onto densely connected physical micro-grids. We improve state-of-the-art by proposing a system organization centered around this crossbar that enables software-defined electrical topologies with the corresponding digital control architecture that handles dynamic and transparent handover and fault recovery operation. This architecture promises a higher level of flexibility, reliability, resilience with respect to the previous ones.

A benchmark of DC microgrid architectures is used as a comparison to the proposed one. For instance, ring and ladder architectures have been identified as a reference to determine the gains in reliability, flexibility and resilience of the proposed architecture. In particular, some first static analyses are performed on this benchmark. First, a flexibility analysis compares the number of redundant paths each architecture offers to connect a source to a load. Second, a static reliability analysis is performed to retrieve the reliability functions of the three considered architectures. The classical reliability theory is used for this analysis. It shows a 2x gain in MTBF of the proposed architecture with respect to the ladder and a 4x gain with respect to the ring. This is due to the redundancy of the terminal connection offered by the crossbar system. In fact, other use cases have been analyzed that insert redundancy of the terminal switches for the ring and ladder architecture as well. Even though the ring and ladder reliability function approach the crossbar-based architecture with these modifications, the MTBF of the crossbar-based architecture is still higher. Finally, an efficiency analysis based on the power losses in the switches is performed. From this analysis, the crossbar based architecture, due to the redundancy and parallelism of busses, presents higher energy efficiency with respect to the other ones.

Then, dynamic operations have been explored in Chapter 4. In fact, the flexibility offered by the crossbar system is best exploited if there are dynamic operations that permit to switch topology without affecting the functioning of the system. For this purpose, the handover operation and fault recovery operations are presented in Chapter 4. The first is the operation that allows the dynamic topology switching. In fact, a transparent topology switching is obtained by synchronizing the operation of crossbar switches and power converters. PSIM simulator is used to validate this operation in an example scenario. The second is necessary in case of a fault condition. In fact, when a fault occurs on a component, the architecture should be able to detect the faulty device, isolate it and find a way to restore the system's functioning. Then, a fault recovery protocol is presented in Chapter 4 and simulated by using the PSIM simulator. In particular, two examples of fault are examined: a fault on a bus and a fault on an energy source. In both cases, the architecture and associated control system permits isolation of the fault and restoring the load's full functioning in few milliseconds.

Furthermore, a dynamic reliability analysis of the DCMG benchmark is performed in Chapter 6. In particular, this analysis differs from the first one of Chapter 4 because it considers the repair of components. In fact, a critical system fault usually occurs as a combination of more elementary faults that happen with their failure rates. Then, suppose the flexibility and redundancy of the architecture permit the recovery of this fault by reconfiguring the topology. In that case, the functioning of the system is not compromised during this period. Then, in this scenario, a critical fault occurs just when consecutive faults on all redundant paths provided by the architecture occurs before the reparation process finish. Since the system can be repaired, we are no longer interested in the reliability function but in the frequency at which a critical fault occurs, represented by the availability and MTBF.

First, constant failure rates are considered. In fact, if the components are replaced before they arrive at their end of life, their failure rate can be considered constant. In this case, Time-homogeneous Markov chains are used to evaluate the availability and MTBF. The Markov model of the DCMG architectures of the benchmark is described in Chapter 5, and results show the high gains in availability obtained by the crossbar system. In fact, when considering the repair of components, the gains of having redundancy of components amplify. For instance, the crossbar-based architecture presents an MTBF order of magnitude higher than the ladder and ring architectures thanks to the redundancy in the terminal devices provided by the crossbar system.

On the other hand, when less strict maintenance policies are used, Markov models are no more applicable. In fact, in this case, the ageing of the components have to be considered that let the failure rate increase after its useful life. Therefore, Monte Carlo simulation is used to analyze the case of components with non-constant failure rates. Results show that even when considering the ageing of components, the crossbar-based architecture presents the highest availability and MTBF with respect to the others of the DCMG benchmark.

Finally, the crossbar-based architecture has been applied to a more realistic case study: a DC powered data center. Several modifications to the standard IV Tier architectures have been made to improve the availability of these systems. For instance, the crossbar-based architecture is applied to the 48V Bus in order to provide Bus redundancy and topology

re-configuration. Since a non-constant failure rate is considered for the power converter, Monte Carlo simulation is used to evaluate the availability of such architectures. Moreover, two maintenance strategies are evaluated in order to estimate maintenance costs. The first consists of replacing the component when a fault occurs on it. The second consists in replacing the component when it reaches its end-of-life phase.

Results show that the crossbar-based architecture doubles the MTBF of a Tier IV data center when used in isolated mode. On the other hand, if crossbars are interconnected together in string or matrix mode, the MTBF reaches four times the value of the standard architecture.

Furthermore, using a strict maintenance strategy does not affect the crossbar-based architecture in terms of availability. This is because each component presents redundancy and that components can be repaired/replaced. Therefore, a less strict maintenance strategy can be used to halve maintenance costs and make these systems more sustainable.

7.2 Perspectives

This thesis proposes a novel DCMG architecture that enables the concept of Softwaredefined Power Domains. Advantages of this architecture in terms of reliability, availability, resiliency have been demonstrated along with this thesis. Moreover, some technical solutions are provided to manage the dynamic topology switching and the fault recovery operation. However, several challenges remain unsolved, making this architecture more attractive in the research and industry field. A list of these challenges is provided as follows:

Control

Although this architecture provides several advantages, the high flexibility poses a serious challenge in its control. This thesis has proposed a multi-level control method that permits the management of the control of the PDs separately in a distributed way. Moreover, the Master-slave control technique is used for the first level of control. However, the coordination of PDs (i.e. the creation, the decision-making protocol), the creation of independent, and the topology re-configuration algorithm in bigger implementations remain a challenge.

Security

On the other hand, the security of the system has to be studied more in deep. For security, we intend both cyber-security and power electronics security. The first acts on the digital control and communication system and protects the system from software or hardware cyber-attacks. The second act on the power electronic devices and protects people and electronic equipment from shock hazards.

Optimization

The high flexibility provided by the crossbar-based architecture opens an avenue for optimization techniques that minimize energy consumption, reduce energy costs, or increase the reliability of critical loads. In fact, based on energy demand and sources condition, the topology can be re-configured in order to reach one of the above-mentioned objectives.

Moreover, the use of machine learning in this architecture could be investigated. In this way, the network could learn from its past experiences and make the best decisions in order to reach a pre-defined objective.

Modelling

In this thesis, Monte Carlo simulation is used to estimates the availability of DCMG architectures when considering the repair of components and non-constant failure rates. This permits the evaluation of the power distribution system availability. However, this model does not give information about energy availability. Moreover, if RES are present in the system, this model does not estimate the overall energy production and consumption.

Therefore, a model that puts the system availability together with the energy availability of RES, ESS and consumption could better show the advantages of using a more flexible architecture such as the crossbar-based. For instance, in the case of computing systems, and energy-driven computing model has been proposed in [31][19] that merge the energy constraints of RES and ESS with the consumption of computing systems. On the other hand, a co-simulation framework has been realized in the course of this thesis that permits monitoring and control a cloud computing system, estimating its energy consumption [18].

Energy Discretization

A first attempt has been made in this thesis to discretize the energy into energy packets by the CEP control (see Appendix B). In the data domain, the advantages of transmitting data in packets have been widely discussed and reviewed. In fact, it permits maximizing the data traffic through the network by using routers. On the other hand, in the energy domain, the discretization of energy has not shown real advantages. This is because existing power distribution systems are centralized. Moreover, energy is a physical quantity that does not contain information. Then, transmitting it in a continuous way or packets seems to be equivalent.

However, in a scenario where the power distribution grid is fitted, and there are lots of EPs connected to it, energy distribution by energy packets could maximize the use of the power network [33].

Data Center powered by a Crossbar-based DCMG

With all considerations and analysis performed in this thesis, we propose, here, the architecture of a data center powered by a crossbar-based DCMG. Figure 7.1 shows a schematic of the implementation of data center supplied by a crossbar-based DCMG.



Fig. 7.1 Topology of a data center powered by a matrix crossbar-based DCMG with renewable energy sources.

In this architecture, RES and ESS are the predominant source of energy for the data center, and the utility grid with the backup diesel generator becomes the auxiliary power supply. In particular, the matrix of crossbar applied to the racks has several access points for the power suppliers. This improves the availability of the system with respect to classic implementations that convey the energy from several energy sources in a single point before distributing it again to the loads.

Moreover, the energy access points are connected between them by a ring of crossbars, as shown in Figure 7.1. In this way, energy can be shared between the Utility grid and ESS attached to the solar power plants so that ESS always presents a good amount of energy, even when there is no energy coming from the solar panels.

7.3 Publications

The list of publications includes:

National Conferences

 Francesco Di Gregorio, Abdoulaye Gamatié, Gilles Sassatelli, Arnaud Castelltort, Michel Robert. Exploration of Energy-Proportional Distributed Systems. 13ème Colloque National du GDR SOC2, Jun 2019, Montpellier, France.

International Conferences

- Francesco Di Gregorio, Gilles Sassatelli, Abdoulaye Gamatié, Arnaud Castelltort. A Flexible Power Crossbar-based Architecture for Software-Defined Power Domains. 2020 22nd European Conference on Power Electronics and Applications (EPE'20 ECCE Europe), Sep 2020, Lyon, France.
- Francesco Di Gregorio, Etienne Dupuis, Arnaud Castelltort, Gilles Sassatelli, Abdoulaye Gamatié. Versatile Software Framework for the Monitoring and Control of Distributed Computing Systems. 2nd International Conference on Embedded Distributed Systems (EDiS), Nov 2020, Oran, Algeria.

Forthcoming journal submissions

- 1. **Francesco Di Gregorio**, Gilles Sassatelli, Abdoulaye Gamatié, Arnaud Castelltort. Dynamic Operations in the Software-Defined Power Domains. (Under progress)
- 2. **Francesco Di Gregorio**, Gilles Sassatelli, Abdoulaye Gamatié, Arnaud Castelltort. Dynamic Reliability of a Reconfigurable DC Microgrid Architecture. (Under progress)
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Appendix A

DCMG Components Reliability

DCMG Components

In this section, the components of a generic DC microgrid are presented. As said, a microgrid is a heterogeneous set of sources and loads able to work in isolated mode or connected mode with respect to the main AC grid. In order to do that, power electronic circuits such as power converters, circuit breakers together with digital control and sensing are needed. Finally, if remote sensing and communication functionalities are added to the microgrid, it becomes a smart grid. In this thesis, the term microgrid is used even if smart functionality such as communication and remote sensing is used.

Power electronic devices are essential to control the power flow of these sources and loads, adapt voltages to a single common bus and protect the EPs from fault conditions.

Figure A.1 shows a schematic that represents the main power electronic devices and circuits involved in a DC microgrid.

Power converters

The role of power electronic converters is to provide power to the user in a suitable form at high efficiency. A power converter can convert alternating current (AC) into direct current (DC) and vice versa; change the voltage or frequency of the current or do some combination of these. For instance, a PV panel needs a power converter to adapt the solar panel's impedance to the DCMG and get the Maximum Power from the sun. In addition, they control the charging and discharging of batteries in systems where batteries are storage elements.

Finally, they can be used to inject the energy of the DCMG into the AC grid by transforming the DC current into an AC current synchronized with the AC grid waveform. Figure A.1 shows an example of DC-DC and AC-DC converter. The first is a bi-directional Buck-Boost



Fig. A.1 Schematic of the main components used to interface energy players to a DC microgrid.

converter used to charge or discharge the battery and adapt its voltage to the common DC Bus. The second is a bi-directional single-phase inverter used to inject energy into the AC grid or take energy from it. The latter needs a more complex control in order to synchronize its frequency and phase with the sine wave of the AC grid.

Common DC Bus

The common DC Bus is the most important part of a DCMG. In fact, all the energy exchanges between EPs passes through this bus. Then, if a fault occurs, all the EPs connected are involved in the fault that propagates through the power network. For this reason, protection devices are important in such systems in order to disconnect and isolate faulty devices and let the remaining part of DCMG work correctly. Even though busses usually present high reliability, a fault on them causes usually bring the whole DCMG down. Then, an accurate reliability model should take into account this component.

Electro-mechanical Circuit Breakers

An electromechanical relay is an electronic, low powered device used to activate a highpowered device. In distribution systems, relays protect feeders and system equipment from damage in the event of a fault by issuing tripping commands to the corresponding circuit breakers in order to interrupt the current produced by the fault.

Solid State Circuit Breakers

The solid-state breaker concept replaces the traditional moving parts of an electromechanical circuit breaker with semiconductors and advanced software algorithms that control the power and can interrupt extreme currents faster than ever before. Solid-state technology guarantees an extremely fast interruption and clears a fault in a few microseconds. In comparison, a mechanical circuit breaker with the same frame size takes a few milliseconds.

The common Bus plays an important role in a microgrid. Figure A.1 shows an example of a simple DC Bus connecting a battery to the AC grid. However, when the number of EPs connected to the same DC Bus increases, it takes different shapes depending on the topology (ring, ladder, mesh, etc.) and is usually segmented in more busses. For instance, the ring configuration always has two available paths available to connect a source-load pair. On the other hand, in ladder and mesh architectures, there are more available paths. Then, the flexibility of these architectures increases despite the increase of complexity in its control.

Finally, circuit breakers and busses permit the interconnection between these EPs and guarantees security. In fact, thanks to the reaction time of ms in the case of Electro-Mechanical Circuit Breakers (EMCB) or μs in case of Solid-State Circuit Breakers (SSCB), a fault is isolated before it can cause faults on the adjacent devices. Figure A.1 shows an example of the implementation of both types of circuit breakers. Researchers actively work on efficient algorithms to detect faults and on circuits capable of interrupting a connection quickly such that a fault does not propagate through the microgrid. These aspects are crucial, especially in DC microgrids, where no zero-crossing point increases the challenge in terms of security.

Reliability of electronic components

Electronic components are often concerned with random failures described by an exponential density function, f(t), as follows:

$$f(t) = \lambda e^{-\lambda t}$$

Figure A.2 shows the exponential density function for $\lambda = 1/130000 failures/hours$.

Since the integral of f(t) from $t = 0 \rightarrow \infty$ is unity, the probability of one or more failures from $t = 0 \rightarrow T$ is given by



Fig. A.2 Exponential density function of an electronic component.

$$F(T) = \int_0^T f(t)dt$$
$$F(T) = 1 - e^{-\lambda T}$$

The probability of success R is related by R = 1 - F, so

$$R(T) = e^{-\lambda T} \tag{A.1}$$

If the failure rate λ is constant then the equation for R(T) above will also give the probability of success for any time interval, T.

Three distinct phases can be identified in the lifetime of electronic components. Early in the lifetime of a device (Burn-in phase), failures are often due to initial weakness or defects, weak parts, bad assembly, etc. During the middle period of device operation, fewer failures occur, and the failure rate, λ , is constant with time. Since the cause of these failures is difficult to determine, these middle-life failures are characterized as random events. As the device wears out, the failure rate, λ , increases again. In a well-designed and tested device, the burn-in phase may be small or even nonexistent. For this static reliability analysis, we will make the usual assumption that our data reflects devices that are all in the normal, middle-life phase where failures are random, and their failure rate (λ 's) is constant.

Figure A.3 shows the typical Bathtub curve representing the failure rate of an electronic device during its lifetime. The vertical axis indicates the failure rate per operation. The horizontal axis indicates the number of operations. The burn-in, middle, and wear-out phases are denoted as I, II and III, respectively.



Fig. A.3 Typical failure rate curve of a relay.

The reliability of a device that meets the stated conditions is given by equation (A.1) where λ is the failure rate or the number of failures per unit time during the useful life and T is the time period involved. R stands the probability of success (no failures) for the time period T. Then, the unreliability or probability of failure is given by

$$F = 1 - e^{-\lambda T}$$

where λ and T are the failure rate and the interval of time, respectively, and F is the probability of failure during T.

Relays

The electrical life expectancy of general-purpose and power relays is generally rated to be 30,000 operations minimum, while mechanical life expectancy may be 1, 10, or even 100 million operations. Electrical life is rated so low compared with mechanical life because contact life is application dependent. The electrical rating applies to contacts switching their rated loads. When a set of contacts switches a load of less than the rated value, contact life may be significantly greater. For example, 25 amp, 240V AC, 80% of the contacts may be expected to switch such a 25 amp load in excess of 30,000 operations. However, if these contacts are used to switch, say, a 5 amp, 120V AC resistive load, life may be in excess of a million operations.

Rated electrical life also takes into consideration arc destruction of the contacts. By use of appropriate arc suppression, contact life may be lengthened. An arc will ignite if both minimum arc voltage and current are exceeded. However, there will be no arc if the load current at a given minimum arc voltage is less than the minimum arc current for that voltage.

Likewise, there will be no arc if the load voltage (or counter emf) is less than the minimum arc voltage of the contact metal. As stated, an arc may be necessary in order to burn off the contacts any sulfidation, oxidation or contamination. However, by its very nature, an arc is destructive. The arc should be suppressed as quickly as possible for maximum contact life as soon as it ignites. Such arc suppression may be accomplished using techniques presented in this application note.

A spark may occur between separating contacts at the voltage and current values of less than those required to ignite an arc. This spark is a capacitive discharge and is weak compared with an arc. Even so, the spark may be sufficient to keep sulfidation, oxidation, and contaminates from building up on the contacts. (Note: arc suppression has little, if any, effect on contact sparking.) Contact life is terminated when the contacts stick or weld or when excessive material is lost from one or both contacts, and a good electrical make is not possible. These conditions result from cumulative material transfer during successive switching operations and material loss due to splattering.

Solid state Circuit Breakers

Although conventional electromechanical circuit breakers have a proven record as effective and reliable devices for circuit protection, emerging power distribution technologies and architectures, such as dc microgrids, require improved interruption performance characteristics (e.g., higher switching speed). In combination with the latest developments of advanced power semiconductor technologies, the need for faster switching operation has spurred an increase in the research and development in the area of solid-state circuit breakers.

Power converters

Power converters are electronic circuits composed of several components such as capacitors, inductors, power switches, etc. Therefore, reliability evaluation of such devices is complex to evaluate and depends on many factors such as mission profile, operating conditions, temperature and humidity. In [65][64] the reliability of power converters for microgrid applications is evaluated using Model-Based System Engineering (MBSE) approaches. The MBSE approaches analyze, assess and enhance the converter reliability taking into

account the physics of failure mechanisms of its components. Moreover, the aging of critical components such as capacitors and power switches is taken into account in the model.

So far, the power switches and capacitors are known as the major source of failure in converters [82]. They are prone to random chance failures, which are typically modelled by a negative exponential distribution function. Furthermore, they are exposed to aging failures, which can be represented by a Weibull distribution function with an increasing failure rate.

In this thesis, both exponential and Weibull models are used. In fact, in the case of preventive maintenance strategy, components are replaced before they arrive in the wear-out phase. In this case, an exponential model is sufficient to study the reliability of the system. On the other hand, components are prone to the aging process when considering a corrective maintenance strategy. In this case, a Weibull function will be used to model its non-constant failure rate.

Appendix B

Constant Energy Packets Control

Another paradigm to control the proposed crossbar-based DCMG architecture is more linked to the data domain. In fact, data are transmitted in packets. This has a series of advantages and demonstrated better network use in terms of bandwidth, latency.

Moreover, taking inspiration from the data domain, a new paradigm can be introduced in the energy domain, where energy is transmitted in packets instead of continuous form. In this paradigm, loads have their energy buffer that permits collecting the energy needed to perform a specific task. An energy buffer consists of a capacitor or supercapacitor device that temporarily stores the transmitted energy and then uses it a second time to supply the computing system for the time it performs its task. A typical example could be a computing system. In fact, if we can estimate the quantity of energy needed to perform a task, the system could request this energy in advance and have a buffer able to store this energy before it uses it. In this way, energy is transmitted in a discrete form to be used just for task execution.

A novel control algorithm is designed in this thesis to adapt to this concept: Constant Energy Packet (CEP) control loop. In particular, the algorithm uses measurements from current and voltage sensors attached to the input and output of a power converter to determine the duty cycle and frequency needed to keep constant the energy packet transmitted each switching period. In this way, energy transmission can be estimated by counting the number of periods of the PWM signal. In the following part, this algorithm is explained in detail and simulated by using PSim simulator.

Constant Energy Packet Control Loop

A power converter is an electronic circuit that transforms the IV pair at its input to a desired IV pair to the output. For instance, a 20V battery that has to connect to a 48V DC Bus needs a power converter to transform the 20V of the battery into the 48V of the DC Bus. This is

done thanks to the charging and discharging of the inductance and capacitor of the power converter. Moreover, this process is regulated by a Pulse Width Modulation (PWM) signal applied on a switching device. Figure B.1 shows a representation of the PWM signal where Δt_1 is the interval of time in which the PWM is high and Δt_2 is the interval of time in which the signal is low.



Fig. B.1 Representation of the PWM signal.

Then, the duty cycle D and the switching frequency f_{SW} are derived with the following relationships.

$$D = \frac{\Delta t_1}{\Delta t_1 + \Delta t_2}$$
$$f_{SW} = \frac{1}{\Delta t_1 + \Delta t_2}$$

Most control algorithms applied to a power converter fix a switching frequency f_SW and regulate the duty cycle D in order to obtain the desired IV pair at the output. However, the relationship between the duty cycle and the output voltage or current is not always linear. For instance, in the boost converter, the relationship between the duty cycle and the output voltage is given by:

$$V_{out} = \frac{1}{1 - D} V_{in}$$

where V_{out} is the output voltage of the converter and V_{in} is its input voltage. Therefore, a simple control algorithm can lead to instability of the power converter, especially when the duty cycle is higher than 40 - 50%. Moreover, a fixed switching frequency limits the functioning range of the converter. In fact, for high load, the converter could benefit from a higher switching frequency that limits current oscillations on the inductance. Therefore, this work presents a novel distributed control method that varies the converter's duty cycle and switching frequency to adapt better to load conditions. The method is based on the fact that the energy packet transmitted from the input to the output is constant for each PWM period. In fact, knowing the input and output IV pairs, one can calculate the Δt_1 and Δt_2 of the PWM signal that allows keeping the transmitted energy packet constant. The advantage of this control technique is that the switching frequency varies according to the load level that increases the operating range of the converter. Moreover, a good load sharing between several sources controlled by CEP control is obtained by regulating the values of energy packets in the charge/discharge step. This can be obtained by a Low Bandwidth Communication (LBC) system that fine-tunes these energy packet values to obtain the best load sharing between the converters.

In order to explain the working principle of this control, the charge/discharge process in the inductance L and capacitance C_{out} in Figure 4.2 are examined. The Boost operating mode is considered in this work. In this operating mode, the switch M_1 is kept ON switches M_2 , M_4 are kept OFF, and the PWM signal is applied on M_3 switch. Figure B.2 shows the equivalent circuit during the charging and discharging step of the PWM signal.



Fig. B.2 Equivalent circuit of the DC-DC converter during the a) charging step and the b) discharging step of the PWM signal.

In fact, in the first phase, the energy of the battery is used to charge the inductance L (see Figure B.2 a)). In particular, the energy packet stored in the inductance during this period Δt_1 is given by:

$$\Delta E_L = \frac{1}{2} V_{BATT} \Delta t_1 \left[\frac{V_{BATT}}{L} \Delta t_1 + 2i(0) \right]$$
(B.1)

where V_{BATT} is the battery voltage, *L* is the inductance of the power converter, and i(0) is the current sensed into the inductance at the beginning of the PWM period. Then, at the end of the Δt 1 time interval, the current in the inductance can be estimated as follows:

$$i(\Delta t_1) = i(0) + \frac{V_{BATT}}{L} \Delta t_1$$

In the second phase, the battery continues to provide its energy, and the inductance releases the stored energy to the output to increase the output voltage. In particular, the energy transmitted during the time interval Δt_2 can be estimated as follows:

$$\Delta E_{C_{out}} = i(\Delta t_1) V_{DCBus} \Delta t_2 \tag{B.2}$$

where V_{DCBus} is the voltage measured on the DC Bus, and $i(\Delta t_1)$ is the inductance current at the end of the charging phase.

Then, imposing as objective the energy packets ΔE_L and ΔE_{Cout} , one can retrieve the time Δt_1 and Δt_2 by inverting equations B.1 and B.2, as follows.

$$\Delta t_1 = -\frac{Li(0)}{V_{BATT}} + \sqrt{\frac{L^2 i(0)^2}{V_{BATT}^2} + 2\frac{L}{V_{BATT}}\Delta E_L}$$
(B.3)

$$\Delta t_2 = \frac{\Delta E_{C_{out}}}{V_{DCBus} * i(\Delta t_1)} \tag{B.4}$$

This method is predictive because the duty cycle and frequency of the PWM signal are calculated based on an estimation of the evolution of the inductance's current. In fact, due to the high values of the switching frequency, a first-order model of the evolution of the current is sufficient to obtain an accurate estimation of the current.

Case Study

In order to test the performance of the proposed control algorithm, a case study is analyzed. In particular, two batteries of voltage level 23V and 17.8V are connected to a common DC Bus by their respective power converters. Moreover, the DC Bus voltage is kept to 25V by these two controllers, therefore working in Boost mode. Figure B.3 shows a schematic of the described case study.



Fig. B.3 Comparison between the performance of the Master/Slave control and CEP control.

In particular, the CEP control is compared with a classical Master-Slave control algorithm. The slave control gives a constant power of 200W. Moreover, the load is varied during the simulation from 900W to 100W in several steps. Then, results are shown in Figure B.4. Notice that at t = 0.08s the Master-Slave control brings the voltage at 30V because the Slave controller is providing more power than needed.



Fig. B.4 Comparison between the performance of the Master/Slave control and CEP control.

Observations

The CEP control is a distributed control algorithm that promises load sharing characteristics and generalized design. In fact, actual implementations use PI controllers to regulate the current and voltage of power converters. Moreover, the PI coefficients are designed to best adapt to the converter characteristics and load values. In fact, a PI optimized to a particular value of load could not work correctly if the load varies a lot from the reference value. On the other hand, a CEP control contains the physical model of the converter and adapts itself to a different condition. However, further investigation is needed in order to assess advantages and limitations of this control technique in a larger scenario.