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Review article

A review on control and fault-tolerant control systems of AC/DC microgrids

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ABSTRACT

Microgrids (MG) treat local energy supply issues effectively and from a point of view of the distribution grid, may be a power supply or virtual load. Despite holding a myriad of benefits, MGs also bear a set of challenges, including a higher fault rate. Currently, many articles focus on control techniques; however, little has been written about the techniques of control, hierarchical control, and fault-tolerant control (FTC) applied to MGs, which is the motive of this bibliographic revision on control systems. A brief comparison of the different approaches in the field of present-day research is carried out primarily addressing hierarchical control and fault tolerance. The objective of this investigation is to attract the interest of researchers to the field of control and fault tolerance applied to MGs, such as: modeling, testbed, benchmark systems, control and hierarchical control strategies, fault diagnosis and FTC.

1. Introduction

Distributed generation (DG) sources constituted by new renewable and non-renewable energy sources such as micro-turbines (MT), photovoltaic systems (PV), fuel cells (FC), and wind generators systems (WGS), propose a more efficient and cleaner technology which in turn are able to supply the growing demand for electricity in interconnected and islanded communities [1, 2, 3, 4, 5, 6, 7, 8].

Over the last three decades, emphasis in research has allowed significant and high-impact contributions in these areas mainly aimed at data acquisition, automation, and control of Microgrids (MG) [1, 9, 10]. MGs have become the latest attraction in the scientific community not only because of its ability of integrating the distributed generation into the Main Grid in a reliable and cleaner way (with the reduction of emissions), but also due to its high reliability and capacity to operate before natural phenomena. Consequently, MGs provide active distribution grids, less energy losses in transmission and distribution (T&D) and less time in its construction and investment [1, 6, 11, 12].

Despite the worldwide exponential growth in the implementation of MGs, there are still countless challenges in its design, control and optimal operation. For example [12], shows an overview of the integration of MGs into conventional electrical systems, its main problems and a summary of the most relevant research, including DGs, applications with energy converters, economic factors, operation and control, protection, and communications. Additionally, other topics such as: resiliency, power quality, application of power electronics, power management, voltage and frequency control, control of power electronic converters, modeling, analysis, testing, islanding modes, fault modeling, and fault analysis are shown in this paper aiming to provide a general vision of the research carried out to date. Rather, there are no research papers presently that summarize the fault tolerance applications applied to MGs.

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When designing a control system for a MG, several functions should be considered such as: the control for voltage and frequency stability, Plug and Play capacity of renewable energy sources, the compensation of voltage and frequency deviations produced by the primary control, electrical and thermal energy management, load management, the synchronization with the main grid. More recently, several research institutions have carried out research and development in the area of FTC for MGs [13, 14, 15, 16, 17, 18, 19]. Due to its multiple functions and the large number of solutions proposed in the literature, the design of control systems for MGs is a complex task [20].

In [21], the paper provides details of the tasks involved in control systems and main types of controllers. Additionally, the author describes the types of controllers used in existing MGs and proposes future areas for research including FTC applied to hierarchical architecture that is mostly dependent on intelligence implemented in control systems.

The standard control problem has the objective to find control laws according to a set of control laws U, so that the controlled system achieves the control objectives O, while its behavior satisfies a set of C constraint, therefore, the solution of the problem is completely defined by $<O, C, U>$ [22]. However, the FTC has as its objective to control the defectives system subject to faults in the plant (controlled system - MG). To achieve this, a change of the control law is necessary without having to change the plant that is in operation regime, or by using the reconfiguration of the system both for the control and the system (MG) itself [23].

Currently, the scientific and academic community lacks scientific publications that show a joint analysis of control techniques and strategies, hierarchical control and the FTC applied to MG AC/DC. For these reasons, the main objective for this literature review is to show researchers and academics (field analysis in control and fault tolerance for MGs), a joint analysis of the different scientific methods applied to control and fault tolerance of MGs. Furthermore, this investigation provides a description of the most relevant complementary investigations that have been carried out in areas related to modeling, dynamic identification, test bench, benchmark, fault and MG fault diagnosis.

This paper is distributed as follows: Section 2 (Electric Microgrid) explains important electrical characteristics of MGs and its architecture. Section 3 (Control Strategies) describe the main and most successful control strategies applied to the MGs. Within the subsections, details are given for the hierarchical control (3.1) and the Secondary voltage control (3.2). Section 4 shows the principal faults in the MGs. Section 5 analyses the fault tolerance scenarios and subsections 5.1, 5.2, 5.3, 5.4, 5.5 and 5.6 are devoted to: The problem, properties and requirements of systems subject to failure, security versus fault tolerance, fault tolerance techniques, impact of faults on the control problem and faut tolerant control strategies respectively. Finally, the conclusions are found in Section 6.

2. Electric Microgrids

MGs have become an attractive option to develop the integration of DG units in the Smart Grid (SG), reducing dependence on fossil fuels and increasing the efficiency of the electrical grid. In contrast, MGs have increased challenges due to the fast dynamics with short response time of DGs, inherent unbalanced nature of MGs, lack inertia and low energy storage capacity, high number and diversity of micro -sources, electronic power converters and other circuits/devices, the high degree of parametric uncertainties and high failure rates [9, 24, 25, 26, 27].

Figure 1 shows a basic architecture for an integrated MG into the electrical power system. As can be seen, the MG not only integrates the DG units, but also, it contains a series of systems and subsystems such as: energy storage, compensation devices, transformation devices, linear and non-linear loads in AC or DC [24]. The MGs can be integrated into the Main Grid through the Distribution Network Operator (DNO) in charge of the operational functions of the system and is responsible for the technical operation of multiple MGs [24]. Instead, the Market Operator (MO) is responsible for market functions [25].

MGs could be defined as:

> "…*electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded* …" [28].

MGs must be robust in order to control the voltage and frequency while having the capacity to protect the Main Grid and the loads connected to the various faults and cyber-attacks that are exposed [13, 24, 27, 29, 30]. In many studies, we can find a definition for MGs as small-scale types of SG. Considering also that MGs provide an interesting solution to improve energy flow in distribution grids which in turn reduces energy losses [5, 6, 21, 24, 27, 31, 32].

At present, studies related to resilience [16, 18, 33, 34, 35, 36, 37], and optimization of the Electrical Power System (EPS) and Energy Management Systems (EMS) have taken on important roles for the scientific community [38, 39, 40, 41]. Undoubtedly, MGs contribute in resolving such problems and play an important role in the new decentralized paradigm of SG. In this regard, MGs are key in the evolution of

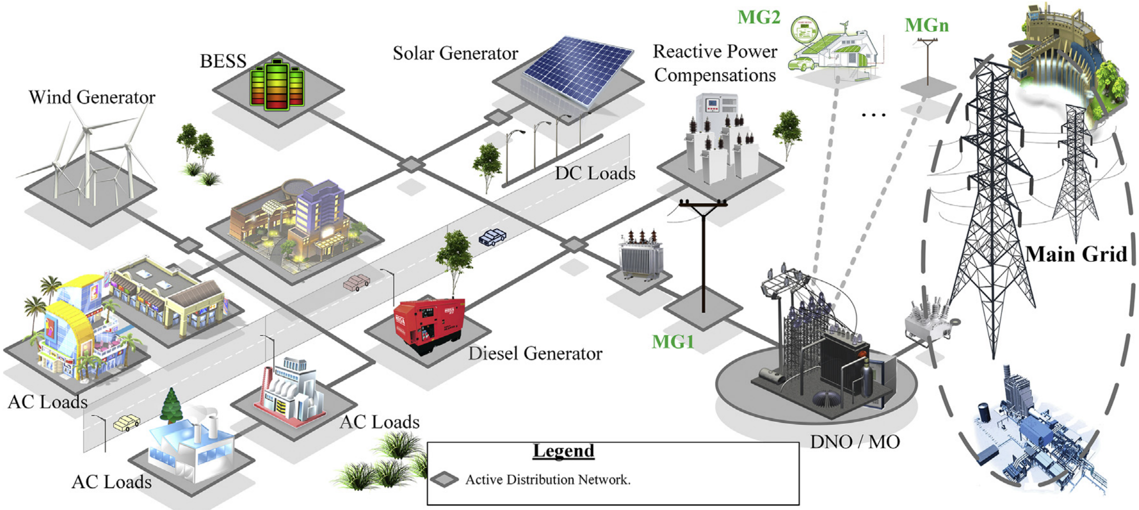

Figure 1. Electric microgrid.

SGs, thereby becoming ideal prototypes for either isolated sites or sites connected to the Main Grid systems.

2.1. Microgrid architectures

Figure 2 lists a summary of different topologies used in MGs. As shown, the MGs operate in parallel to the main electrical grid, in islanded mode (autonomous power) and in interconnected mode (uses the Main Grid reference) [1, 3, 6, 9, 11, 24, 27, 32, 42, 43, 44, 45].

Three important definitions considered around the MG are: Microgrid, Nanogrid and Picogrid. As shown in Figure 3 and described in articles [19, 24], three basic configurations are generally implemented for a MG: series (Figure 3a), parallel (Figure 3b) and switched (Figure 3c) [24, 27, 46].

The AC/DC Hybrid Microgrid (HMG) is the combination of the AC MG and DC MG configurations (Figure 4). This type of MG proposes a more optimal approach, combining the main advantages of MG in AC and DC MG [6, 24]. Features such as modeling, fault tolerance, design and control structures and scalability need more research to achieve better integration of distributed energy resources and HMGs to the Main Grid [24, 32, 47].

Most studies focus mainly on AC and DC MG architectures; however, the HMG represent a compelling solution and combine the advantages of the AC/DC configurations [24].

2.2. Microgrids modeling

To carry out the design, analysis, and implementation of control systems, and evaluate the effect of failures, the study of FTC methodologies is of vital importance to understand the dynamics of the different systems and subsystems that comprise the HMG. Additionally, if desired, the implementation of modeling methodologies [24, 48, 49]. Although MGs are considered as small-scale electrical systems, they present an extremely high dynamic complexity compared to the conventional energy system [49].

Particularly, when the MG operates in fault mode, major challenges are presented [50]. MG models are dynamic and can change depending on the configuration and type of topology which are the cause that different modeling methodologies are required. As described above, the models have to deal with rapid dynamic, short response time of DG, an inherently unbalanced MG nature, low energy storage capacity, lack of inertia, a high number and diversity of micro-sources, electronic power converters/other non-linear circuits, high degree of parametric uncertainty, and high fault rates [9, 25, 26, 27].

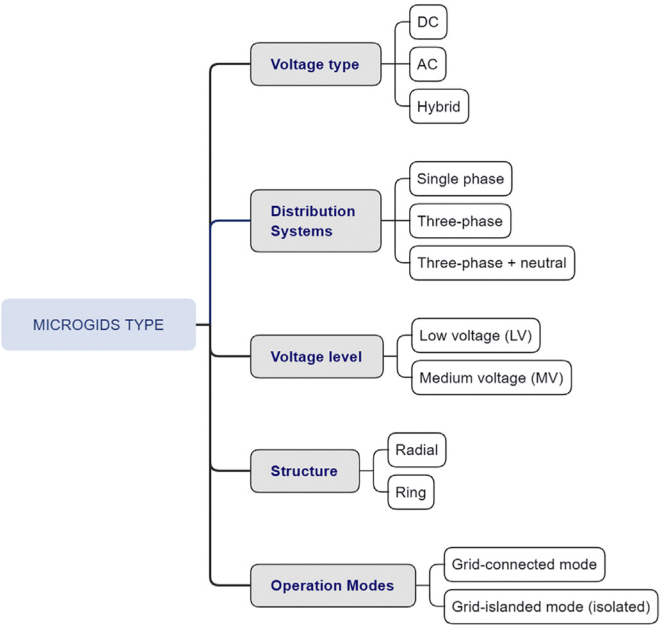

Figure 2. Typology.

Some authors seek to model each source of DG by obtaining a model of reduced order, linear time-invariant (LTI) with a constant of time and a factor of gain, nonetheless, neglects the dynamics of the grid. Authors usually represent MGs by means of a DC source connected to the main bus by means of a VSC, an RL filter, an elevator transformer, and a circuit breaker. In this way, a low-order dynamic model is obtained. This model can be easily used for analysis purposes and the design of its controllers [24, 25, 27].

On the other hand, there are also other approaches with inverter based DGs, for example, in [46], the full dynamic model of the entire grid was considered. In this way, the analysis of the MG system is divided into three subsystems: inverter, grid and loads. Included in the mathematical model of the inverter are the dynamics of the power source, the controller, the output filter, and the coupling transformer. Also, the status equations of the grid and loads are represented in one of four-quadrant (nQ) single inverters, assuming it as a common reference. Then, using the technique of transformation, the other inverters are transformed into nQ framework and models each subsystem in state-space combined in the common reference frame nQ. In [51], the authors developed a model in an LTI state space, then analyzed the eigenvalues to study the dynamic behavior of the MG. It should be noted that the linearization is carried out around a specific point of operation, therefore, if the operating conditions change, the model in the LTI state space should be obtained again.

On the contrary, other investigations as in [52] propose a model based on the nominal values of the set point of (frequency and voltage) of the inverters and the set points (active and reactive power) of the PQ inverters. This type of dynamic model, also obtained in state space, is useful for evaluating and improving the stability of small signals. In this sense, the model is helpful for designing and implementing hierarchical control systems with distributed or centralized secondary controllers. Obviously, it is necessary to consider the dynamic characteristics of storage systems.

Articles such as [48, 49] have also included new trends towards the modeling of AC/DC MGs using identification algorithms. In [48, 49] the authors propose a new method based on "Autoregressive with exogenous inputs (ARX)" and Petri nets (PN). In this paper, the nonlinear dynamic systems that make up the MG are analyzed as a black box and an algorithm capable of obtaining the linear models in the dynamic state-space of the DGs and others are shown. Finally, the method provides a bank of linearized models of the different operating points of the systems that make up MG, such as: VSC (unidirectional or bidirectional), BESS, PV, DiG, among others. The resulting models are very important because of they can be used to obtain the line parameters used in several techniques, for example, state estimation by using a Kalman Filter, adaptive voltage drop, identification and accommodation technique, virtual frame transformation methods, fault detection, and applications of Fault Tolerant Control.

2.3. Microgrids: “testbed” and “benchmark”

In [5, 24, 25, 31, 42, 46, 53, 54, 55, 56, 57] real MGs are implemented around the world including MG "benchmark" types, for example, the Consortium for Electric Reliability Technology Solutions (CERTS) in the US, NEDO in Japan, and others in Europe. The Office of Electricity Delivery and Energy Reliability (OE) is a program office within the United States Department of Energy. It focuses a large part of its efforts on the development and implementation of MGs for the year 2020 with its aim of increasing the reliability and resiliency of the distribution grid. The objectives of this program are to develop commercially-scaled MGs (capacity under 10 MW) that are capable of reducing the interruption time for the user by less than 2% and at a lower cost, additionally, reducing

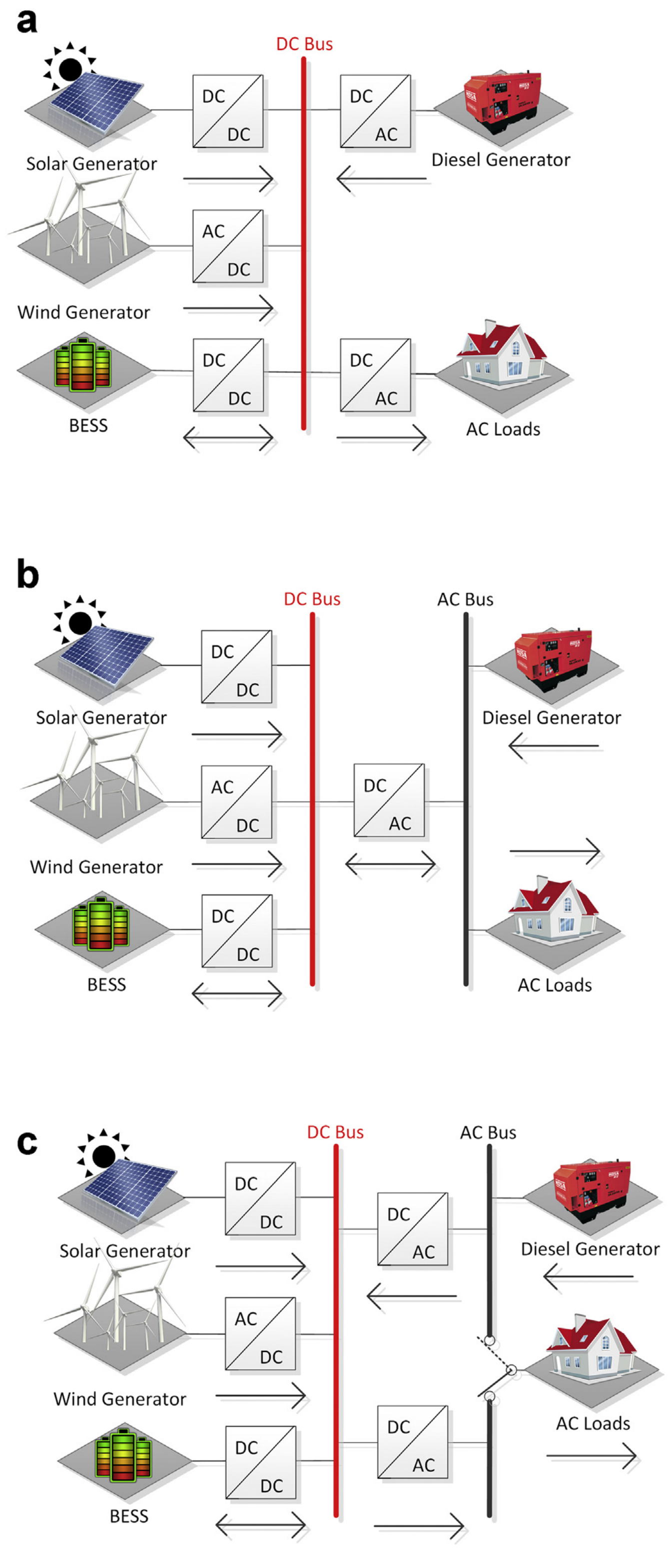

Figure 3. Hybrid AC/DC system configurations: (a) Series; (b) Parallel; (c) Switched.

emissions by more than 20%, and improving energy of EPS greater than 20% [56].

In [5] a more detailed summary on benchmark system types and testbeds can be found. The article composes a review of the MGs of existing testbeds around the world until the year 2011, including some simulated grids present in the literature and a table summary for comparison of the various testbed and benchmark systems. On the other hand, the study focused not only on the testbed systems, but also on available control options. Finally, the investigation also raises the need to create and develop a generic simulation model that reflects the properties and dynamics of current systems and MGs which would also facilitate research and evaluate the performance of transient stability, control and protection strategies, and the development of design standards and guidelines [5, 31].

Fortunately, with digital technology advancement and the evolution of computing algorithms, detailed test systems have been proposed for AC/DC HMGs based on simulations [24, 58] and that can be easily brought to a real-time simulation environment for OPAL- RT, RTDS, the Real-Time Target Machines series by Speedgoat among others.

Specifically in [24, 58] the authors propose a test model of an AC/DC HMG based on the IEEE 14-bar distribution system. This benchmark may be used as a base case for the analysis of power flow and quality variables related to the SG that contains distributed energy resources. This model developed in MATLAB/Simulink environmental simulation platform could be an important research tool for the analysis of HMG in its transition to Smart Grids (SG) and its dynamics.

3. Control strategies in microgrid

In general, the control problem is defined by an objective (*O*), a set of constraints (*C*), and a set of control laws (*U*). The main objective is to find an acceptable control law from a large set of existing control laws, so that the system/MG to be controlled is able to achieve its objectives while maintaining a behavior that satisfies the set of restrictions. The solution of the control problem can be defined by the triple $<O, C, U>$ [23].

As shown in Figure 5, various well-defined strategies for the design of MGs regulators and controllers can be found in the literature, wherein the vast majority are grouped in the centralized, distributed, hierarchical, intelligent and FTC control [1, 4, 9, 16, 17, 18, 19, 20, 25, 36, 44, 47, 53, 54, 59, 60, 61, 62, 63, 64, 65, 66].

There is no doubt that the MGs have different inherent characteristics (high degree of unbalance, diversity of DG units) that impose great challenges for the design of viable control strategies for all operational scenarios [66]. Not to mention that in order to complement the two modes of operation (islanded and interconnected to the Macrogrid) together with the transition requirement between these two modes further increases the complexity of the control scenario for the MG.

In the interconnected mode, each DG unit includes a local control (LC) or primary control that operates the unit as a function of current, frequency, and locally-sensing voltage. The secondary control system and energy management system (EMS) generate reference signals for the primary control of the DG, which are necessary in coordinating the operation of the DGs units and also have the option to obtain information from the MG [4, 9, 20, 44, 60, 61].

Control strategies for interconnected and islanded modes are often quite different; for instance, in the case of the MG connected to the Main Grid or Macrogrid all the DG units can work in PQ-control mode in contrast, in islanded mode, the set of DG units need to operate in the voltage control mode. In the case of the secondary control, the supervisory control and EMS determine the control instructions for the primary controllers or LC, the transition between controllers, and the administration of the MG [4, 9, 20, 44, 60, 61, 65].

In [20] the authors show several main roles of a control structure for MGs such as:

- Regulation of voltage and frequency profiles both in islanded mode and in interconnected operation mode.
- Adequate exchange of cargo and coordination and dispatch of DG sources
- Synchronization with the Main Grid or MG.
- Control of power flows between the MG and the main grid.
- Optimize the cost of operation of the MG.

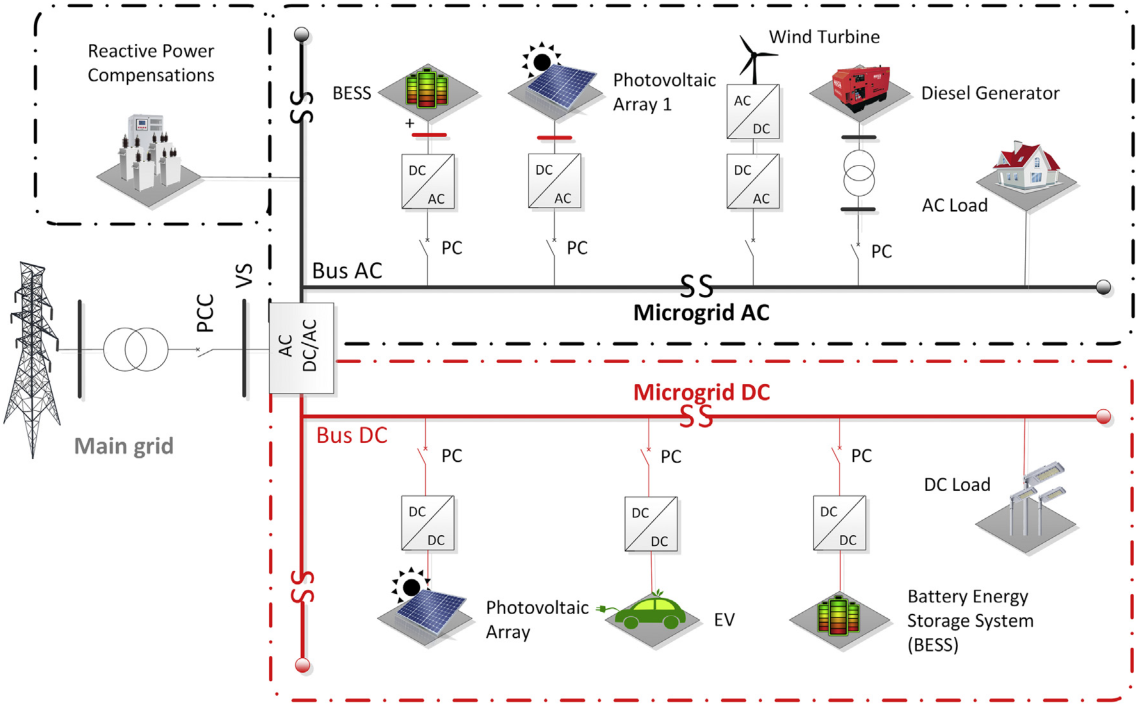

Figure 4. Hybrid AC/DC microgrid.

3.1. Hierarchical control

The two-level hierarchical control structure especially for the centralized approach, provides power, voltage, and frequency setpoints for LC or primary control. At this point, the bidirectional communication between MG and LC is of vital importance for the reliable and efficient operation, where faults in the communication channel between the MG and LC may interrupt the efficient electricity service and produce a blackout in the MG. The trend for decentralized secondary control is to develop a second level of control located in the LC, using local measurements to regulate the distributed energy resources (DER) units and not depend on the control action of a central controller remote.

However, the two level centralized control strategy benefits from: Online optimization of input parameters, operating setpoints, constraints, grid parameters, and information to estimate and prevent faults [20, 69]. On the other hand, the decentralized approach allows the decision-making in a distributed and local way with the possibility of plug and play. The decentralized control allows the design of interconnected local controllers, however its control decision depends on the local and global environment [65, 69, 70]. In the following figure, the structure of both controls can be appreciated (see Figure 6).

In Figures 7 and 8, a hierarchical control structure can be seen based on three main levels: primary (PC), secondary (SC) and tertiary control (TC). The primary control oversees the voltage and frequency stability once the MG isolation process has been carried out. This level includes the control hardware or also known zero level, and contains internal voltage and current control loops of the DG systems [4, 9, 20, 44, 60, 61, 65]. The primary control as a decentralized control is responsible for providing the references for the DG voltage and current control loops. These internal control loops are considered as zero level control and usually implements in PQ mode or voltage control [20, 65].

Figure 7 shows the centralized secondary control and the decentralized or distributed control in Figure 8 [44].

Some strategies in the primary control [44, 65] (mainly based on droop control) have a proper behavior at the time of its implementation in AC, DC and HMGs, however, these conventional control strategies also present disadvantages such as: inability to share non-linear load, load-dependent frequency deviation, compensation between voltage regulation and current exchange between converters, handling of system failure, among others.

In hierarchical control, the three categories (AC; DC; AC/DC-hybrid) of MGs follow a similar pattern. The main difference lies (case of the centralized approach) in the droop control characteristics involved in the primary control and the application of secondary and tertiary control for different operation modes.

The center of the hierarchical control system of the MGs is the EMS, but if the SC fails, the primary controllers will not work properly either and eventually cause instabilities and saturations in the control actions. In contrast, the distributed SC is less reliable than the centralized SC because LCs cannot function accurately due to the lack of information on the MG operational status.

Below is a comparison (Table 1) of the main characteristics of centralized and decentralized control architectures.

3.2. Hierarchical control: secondary voltage control

In the centralized second level of the hierarchy control, the SC is in charge of the reset of the voltage, product of the deviations caused by the primary control due to the re-synchronization of the MGs to the main grid. The SC should guarantee an optimal and coordinated operation of all the DG units [44]. At this hierarchy level, the dynamic response is slower than at the primary level, which justifies an uncoupled dynamics of the primary and secondary loops, and facilitates its designs individually [20].

The SC may be far from the DGs and from the point of common coupling (PCC). Therefore, as shown in Figure 9, the SC is connected through a low bandwidth communication link (LBCL) in charge of sending the PCC voltage information to the SC. In addition, the LBCL transmits the unbalance compensation reference for voltage unbalance compensation to the primary level, as shown in Figure 10.

The SC is responsible for processing information concerning frequency deviations and voltage error with the aim to produce control actions represented by:

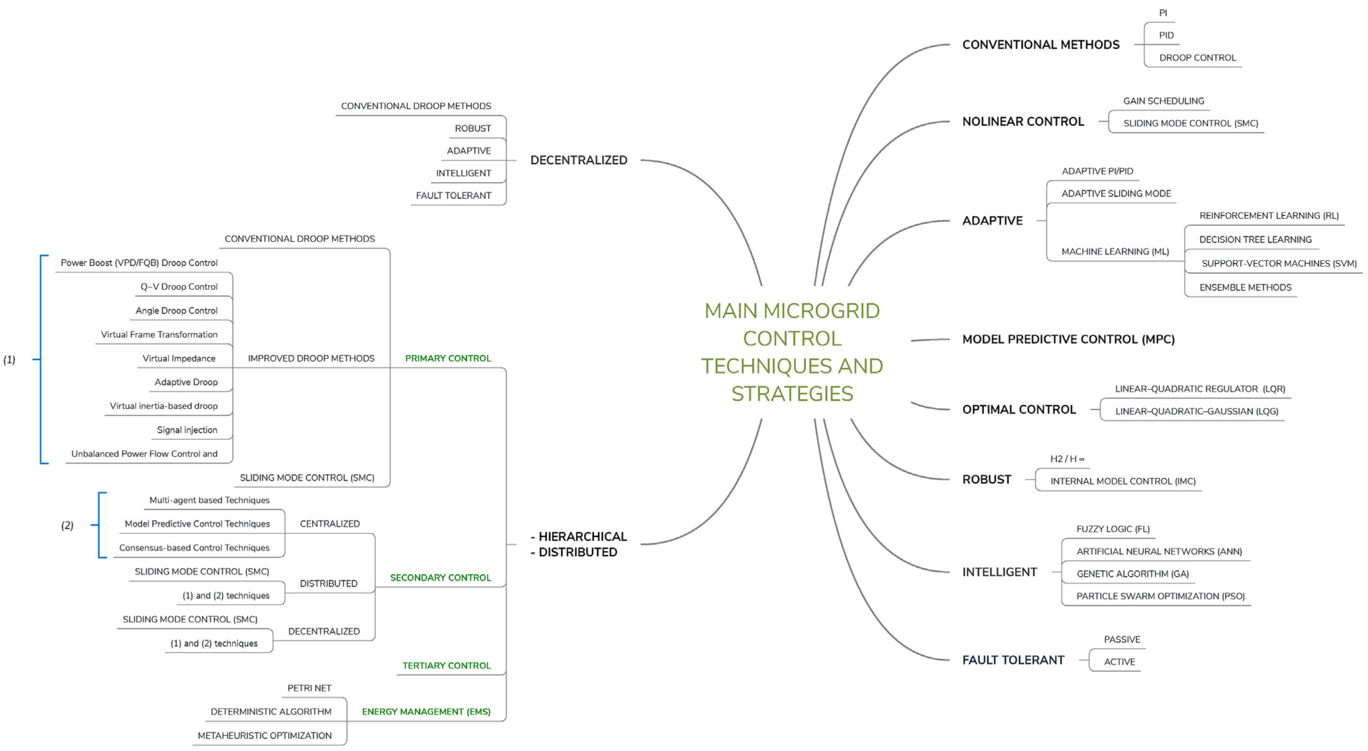

Figure 5. Main control strategies for Microgrids [1, 4, 9, 20, 25, 27, 44, 47, 60, 61, 63, 64, 65, 67, 68].

$$\delta\omega = H_{P\omega}\left(\omega_{mg}^{*}-\omega_{mg}\right)+H_{I\omega}\int\left(\omega_{mg}^{*}-\omega_{mg}\right)dt+\Delta\omega_{mg} \qquad (1)$$

$$\delta V = H_{PV}\left(V_{mg}^{*}-V_{mg}\right)+H_{IV}\int\left(V_{mg}^{*}-V_{mg}\right)dt \qquad (2)$$

Where:

$H_{P\omega}$, $H_{I\omega}$, H_{PV}, H_{IV}; are the controller's closed-loop transfer functions
V_{mg}, ω_{mg} is the output voltage and frequency in the AC bus respectively
$\omega_{mg}^{*}$and V_{mg}^{*} are the desired references (fixed for the case of islanded MG)

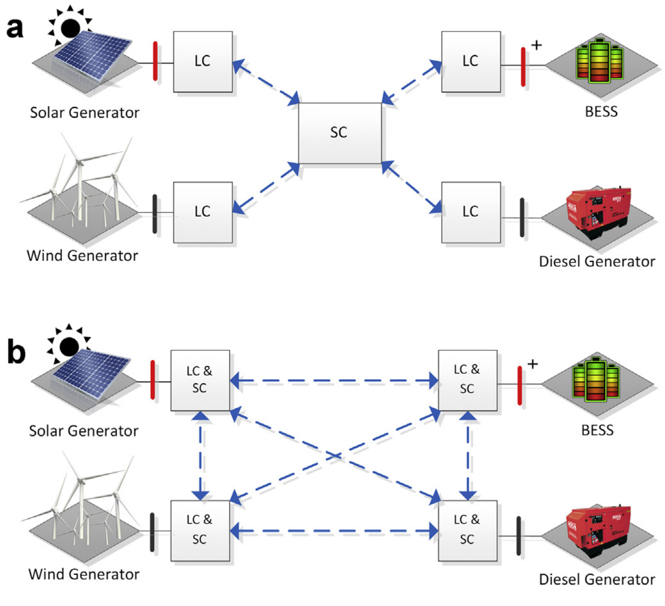

Figure 6. Secondary Control: (a) centralized; (b) decentralized.

δV and $\delta\omega$; is the correction in voltage and frequency
$\Delta\omega_{mg}$ is considered frequency controller in (1) to facilitate synchronization of the MG to the main grid. In the islanded operating mode this term is zero.

The block diagram of this process is shown in Figure 9.

In the field of hierarchical control, the three categories of MGs (AC; DC; AC/DC-Hybrid) follow a similar pattern. The main difference lies (in the case of the centralized approach) in the characteristics of the droop control involved in the primary control and the application of secondary and tertiary control for different modes of operation. The EMS is the center of the MGs' control system. If by any chance the central control or EMS fails due to communication failure, or by errors in the set of MG sensors, the primary controllers may not function properly and would end up causing instabilities and saturations in control actions. On the other hand, distributed secondary control is less reliable than centralized because the LCs cannot function optimally due to a lack of information about the operating state of the system/MG in general.

The secondary controller (see Figure 10) compensates for the unbalance by sending the appropriate control signals to the LC. In [71] the authors show the effectiveness of the centralized secondary control structure to compensate for the voltage unbalance. In the article, a secondary control strategy capable of compensating the voltage unbalance (VU) in the PCC at reference value of quality, is obtained and presented by simulations while the active and reactive powers are correctly balanced. Other control methodologies are developed in [72, 73].

The Voltage Unbalance Factor (VUF) is defined by the following equations:

$$VUF = f\left(V_d^{+}; V_d^{-}; V_q^{-}; V_q^{+}\right) \qquad (3)$$

$$VUF = \frac{\sqrt{\left(V_d^{-}\right)^2+\left(V_q^{-}\right)^2}}{\sqrt{\left(V_d^{+}\right)^2+\left(V_q^{+}\right)^2}} \qquad (4)$$

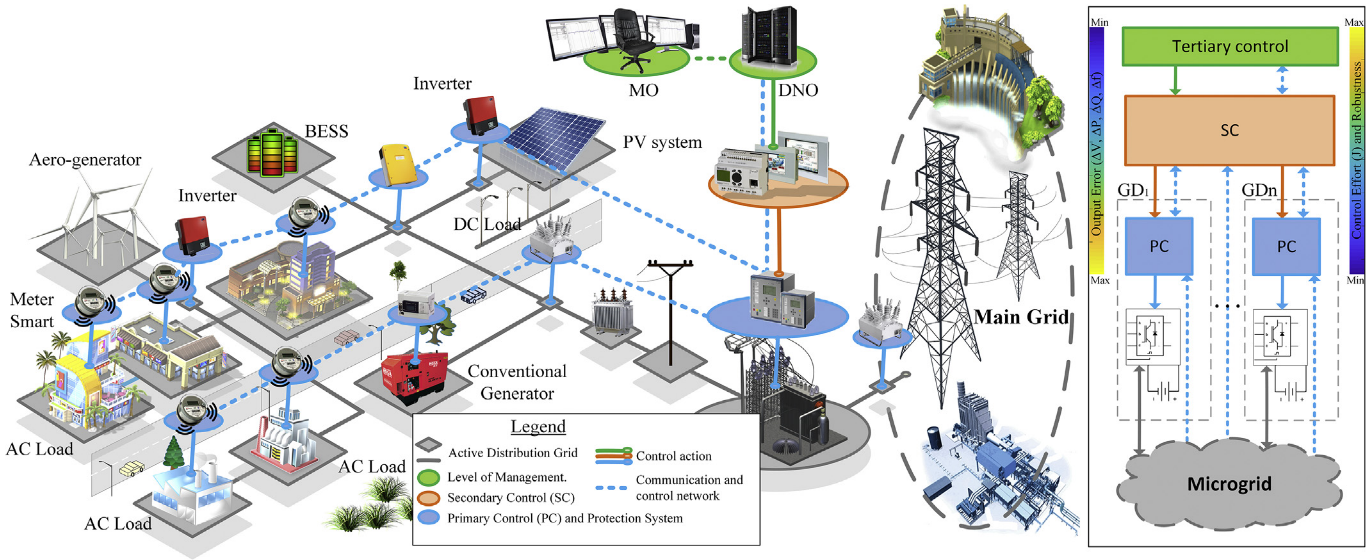

Figure 7. Centralized hierarchical control.

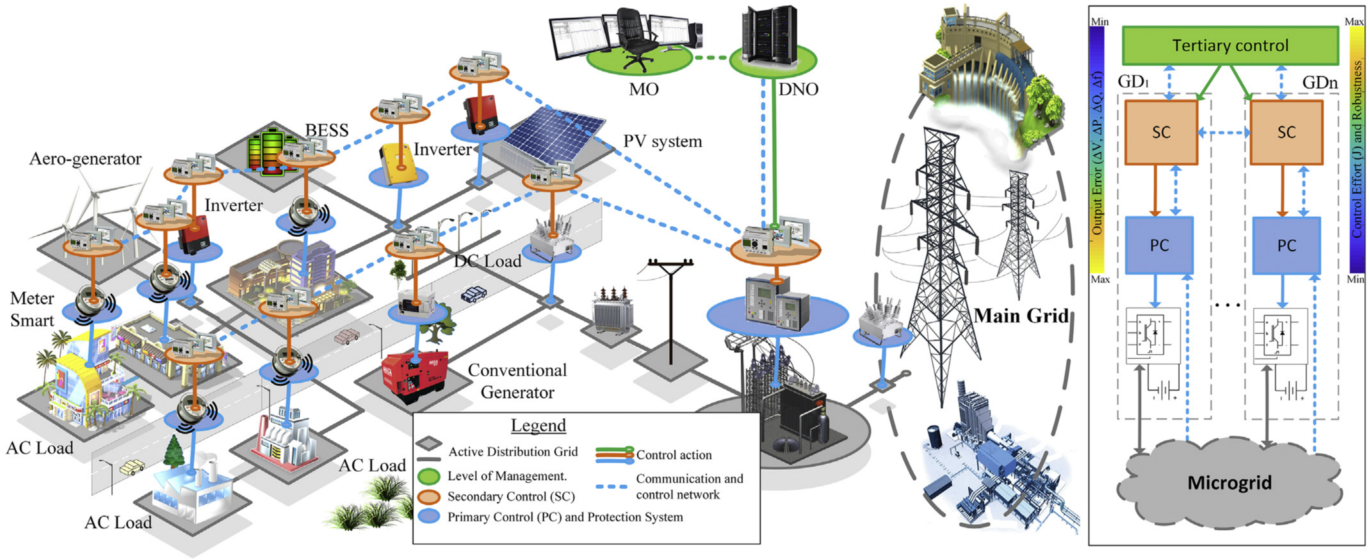

Figure 8. Distributed hierarchical control.

VU between the phases are very common among the various power quality phenomena and can cause adverse effects on equipment and the power system. Under unbalanced conditions, the MG has more losses and is less stable. Moreover, the VU leads to negative impacts on induction motors, additional power and energy losses, additional machine heating (limiting the nominal load capacity), the propagation of the unbalance to other MGs connection modes, in electronic power converters or VSCs and adjustable speed drives (ASDs) [71, 74]. One of the most important

Table 1. Comparison of the main characteristics of centralized and decentralized control [47, 61].

Characteristics	Centralized	Decentralized
Objectives according to GD owners	Single owner	Various owners
Availability of operational personnel (monitoring, low-level management, special switching operations)	Available	Unavailable
Market participation	Implementation of complicated algorithms	Owners unlikely to use complex algorithms
New equipment installation	Requires specialized personnel	Should be Plug-and-Play
Optimality	Optimal solutions	Mostly suboptimal solutions
Communication requirements	High	Low
Market participation	All DG units collaborate	Some DG units may be competitive
Microgrid operation is attached to a larger and more critical operation	Possible	Not possible

causes of the VU is the connection of unbalanced loads (single-phase loads between two phases or between phase and neutral).

The International Electrotechnical Commission (IEC) recommends the 2% limit for VU or voltage unbalance factor (VUF) in electrical systems [72, 73, 74]. IEC 61000-2-5 proposes two grades: Grade 1) VUF* $\leq$ 2% and Grade 2) VUF* $\leq$ 3%; IEC 61000-2-12 VUF* $\leq$ 2%. On the other hand, international regulations establish between 10% (in Europe) and 15% (in America) as the maximum permissible VUF range for the electrical system to remain in operation, however, an islanded MG will hardly be able to move into connected mode to the grid if its VU exceeds 3%.

The centralized secondary control can be found anywhere in the MG (it can be found away from the LC, the PCC, or the critical bus), so the data transmission between the secondary and primary control is carried out in the reference frame *dq*, thus ensuring that a low bandwidth is sufficient.

4. Fault in MGs

4.1. Fault

In [75, 76] the authors classify the faults according to eight basic points of view that lead to the elementary classes of faults by: objectives, system limits, phenomenological causes, stage of creation or occurrence, its persistence, and by dimension. These unwanted or controllable phenomena can be manifested through different modes of faults in the same component. Therefore, performing a timely diagnosis followed by maintenance actions may prevent faults that lead to instability, insufficient power generation, and other losses.

When it comes to improving resilience and reliability in the EPS, MGs are the main attraction of all possible solutions. However, the resilience provided by other methodologies is severely affected if it is not protected against fault events, both internal and external. In addition, distributional protection devices cannot reliably protect the MGs in its entirety due to the variable short-circuit capabilities. Many investigations have addressed the problem from protection systems, however, research in the field of MG protection has not achieved a commercially available relay and has little chance of reaching that level in the near future [77].

As described by the author in [33], the difference between reliability and resilience is demonstrated by the survival capacity of power systems when extreme events are experienced. Controllable MGs can help to improve the resistance of Smart Grids under extreme fault conditions. The resistance of the Smart Grid, especially of the MGs, can be improved by means of the optimal control of fixed and controllable loads, of the dispensable and non-dispensable DG units, and the energy storage systems.

In Figure 11, the four operating states (normal state, contingency, MG status, fault tolerant control system (FTCS) state) and the impact of MG deployment in the EPS are shown. As seen in Figure 11 a), shows that when a fault event occurs in time $t_{1,}$ the power supply of the Macrogrid is interrupted, the electrical system is out of power up to t_4. This is due to the delay in fault location techniques until the repairing on t_2 begins. However, Figure 11 b) shows the transition between the three states are different when the EPS presents a MG. The MG starts operating in islanded mode at time t_1 and the local power supply is interrupted in t_3 for when the available fuels are exhausted. In this circumstance, the resilience of the EPS is improved by equipping with MGs that contain enough energy to extend the local supply to t_4. With the incorporation of the MGs, the interruption time is reduced from t_4-t_1 to t_4-t_3 [33].

Once the MG begins to operate in islanded mode, it is susceptible to the appearance of fault modes of the power system (plant), or the control system (sensors, actuators). When a fault appears at time t1 (Figure 11 c)), the CTFS (t_4-t_1) provides the ability to maintain reliable service and prevent the protection system from acting against tolerable faults. During this time interval, the FTCS goes through two main stages, the fault detection, and the recovery system. The technique of recovery system is based on two main mechanisms: management failure and handling of faults (diagnosis, isolation, reconfiguration and reset) [75, 78].

On the other hand, considering that the MGs work mostly in the two modes (interconnected or islanded), the faults that affect the system go beyond the fault modes in the Macrogrid or main grid. In the interconnected operation mode, the fault currents have high values that involve the action of the protection systems such as fuses and switches, causing the output of a part of the electrical grid. In contrast, that does not happen in the same way in the islanded mode because the nominal power of the electronic elements is well below the power managed by the Main Grid [79].

There is no doubt that focusing the problem of reliability and resilience of the Smart Grid and MGs would be very conservative if only a MG in support of the Main Grid is considered. In [13] and [14] the authors conducted a fairly complete study summarizing other modes of fault affecting the MG. These fault modes are divided according to the element

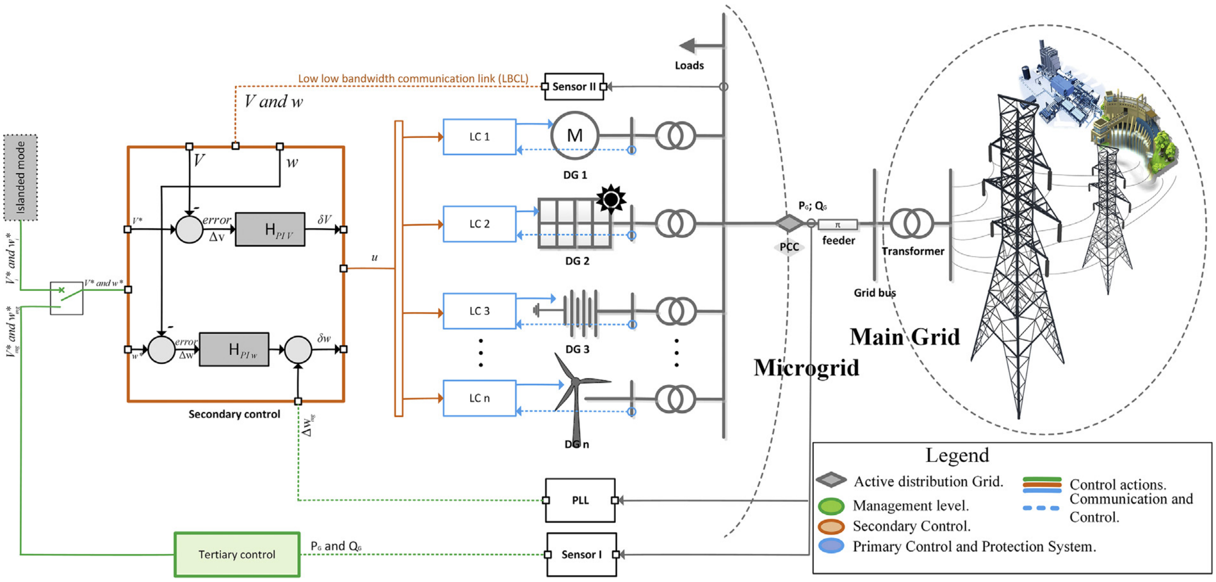

Figure 9. Block diagram of the secondary controls.

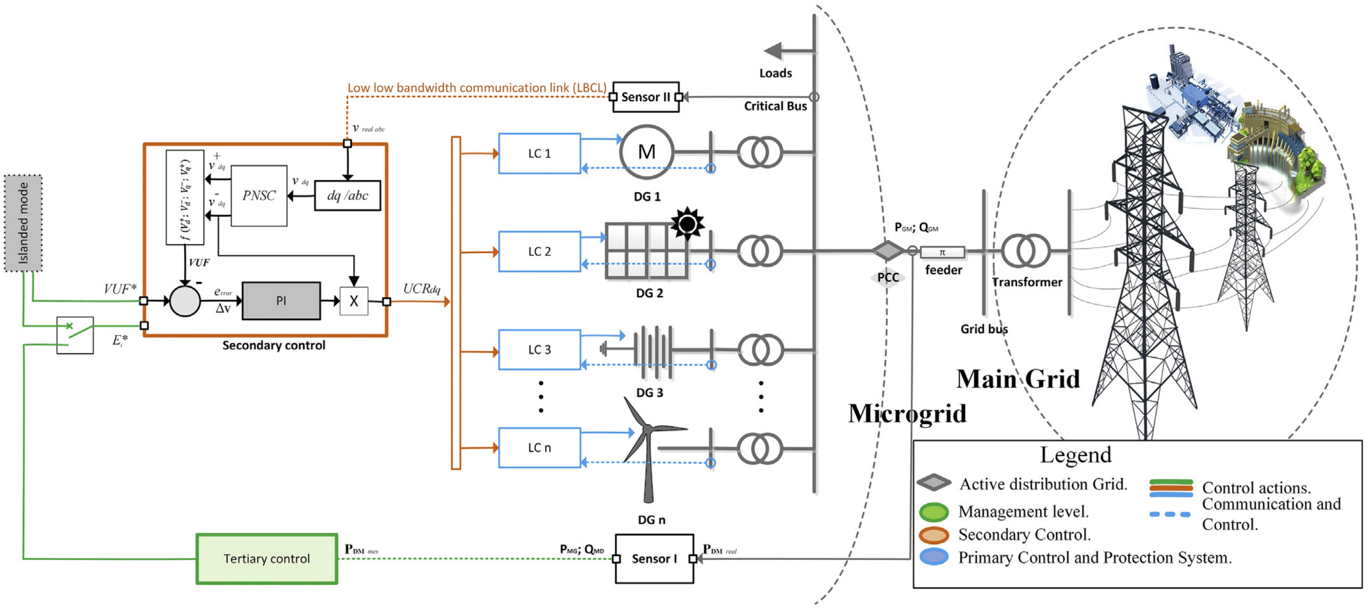

Figure 10. Secondary control block diagram for compensation of voltage unbalance.

in which the fault occurs (cables and transmission lines, photovoltaic systems, wind turbines, conventional generators, monitoring and control elements).

The control systems are made up of various sensors and the MG controllers are not exempt either. More precisely, the control systems handle the information of the most important variables of the MG such as voltage, current and frequency. Since these sensors are largely power transformers (PT) and current transformers (CT), the faults and errors in the sensing system elements are normally measured according to: magnitude error, phase error, harmonic error, partial or total signal loss [16]. It is important to consider that the fault modes of the sensors mentioned above are not possible in its majority to evade and can be originated by various agents (internal or external) [35].

The extraordinary advances in the industrial communication networks have been fundamental for the evolution and development of MGs. These advances are by far, the technological foundation of the current Smart Microgrid (SMGs). Nevertheless, in the same way that SMGs develop more functions and achieve better performance with the use of communication networks, they have also become more vulnerable to cyber-attacks which can affect partially or completely their operation [30, 80].

Another threat to the normal operation of the secondary controller in a SMG could be by cyber-attacks to the communication system, which in turn, affects the information between sensors, controllers, and local actuators. This threat would greatly affect the SC and TC information which may cause the saturation of its control actions. The experimental results in [16, 17, 81] clearly demonstrate the impact of the sensor's erroneous data on the performance and dynamic behavior of the MG.

This is the main reason why the detection and location of cyber-attacks and the enhancing of the SMG resilience against cyber-attacks have become current and essential research topics. Both detection and location of cyber-attacks may be considered as a cyber-complement of the fault detection and location and FTC of the industrial security.

Related with the MG resilience to cyber-attacks, several approaches have been developed by the researchers. Some examples are: in [82], the authors adopt the philosophy of treating cyber-attacks as events and develop an event-driven resilient control scheme to detect two categories of stealth attacks and improve the resilience. A novel Cyber-Physical Resilience Metric (CPRM) which uses vulnerability information available publicly is presented in [83, 84] to support the decision making of the operators in MG. The authors in [85] develop a fully distributed attack-resilient secondary control framework for DC MGs, in the presence of unknown unbounded attacks on control input channels. Other strategies and methodologies are presented in [86, 87, 88, 89].

4.2. Diagnostic techniques

The scientific community has successfully developed various real-time automated diagnostic tools for the detection and identification (DI) of faults in MG components.

The authors at [13] perform a fairly detailed review of the various techniques and approaches used in the field of fault diagnosis. As it can be seen in the article, there are many approaches that have been implemented with model-based methods or based on the data acquired by the monitoring and control systems. Many researchers have dedicated their careers to the study and optimization of algorithms for diagnosing and location of faults in the Smart Grid [90] and MGs. However, these investigations are not only to show the operators the various possibilities of fault occurrences of MGs; additionally, the algorithms are also part of a first phase of FTC methodologies named mitigation and error management.

The occurrence of a fault in the power system interconnected to a Macrogrid may cause other regions of the grid to overload or isolate due to the switch (protection) action. In turn, this continuous load redistribution often becomes a cascading phenomenon that spreads through the energy system and leads to a catastrophic failure leading to large power outages, causing social and economic impacts [91, 92]. For example, according to the studies shown in [91] based on the information of the NERC (North American Electric Reliability Corporation), until then the main causes of blackouts were: 1% by earthquakes, 3% by tornadoes, 7% by hurricanes or tropical storms, 9% by ice storms, 8% per operation, 22% for equipment failures, 24% for wind and rain, among other causes.

With the development of communications and the infrastructure of the SMG, the objective faults, and malicious ones introduced to the measurement system which cause damage to the communication system of the MG, have become a serious problem for the design and implementation of the hierarchical control. In addition to the dependence of the SC and TC of the modern communications network in order to receive information such as V_{abc}, I_{abc}, V_{gd}, I_{gd}, f, coming from the measuring system; the faults due to malfunction or cyber-attacks have become a serious problem for the development of hierarchical control methodologies.

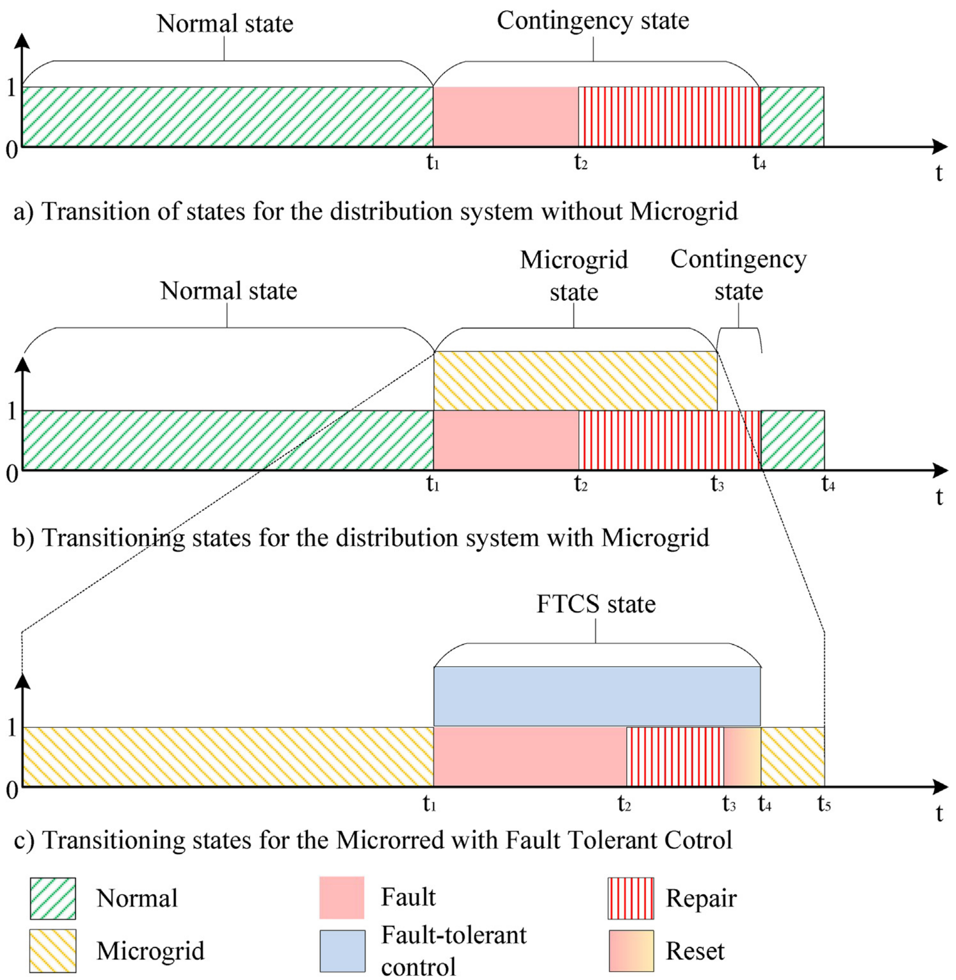

Figure 11. Regions of states requirements and performance degrade.

Various techniques have been presented in the scientific literature related with the cyber-attack detection. Among the most used strategies are the Kalman filter [80, 93], optimization approaches [94], state estimation techniques [95, 96] and computational intelligence tools [97, 98, 99].

In order to lessen this problem, the authors in [100] propose a strategy for the diagnosis and mitigation of sensor faults by cyber-attacks in DC MG. The theory of fault diagnosis estimates the error based on the design of an observer by sliding mode. The estimation of this type of error is used to perform mitigation actions and rectifies the damaged measurements in such a way as to ensure the resilient function of faults and cyber-attacks.

The diagnostic methods of faults applied to the systems of a MG are mainly grouped into two categories: model-based and data-based approaches. Model-based approaches need identification and the detailed model of each component function. Data-based approaches perform analysis on measured data from the actual physical system [13].

In [13] the authors show a very detailed state of art that expose and briefly explain several techniques mostly used to diagnose faults in MGs using various methods based on: Threshold, Fuzzy Logic, state estimation, Classification, Neural Network, Decision tree, Support Vector Machine (SVM), Feature extraction, Domain transformation, Fourier transform, Wavelet Transform and Compressive Sensing [13]. Due to the difference in the formulation of the problem in each of the methods and depending on the installed monitoring technology, the communication infrastructure, the availability of physical models and measure data, some methods work better than others.

5. Fault tolerance

Together with the development of the MGs throughout the years, the problem of fault tolerance has been treated from different points of view, thus considering two main classes: passive control and active control. From this point of view, a passive control is defined as a robust control which requires a prior knowledge of the possible faults that would affect the stability of the system and therefore implies to design a law of control to compensate those faults.

The interest of this approach is not precisely the need for on-line information, meanwhile the structure of the law of control remains unchanged. The main idea of this type of control is the consideration of all possible faults and uncertainties to be taken into account in the design of FTC [101]. Therefore, the structure of the uncertainties (faults) are not considered at the moment of leading to a problem of convex optimization. Due to the fact that the types of faults considered are very limited, it makes it a risk to use only passive control fault [78, 101, 102].

5.1. The problem

The contingencies for the design of control systems are selected based on greater probability of occurrence. Therefore, stability in the face of major disturbances and faults always refers to achieving equilibrium in a region of the required finite yield space; the greater the region, the more robust the system is regarding the major disturbances. Instead, the optimum performance space region dynamically changes with the operating conditions of the electrical distribution system, DG sources, and loads.

If the FTCS design defines among its objectives faults in the measurement systems (sensing) or in the action systems (actuator), it is necessary to restructure the control law. A total failure in these components interrupts the control loop. For these reasons, a simple adaptation of the control law parameters will not be possible and alternative sensors or actuators must be considered, preferably those that have similar interactions with the plant/MG and are not under fault [103].

According to the authors in [61], the theme of MG control is considered one of the most interesting and most studied topics by the scientific community. Under no circumstances can a MG be implemented if it has no stable and precise control. Although AC MG has been widely investigated, it must be taken into account that in recent times the DC MGs and the AC/DC HMGs have gradually gained the interest of the scientific community for its reliability, minimization of losses and efficiency. Unwanted sudden changes in the operating conditions, line output of sensors or control components, by limits or wear of the measuring system itself and the control substation, trigger the change of the control problem and its mathematical model. In the SMG, the communication is bidirectional between CFMS and LC considering itself of vital importance for the reliable and efficient operation of the whole system. However, a failure in the communication channel between the SC and LC or the sensor would lead to instabilities or in some cases interruption in electricity services [20, 44].

The following questions arise:

- Is it possible to improve the linear and nonlinear dynamics of MG models, which enable to evaluate and characterize their behavior against errors and internal faults?
- Is it possible to implement hierarchical control structures and complement it with advanced passive/active fault tolerance techniques to avoid the regions of unstable states or in danger for the MG?
- How do the faults of the different MG systems affect the voltage, VU and power quality indicators for the hierarchical control compare to a fault-tolerant hierarchical control?

In the literature, there are many variations when it comes to adopting an architecture and a control design, and more so, if fault tolerant techniques are implemented. Researchers and developers will always look for a common perspective making these key requirements: reliability, optimal integration of distributed generation sources, identification of reliable control strategies and fault tolerance, and use them to further enhance the reliability of the system [5, 31].

5.2. Properties of systems subject to failure

Reliability and safety follow converging paths: Reliability highlights the restriction to non-malicious faults, orienting itself only to part of the problem; where security is aware of the main objective exposed to confidentiality, which would need to be augmented with integrity and availability. Security recognition was the next important step as an integration of the attributes of confidentiality, integrity and availability and the addition of types of non-malicious faults, along with the analysis of inadequate system specification problems [76, 102].

Reliability as an integral concept covers the following attributes [76, 102]:

- *Availability*: preparation for the correct service.
- *Reliability*: the continuity within the tolerance margins of the service.
- *Security*: No catastrophic consequences for the user (s) and the environment.
- *Integrity*: Absence of incorrect system alterations.
- *Maintainability*: Ability to undergo modifications and repairs.
- *Resilience*: Ability to overcome and resist adverse electrical system situations such as disturbances or failures.

In recent years, many means have been developed to achieve the different attributes of reliability and security. These means can be grouped into four main categories [76, 78]:

- *Prevention of failure*: which means preventing the appearance or introduction of failures.
- *Fault tolerance*: which means to avoid faults in the service, in the presence of failures.
- *Elimination*: which means reducing the number and severity of the faults.
- *Failure forecast*: which means estimating the present number, future incidences, and probable consequences of failures.

5.3. Safety versus fault tolerance

Figure 12 shows the different performance regions that must be considered when analyzing a dynamic system and its fault tolerance [23, 102, 104].

Assuming that the performance of the system can be described using two variables y1 and y2. A *safety* systems or protection systems interrupts the operation of the entire system to avoid hazard, and at the same time, protecting it. The safety system is involved when the external frontier of the region of unacceptable performance is exceeded This shows that the security system and the FTCS operate in separate regions in space and fulfill their complementary objectives. Due to this separation state, it is possible to design fault-tolerant controllers without breaching safety standards [23]. In other words, fault tolerance aims to provide reliable service unlike elimination and forecasting faults that only try to reach reliability [102]. Therefore, a modern automated fault-tolerant system is one that maintains its working capacity, with the minimum permissible quality in spite of different elements, or of the control system itself [23, 75, 102].

5.4. Fault tolerance mechanism

Faults may cause structural changes due to the isolation of the faulty element, which in turn alter the normal operation or configuration of a circuit. MG faults affect consumers and subsystems installed throughout the grid. In an MG, small disturbances occur continuously in the form of load changes; therefore, the system must be able to adapt to changing conditions and function successfully.

In order to provide system/MG service continuity, fault tolerance is achieved through the following techniques [75, 78, 103]:

- *Fault detection:* it consists of the appearance of a fault in the system/MG [75, 76, 103, 105].
- *Recovery system:* it consists of the replacement by means of failure state events by another secure state. Two main mechanisms define this phase [75, 103]:
  - Fault management: each erroneous state of the system/MG is cleared by eliminating the fault. For this mechanism, Rollback, Rollforward and compensation are assessed.
  - Fault handling: this can be resolved in the following manner:
    - Diagnosis: identifying of cause, type, and location.
    - Isolation: separation of flawed components or disabling faulty zone.
    - Reconfiguration: allocates new objectives to components that are operating in normal state.
    - Reset: check, update, and register the states.

Figure 13 shows a representation of the fault effects on a MG and how the FTCS would operate to achieve the transition of its five states: operation, fault elimination, reconnection, and fault tolerance.

The old and new driver differs from the input and output signals used. In the normal operating state, the nominal controller reduces disturbances $\boldsymbol{d_i}$ and assures converging work to the reference point and other requirements in closed loop systems. The main control activities occur at the execution level (PC). At the level of supervision, the diagnostic block simply recognizes that the closed loop system has no faults and no change is necessary in the control law. If a fault f_i occurs, the monitoring level causes the control loop to be fault tolerant. The diagnostic block identifies the fault and the re-design controller block adjusts the controller to the new situation. Subsequently, the level of primary and secondary control continues to operate to meet the objectives of the MG.

As shown in Figure 14, there are countless techniques that address the problem of FTC, which are grouped into two main classifications: the Passive Fault Tolerant Control System (PFTCS) and the Active Fault Tolerant Control System (AFTCS) [23, 102, 103].

The PFTCS approach imposes a system/MG that can tolerate only a limited number of faults, which are estimated by prior knowledge, just before the design of the controller. Once the controller is designed, it is provided with a control law with features to compensate for the expected faults without the need for on-line access to the fault information [23, 102].

Most conventional control systems are designed for systems without faults and the possibility of their occurrence is not considered. The system/MG may have limited physical redundancy, preventing the hardware configuration from being increased or changed due to the cost or constraint of the system/MG. In these cases, the design of fault tolerance using the AFTCS approach is very important. For the AFTCS approach, controllers can be designed to take advantage of the available resources of the system/MG. With the use of redundancy (physical and/or analytical), the decision control system is provided to deal with unexpected faults [23, 102].

Therefore, the AFTCS approach compensates for the effects of faults by selecting a new law of control previously calculated, or by synthesizing on-line and real-time the new law of control. Both approaches present an algorithm for the management of faults, which considers the detection and identification (FDI) of these to identify and classify the problem occurred. Currently, the design methods for reconfigurable AFTCS can be classified according to the following approaches [103]: linear quadratic, pseudo-inverse/control mixer, intelligent control using expert systems, neural networks, fuzzy logic, learning methodologies, gain scheduling, adaptive control, model following, eigenstructure assignment, feedback linearization, robust controls (H_2, $H\infty$ and other), model predictive control, linear matrix inequality, variable structure and sliding mode control, and internal model control.

The PFTCS and AFTCS present the following characteristics:

- Take advantage of the benefits of robust control.
- Employs the analytical redundancy of the system.
- Uses FDI algorithms and controller reconfiguration.
- Accepts gradual degraded performance in the presence of internal and external system failures.
- Increases the reliability and reliability of the system.

5.5. *Impact of faults on the control problem and strategies*

Because the control algorithm only implements the solution for a control problem, and the fault directly affects a change of the control or system/MG, for that reason, the control problem changes due to its effect [23, 102, 103].

The impact of the faults on the control problem defined by $<O, C(\theta), U>$, where $C(\theta)$ demonstrates the dependency of the C constraint on the control objective O or that is in dependency of the fault [23]. The objectives of the system/MG are associated with the user and the nature of the FTC. Despite the occurrence of failures in the system, the FTC will try to achieve these objectives. The stages of control (modeling, analysis and design) are designed in order to meet the objectives of the system/MG and not change with the occurrence of failures, however, this may or may not be possible [23, 102]. The success of these control strategies depends greatly of the failure that acts on the system/MG.

There are two cases:

1. The system is fault tolerant with respect to the objectives and errors of the system, and there are means to achieve the objectives of the system in the presence of certain failures, therefore, the objective of the design of the law of control is that it is able to do it.
2. The system is not fault tolerant with respect to the objectives and because of these errors, the objectives cannot be reached in the presence of the defects already considered. However, this conclusion is not enough, we must provide the instructions on what to do with the system because the current objectives cannot be achieved. The focus of the problem becomes the search for new objectives of interest in the new situation and to design the law of control capable of achieving these new objectives.

Faults can change the constraint C (θ) of the control problem into two main variants:

First: it does not change the constraint, instead, its parameters can change, therefore transforming the control problem $<O, C(\theta_n), U>$ to $<O, C(\theta_f), U>$. Where θ_n and θ_f are the nominal parameters and the fault system/MG.

Second, the constraints change, transforming the problem denoted by $<O, C_n(\theta_n), U>$ into the problem $<O, C_f(\theta_f), U>$. Where C_n is the set of nominal constraints and $C_f(\theta_f)$ is the set of new constraints with new associated parameters.

Both cases can be summarized as $C_n(\theta_n)$ within $C_f(\theta_f)$ from the change of the parameters, being a particular case, described by $C_f = C_n$ [23].

A balanced energy system/MG can be stable for one disturbance or physical failure, and unstable for another. In reality, it is impractical and costly to design a control systems that are stable for every possible disturbance [106]. Contingencies for the design are selected based on the highest probability of occurrence. Therefore, stability in the face of major perturbances and faults lead to achieve stability in a region of the required performance finite space; the larger this region, the more robust the MG control system and the MG would be inherent to greater disturbances.

Failure accommodation is an FTC strategy associated with cases 1 and 2. They solve the problem $< O, \widehat{C}_f(\widehat{\theta}_f), \widehat{U}_f >$or $< O, \widehat{\Gamma}_f(\widehat{\Theta}_f), \widehat{U}_f >$ associated with fault system control. The situation in error can be accommodated with respect to the objectives or when the problem has a solution, which is resolved by the new control problem $< O, \widehat{C}_f(\widehat{\theta}_f), \widehat{U}_f >$,

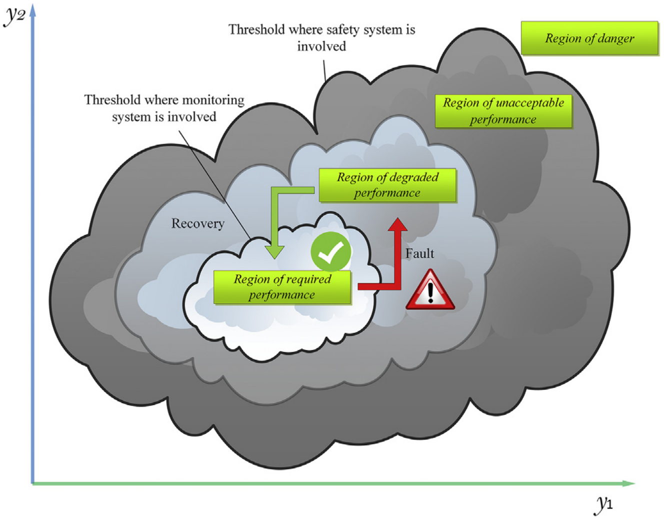

Figure 12. Regions or operation states and degraded performance.

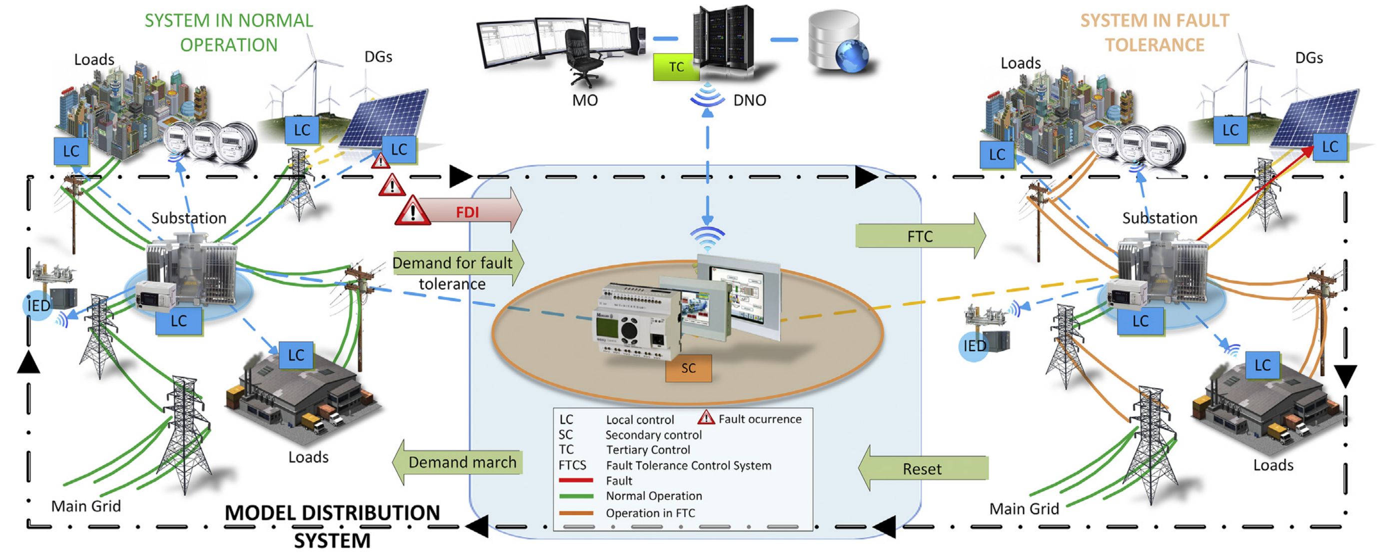

Figure 13. Faults on the distribution system and a fault tolerance architecture.

where $\widehat{C}_f(\widehat{\theta}_f)$is the current constraint estimate provided by fault diagnosis algorithms [23].

The reconfiguration of the system/MG is another strategy of FTCS, which is associated with the case where the defective [107, 108] is unknown. This means that any control problem can turn off the defective components and try to reach the objectives using only the remaining optimal. Leaving $C_f(\theta_f) = C'_n(\theta_n) \cup C''_f(\theta_f)$ where $C'_n(\theta_n)$ is a subset of the constraints associated with an optimal part of the system/MG, and $C'_f(\theta_f)$ is the subset of the constraint that are associated with the defective part [23, 101, 102, 108]. In such cases, reconfiguration finds the new set of system/MG constraints $C_f(\theta_f)$ so that the control problem $<O, C_f(\theta_f), U>$ has a solution, and activates this solution [23, 102]. The $C'_n(\theta_n)$ constraints are known while $C''_f(\theta_f)$ are unknown, allowing $U_f = U_n \cup U_f$. Then the reconfiguration strategy gives solution to the problem $<O, C'_n(\theta_n), U_n>$, that is, it tries to achieve the objectives of the system/MG by controlling only an optimal part of the system/MG.

If the accommodation and reconfiguration strategies do not provide a feasible solution, then there is no possibility of achieving the control objectives using the fault system (accommodation) or a subset of it (reconfiguration). For these reasons, the system must provide another objective that proposes a new control problem defined by $< O, S, \Theta, U >$, where O is a new set of possible control objectives. This problem is called a monitoring problem [23, 102].

In practice, most control systems are designed to meet multiple poorly described objectives [109, 110] using a single performance measure as is generally proposed in the literature. This has led to the development of

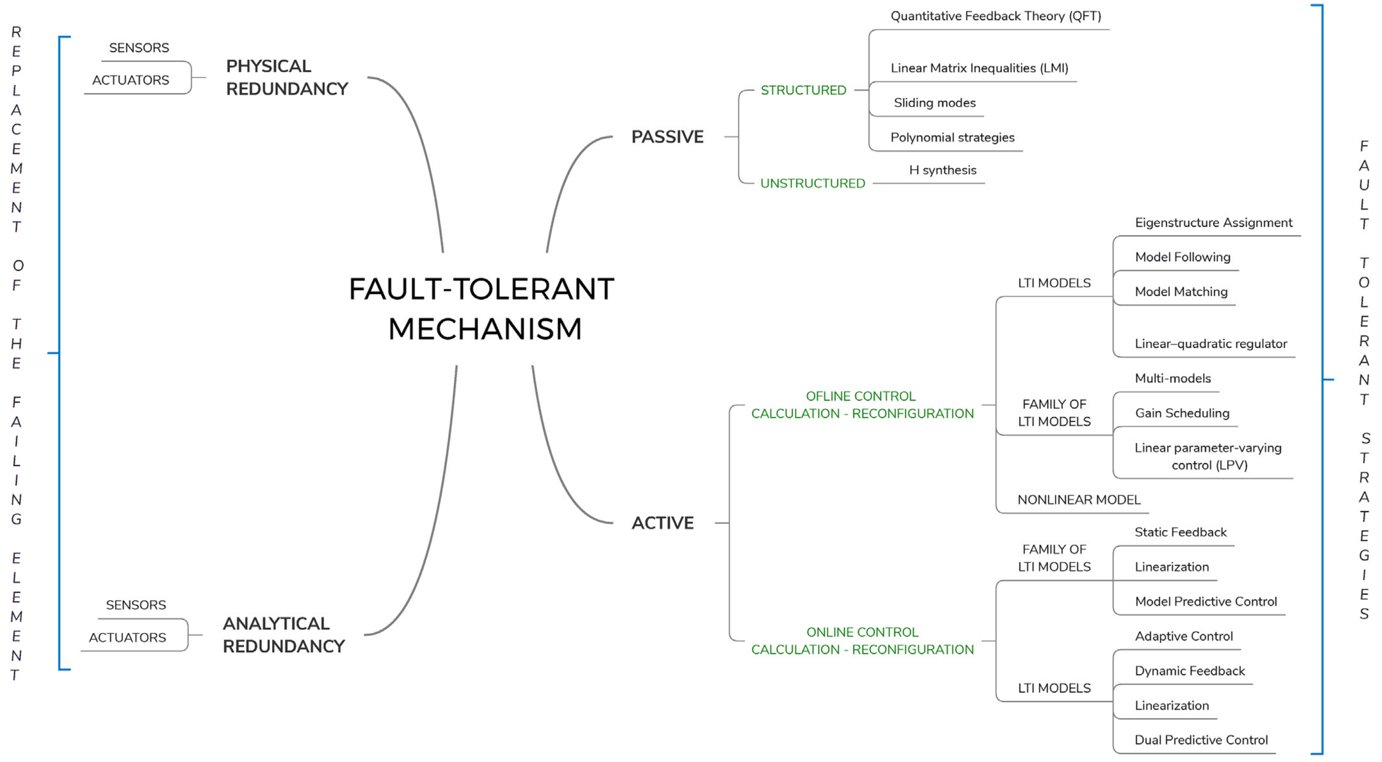

Figure 14. Fault tolerant mechanisms.

Table 2. Bibliographic review.

Analyzed papers			Problems				FTCS solution									
Item	Paper	Publication year	Internal faults	External faults	Sensor faults	Voltage control	Sliding mode	LQR/QG	H2/H∞	Robust method	PI/PID	Predictive method	Adaptive method	Intelligent method	Augmented backstepping	Multiple methods
1	[37]	2020		X		X										X
2	[113]	2020		X		X									X	
3	[34]	2020		X	X	X			X							X
4	[114]	2020	X													
5	[115]	2019		X		X										X
6	[116]	2019	X			X								X		
7	[117]	2018	X									X				
8	[118]	2018	X													
9	[119]	2018	X													
10	[120]	2018		X	X	X	X		X							
11	[17]	2018	X		X					X						
12	[100]	2018	X		X	X	X									
13	[121]	2017	X													
14	[122]	2017	X		X									X		X
15	[16]	2016	X		X		X									
16	[13]	2016	X	X	X											X
17	[19]	2016		X		X	X							X		
18	[18]	2016		X		X										X
19	[123]	2016				X										X
20	[59]	2016		X		X					X					
21	[124]	2016	X	X												X
22	[15]	2013	X										X			
23	[111]	2010		X		X										X

numerous control structures with varying degrees of freedom, and with each degree of freedom, the controller tries to treat some subset of the control objectives [14, 111].

To minimize the impact of faults on control systems and the MGs, several strategies based on different fault tolerance techniques have been developed and documented as shown in Table 2. These strategies were implemented in real cases, testbed or typical MGs (benchmark). Among the most implemented techniques to solve this type of problem are: sliding mode, LQR/LQG, H2/H∞, robust methods, adaptive methods, intelligent methods, multiple and hybrid methods, among others. All these previously mentioned methods have obtained very satisfactory results but are difficult to compare because they have attacked problems and faults with different characteristics. Consequently, it cannot be indicated if one method or algorithm is better than another, it depends largely on the fault for which it was applied, in other words, the "no free lunch" (NFL) theorem of David Wolpert and William Macready is met [112].

As shown in Table 2, authors have opted for fault tolerance strategies as the main mechanism to provide MGs with resilience and greater reliability.

6. Conclusions

With the latest technological and computing advances, fault-tolerant control systems have taken on great importance in recent decades for which studies have been implemented to improve the reliability of MGs. The present study attempts to cover main research on control and its fault tolerance in MG applications, in addition to allowing educators, researchers and developers obtain detailed and valuable information to resolve associated problems related to MGs.

The passive (robust) and active approach are not only capable of reconstructing the sensing signal to ensure robustness during variations in voltage unbalance (VU) and other variables; but also, operate under normal and fault conditions (worst case scenario with a degraded performance). Once the faulty sensor is repaired, the controller would return to its nominal operating situation. The fault tolerant control approach has as its main objective to avoid the region of unacceptable performance and danger states (protections action/full shutdown). Thus, the FTCS is not only capable of mitigating the impact of faults and errors (malicious cyber-attack) of the sensor associated with hierarchical control, but also to ensure the safe and reliable operation of GD units coupled to the islanded MR.

Therefore, the controllers with fault tolerance methodologies will not only decrease the impact of faults and errors associated with the control loop or the islanded MG, but also guarantee the safe and reliable operation of the coupled DG units.

The greater impact of this type of control strategy would be on the side of the end user or consumer, providing a considerable increase in energy quality (reactive control and voltage, consideration of critical subsystems PCC/loads). As a result, the FTCS increases the reliability of renewable energy sources, anarchic control systems, and the MG in error and failure situations, in addition to the economic benefit for MG operators.

Despite all that has been published, the MG cybersecurity has great challenges for researchers, such as the issue of locating the physical element of the MG where the cyber-attack is taking place, just to mention one of them where very few results have been obtained.

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