Efectos del control de Tensión y Frecuencia en una operación aislada por Micro-redes con Pequeñas Centrales Hidroeléctricas: Estabilidad Transitoria

Effects of Voltage-Frequency Control in a Microgrid Islanded Operation with Small Hydropower Plants: Transient Stability

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RESUMEN

Una Micro-red es una fracción del sistema eléctrico de distribución que puede operar de forma autónoma ya sea en paralelo o aisladamente con la red principal. La flexibilidad de una Micro-red reduce la vulnerabilidad del sistema de potencia al igual que previene costosos apagones. En Colombia se presenta un gran potencial para la creación de Micro-redes que utilizan generación de potencia por medio de Pequeñas Centrales Hidroeléctricas, las cuales se consideran como una tecnología de bajo impacto ambiental. Las Pequeñas Centrales Hidroeléctricas actualmente están deshabilitadas para operar aisladamente, dado que no presentan los mecanismos requeridos para mantener unos niveles de estabilidad de tensión y frecuencia luego de la desconexión con el sistema interconectado. En este artículo, se propone la idea de planear una Micro-red usando datos reales del sistema de distribución que tiene instalado una Pequeña Central Hidroeléctrica que permita evaluar el comportamiento transitorio cuando se simulan perturbaciones. Diferentes estrategias del sistema de control son implementadas, con el objetivo de determinar el mejor desempeño.

PALABRAS CLAVE

Generación de Potencia Hidroeléctrica; Micro-red; confiabilidad; redes inteligentes.

ABSTRACT

A Microgrid is a part of an electrical distribution system that can operate autonomously either in parallel with the main grid or isolated from the main grid. The operational flexibility of a microgrid reduces the vulnerability of the power system and also helps to avoid costly blackouts. In Colombia there is great potential for the creation of microgrids that use power generated by small hydropower plants, which are considered as a low environmental impact technology. small hydropower plants are currently unable to operate in isolation as they do not have the mechanisms required to maintain stable frequency and voltage levels after disconnection from the interconnected system. In this paper, we propose the idea of planning a Microgrid using real data from a distribution system that has an small hydropower plant installed in order to evaluate its transitory behaviour when faced with disturbances. Different control strategies are implemented, with the aim of determining which system shows the best performance.

KEYWORDS

Hydroelectric power generation; Microgrid; Reliability; Smart grids.

1. INTRODUCTION

An intentional electrical island or MicroGrid (MG) is a contiguous section of the grid and its Distributed Energy Resources (DERs) that can operate as an independent electrical island disconnected from the rest of the grid [IEEE1547.4, 2011]. DERs technologies include Distributed Generation (DG), storage technologies and controllable loads [Chowdhury, 2009].

The DERs operating within a MG are under study at present, given that they promise numerous benefits in technical, economic, environmental and social scenarios [Chowdhury, 2009; Sioshansi, 2011]. The level of benefits is different in each MG, because each MG uses a different type and amount of DERs [Anastasiadis & Tsikalakis, 2010]. Typically, the MGs can reduce the blackouts, line losses, and interruption costs for the customer [Kroposki, et al., 2008]. Also, MGs may reduce greenhouse gases because the generation usage is smaller.

The operation of a MG resembles a small-scale operation of a traditional electric power system with advanced telecommunications [Sioshansi, 2011]. The most operative complications that occur in the electrical power system, may present in MGs [Lasseter, 2007]. Therefore, in a MG it is indispensable to have support services such as black start service, voltage control and frequency control [Dobakhshari et al., 2011].

To maintain an acceptable voltage profile within an intentional electrical island, MGs are equipped with control devices known as automatic voltage regulators (AVRs) that vary the excitation of rotating generation. Frequency is regulated via the control of generated active power through the modification of water flow entry into the corresponding turbine [Kundur, 1994].

MG which is part of this research uses Small Hydropower Plants (SHPs) installed over 50 years ago. Such plants generally use electromechanical controllers whose response times do not comply with the speed necessary to form a stable MG [Carvajal et al., 2012]. Currently, when final users become disconnected, generator speed becomes uncontrollable and therefore, the generator may explode [Weber, et al., 2003].

In this paper the performance of the control modes of the governor of a hydraulic turbine is analyzed, to enable operation by a MG in the local distribution system. Implement an operation in a distribution system that was not designed for that purpose has technical challenges that must be studied in detail. Comparisons between different systems of primary control (hydraulic turbine governor) were carried out, with the aim of analysing their behaviour when faced with tri-phase failures during the switch to isolated mode (MG formation) and operating independently from the network. In the simulations, it was shown that the current behaviour of the control system (fixed control) and the governor for the hydraulic turbine were not efficient enough to be considered within the planning for the MG. Equally, it was found that the controller presented by Woodward PID demonstrated an adequate performance, and its technical characteristics are of simple implementation in the SHP of the case study.

This paper is organized as follows. In the second Section there is an overview of MGs and a SHP model is presented. In the third section, the control modes of the hydro-turbine governor are explained so that it can operate as a MG.

2. SUCCESSFUL MICROGRID OPERATION

A Microgrid is defined as being a part of an electric power system that is made up of distributed generation resources and controllable loads (with control options for both critical and non-critical loads) [Sioshansi, 2011]. It operates as a single autonomous grid, whether in parallel with or in isolation from the energy supply network. A very important factor is that the microgrid must be planned intentionally [IEEE1547.4, 2011]. Over the last few years, studies conducted on MG operation have found associated benefits such as an increase in the quality and reliability of the system [Zeineldin & Salama, 2005; Mathur, 2010], the decentralization of generation, a reduction in the cost of electricity (in terms of both transport and distribution), the optimization of the use of renewable energy technologies via the integration of MGs [Barker & Mello, 2000] and the use of MGs as a backup mechanism for preventing blackouts [Aghamohammadi & Shahmohammadi, 2012]. These benefits are stimulating an increased global demand for MGs. According to a report by PikeResearch [PikeResearcch, 2012], the capacity of MGs around the world will experience a growth of more than 22% in the next five years, reaching 4.7 GW by 2012 and taking as a point of reference 140 modern projects that will amount to more than 1.1 GW combined across the word. So far MGs have been studied for medium voltage operation, but the same concept could be extended to include high voltage levels.

In regulation [IEEE1547.4, 2011], a series of recommendations are established that help network operators and small generators to design systems which take MGs and islanding into account.

The following is a summary of the most important points in the planning and operation of a MG [Bakar, et al., 2011]:

Operation and administration: A good planning strategy for the MG permits problem-free operation. Within this strategy, island detection techniques, MG operation when connected to the network and when operating in isolation and the mode of reconnection to the network should all be considered. Various strategies have been proposed for the operation of a MG [IEEE1547.4, 2011; Mathur, 2010].

Generator governor: The governor should be designed and modelled for two operational modes: connected to the network and island operation. In isolated mode the governor should have the capacity to maintain power quality in the MG as well as keeping within the limits permitted by the system operator. In order to avoid a loss of synchronism during reconnection with the network, the SHP governor should be equipped with a control unit designed to regulate the frequency, voltage and phasor of the MG so as to remain close to network parameters.

Communication - Smart Grids: A fast and reliable communication link is required in order to transmit data and control information [Ropp, et al., 2000].

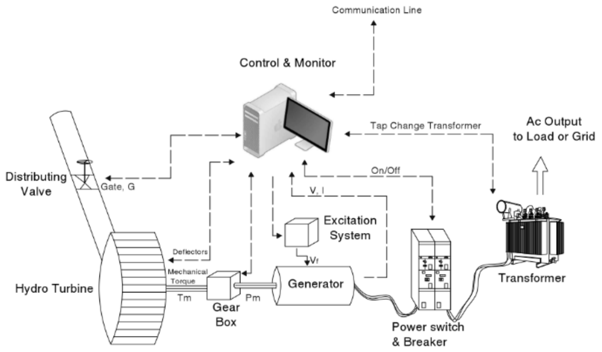

Figure 1. Operation of a modern Small hydro power plant.
Source: [Carvajal et al., 2012]

Integrating SHPs into a MG allows the frequency to be maintained within acceptable operational limits thanks to the use of synchronous generators, wich are considered as a controllable technology. The control is carried out through the turbine governor. The operation of an SHP is shown in Figure 1.

Small Hydropower Plants Model

SHPs are comprised principally of a governor, a turbine and a generator to convert mechanic energy into electrical energy.

Linear Turbine/Generator Model:
The representation of this model is based upon the following considerations: (i) Hydraulic resistance is not considered; (ii) Water velocity is proportional to the position of the sluice gate; (iii) The turbine exhaust is proportional to the product of the addendum and the flow volume; and (iv) The walls of the pressure pipe are smooth and the flow of water is non-compressible.

The transfer function that relates torque increase and sluice gate variation is given by [Kundur, 1994].

$$\frac{\Delta Pm(s)}{\Delta G(s)} = \frac{(1 - sTw)}{(1 + s0.5Tw)} \tag{1}$$

This linear model will be considered in the case study simulation.

3. HIERARCHICAL CONTROL OF MICROGRIDS

The operation of a MG requires an energy management system and classification of a control strategy \cite [Palizban, et al., 2014]. The control strategy of MG should consider controlling the flow of active power, the resynchronization between the MG and system parameter settings voltage, the frequency in both modes of operation and the improved efficiency in the MG [Carrasco, et al., 2006; Guerrero, et al., 2011].

Levels of hierarchical control in a MG depend on the concepts and criteria used. Some authors define hierarchical level in three levels [Carrasco, et al., 2006; Katiraei, et al., 2008; Planas, 2013] and others define four levels [Guerrero, et al., 2011; Palizban, et al., 2014]. This paper adapts the definition of hierarchical control of four levels (zero to three) presented by the authors [Guerrero, et al., 2011; Palizban, et al., 2014]. Level zero is the inner control loop for controlling the output voltage and current from the sources. The reference value for the inner control loop is generated by primary control (level one). Then, secondary control in the next step monitors and supervises the system with different methods. Finally, the last level is tertiary control which manages the power flow and the interface between the MG and the main network.

The MG concept of the Consortium for Electrical Reliability Technology Solutions (CERTS) establishes that a key element of the monitoring design of MGs is that communication is unnecessary for microsources among basic MG operation [CERTS, 2002]. In this way, each MG controller must be able to respond effectively to system changes without requiring data from other sources or locations [Planas, 2013]. Droop methods are presented such as wireless monitoring techniques that satisfy this characteristic. Apart from this, many publications suggest that droop methods are the best option for controlling DERs in MGs [CERTS, 2002; Katiraei, et al., 2008; Chowdhury & Crossley, 2011]. Moreover, almost all the experimental MGs droop implemented methods [Lidula, 2007]. In order to analyse these control methods in greater detail, a study of these methods is presented in the droop subsection.

Internal control loop - Level Zero
The objective of this level of control is to manage the power of DG [Palizban, et al., 2014]. This control depends mainly on the type of DG to control and its technological capabilities. . The technological capabilities should be analysed separately for the grid-coupling converter, as it is the entity which connects the DER unit to the grid and defines many of technological capabilities of the DER unit. This coupling device can be different for the same type of unit, e.g. a wind turbine can be connected to the network with an induction

generator, a double-feed induction generator, an inverter or a synchronous generator [Braun, 2008].

A synchronous generator uses Automatic Voltage Control (AVR) and turbine control [Guerrero, et al., 2011]. Although such devices are not designed with large contingences likely to take place in stressed condition, they still provide useful support in these conditions. This is particularly true for AVRs that regulate high side voltages of generator step-up transformers through compensation of their leakage reactance. The compensation AVR is more effective than other types because it regulates voltage closer to the loads [Kueck, et al., 2006]. In the case of DG non-controllable such as photovoltaic generation, Maximum algorithms Power Point Tracking (MPPT) can be used [Blaabjerg, et al., 2006].

Primary control
The purpose of this level control is to regulate the reference frequency and the voltage amplitude, given the voltage and current values changed by the zero level. The primary control must have a characteristic rapid response to changes in demand or generation (in the order of thousandths of a second) [Vásquez, et al., 2010]. DERs can work when disconnected or connected from and to the grid. When they work connected to the grid, real and reactive generated powers are controlled. In the case of several DERs working autonomously, some form of control is needed in order to avoid circulating currents between them and to establish the voltage and frequency of the formed grid. The proposed controls are classified basically in communications based techniques and droop methods [Planas, 2013].

Droop Methods: Droop Methods are based on the behavior of synchronous generators. The equivalent circuit of a synchronous generator connected to the grid is presented in Figure 2. The real power injected into the grid can be expressed as:

$$S = P + jQ \tag{2}$$

Where P and Q are the active and reactive powers respectively. In Figure 2. an impedance ZΘ between the network and the generator shown, this impedance is formed by the synchronous generator or internal impedance of the generator and the impedance between the generator and the grid.

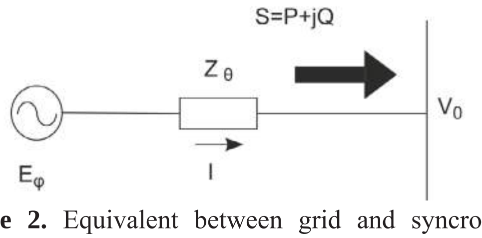

Figure 2. Equivalent between grid and syncronous generator
Source: own elaboration.

The impedance of the equivalent circuit is considered inductive, so the active and reactive powers can be expressed as:

$$P = \frac{EV}{X} sen(\varphi) \tag{3}$$

$$Q = \frac{EVCos(\phi) - V^2}{X} \tag{4}$$

It is considered that the difference of phase between *E* and *V* is small, thus sin Ø≈ Ø y CosØ ≈1. Taking this into account and using the equations (2) and (3), it can be observed that *P* and *Q* depend primarily on Ø y *E*, *V* respectively.

Secondary control
The objective of this level is to ensure that the variations of frequency and voltage are taken to zero, following the changes in demand and generation in the MG [Palizban, et al., 2014]. The secondary controls in the power systems serve to correct the variations of the frequency in the network and maintain the variations within the permitted limits according to the system operator.

The speed of this secondary control response is slower than that of the first level (primary control) by a matter of seconds. This level of control can be divided into centralised – named Microgrid Central Controller (MGCC) - and non-centralised, by independently using an intelligent control for each unit.

Tertiary control
The objective of this level of control is to manage the power flow via the regulation of the voltage and the frequency when the MG is operating in interconnected mode. This level of control is slower (by a matter of minutes) and ensures the optimum functioning of the MG, both technically and economically [Carrasco, et al., 2006].

In general, the control of the DG will be under droop control when it is operating in interconnected mode with the network. When the MG operates in isolated mode, a generator governor control will change it to isochronous mode whilst the rest of the DG will continue in droop or fixed power output mode [Majed, et al., 2011]. In this mode, it should be found that a MG will show at least a source of controllable generation (technologies with synchronised generators such as CHP, SHP, gas turbine etc.), thus guaranteeing efficient system performance when faced with unexpected changes in the demands or generation [Carvajal, et al., 2012].

4. CASE STUDY: TRANSIENT STABILITY OF A MG WITH SHP IN THE LOCAL DISTRIBUTION SYSTEM

The isolated operation of a MG is employed to prevent the interruption of the power supply to important loads and users during a system failure or maintenance schedule . In this way, levels of service reliability are increased for users located within the MG.

The following study examines a MG before a system failure and during isolated operation from the network. It will analyze frequency behavior and the actions of the controllers in the synchronous machine of the SHP.

System Characteristics

The local distribution system has voltages of 13.2 kV and 33 kV, is connected to the Colombian Electrical Power System by the 115 kV lines. This system is made up of more than 500 different elements such as generators, loads, transformers and subtransmission lines.

The topology of the studied network has the necessary conditions for a MG to be configured as a lateral island within it. As such, said network was used in this study and, using the definition set out in regulation 2011 [IEEE 1547.4, 2011] we proceeded to carry out the simulation and subsequent analysis of this operation.

The analysis of frequency behavior was conducted by incorporating a MG operation into the local distribution system.

Simulation Considerations

The model was constructed using real data about the distribution network that is connected to the three SHPs. This data was taken from the web page of the network operator

Electrical distribution system: The system was simulated in its entirety using the DIgSILENT tool. For the purpose of our case study, the formed MG was considered and transient stability were analyzed.
Control governor: (i) gov_HYGOVMmodif; (ii) gov_HYGOV: Hydro Turbine Governor; (iii) Woodward PID Hydro Governor and (iv) Currently controller were analyzed.
Automatic Voltage Regulator (AVR): AVR IEEET1: 1968 IEEE Type 1 Excitation System. SHP was equipped with an AVR controller that is part of the DIgSILENT Power Factory simulation tool. This is essential in order to have complete control of the steady state and transient state.

The simulation shows the response of the generators and the behavior of the MG when a number of contingencies were tested on the generating groups.

Simulation of the Model

The case study MG is presented in Figure 3 and was planned using the criteria of IEEE standard 1547:2011

In Figure 3, the diagram of the unifilar connection of the distribution substation 33000/13200V "Salamina" is shown. This substation possesses three feeders of Medium Voltage, named SLM23L12, SLM23L13 y SLM23L15. The feeder SLM23L12 is connected to a SHP of 0,5 MW. In this paper, we propose to study the transitional behaviour of the system when there is a failure in the Salamina substation and the SLM23L12 is isolated to operate in the form of an MG.

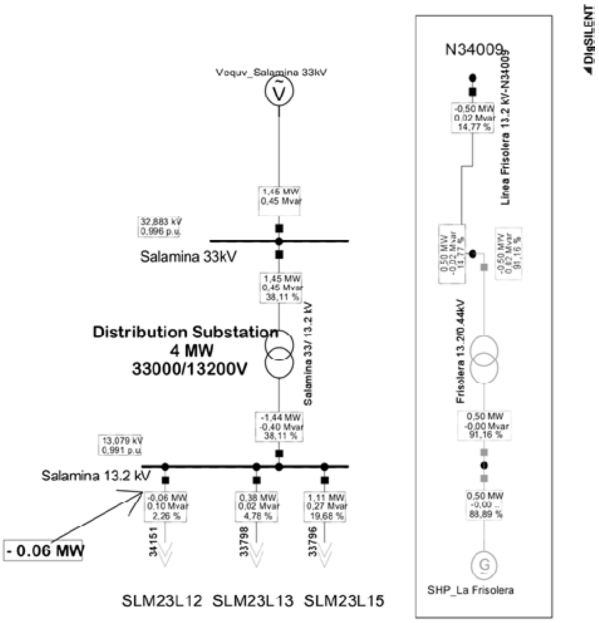

Figure 3. MG proposed simulation with SHP.
Source: own elaboration.

Results and Discussion

The results show that during an output event in a generating unit, the MG operates within stability limits so long as it has the kind of loads that can be disconnected in such an event, allowing a balance to be reached between the power generated and the power consumed. Disconnectable loads are known as non-critical loads and are defined as power system users that can be disconnected without risking the security of the country or incurring excessive costs as a result of a blackout (industrial users.)
For MG operation it is necessary to have controllable loads with the option to choose between critical and non-critical loads. In the case study, a range of possible contingencies within the MG were examined. Similarly, given that energy generated in the MG in islanding operation cannot be supplied to the rest of the network, it becomes necessary to disconnect certain loads in order to achieve a permanent state of stability in the MG.

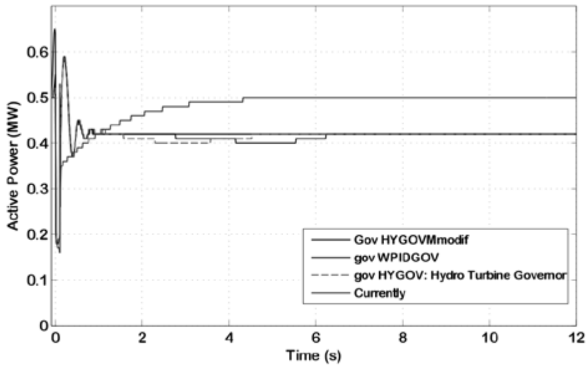

Figure 4. Transient Power of the SHP during the 3-phase Short-Circuit.
Source: own elaboration.

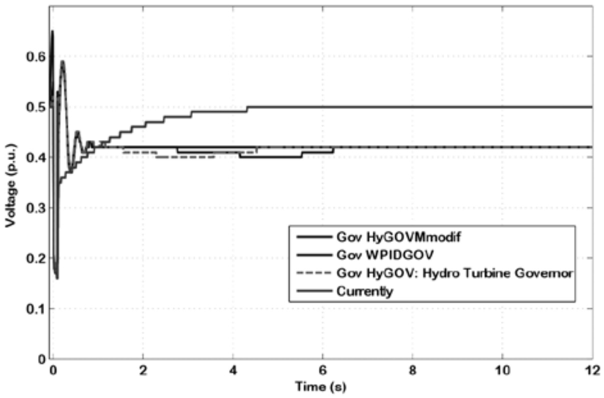

Figure 5. Transient Voltage of the SHP during the 3-phase Short-Circuit.
Source: own elaboration.

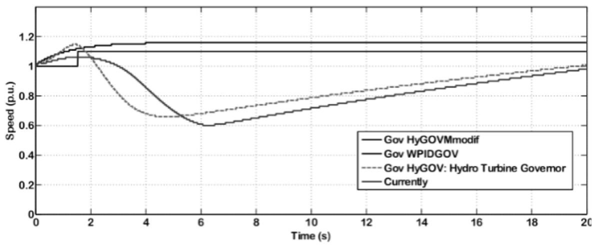

Figure 6. Transient Speed of the SHP during the 3-phase Short-Circuit.
Source: own elaboration.

A simulation of a 3-phase Short-Circuit in the bar of 13,2 kV of Salamina was carried out, followed by a clearance event and opening of the feeder SLM23L12 100ms afterwards. The previous events were simulated with the aim of observing the transitory behaviour during the MGs switch from interconnected mode to isolated mode.

The simulations show that when compared to different turbine governors, the WoodWard PID governor shows an adequate performance, maintaining the electrical parameters within the recommended limits of the system operator [IEEE, 2008].

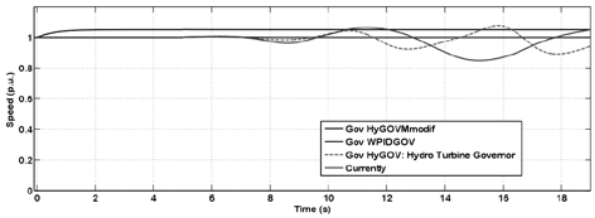

Figure 7. Transient Power of the SHP during the 3-phase Short-Circuit at 5s in islanded operation.
Source: own elaboration.

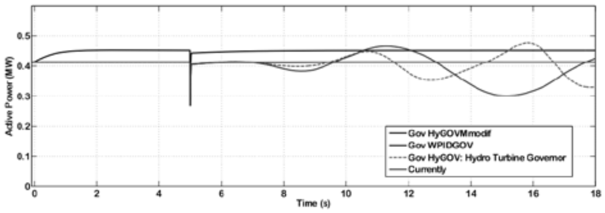

Figure 8. Transient Voltage of the SHP during the 3-phase Short-Circuit at 5s in islanded operation.
Source: own elaboration.

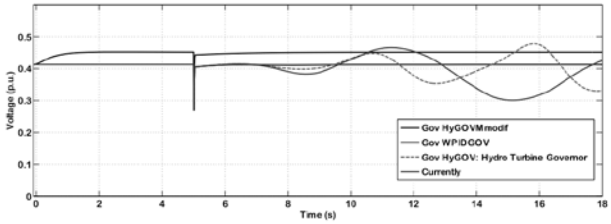

Figure 9. Transient Speed of the SHP during the 3-phase Short-Circuit at 5s in islanded operation.
Source: own elaboration.

In figures 7, 8, 9 a simulation of a system operating in isolated mode is carried out, simulating a tri-phase failure at 5 seconds, then a clearance event 100ms afterwards (5.1 seconds). The simulations show that the current conditions of the turbine governor HyGov (found in various SHP in the region) do not display a good level of performance. On the contrary, the Woodward PID and Modified HyGOV governors show unacceptable levels of performance for operating in the form of an MG.

5. CONCLUSION

An important element during the planning of a system to operate as a MG, is the analysis of the behaviour during the change to isolated mode and operating independently from the system. The analysis carried out in this paper shows that with a suitable choice of turbine governor, and when faced with failure events, the system manages to maintain within the permitted ranges and is able to stabilize itself within an acceptable time. However, during the reset time for the failure, depending on the established criteria by the network operator - which in our case was 100 ms - a drop in transitory voltage was shown that could cause system failure and prevent an adequate islanding operation. Thus, it is recommended that the SHP include within the basic MG planning, the capacity for autonomous start-up and ensures that it has synchronised devices.

For further research projects is proposed to make a regulatory frame work that include a set of principles, rules and incentives which addresses sensibly both technical and economic issues of DERs connections to microgrids. Technical issues encompass new standards of DG technologies, interconnection practices, protection schemes, environmental issues, ancillary services and metering. On the other hand, economic issues deal with various incentives and the internal market settings for MG.

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