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Distributed Control Strategy for Isolated Electrical Hybrid Power Systems

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Abstract. This paper presents a distributed control for isolated electrical hybrid power systems to manage the energy generated by the elements of the microgrid. Unlike other control strategies seen in the literature, this distributed control strategy takes into account the dynamic behavior of the synchronous generators and the spinning reserve requirements. The distributed control offers a simpler implementation than other proposals, a better integration of renewable generation, a greater reliability against communication failures and it reduces the energy costs. The main objectives of the controllers are minimizing fuel consumption and maximizing renewable generation. Simulation results are obtained using MATLAB/Simulink to verify the effectiveness of the proposed control strategy.

Key words. Energy storage, isolated microgrids, diesel generator, spinning reserve, hybrid system.

1. Introduction

The market for off-grid solar systems has grown exponentially over the past decade, with estimated sales reaching 23.5 million units in 2018, up from only 0.9 million in 2010. Around 7.6 million off-grid solar products were sold globally in 2018, comparable to the sales volume of the previous year; however, sales in 2018 resulted in a 45% increase in the total installed capacity of off-grid solar products, to around 58.8 megawatts (MW) (up from 40.7 MW in 2017) [1]. This growth is due to factors such as:

1) The rapid decreases in photovoltaic (PV) module costs. Since 2009, for instance, the costs have fallen by more than 80% while, globally, the cost of solar PV power declined by 73% from 2010 to 2017 [2].
2) The increase in the cost of fossil fuels for conventional generation and the reduction of dependence on fossil fuel imports [1].
3) The emergence of new energy storage technologies such as electrochemical batteries [1].
4) The urgent action to increase mitigation of climate change [1].

Although the growth of renewable energies in isolated microgrids reduces the reliability due to the intermittency of renewable resources, it also increases the power electronics and reduces the synchronous generation. Therefore, isolated microgrids have low inertia and need robust control systems to ensure proper operation [3]. In addition, the integration of Battery Energy Storage Systems (BESS) can reduce losses and increase reliability [4].

There are three levels of control in a microgrid: primary, secondary and tertiary [4], [5] and [6]. The primary control is responsible for the microgrid stability, i.e. the voltage control as well as the power sharing and balancing. It is based on droop control [7]. The secondary control restore voltage and frequency deviations to their reference values [4]. It also has the functionality of an Energy Management System (EMS). Although in [8] and [9] the EMS is integrated within the tertiary control. The tertiary control manages the power flow between the microgrid and the external electrical distribution system, in case it is grid-connected [10].

There are many different solutions to develop an EMS. In [11], [12], [13] and [14] it can be formalized using a state machine approach. In [15], [16], [17] and [18] the optimal operation of the microgrid is obtained by a mixed-integer linear programming (MILP) and by a mixed-integer nonlinear programming (MINLP) in [19]. In [6], [20] and [21] the control action for the next time step is obtained by solving an online finite horizon open-loop optimal control problem, using the current state of the plant as the initial state, known as Model Predictive Control (MPC). In [22], [23], [24], [25] and [26] the EMS is carried out from a dynamic control model of the elements in the microgrid, which calculates the optimal operation taking into account stability and frequency constraints.

In a state machine, the system makes a transition from one state to another, provided that the condition defining the change is true. It is necessary to define all possible states. Thus, if the EMS is large and complex, the state chart will also be complex. As shown in the literature, MILP, MINLP and MPC optimizations are static solvers that solve a power balance and they do not take into account the dynamic behavior of the synchronous generators.

Also, in the previous literature review only [16] and [17] take into account the spinning reserve of the diesel generators for the control of isolated microgrids. In electrical power systems are required to maintain adequate amount of spinning reserve to mitigate deviations or the lost power at renewable generators in case there is not enough renewable resource. To maintain the spinning reserve has a drawback since it reduces the penetration capacity of renewable generation. Therefore, it must be considered during the operation and schedule of isolated microgrids.

This paper focuses on a control strategy for isolated microgrids, taking into account the dynamic behavior of synchronous generators and the spinning reserve requirements. Three local controllers are established by two Power Plant Controllers (PPC) and an EMS, and each one of them has two levels of performance. On the lower level are the fundamental controls of the elements, while in the upper level are the controls that give the operating commands of the elements. The lower level controls are not discussed in this study, but they have been simulated. In addition, communication between local controllers is necessary to optimally manage the isolated microgrid.

This paper is structured as follows. Section 1 is the introduction and the literature review. Section 2 overviews the microgrid description and modelling. Section 3 is the explanation of the isolated microgrid control configuration. Section 4 describes the Diesel PPC. Section 5 describes the PV PPC. Section 3) describes the BESS EMS. Section 7 presents the results. Finally, some conclusions are discussed in Section 8.

2. Isolated Microgrid Description and Modelling

For the development of this paper, the data of the solar irradiation and the load demand have been obtained from a real isolated microgrid located in Colombia. As well as the configuration (Fig. 1) and the different elements (Table. I), that make up the isolated microgrid.

The verification of the proposed control strategy has been done through the simulation of a 24-hour scenario in MATLAB/Simulink. Therefore, it has been necessary to model an isolated microgrid with all its elements using the Simscape toolbox [27]. The PV plant includes the PV modules and the PV inverter with a maximum power point tracker (MPPT), the BESS has a lithium-ion battery pack with a battery management system (BMS) and diesel generators which include a model of synchronous machine, a speed governor and an excitation system.

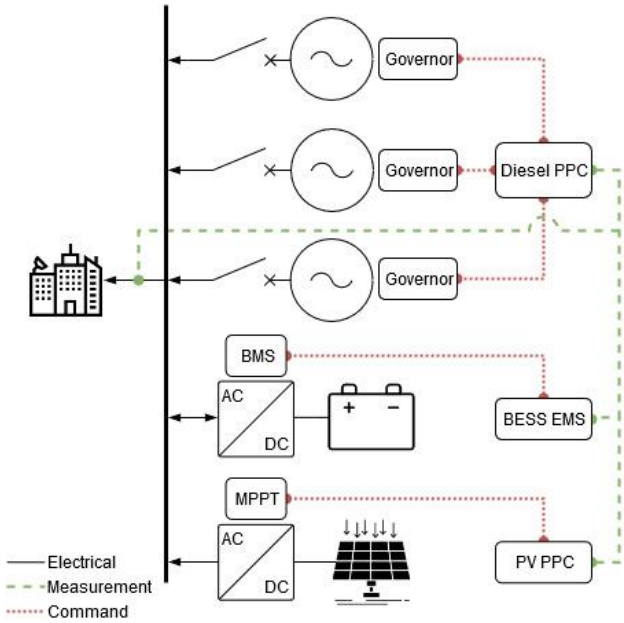

Fig. 1. Isolated Microgrid Configuration.

The wiring layout of the microgrid is shown in Fig. 1, in which the electrical connections, the measurements of the local controllers and the commands are differentiated.

Table. I Isolated Microgrid Elements.

Diesel Generator x 3	
Rated Power (kW)	2000
Minimum Rated Capacity (kW)	400
Spinning Reserve (kW)	700

PV Plant		BESS	
AC Power (kW)	4000	Power (kW)	1200
DC Power (kWp)	5000	Capacity (kWh)	3600
		Roundtrip Efficiency (%)	90

3. Isolated Microgrid Control Configuration

To carry out the distributed control of the isolated microgrid, it has been divided into 3 independent local controllers (Diesel PPC, PV PPC and BESS EMS), one for each element of the microgrid. Each controller has a different function, as it can be seen in Sections 4, 5 and 3).

For the management of the isolated microgrid to be optimal, it is necessary to establish communication between the different local controllers. The Diesel PPC does not need information from other controllers to carry out its operation. However, the PV PPC needs the number of diesel generators turned on and the power produced by each one. Like the PV PCC, the BESS EMS also needs information from other controllers, such as the power demand, the number of diesel generators turned on and the power produced by the PV plant.

The desired objectives of the control strategy are:

1) Minimize Diesel Power Generation.
2) Maximize PV Power Generation.
3) Charge BESS with PV Surplus and Discharge it with lack of PV Power.

Therefore, there is no need for a control level above the local controllers, since they are not necessary as demonstrated in this paper.

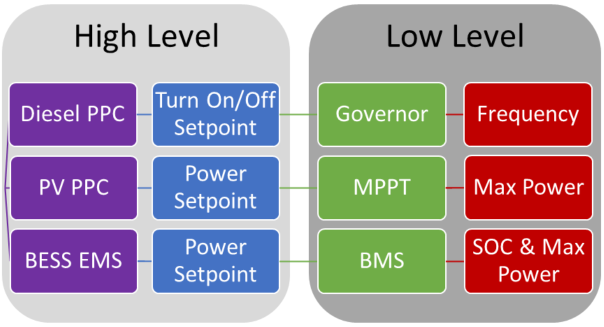

Fig. 2. Scheme of Control Levels Functions.

Fig. 2 shows what actions are carried out at each of the control levels. At the low level of control, the governor carries out the grid voltage and frequency control. The MPPT extracts maximum power available from PV modules. The BMS manages the charge/discharge and provides notifications on the status of the BESS. While at the high level of control, the Diesel PPC sets the on-off state of the diesel generators. The PV PPC establish the power limit to the PV inverter. The BESS EMS sends the power command to the Power Conversion System (PCS).

4. Diesel PPC

The Diesel PPC is responsible for controlling diesel generators and their governors have an Automatic Generation Control (AGC) to restore the frequency to the specified nominal value. This is accomplished by adding an integral control, which acts on the load reference settings of the units' governors. The integral control action ensures zero frequency error in the steady state [28]. In case there are more than one synchronous generation unit, a droop control is used, which allows several synchronous generators to operate in parallel and share the load proportionally to their nominal power [3]. The Diesel PPC oversees starting and stopping the units, depending on the available spinning reserve and the minimum rated capacity of the generators respectively. In addition, due to the synchronous generators carry out the grid voltage and frequency control, a unit must always be on for the task of grid forming. This decision has been made based on two fundamental characteristics of synchronous generators: to provide inertia and to keep the power balance.

For the management of the spinning reserve of diesel generators a strategy is established, in which the equations (1-3) yield the on-off state of the diesel generators.

$$N_{GTotal} = \sum N_{Gn} \qquad (1)$$

$$P_{Gn} \geq SR \Longrightarrow N_{Gn} = 1 \qquad (2)$$

$$P_{Gn} < P_{Gmin} \Longrightarrow N_{Gn} = 0 \qquad (3)$$

Where:

1) N_{Gn} is the number of diesel generators turned on.
2) P_{Gn} is the power generated by diesel generators.
3) P_{Gmin} minimum rated capacity of diesel generators.
4) SR is the spinning reserve of diesel generators.

5. PV PPC

The PV PPC is responsible for controlling PV plant, since it adjusts the power of the PV plant to operate diesel generators to their minimum rated capacity. The integral regulator of the Fig. 3 is used. The PV inverter can restrict the power delivered by the PV plant due to its MPPT has less power available than required by the controller.

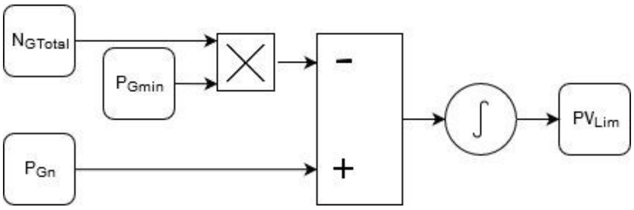

Fig. 3. Block Diagram of PV PPC.

Where:

1) N_{Gn} is the number of diesel generators turned on.
2) P_{Gn} is the power generated by diesel generators.
3) P_{Gmin} minimum rated capacity of diesel generators.
4) PV_{Lim} is the PV power limit.

6. BESS EMS

Finally, the BESS EMS is responsible for controlling the BESS, and its BMS calculates the State of Charge (SOC) and the available charge/discharge power. The BESS EMS strategy discharges the BESS to operate the diesel generators to their minimum rated capacity when the PV plant has not enough solar resource, while it charges the BESS to store the surpluses of the PV plant. The BMS can restrict the power delivered by the battery due to its SOC.

The charge/discharge power is calculated through the power balance given by the following equation (4).

$$P_{ESS} = P_{Load} - (P_{Gmin} \cdot N_G + P_{PV}) \qquad (4)$$

Where:

1) P_{ESS} is the BESS charge/discharge power.
2) P_{Load} is the power by load demand.
3) N_G is the number of diesel generators turned on.
4) P_{PV} is the power generated by PV plant.
5) P_{Gmin} minimum rated capacity of diesel generators.

To carry out the coordination of the two controllers, the value of the minimum rated capacity of the diesel generators in the BESS EMS is 12.5% less than the PV PPC value.

7. Results

The results obtained in MATLAB/Simulink of the proposed control strategy are shown below, in Fig. 4.

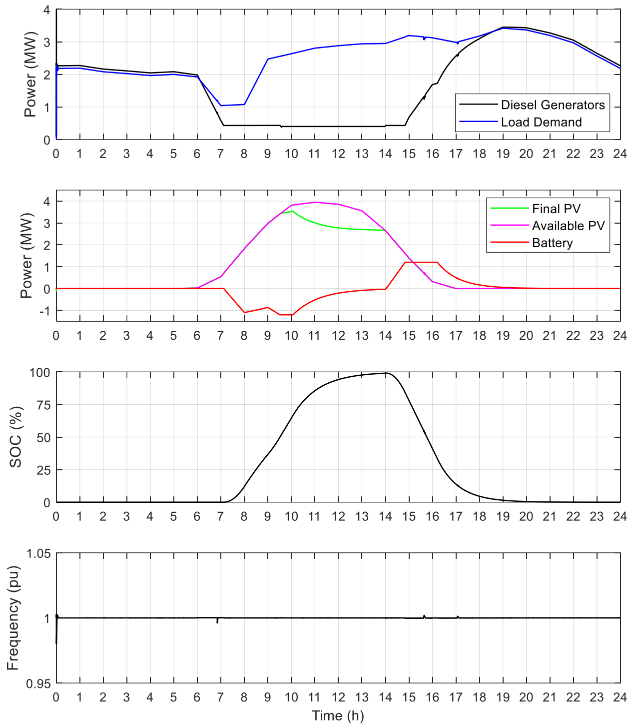

Fig. 4. 24-hour Simulation of Isolated Microgrid.

The first plot in Fig. 4 shows the load profile (blue) and the power generated by all diesel generators (black). The second plot in Fig. 4 shows the available PV plant power (purple), the final PV plant power (green) and the BESS charge/discharge power (red). The third plot in Fig. 4 shows the SOC of BESS, with a single daily charge/discharge cycle. The last plot in Fig. 4 shows the frequency of the system.

From the Fig. 4, it is observed four different moments in the simulation:

1) In the ranges of 0-6 hours and 19-24 hours, when there is not solar resource and the BESS is at 0% SOC, the diesel generators adjust their power output as demand, it is also known as load following.

2) In the range of 6-10 hours, the sun begins to rise, and the PV power increases. Therefore, the power produced by diesel generators is minimized. In addition, the BESS is charged with the surplus of PV plant, because the load demand is already covered.

3) In the range of 10-14 hours, the BESS is fully charged. Thus, the MPPT must curtail the PV plant power and some of the available solar resource is wasted. While diesel generators continue to operate at their minimum rated capacity.

4) In the range of 14-19 hours, the sun begins to set, and the PV power decreases. Immediately, the BESS starts to discharge but it does not have enough power. Hence the diesel generators ramp up their power to cover the load demand.

Fig. 4 presents the simulation results, in which it is observed that the proposed control operates the isolated microgrid correctly since all the objectives set in the section 3 are fulfilled. Besides the frequency is within acceptable values, therefore there are not stability issues.

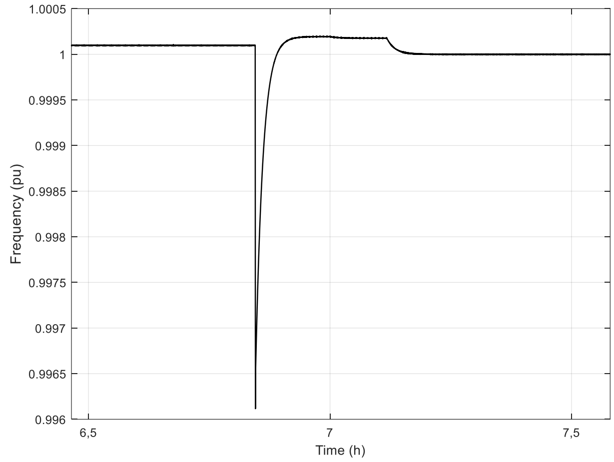

Fig. 5. Isolated Microgrid Frequency Zoom.

Fig. 5 illustrates the behavior of the system frequency when turn off the diesel generator number 2 a few minutes before seven in the morning. It is observed a slight decrease (0.4%) in the frequency, but it is restored in a few minutes. The diesel generator number 2 is turned off because PV power increases and load demand decreases.

8. Conclusions

This paper presents a distributed control strategy for isolated microgrids adapted to the dynamic behavior of synchronous generators and it ensures the requirements of spinning reserve. The control implementation is simpler than other proposals in the literature.

In this case with the proposed control strategy and for the sizing of the isolated microgrid, the surpluses are reduced up to 50% and it saves 10-15% on fuel costs annually.

Also, it provides greater reliability against communication failures between controllers, because the microgrid needs the minimum information shared sent by generation units to be operated and scheduled. Even if there is a total failure in communications, the isolated microgrid will continue to operate only with diesel generators, since the diesel generators are responsible for maintain the voltage and frequency of the isolated microgrid. Therefore, the system is not dependent on the other generation units (PV plant and

BESS) to maintain stability and no need a centralized controller.

The results show the fulfillment of the initially established objectives, i.e. minimize the fuel consumption of diesel generators, while the PV power is maximized. The BESS is charged with surpluses from the renewable generation, and it is discharged to reduce the use of diesel generators.

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