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A methodology for smart grid reconfiguration

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Abstract: In this work, it is presented a methodology for the reconfiguration of smart grids that is applied to a smart grid formed by two microgrids that can be electrically interconnected in contingency situations. Each microgrid is also connected to an Electric Power System (EPS) when operating in the normal state. Moreover, the smart grid includes energy storage devices (batteries) located at strategic points. Serious faults that isolated the microgrids of the EPS and, moreover, considerably reduced the generation capacity of such microgrids are simulated. The proposed methodology is applied to reconfiguration in scenarios involving cooperation between microgrids and/or the use of energy storage devices. Performance indices are also proposed to enable a quantitative analysis for each scenario. It is shown that intelligent cooperation between microgrids and the smart-use storage energy is the best option for reducing the impacts in a contingency scenarios.

Keywords: Smart grids, microgrids, grid reconfiguration, computational intelligence, genetic algorithm.

1. Introdução

Microgrids, in turn, are electric power networks with several consumer units (loads) and several strategically distributed low-power generators. Both loads and generators are located geographically close (Lasseter, 2011), allowing different manners of connection, that is, different topological changes. Thus, it is possible that for a fault event at one or more points in the microgrid, all adjacent energy sources and loads can be immediately disconnected (isolated) to prevent the problem from spreading. However, the remainder of the microgrid that is not affected by the fault should continue operating normally.

Solving the problem of reconfiguration involves providing alternative ways to establish connections between loads in regions with no failures and the non-disconnected sources. Thus, reconfiguration contributes to the continuity of the power supply in contingency situations, such as the occurrence of a short-circuit (Shariatzadeh *et al*., 2011), and can be initiated for at least three reasons, i. e. power failure, disequilibrium in the power balance, or maintenance activities on Power network components (Cebrian and Kagan, 2010). In the first two cases, some lower priority loads are likely to be rejected, i.e. disconnected from the microgrid.

In short, solving the problem of microgrid reconfiguration includes the following processes: topology changes in the microgrid; possible rejection of lower priority loads, i.e., disconnecting them from the microgrids; and maintenance of the power balance for ensuring the operational continuity of priority loads. Therefore, the main objective of this paper is to propose a reconfiguration methodology for smart grids.

2. Literature review

A methodology and system for automatic reconfiguration of distribution network in real time was presented in (Pfitscher *et al*., 2011). The authors state that the reconfiguration of distribution network can reduce losses, balance loads and improve quality indicators when in normal operation. However, none contingence scenario is considered in that work. So, in this paper is presented a methodology for reconfiguration under a severe contingence scenario. Such methodology consists of a microgrid protection systems controlled by a reconfiguration system based on computational techniques.

2.1 Microgrid protection system

The protection system of a microgrid is fundamental to the reliable, safe and economical operation. It was reported in (Glover *et al*., 2012) that a protection system must continuously monitor the electrical network to detect abnormal conditions, remove the smallest possible portion of the electrical system to isolate the faulty equipment, and allow the remainder of the network to continue to generate and distribute energy.

Studies on protection schemes for distribution systems with microgrids have been conducted since the beginning of the XXI century, when a group of researchers initiated the Consortium for Electric Reliability Technology Solutions (Lasseter, 2011). The main requirement of a protection system for microgrids is to ensure safe and stable operation both in interconnected and islanding modes (Haron *et al.*, 2012).

2.2 Computational techniques applied on smart grids

Graph theory has been used in the modeling, simulation and analysis of power grids (Correa and Yusta, 2013). Heuristic methods, graph search methods and spectral methods have been widely used to solve combinatorial optimization problems and graph-cut problems (Ding *et al*., 2014).

Optimal load-shedding strategies in distribution networks have been applied by other authors. Such a solution was used in (Padamati *et al*., 2007) to address an 8-bus shipboard power system (SPS), and was applied in modified CERTS (Consortium for Electric Reliability Technology Solutions) microgrids by (Shariatzadeh *et al*., 2011). Several methods of computational intelligence have been used to address the reconfiguration issue, e.g., ant colony methods (Vuppalapati and Srivastava, 2010) and genetic algorithms (Padamati *et al*., 2007).

3. Problem formulation

In this paper, it is addressed the problem of smart grid reconfiguration. Such a power grid is formed by two microgrids that can cooperate with each other in the case of a contingency situation. Fig. 1 presents possible states of a power grid. One can observe four states, namely, normal, emergency, reconfiguration and restoration. In the first state, the smart grid operates normally. However, the system is set to the emergency state when any problem is detected, affecting the power quality.

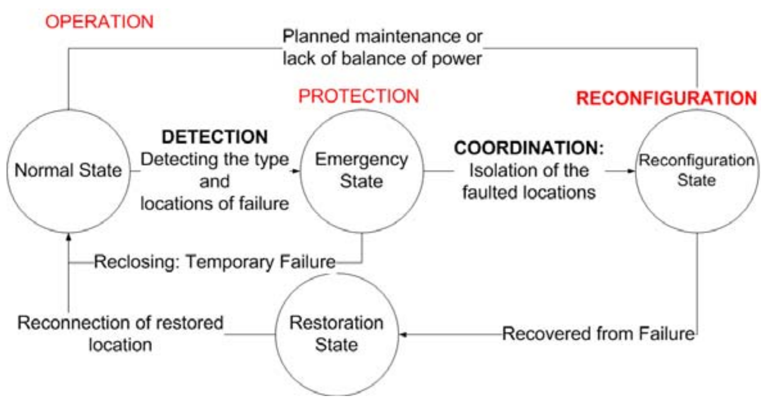


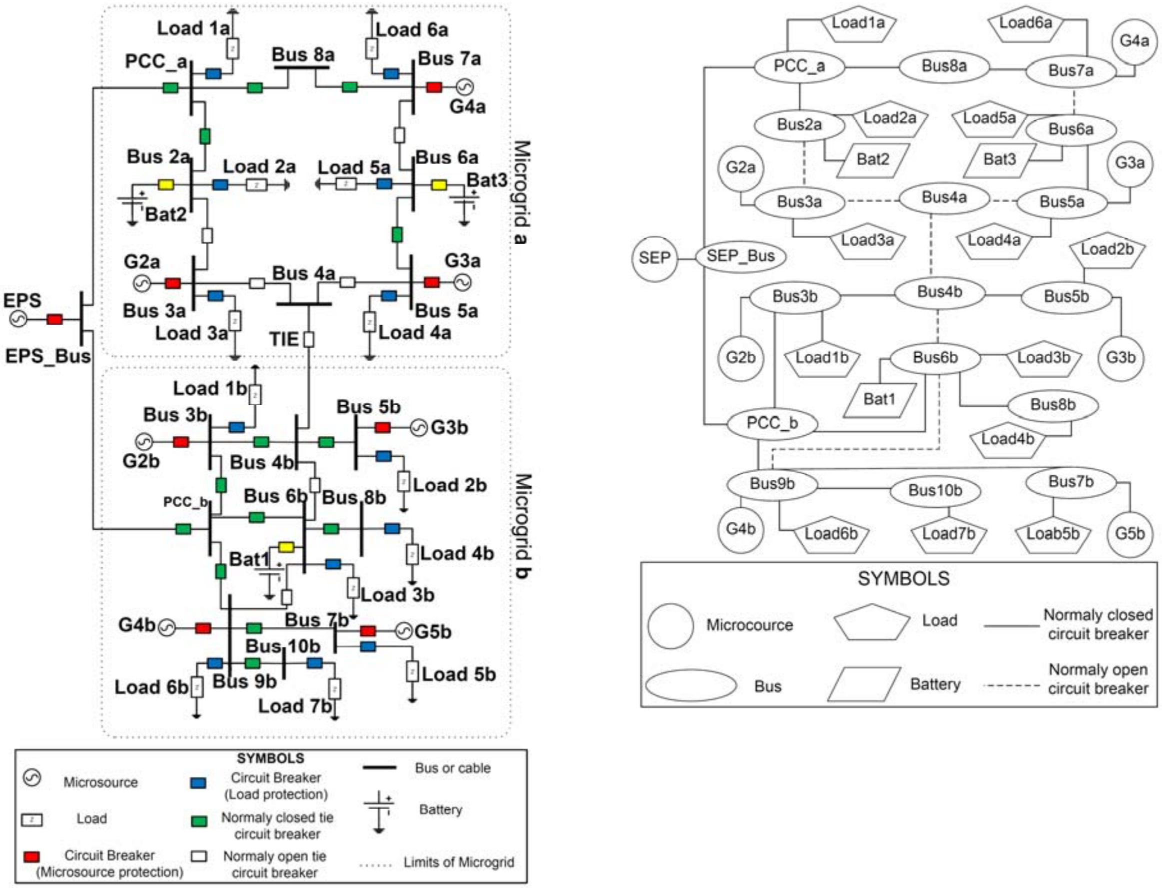
Figure 1. State diagram of the smart grid system.

Therefore, the protection system should actuate in the sense of identifying and isolating all fault zones, taking the smart grid to the reconfiguration state. In this state, the power network can suffer changes in topology to maintain service to priority loads. Recovered from the failures, the system proceeds from the reconfiguration state to the restoration state. Thus, the reconnection of the restored location is performed so that the smart grid returns to the normal state, where its original topology is re-established.

In addition to unexpected faults, planned maintenance or unbalanced power flows can move the smart grid from the normal state directly to the reconfiguration state, where the network topology can be changed. Finally, brief failures, which are very common in power systems, can move the smart system from the normal state to the emergency state, returning to the normal state without a change in the network topology.

3.1 Testing network

Fig. 2a shows the single-line diagram of the smart grid under study. Each bus directly connected to circuit breakers is defined as a zone in the protection scheme. Fig. 2b presents the graph generated from such diagram, considering the correlation given in Table 1.



a) Single-line diagram.

b) Graph diagram.

Fig. 2. Representations of grid under study.

Table 1. Microgrid representation as a graph.

Component of Microgrid	Elements of Graph
Microsource, bus, load and battery	Vertices
Circuit breaker	Edge

3.2 Mathematical formulation

To simplify the problem addressed here, is considered stable operating condition, that is, loads, generators and batteries are consuming or supplying its rated power. Thus, both the intermittency of renewable sources and the charging/discharging of the storage devices (batteries) are neglected, leaving transient analysis to be addressed in future work.

In this work, the objective function is used to maximize the total power delivered to the load, balancing the generating capacity and the demand of loads not rejected, i.e.,

$$\mathrm{P}_{\mathrm{Load}} = Max\left(\sum_{i=1}^{n} L_i\right), \quad \forall n \in \mathrm{Z}^{+}, \tag{1}$$

subject to $P_{gen} \geq P_{load}$, where L_i is the power demanded by a load i after isolation of a fault, P_{gen} is the total power generated and P_{load} is the total power demanded by n loads that continue to demand power after fault isolation.

The follow evaluation function is defined to measure the quality of a solution:

$$f(\mathbf{x}) = \mathbf{W}_M \mathbf{x} \mathbf{L}^t + \mathbf{W}_P \mathbf{x} \mathbf{L}^t , \quad (2)$$

where: $\boldsymbol{x} = [x_1, x_2, \dots x_n]$ is a vector in which each element corresponds to the configuration of a circuit breaker responsible for connecting/disconnecting a load, where $x_i = 1$ indicates that the load is connected *and* $x_i = 0$ indicates that the load is disconnected, with $i = 1, 2, \dots n$; $\boldsymbol{L} = [L_1, L_2, \dots L_n]$ is a vector with the values of the power required by each load; $\boldsymbol{P}^{nxn}$ is a diagonal matrix with the priorities of the loads; and $\boldsymbol{W}_P$ and $\boldsymbol{W}_M$ are weighting factors assigned to the priority and magnitude of the loads, respectively, with $\boldsymbol{W}_P = 1 - \boldsymbol{W}_M$.

4. Proposed methodology

Fig. 3 shows a flowchart of the proposed methodology. One can observe that the detection of a failure triggers a series of events, among which is the power balance event. This is possible due to the existence of a protection system, which continuously monitors the power owing through each circuit breaker, allowing a rapid location and isolation of the fault zone. Subsequently, it is possible to identify the balance of power at areas not affected by the failure, considering the data stored before and after the failure. Next, the existence of areas with a negative balance of power, i.e., areas with demands of loads not being supplied, is verified. A single negatively unbalanced zone is sufficient to start a search for one or more paths having a positive balance of power. However, if such positive balance is not possible, the power grid is reconfigured to supply electrical power to priority loads and to shed low-priority loads.

4.1 Load shedding

Reconfiguration with load shedding is a multi-objective optimization problem that includes Boolean variables and continuous variables. Thus, several optimization techniques can be applied. In this paper has been used Genetic Algorithm due to the simplicity of implementation.

Table 2 presents the basic parameters and the stopping conditions used by the genetic algorithm proposed here. Therefore, the process of load shedding begins by evaluating this standard population and by applying the evaluation function (Equation 2]). Selection criteria (Equation 1) is applied to the current population. A combination of chromosomes of two individuals from a population is performed when such criteria are not met, thus forming two new chromosomes. These new chromosomes can also be mutated, that is, a gene manipulation using a random process, causing changes in alleles. Thus, it generates a new population that can reproduce if the selection criteria are not met, repeating the process. The chromosome is composed of a vector of bits, where each bit corresponds to a circuit-breaker of the microgrid under test (graph edge).

Table 2. Basic parameters of the genetic algorithm.

Parameter	Value
Population type	Bit vector
Population size	40 individuals
Mutation rate	10%
Initial population	Randomly generated
Possible size of the initial population	0 to 2^{nVars}
Type of crossing	Scattered crossover
Type of selection	Stochastic universal sampling
Chromossome size	45

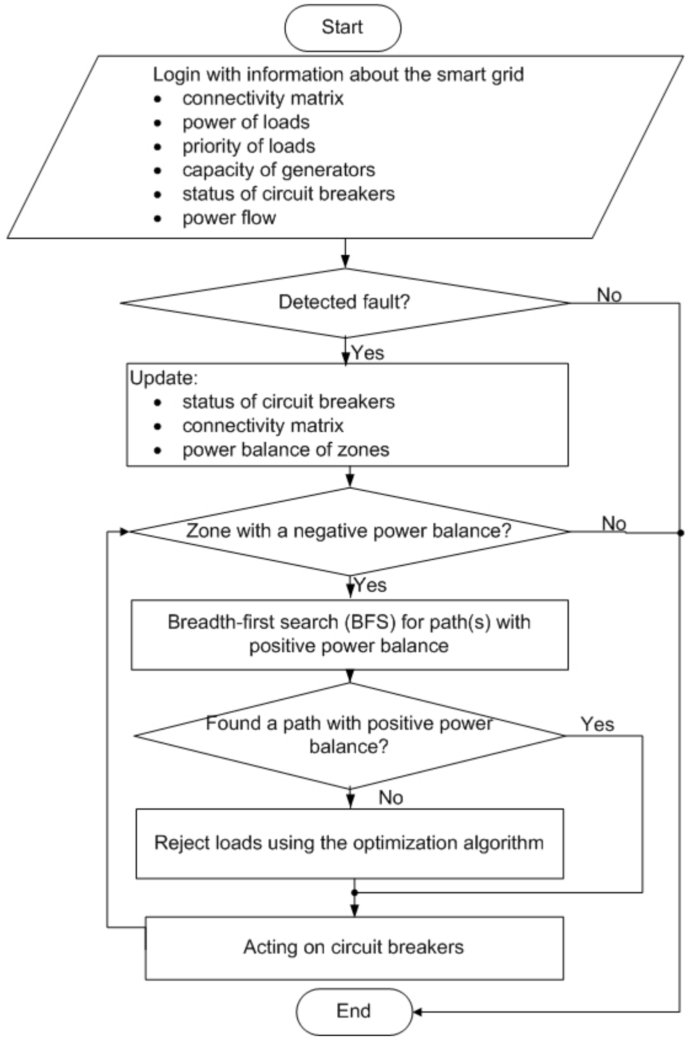


Figure 3. Flowchart of reconfiguration methodology.

4.2 Performance indicators

Some indicators are defined in order to allow a quantitative analysis of the results involving the application of reconfiguration of the network in case of contingency. Thus, be

$$C_i = \sum_{k=1}^{N} g(k), \tag{3}$$

the Installed Generation Capacity, where $N \geq 2$ is the number of generators in a microgrid and g is the nominal power of a generator in the microgrid. It is noteworthy that faults in the microgrid do not change C_i.

Be

$$L_n = \sum_{k=0}^{M} l(k), \tag{4}$$

the total load supplied during normal operations of the microgrid, where $M \geq 0$ is the number of loads in the microgrid and l is the power of a load of the microgrid, with $l(0) = 0$.

Assuming that in the normal state, the microgrid is self-sufficient, $0 \leq C_n \leq C_i$. Therefore,

$$f_n \equiv \frac{C_n}{C_i}, \tag{5}$$

is defined as a usage factor for normal operations of the microgrid.

Note that a microgrid with f_n close to 0 (zero) is of great interest because it indicates a greater ability to recover from failure situations without suffering large losses with respect to the quantity of loads supplied. In contrast, a microgrid with f_n close to 1 (one) is undesirable because although the grid may be self-sufficient under normal operations (by assumption), any failure could result in an imminent need of importing electrical power and/or load rejection.

Now, be

$$C_R = \sum_{k=0}^{M'} l(k), \tag{6}$$

the non-rejected total load after a reconfiguration, where M' is the number of non-rejected loads in a microgrid after such a reconfiguration, with $0 \leq M' \leq M$.

It is defined

$$f_R \equiv \frac{C_R}{C_i}, \tag{7}$$

as a usage factor after a reconfiguration, where $0 \leq f_R \leq 1$.

Now, from Equations 6 and 7 has

$$I_{CA} \equiv \frac{f_R}{f_n}, \tag{8}$$

By substituting Equations 5 and 7 into 8, obtains

$$I_{CA} = \frac{C_R}{C_n}, \tag{9}$$

where $0 \leq I_{CA} \leq 1$.

Note that I_{CA} is independent of the Installed Capacity (C_i). In addition, note that $I_{CA} = 0$ if and only if $C_n = C_R = 0$ or if $C_n \neq 0$ and $C_R = 0$. The first case indicates a microgrid with no load connected. In the second case, where $C_R = 0$, there is no load supplied by the new configuration of the microgrid. In fact, the closer I_{CA} is to 0 (zero), the worse the result caused by a failure. In contrast, the closer I_{CA} is to 1 (one), the smaller such a consequence is. Therefore, $I_{CA} = 1$ implies that, even in the face of a possible failure or a planned maintenance of the power system, all loads supplied before a reconfiguration event are supplied after such an event. Therefore I_{CA} can be used to compare the different solutions found, and the solution whose I_{CA} is closest to unity will be the most efficient.

Extending the performance index of Equation 9 a set of microgrids takes to

$$I_{CAM} \equiv \frac{\sum_{i=1}^{R} I_{CA}(i)}{R}, \tag{10}$$

is defined as the average index of the load supplied, where $0 \leq I_{CAM} \leq 1$.and $R \epsilon Z^{+}$ is the number of microgrids controlled by the smart grid. Note that I_{CAM} has the same characteristics that I_{CA}.

5. Results

Table 3 summarizes the most relevant results obtained in this work. Firstly, it observes the *scenario1* where each microgrid is electrically connected to the SEP (on-grid). In this case, both I_{CA} and I_{CAM} are equal to unity, i.e., all loads are being supplied normally. The others scenarios result from simulations of simultaneous failures in areas of great importance, which provoke islanding of the smart grid (faults at the buses *PCC a* and *PCC b*) and loss of self-generation capacity (fault at the bus *Bus7b*).

Fig. 4 illustrates such simultaneous faults, where can be seen the fault at *Bus7b* isolates the generator *G5b* of Microgrid b, i.e., the generator is not able to supply electrical power to any load. Note that *G5b* is the main generator of Microgrid b, with a nominal power equal to *150kW* (see Figure 3.1). Therefore, the fault at *Bus7b* provokes a loss of approximately *33%* of the Installed Capacity (C_i) of the smart grid. This is a working critical situation of the electrical system, which is indicated by $I_{CAM} = 0{:}49$ (see Table 3), meaning that only *49%* of the power normally demanded by the smart grid is being supplied. Table 3 also shows the loads rejected as well as the reason for rejection.

Table 3. Results of case studies on smart grid with faults in PCC a, PCC b and Bus7b.

Scenario	Battery	Cooperation	Rejected Load	Reason for Load Shedding	I_{CA}		I_{CAM}
					a	B	
1	no	no	none	none	1	1	1
2	no	no	Load1a	Fault isolation	0.54	0.44	0.49
			Load2a	Power flow unbalanced			
			Load2b				
			Load3b				
			Load4b				
			Load5b	Fault isolation			
3	no	yes	Load5b	Fault isolation	0.50	0.53	0.52
			Load1a	Fault isolation			
			Load3b	Power flow unbalanced			
			Load4b				
			Load6b				
			Load4a				
			Load5a				
4	yes	no	Load1a	Fault isolation	0.96	0.78	0.89
			Load2b	Power flow unbalanced			
			Load5b	Fault isolation			
5	yes	yes	Load5b	Fault isolation	0.96	0.94	0.95
			Load1a	Fault isolation			

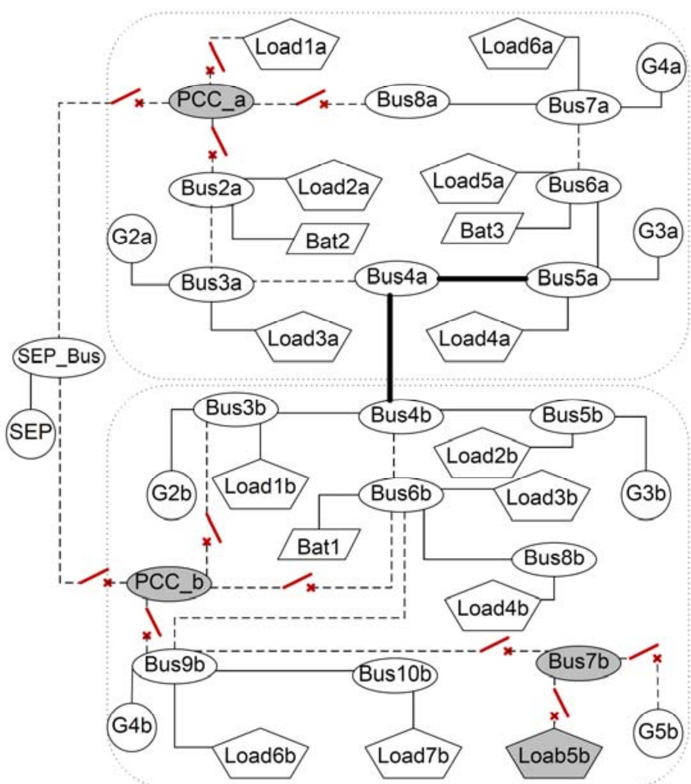


Figure 4. Smart grid in reconfiguration state after failure in PCC b, Bus7b and PCC a (Scenario 5).

Scenarios 3, 4 and *5* present the three attempts to improve the performance of the smart grid after the faults introduced in *Scenario 2*. The first one introduces a cooperation mechanism between microgrids by closing the circuit breaker TIE from Fig. 3a, which is controlled by the application of the methodology for reconfiguration shown in Section 4, resulting in a performance improvement compared to the previous scenario, i.e., I_{CAM} increased from *0:49* to *0:515*.

In *Scenario 4* three batteries were added at strategic points: two batteries in *Microgrid a* connected to the busbars *Bus6a* and *Bus2a*, which have no generator directly connected to them, and a third battery in *Microgrid b* connected to *Bus6b*, which also has no generator directly connected to it and can supply many parts of the microgrid by closing some circuit breakers that are normally open. So, it can observe that I_{CAM} increased to *0:89*.

It is assumed here that the batteries have a discharge time large enough that the contingences are remedied and the system returns to normal operation.

Finally, both cooperation by reconfiguration and batteries are used in *Scenario 5*, increasing the *ICAM* index to *0:95*. Therefore, the most of the loads supplied pre-failure continued to be supplied after such failures, which means that the consequences of the failures (see *Scenario 2*) were mitigated.

5. Conclusion

In this paper, it has been shown that microgrids can be taken to critical situations when islanding and internal fault(s) are combined. It was also shown that such situations can be mitigated when batteries are strategically introduced in the microgrid. However, batteries are expensive solutions. This led to the introduction of an intelligent reconfiguration scheme, aiming at cooperation between microgrids. Although the results have shown that cooperation between microgrids has not had such a positive effect as the introduction of batteries, it was noted an improvement in fact without adding any extra monetary cost on the grid.

The main focus of this work was on developing a methodology for reconfiguration to maintain the electrical power balance of portions of a smart grid not affected by failures, so that to minimize load shedding, especially for higher priority nodes with greater power requirements. The methodology was applied to a smart grid that was also proposed in this paper, which contains two microgrids that operate individually under normal circumstances but that can cooperate to mitigate the impacts of failures. The results obtained were characterized qualitatively through graphs and quantitatively via formalized performance indicators.

Acknowledgments

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