RESILIENT OPERATION OF DISTRIBUTED RESOURCES AND ELECTRICAL NETWORKS IN A SMART CITY CONTEXT

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The alarming number of severe outages that have occurred over the last decades raised the awareness regarding the importance of resilient power systems. As fundamental component of the Smart City concept, the energy infrastructure must adapt to the new challenges in terms of major blackouts, natural or human-caused. In distribution networks, the intentional islanding operation proves itself an efficient solution to maintain the energy supply during emergency conditions, made possibile by the Smart Grid technologies, such as distributed generation and energy storage. However, the limited resources present at the distribution level require a good management strategy, in order to minimize the adverse effectes of a long-term interruption. The scope of this paper is to develop an efficient coordination model of load, generation units and energy storage devices under islanding conditions for a smart distribution network. In this regard, a mixed-integer second-order cone programming (MISOCP) method is approached in order to increase the network resilience based on the unsupplied load minimization, while maintaining proper operational parameters for the IEEE 33-bus test distribution network.

Keywords: energy storage, island operation, resilience, urban distribution networks

1. Introduction

Additional to the increasing population, future cities face significant challenges in terms of climate change, terrorism, and more frequent natural disasters. In these new circumstances, Smart Cities must be capable to adapt in dealing with these challenges by developing appropriate resiliency strategies [1]. Originating from the desire to solve various urban problems, the Smart City concept aims to improve the living conditions by properly managing local resources, whether hardware or software [2]. In the context of smart urban planning, the energy sector represents an essential component in designing proper resilient and sustainable strategies, as the electrical infrastructure failure affects numerous other critical infrastructures (such as fire and medical facilities,

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communications, and mobility). The vast expansion and exposure of power grids makes them vulnerable to a multitude of problems that lead to long-lasting outages in electricity supply. Added to the extreme weather events, the human attacks (cyber or vandalism) represent a new threat to power systems. As one of the most critical infrastructures in the modern world, power system's resilience against these threats is attracting more and more attention to studies due to the disastrous social and economic impact of a major blackout [3].

Power systems undergo demanding transformations at every level, especially in the distribution sector, due to the increasing distributed generation (DG) penetration. Among these distributed sources, numerous generation units rely on renewable energy (solar and wind), creating problems such as intermittency and uncertainty. As regulatory agencies are currently committed to expand the integration of renewable energy sources (RES), likewise, various energy storage systems (ESS) technologies are being developed and deployed at different levels of the network, in order to support the stochastic output power of RES. Many Smart City projects are currently investigating the potential of connected ESS to support more renewable sources integration, to improve the grid operation during steady-state and emergency conditions as well. An innovative procedure for coordinating DGs and ESSs is required for the proper management of electrical networks, both under normal and abnormal conditions. Moreover, it is important to note that, from a technical standpoint, these smart applications require a very good level of the network observability and a high level of automation. Nowadays, the observability is a major deficiency at distribution level due to the lack of measurement devices (no redundancy) but this flaw is being mitigated [4], [5]. On the other hand, Distribution Management Systems (DMS), such as ones presented in [6], [7] and [8], represent a mature solution for the supervision and control of the distribution networks and their contained devices. Smart distribution networks address these concerns based on modernized electricity grids that incorporate information and communications technology (ICT) for data acquisition and processing in an automated manner to improve reliability, efficiency, and sustainability of the energy use.

Resilience of electric power systems reflects their capability to withstand high impact and low probability disturbances, by quickly recovering from these disruptive events, adapting their operational conditions and continuing the energy supply [9]. Considering the high penetration of distributed resources, intentional islanding operation of distribution power systems is gradually acknowledged as an essential solution to increase the system reliability and resilience. In this regard, the sustained restoration of critical loads is considered the main objective, while satisfying the system operational constraints. Several studies have been carried out to analyze the islanding operation potential to increase the resilience of electrical distribution systems, based on distributed resources integration.

Advanced procedures to assure island operation feasibility have been studied in [10] using genetic algorithms. Heuristic search algorithms were also approached in [11], aiming to identify the optimal island partition with maximum load restoration. However, considering the main drawback of these methods of not always finding the global optimum, numerous studies propose algorithms to solve the islanding problem based on deterministic methods, such as linear or quadratic programming. A linear version of the islanding operation model is formulated in [12]; this approach filters the integer variables in order to mitigate the high computation time of non-linear models. Authors of [13] introduce a two-stage stochastic linear programming model that aims to maximize load and generation under islanded conditions, while a convex relaxation is applied in [14], to obtain a mixed-integer quadratically constrained programming model that optimize the islanding operation of active distribution networks. Considering the better convergence proprieties to the global optimum of the latter approach, the mixed integer second-order cone programming (MISOCP) method has been applied in this study. The MISOCP-based model developed in this paper aims to optimize the islanding operation of an urban distribution network by identifying the best coordination of DG, ESS and consumption, in order to minimize the unsupplied load. By introducing a prioritization criterion, the objective is to increase the resilience of the electrical network by maintaining the continuity in supply of critical loads during a major interruption.

2. Problem formulation

As result of faults occurrence, parts of the distribution network might be separated from the main grid, leading to unsupplied network areas. Among these, some can be reconnected to the main grid using the reconfiguration process due to the tie switches installation, while others remain islanded. Thanks to the distributed resources deployment in distribution networks (such as DGs and ESSs), the islanded partitions could be further supplied, even during the disturbances that led to their separation. However, these resources are limited, and an imbalance between generation and consumption can occur, affecting the power quality parameters. Hence, an optimized operation of these local resources is needed in order to maintain a reliable supply to the fault affected users. Moreover, considering the generation shortage in distribution networks, load shedding strategies must be applied during long-lasting outages to support the critical users.

The optimal resource allocation in emergency conditions can be formulated as an optimization problem that aims to minimize the unsupplied load, while satisfying the technical constraints of the power system.

$$\min \sum_{t\in T} \sum_{j\in N} w_j P_{j,t}^{sh} \tag{1}$$

In equation (1), $P_{j,t}^{sh}$ is the shedded load at bus *j*, during the time interval *t*, in order to maintain the power balance in the distribution system. A priority coefficient, w_j, is associated to each bus, as critical load supply must be prioritized during emergency conditions. *T* defines the time horizon, while *N* is the set of buses. The objective function (1) is subject to a set of constraints further described.

2.1. Power flow equations

These constraints are formulated by adapting the Distflow branch model presented in [15], as follows:

$$\begin{cases} \sum_{k\in\delta(j)} P_{jk,t} - \sum_{i\in\pi(j)} (P_{ij,t} - r_{ij} I_{ij,t}^{sq}) = P_{j,t}^{DG} - (P_{j,t}^{L} - P_{j,t}^{sh}) + (P_{j,t}^{disch} - P_{j,t}^{ch}) \\ \sum_{k\in\delta(j)} Q_{jk,t} - \sum_{i\in\pi(j)} (Q_{ij,t} - x_{ij} I_{ij,t}^{sq}) = Q_{j,t}^{DG} - (Q_{j,t}^{L} - Q_{j,t}^{sh}) \end{cases} \tag{2}$$

$$V_{j,t}^{sq} = V_{i,t}^{sq} - 2\left(r_{ij}P_{ij,t} + x_{ij}Q_{ij,t}\right) + (r_{ij}^2 + x_{ij}^2)\cdot I_{ij,t}^{sq} \tag{3}$$

$$P_{ij,t}^2 + Q_{ij,t}^2 \le I_{ij,t}^{sq}\cdot V_{j,t}^{sq}, \quad \forall j\in N, \forall ij \in L \tag{4}$$

The set of constraints (2) defines the active and reactive power balance of bus *j* at the beginning of the time interval *t*, while (3) models the voltage drops on each line, that has the resistance r_{ij} and reactance x_{ij}. $P_{jk,t}$, $P_{ij,t}$, $Q_{jk,t}$ and $Q_{ij,t}$ represent the power flow through the lines connecting buses *j* and *k*, and *i* and *j*, respectively. The set *δ(j)* contains the upstream neighbour buses of *j*, while *π(j)* is the set of downstream neighbour buses of *j*. $P_{j,t}^{DG}$ and $Q_{j,t}^{DG}$ represent the power produced by the DG units, while $P_{j,t}^{ch}$ and $P_{j,t}^{disch}$ are the charging/discharging powers of the ESSs. $P_{j,t}^{L}$ and $Q_{j,t}^{L}$ define the power demand at each bus at time *t*. A relaxed quadratic constraint is introduced by (4), for the squared current magnitude ($I_{ij,t}^{sq}$) calculation on each line *ij*, based on the power flow and the squared voltage magnitude ($V_{j,t}^{sq}$). *L* represents the set of lines in the network.

2.2. Topological constraints

In addition to the optimal management of local resources during the outage, the proposed model aims to determine the optimal island formation of the distribution network. Despite the isolated operation, radial configurations are desired. For this purpose, the graph theory-based methodology proposed in [16] was used. A fictitious network with the same configuration and connectivity as the original distribution system is considered to define the topological constraints. In order to ensure the radiality, each island configuration is described by source buses serving as the root of a subgraph. Several buses are predefined as potential root buses in the distribution network. The number of active root buses (i.e.

islands) is obtained as result of the optimization process, and the determined roots are defined in the model by the binary variable $\gamma_{j,t}$ ($\gamma_{j,t}$=1 indicates the buses activated as root bus, while $\gamma_{j,t}$=0 is associate to the inactivated roots). The demand in the fictitious network is described by a load ($P_{f,j,t}$) equal to the unit, according to (6). While the activated root buses represent unlimited power sources in the fictitious network (acting as slack bus for the island), inactivated roots are modeled as load buses ($P_{f,j,t}$=1), according to (7). Here, *M* represents a very high coefficient. The power balance at each bus is defined in (5), while the power flow on the disconnected lines is limited to zero using (8). By satisfying the fictitious load required in each bus, at least one path between the source buses (roots) and the load buses exists, resulting in a connected topology.

$$-P_{f,j,t} = \sum_{k \in \delta(j)} T_{jk,t} - \sum_{i \in \pi(j)} T_{ij,t} \tag{5}$$

$$P_{f,j,t} = 1, \quad \forall j \in N \setminus R \tag{6}$$

$$-M \cdot \gamma_{j,t} + 1 \le P_{f,j,t} \le M \cdot \gamma_{j,t} + 1, \quad j \in R \tag{7}$$

$$-M \cdot \lambda_{ij,t} \le T_{ij,t} \le M \cdot \lambda_{ij,t}, \quad ij \in L \tag{8}$$

The radiality of the configuration is ensured by (9), where $\lambda_{ij,t}$ is the status of line *ij* at time *t* (connected/disconnected).

$$\sum_{ij \in L} \lambda_{ij,t} = N - \sum_{k=1}^{R} \gamma_{k,t} \tag{9}$$

Once the optimal island formation is determined, the network configuration remains the same during the entire outage, starting with the moment of its occurrence (T_{outage}).

$$\lambda_{ij,t} = \lambda_{ij,t-1}, \ \forall t > T_{outage} \tag{10}$$

$$\gamma_{j,t} = \gamma_{j,t-1}, \ \forall t > T_{outage} \tag{11}$$

2.3. DG operational constraints

The operational constraints of the distributed sources are formulated as follows:

$$P_{G,j}^{\min} \le P_{j,t}^{DG} \le P_{G,j}^{\max}, \quad \forall j \in DG \tag{12}$$

$$-P_{j,t}^{DG} \cdot \chi_j \le Q_{j,t}^{DG} \le P_{j,t}^{DG} \cdot \chi_j, \quad \forall j \in DG \tag{13}$$

$$\chi_j = \frac{\sqrt{1-\cos^2 \varphi_j}}{\cos \varphi_j} \tag{14}$$

$$\left(P_{j,t}^{DG}\right)^2 + \left(Q_{j,t}^{DG}\right)^2 \le \left(S_{j,t}^{DG}\right)^2 \tag{15}$$

Constraint (12) assumes that the generated active power can vary between a minimum and a maximum value, while the reactive power generation must satisfy a pre-specified power factor (cosφ_j), according to (13) and (14). The capacity constraint is defined by equation (15). Here, parameter $S_{j,t}^{DG}$ represents either the stator thermal limit for conventional synchronous generators or the converter limit in case of full-converter renewable generation (e.g. photovoltaic). Moreover, in the latter case, $P_{G,j}^{\min}$ takes null values.

2.4. ESS operational constraints

Currently, ESSs find their application more and more in distribution networks, as a result of their various advantages offered in terms of reliability, economics and stability [17]. The generic ESS model presented in [18] has been used in this study, which is defined by the constraints (16)-(19).

$$P_{j,\min}^{disch} \cdot e_{j,t}^{ESS} \le P_{j,t}^{disch} \le P_{j,\max}^{disch} \cdot e_{j,t}^{ESS} \tag{16}$$

$$P_{j,\min}^{ch} \cdot (1 - e_{j,t}^{ESS}) \le P_{j,t}^{ch} \le P_{j,\max}^{ch} \cdot (1 - e_{j,t}^{ESS}) \tag{17}$$

$$SOC_{j,t} = SOC_{j,t-1} + \left[\eta_{j,t}^{ch} \cdot P_{j,t}^{ch} - P_{j,t}^{disch} \big/ \eta_{j,t}^{disch} \right] \tag{18}$$

$$SOC_{j,\min} \le SOC_{j,t} \le SOC_{j,\max} \tag{19}$$

In the above equations, (16) and (17) introduce the charging and discharging power boundaries, while (19) limits the capacity of the ESS. The state of charge (SOC) of the ESS located at bus *j* at the beginning of the interval *t* is calculated in (18) based on the SOC in the previous interval (*t*-1) and the power stored/injected during the current time interval, while taking into account the charging and discharging efficiencies, $\eta_{j,t}^{ch}$ and $\eta_{j,t}^{disch}$. In order to avoid the simultaneous charging/discharging of the ESS, the binary variable $e_{j,t}^{ESS}$ has been introduced in (16) and (17). The charging or stand-by mode of the ESS is defined by the value $e_{j,t}^{ESS} = 0$, while the value $e_{j,t}^{ESS} = 1$ describes the discharging mode.

2.5. Load shedding strategy

Considering the limited generation resources in the network in times of emergency, load shedding must be applied to avoid the frequency and voltage declining. While the tripped active power can vary from 0 to the total demand at bus *j*, for the reactive power, the initial power factor must be maintained, according to (20).

$$\begin{cases} 0 \le P_{j,t}^{sh} \le P_{j,t}^{L} \\ Q_{j,t}^{sh} = P_{j,t}^{sh} \cdot (Q_{j,t}^{L} / P_{j,t}^{L}) \end{cases}, \quad \forall j \in N, \forall t \in T \tag{20}$$

3. Case study

In this section, the proposed model is applied on the modified IEEE 33-bus test system. The simulations were performed on a personal computer with an Intel Core i7 and 8 GB of RAM (32-bit system), in the General Algebraic Modelling System (GAMS) optimization software, using the CPLEX package. The modifications made to the network consist of the installation of ten DG sources and three ESSs. The ten DGs include three controllable generation units (CG), installed at buses 8, 24 and 32, each with a capacity of 450 kVA, and seven photovoltaic installations (PV) deployed at buses 3, 7, 14, 19, 21, 25 and 30, with an individual capacity of 200 kVA. Both generation technologies present a minimum power factor of cosφ=0.9. To compensate for the variable nature of the PV generation, three battery ESSs are installed at buses 14, 21 and 30, with a capacity of 150 kW. The considered operational parameters of the ESS are presented in Table I. The IEEE 33-bus system contains one slack bus and 32 load buses. Its meshed configuration composed of 32 lines and 5 tie switches, as well as the implemented modifications, are presented in Fig. 1. All parameters of the test network can be found in [15].

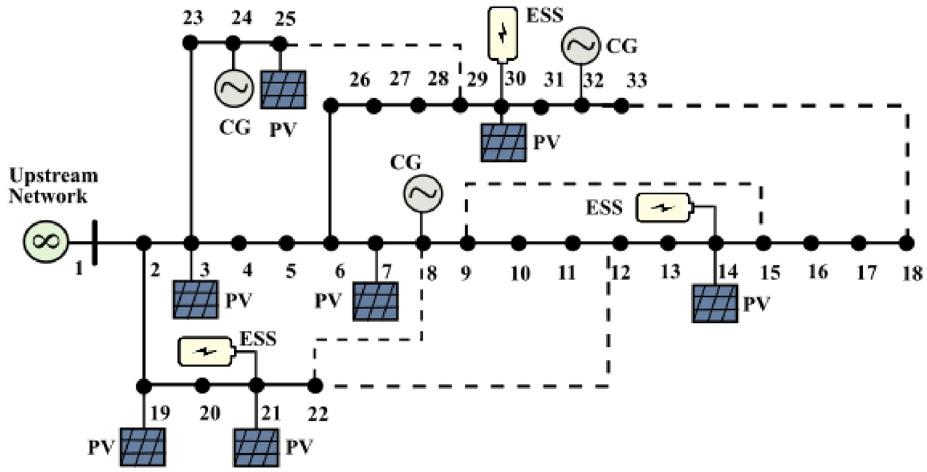


Fig. 1. The modified IEEE 33-bus system

Table I.

The operational parameters of the energy storage systems [17]

Parameter	Value	Parameter	Value
$P_{\min}^{disch}$	0%	$P_{\max}^{disch}$	35%
$P_{\min}^{ch}$	0%	$P_{\max}^{ch}$	20%
$SOC^{\min}$	20%	$SOC^{\max}$	98%
η_t^{disch}	0.9	η_t^{ch}	0.85

Given a 24-h analysis period with one-hour time step, the daily operation curves of several typical urban loads are considered, as depicted in Fig. 2. Based on these curves and the maximum power demand provided in [15], the daily load variation is obtained. The forecasted PV output is presented in Fig. 3.

A priority weight is associated to each load, based on their type. High-priority loads are considered to be connected at buses 8, 14, 21 and 24 (w_j=100), medium-priority loads are connected at buses 7, 19, 25, 30 and 32 (w_j=50), while the rest of the loads are considered non-critical load (w_j=1).

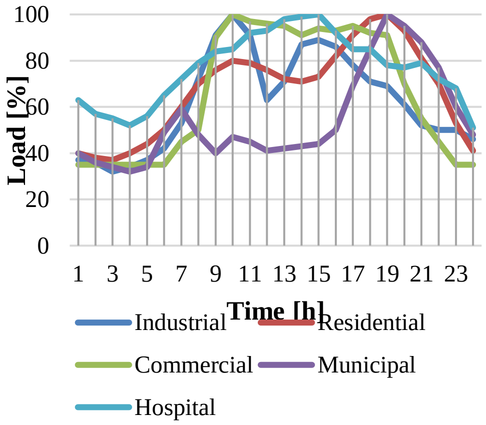


Fig. 2. Load profile based on type

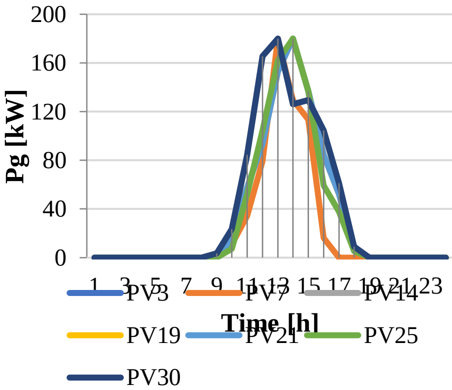


Fig. 3. PV output forecast

4. Results and discussions

It is assumed that a fault occurs of line 1-2, leading to the incapacity of the distribution network supply from the upstream network. Under these conditions, the efficiency of the proposed model to identify the optimal islanding operation of the local resources is further assessed, in order to minimize the unsupplied load.

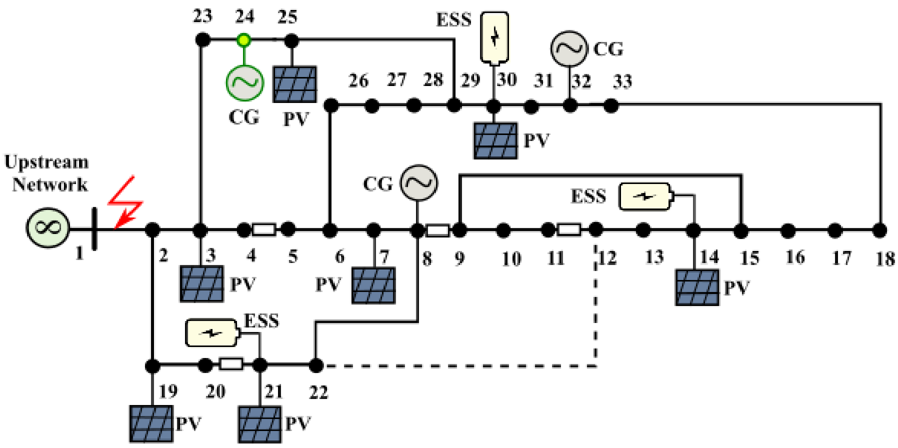


Fig. 4. Network configuration during the outage at hour 00:00

The major outage is considered to occur at the beginning of the first interval of the day (00:00 a.m.), resulting in a 24-hour interruption of the distribution network supply. The optimal coordination of DGs and ESSs is required for the proper management of electrical networks resources. To maximize the DG benefits in terms of critical load supply, the network remains connected in a sole island. However, in order to minimize the losses and improve the power flow, a reconfiguration process takes place, as can be seen in Fig. 4. Bus 24 fulfills the role of root bus, while lines 3-4, 8-22, 12-13, 17-18 and 19-20 are disconnected to further maintain the radiality of the network topology.

In order to ensure the critical loads supply, all generation sources operate at the maximum capacity during the outage, as presented in Fig. 5.

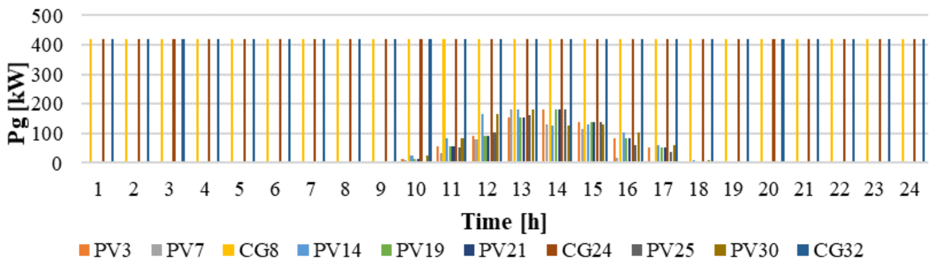
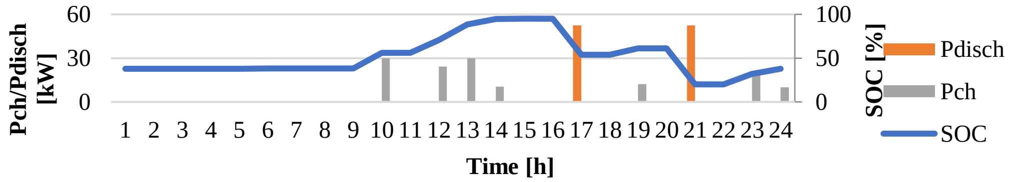
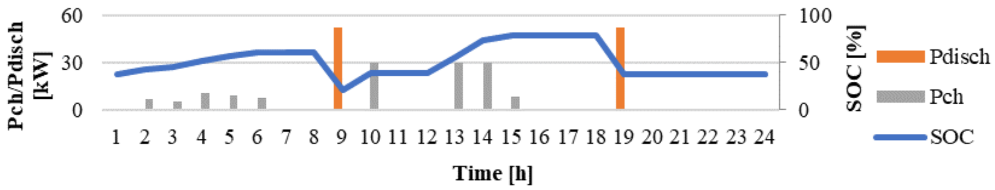


Fig. 5. Active power generation during the outage

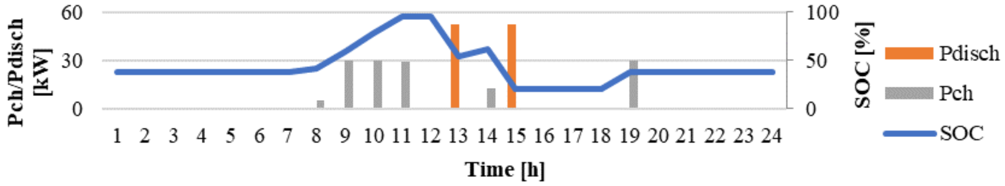
However, the optimal power dispatch is obtained by the proper coordination of the ESSs. Figs. 6. (a), (b) and (c) depict the three ESSs operation during the outage.



(a) ESS operation at bus 14



(b) ESS operation at bus 21



(c) ESS operation at bus 30
Fig. 6. ESS operation during the outage

With a differentiated behavior based on the generation resources nearby, it can be observed that the injection of power takes place during load peak periods (day peak or/and evening peak), while the ESS recharging takes place during load valley or during the PV generation.

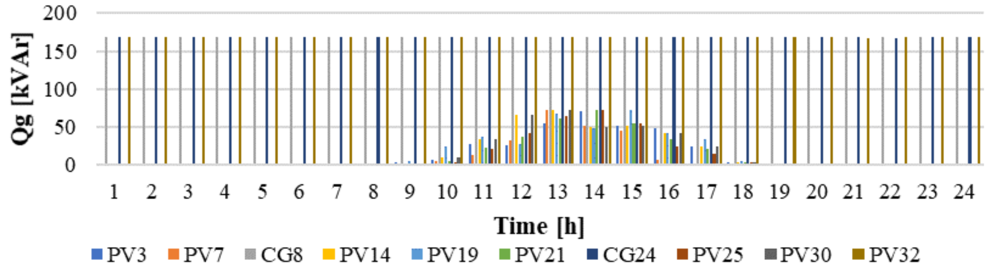


Fig. 7. Reactive power generation during the outage

Both the controllable generators and the converters of the photovoltaic installations participate in the voltage regulation process through the injection of reactive power (Fig. 7). Due to the light loading of the network resulted from the emergency load shedding, it can be observed that the voltage level is maintained closer to the upper limit during the entire interruption, while voltage variations are kept between 0.95 and 1 p.u. The minimum, average and maximum values of the bus voltage corresponding to each hour of the interruption are presented in Fig. 8.

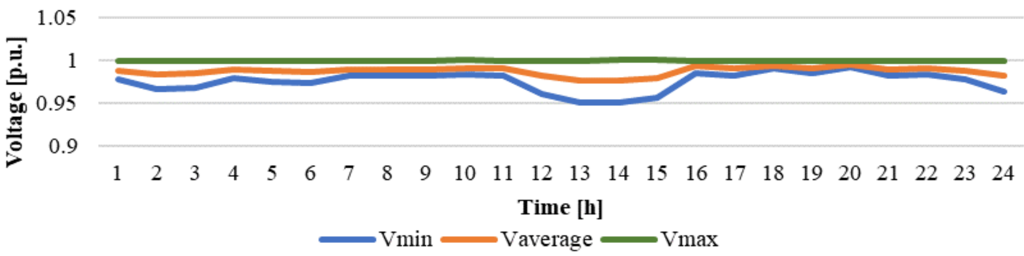


Fig. 8. Voltage profiles during the outage

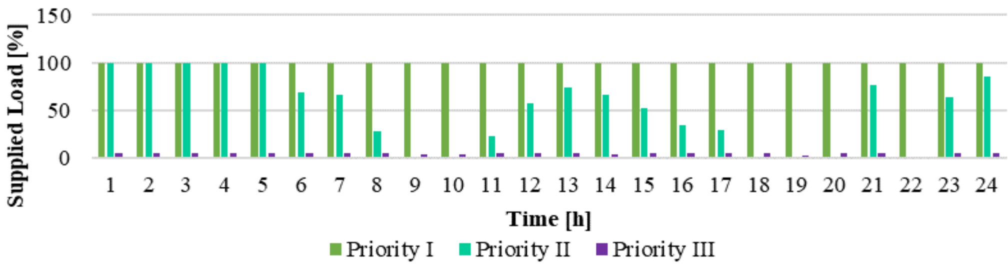


Fig. 9. Priority loads supply during the outage

Considering the limited generation resources in the network, emergency load shedding is applied. However, the most critical loads continue to be totally supplied during the entire outage (100%), while the medium and low priority loads are partially supplied, based on the available generated power. In Fig. 9, it can be observed the reduction in supply of Priority II and Priority III loads during the peak load intervals (08.00-11:00 a.m. and 17:00-20:00 p.m.).

5. Conclusions

In this paper, a MISOCP-based model has been implemented in order to minimize the total unsupplied load during a major outage in a test distribution network. Considering the intermittency and uncertainty of renewable sources, the optimal coordination of DG units and ESS is analyzed in this study, in order to optimize the local resources dispatch, as a resilience increasing strategy. The benefits of ESSs in ensuring the critical loads supply during the blackout, while maintaining acceptable operational parameters for the network, have been emphasized in this work. In these circumstances, it can be concluded that an efficient allocation of distributed resources can help increase the resilience of urban electricity networks by supporting the important components in times of crisis.

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