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Optimal Operation of Grid-Connected Microgrids with Photovoltaic Generation and Storage

Jairo Jamaica-Obregón[1], Ricardo Moreno-Chuquen[1], Oscar David Florez-Cediel[2]

Abstract – *A key motivator for wider deployment of microgrids (small electric networks with distributed generation connected that operate either connected at low and medium voltage levels or isolated mode) is to bring about the decentralization of the generation. This goal is because microgrids use renewable power sources and storage energy systems. However, the microgrids operation represents various challenges for grid-connected microgrids about the power interchanges with the distribution network. If the operation is performed under optimal conditions, there are benefits for microgrid investment. This paper proposes a detailed formulation to operate microgrids with photovoltaic systems and storage. The model can be used with multiple microgrids interconnected considering electricity prices and tariffs. The model corresponds to an optimal power flow approach for microgrids considering some energy storage systems. The mathematical model considers explicitly electricity tariffs. Illustrative results indicate the optimal operation of microgrids considering a load curve; specifically, the microgrid is designed to operate at different operational circumstances. A case includes multiple microgrids interconnected at different electricity prices. The electricity tariffs determine the power interchanges between the distribution network and the microgrid. Such insights about the optimal operation of microgrids provide a wide range of applications, particularly in operation and feasibility of projects.* ***Copyright © 2021 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Distributed Generation, Microgrids, Optimal Power Flow, Photovoltaic, Storage, Tariffs*

Nomenclature

i	Index for generating units
t	Index of time (hours)
j	Index of buses in the microgrid
W^t	Index of available units at time t
p_i^t	Active power injection for unit i at time t
q_i^t	Reactive power injection for unit i at time t
$p_{i,\pm}^t$	Up/down deviations of power for unit i at time t
$k^t(\cdot)$	Power flow equations at time t
$v^t(\cdot)$	Network restrictions at time t
$P_{\min}$	Minimum limit for active power generation
$P_{\max}$	Maximum limit for active power generation
$Q_{\min}$	Minimum limit for reactive power
$Q_{\max}$	Maximum limit for reactive power
C_i^t	Cost function for power unit i at time t
$C_{i,p\pm}^t(\cdot)$	Cost for up/down power deviations at time t
$\tilde{C}_p^i(\cdot)$	Expected cost of power injections
θ_j^t	Phase angles in each node j at time t
V_j^t	Magnitude of voltages in each node j at time t

I. Introduction

The microgrids can operate connected to the electrical network or in isolated mode. The integration of microgrids to electrical networks to export or import power represents various challenges [1]. The microgrids could have the potential to provide ancillary services to the main grid [2]. The frequency and the voltage during the dispatching of power units in microgrids have been addressed in various papers [3]-[5]. The microgrids connected to the electrical networks use renewable generation such as photovoltaic generation with storage in order to store energy during the day and used in the nights. If the microgrid is connected to the electrical network, then there is an uncertainty due to the decisions to export or to import from the power network [6], [7].

The Optimal Power Flow (OPF) is used to determine a dispatching strategy for electric power generating plants in microgrids in order to meet the demand in microgrids.

The OPF is determined solving an optimization problem complying with the boundary conditions of the system. Using the optimal power flow formulation for multiple periods and scenarios is done. This application ultimately calculates the optimal power flow in a 24-hour period with the integration of renewable generation complying with the necessary requirements. Some papers have used the OPF to minimize the operating costs with

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various generating units [8]-[11]. For instance, the authors in [12] and [13] have implemented an optimal power flow formulation in order to characterize the uncertainty of renewable power sources considering network and operational restrictions. The management of isolated microgrids has been explored in [14]. Other works have reported about the operation of microgrids including storage and various renewable sources [15].

Moreover, [16] has evaluated the costs and the benefits of a microgrid in a university campus using an optimal power flow in order to ensure an optimal operation. The operational challenges are similar for either isolated or connected microgrids. In [17], the authors have proposed strategies for synchronization during the connection of the microgrid to the electrical network. Given the integration of different distributed resources to electrical networks, there are different approaches and methods to integrate those considered electrical restrictions. For instance, an algorithm is used to do management of various sources with different weather conditions in [18]. This microgrid incorporates electrical vehicle stations and photovoltaic systems and it is tested with Matlab/Simulink simulations. Another approach has been proposed in [19] for heterogeneous autonomous DC microgrid systems considering the intermittent nature of renewable resources. In this paper, the authors have recognized the complexity for microgrid operation for different sources of uncertainty; the results are tested with Matlab/Simulink. For microgrids, energy storage is an option given that prices have decreased during the last years [20]. The storage increases the flexibility of the electrical networks given that the power generated for renewable sources could be stored in batteries to be used in other periods. For instance, the authors in [21] have formulated a neural network to determine optimal size and location of battery storage systems. The results show that losses can be reduced with storage systems installed in optimal sites. Moreover, the voltage stability is improved in microgrids with storage. In addition, in [22], the authors have used a particle swam optimization in order to find optimal sites for storage systems. This algorithm includes load shedding a demand response in the microgrid. Another approach has been explored in [23]; a multi-agent system is formulated in order to ensure an optimal performance of microgrids involving photovoltaic systems, hydrogen cells and storage systems. Recently, an adaptive Proportional Integral (PI) controller has been developed to control microgrids with different power sources. In particular, in [24], a model has been proposed to control both grid connected microgrids and stand alone; those results are tested in PSCAD. In [25], the authors have proposed a fuzzy integral proportional controller for AC microgrids; the results indicate the improvements over the PI controller given that the fuzzy approach has a range of control over the variables. Other aspects should be considered for the reliable operation of microgrids. Given the interconnection of distributed resources connected in the microgrid such as photovoltaic systems, storage systems, electric vehicles, among others, there are current flows in the electrical network. Then, an appropriate protection scheme is needed to protect the microgrid from fault currents [26]. Different approaches have proposed to consider protection schemes for operating modes and voltage levels. For instance, a multiple protection zone has been designed in [27] as a protection scheme for microgrids operating at island mode; particularly, the protection system includes low-voltage-ride curves for generating units. The communication infrastructure could play an important role for an appropriate protection scheme performance [28]. The microgrids are usually connected to low and medium voltage levels close to consumers. In fact, the microgrids represent a way to decentralize the generation of electricity. For instance, in [29] the authors have presented a design of a photovoltaic system in order to supply power to an office building. Another application for end users has been reported in [30], specifically, the author presents a novelty about the programming of an artificial neural network in order to control a photovoltaic system for a lighting application. The microgrids use distributed generation such as photovoltaic systems. These solar systems are installed in the site where the electricity is needed. The research wok during the last years has addressed various topics related with design and operation of photovoltaic system. For instance, in [31], the authors have presented a mathematical model to estimate parameters of a photovoltaic system working in a microgrid. The author in [32] has presented a detailed explanation of the photovoltaic models based on the circuit equivalents and three cases with different topologies of modules. In [33], the authors have proposed an advanced control strategy to manage a three-phase grid connected photovoltaic system; additionally, in the results, there is a comparison with others methods. The photovoltaic systems can improve the power quality in microgrids in order to increase the reliability. For instance, in [34] there is a proposal about the implementation of an active power filter with a DC/DC converter; specifically, the simulations show the improvements in the mitigation of harmonics. Microgrids in rural areas have a potential to supply power in rural areas. Particularly, in [35], the authors have presented a methodology to optimize the energy efficiency of a hybrid microgrid with storage. In fact, the authors have included a criterion about the battery depreciation. In [36], the authors have shown a novel system developed to be used as back-up of a conventional storage system, in order to increase its autonomy and to warrant continue operation for long periods of time in the case of a power failure in the public grid. The system is constituted by a conventional storage system connected in parallel to a standalone PV system and an electronic system with facilities to control the charge and discharge of the battery bank of the PV system and to keep the UPS functioning when power cut occur. The dynamism required to maintain the quality of the energy is proportionally higher as it affects the reliability, protection, and operation of energy systems. An analysis of the literature shows that the Battery Energy Storage System (BESS) is a solution that has attracted much attention lately. The studies about the implementation and the control of a BESS in a photovoltaic solar power plant connected to the electric grid, providing power control and offering reserve of energy in case of contingencies have been presented in [37]. [38] has evaluated different battery technologies using HOMER (Hybrid Optimization Modelling Software) simulation software in order to compare different available battery technologies to different technical specifications from an economic point of view.

The essential primary outcome of the simulation is the cost of the electricity stored in each battery technology that can be used to optimize the battery storage system size for each type of battery. The simulation has been made for a photovoltaic system in Jordan, connected to the grid, and with different kinds of battery technologies with varying sizes in order to understand their effect on the final cost of energy, and to know the needed minimum tariff that will encourage investors in the field of renewable energy to invest more in battery electricity storage.[39] has made a research on the effective the Feed-In-Tariff (FIT) policy's effect on the photovoltaic-based microgrid PV-MG investment. Firstly, this paper sets up PV-MG business model and analyzes the income distribution among the participants. Then, this paper puts forward three kinds of FIT model, that are the Fixed FIT(FFIT), Constant Premium FIT(CPFIT) and Variable Premium FIT(VPFIT) model. The market price that the main grid of the electricity has imported from grid is divided into fixed price and Time of Use price. Based on this classification, this paper develops the optical charge and discharge strategies of battery storage system and the PV-MG overall operational strategies under multi-scenarios. Through MATLAB simulation, this article can get the power flow and the income distribution among relevant participants in PV-MG, and it makes sensitivity analysis on relevant parameters. Recently, in the context of photovoltaic system operation, the authors in [40] have presented an approach to improve transient stability using solid-state transformers; particularly, in the paper, there is an optimization approach to control transformer state variables. This paper proposes a dispatching strategy for microgrids with storage units in order to determine an optimal strategy to import or export power from the electrical network. Specifically, the strategy is performed two times in each period in the planning horizon and the dispatching problem is combined into a single problem according to each mode. The storage units or batteries are implemented as a generator with the available energy; the unit has upper and lower limits. The dispatch program can be restricted by placing restrictions on the states of a time-varying linear system whose entries are the expected dispatches in each period. For photovoltaic generators, the power generation behavior is structured when the solar resource is available. This is defined in a matrix that contains an amount of power for a specific time of day. The load can be variable over time with the objective of calculating the cost of operation, in order to define the scenario of lower cost. With the dispatch program, the microgrid has the possibility of defining the mode of operation. The electrical energy sources that the system has, as the photovoltaic generator, have energy available when they have a solar resource. The microgrid can classify priorities in the use of energy to supply power to the load 24 hours a day.

The paper is organized as follows. The problem formulation is presented in Section III based on a linear mixed-quadratic optimization problem. In Section IV, a study case is explained and the parameters for the photovoltaic system. The proposed formulation is tested at different circumstances considering multiple interconnected microgrids in Section V. Section IV provides some concluding remarks and research directions.

II. Formulation for Optimal Operation of Microgrids

The formulation for optimal operation of grid-connected microgrids can be expressed as a linear mixed-quadratic optimization because the problem involves real and binary variables.

The operation is optimal if the generating cost is minimum. Then, the objective function consists in the minimization of the generation cost considering all the restrictions. The objective function is expressed in Eq. (1):

$$\min_{x} f\left(x\right) \tag{1}$$

The objective function is expressed in terms of the power generated for each unit and the deviations cost of each one of them as expressed in Eq. (2):

$$f\left(x\right)= f\left(p_i^t, p_{i,\pm}^t\right) \tag{2}$$

The total cost is given by the expected cost of power injections and the cost for up/down power deviations at time *t* as expressed in Eq. (3). The total cost corresponds to the cost for a dispatch period. For this case, the dispatch period is 24 hours. For storage, the cost is expressed as a generating unit given that the batteries can be dispatched at any time if they have available energy:

$$f\left(p_i^t, p_{i,\pm}^t\right)= \sum_{i\,\in\, W^t}\left[\tilde{C}_p^i\left(p_i^t\right) \;+\; C_{i,p\pm}^t\left(p_{i,\pm}^t\right)\right] \tag{3}$$

The power flow equations are given by Eq. (4). The power flow equations for a microgrid correspond to the equations involving the angles in each node and the voltages (magnitude) in each node, and the injections of active and reactive power in each node for each unit at time *t*:

$$k^t\left(\theta_j^t, V_j^t, p_i^t, q_i^t\right) = 0 \qquad (4)$$

The network and the operation restrictions are given by Eq. (5). The voltages in each node are restricted to an operating range operation between 0.9 p.u. and 1.1 p.u.

The power injections include the operating rating of each unit according to the power curve of each case:

$$v^t\left(\theta_j^t, V_j^t, p_i^t, q_i^t\right) \le 0 \qquad (5)$$

Specifically, Eq. (6) gives the restrictions for minimum and maximum values of active power and Eq. (7) gives the restrictions for minimum and maximum values of reactive power:

$$P_{\min} \le p_i^t \le P_{\max} \qquad (6)$$

$$Q_{\min} \le q_i^t \le Q_{\max} \qquad (7)$$

This formulation represents the operation of microgrids with generation and storage and it includes an interconnected network. The next section illustrates a case based on a real pilot in order to evaluate costs and microgrids performance. A flow chart about the optimal operation of microgrids is shown in Fig. 1.

III. Case Study

The pilot case is based on a microgrid connected to the distribution network. This microgrid has a photovoltaic and a storage system. The microgrid operates connected at it; it means that the microgrid can either import or export power to the grid according to the financial benefits and costs. This microgrid is designed in order to operate in a residential site. The load consists of 132 houses that have a load profile as shown in Fig. 2 with a total power of 31 kW. The photovoltaic system has a capacity of 28 kWp and the topology connection includes four subsystems according to the microgrid connection. There are two photovoltaic systems of 6 kWp each and two photovoltaic systems of 8 kWp. The four photovoltaic subsystems are connected to the combiner box. The system is shown in Fig. 3.

The information of each photovoltaic module is given in the Table I.

It presents the maximum power of each module, the voltage and the current ratings, the open voltage circuit, the short-circuit current and the temperatures parameters.

These parameters indicate a recommended range of operation.

Table II and Table III show the parameters of each inverter according to capacity. The inverters parameters correspond to input and output voltage and nominal current. The parameters considered for the microgrid design are the minimum and the maximum voltage values. The nominal current is used to set up the connection with the photovoltaic subsystem.

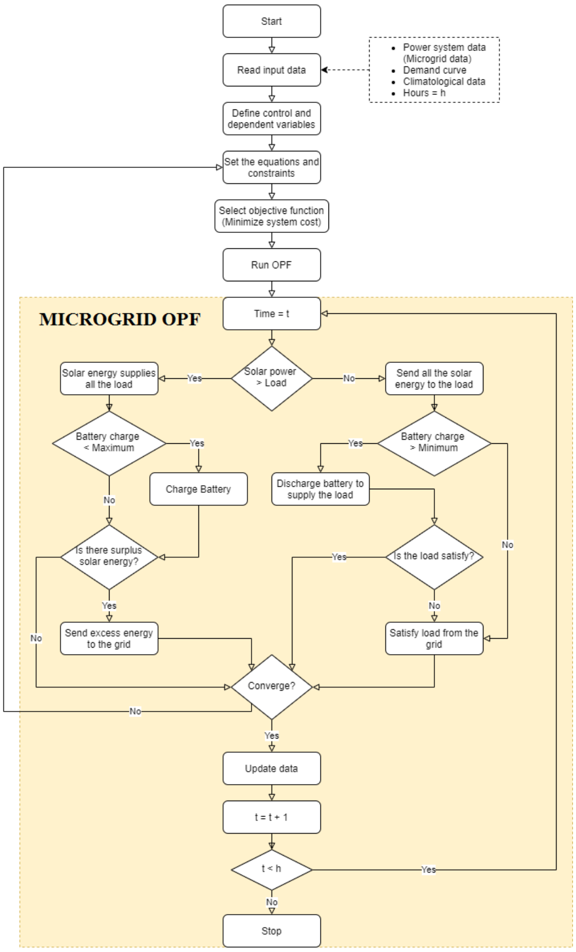

Fig. 1. Flow chart for the optimal operation of microgrids

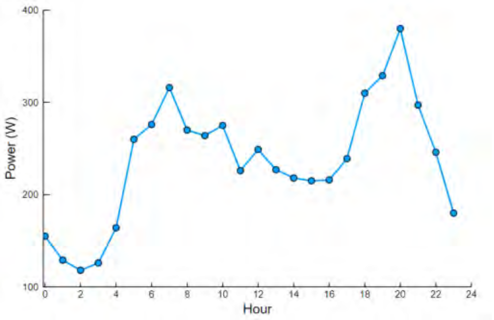

Fig. 2. Load curve for the microgrid

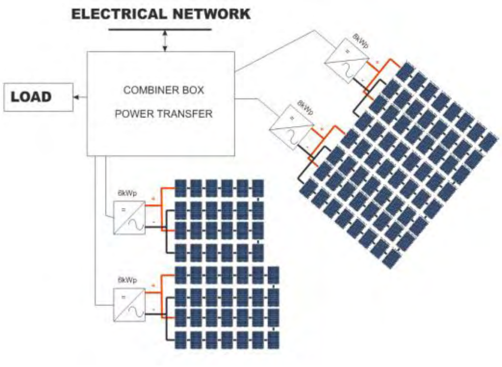

Fig. 3. Photovoltaic systems with a capacity of 28 kWp

TABLE I
SOLAR PANEL 250 W AMERISOLAR AS-6P30-250 W

Characteristic	Value	Units
$P_{\max}$	250	W
V_{mp}	30.75	V
I_{mp}	8.14	A
V_{oc}	37.31	V
I_{sc}	8.59	A
Temp,min	-10	°C
Temp,max	70	°C
B	-0.52	%/°C
T_{onc}	45	°C

TABLE II
INVERTER 6 kWp

Characteristic	Value	Units
$V_{in,\max}$	900	V
$V_{in,\min}$	335	V
$I_{nominal}$	19	A
$I_{in,\max}$	26.1	A

TABLE III
INVERTER 8 kWp

Characteristic	Value	Units
$V_{in,\max}$	900	V
$V_{in,\min}$	335	V
$I_{nominal}$	25.4	A
$I_{in,\max}$	35.8	A

The generation cost with the photovoltaic system is set in 0.10 $US/kWh during the day, and at night at a cost of 0.25 $US/kWh. The microgrid is connected to the distribution network and the microgrid can interchange power with the grid. The electricity tariff is 0.16 $US/kW and it corresponds to the price for importing power from the grid. The microgrid connection with capacity values is shown in Fig. 4.

IV. Results and Analysis

This section presents the results about the optimal dispatching and the performance for the microgrid described before. Various cases are presented in this section in order to evaluate different operation schemes.

The results show that this approach has a practical value given that it provides important information as the generation cost for different configurations. The results show that this approach includes the tariff of electricity as input in order to determine the optimal operating cost.

This information would be valuable for distributed generation agents. All the simulations have been completed by computer (PC) running Windows R with a processor Intel Core I3+ 8000H @ 1.9 GHz with 8 GB RAM, under the Matpower 7.0b1 platform [41]. Fig. 5 shows the dispatching during the day with a total cost of generation of 80 $US/day approximately. The storage is not dispatched during this period, because it turns out to be the most expensive. The photovoltaic generator delivers power to the system. The distribution network supplies power to the microgrid during the night. Fig. 6 shows the result of the dispatching when all the power is exported from the grid. The total cost in this case is 119 $US/day, with a difference of 39 $US/day with respect to the dispatching case with the photovoltaic system. In order to evaluate the microgrid performance with variations in the storage cost, Fig. 7 shows the case with a price of 0.25 $US/kWh. The generation cost using the OPF is equal to 80 $US/day. If the power is exported from the grid, then the generation cost is equal to 127 $US/day. In order to evaluate multiple microgrids interconnected and the performance, the formulation is expanded to include this case. Fig. 8 shows the case with multiple microgrids and the corresponding parameters.

Each microgrid offers power and the dispatching is adjusted in order to evaluate the power interchanges. In this case, the generation cost is equal approximately to 276 $US/kWh. The power dispatching for a period of 24 hours is shown in Fig. 9. The dispatch indicates that the power is delivered for the microgrid with a capacity available of 50 kW. In order to evaluate the microgrid performance when the power is injected from the grid, Fig. 10 shows the dispatching and the total cost. The cost is higher than the case presented in Fig. 9.

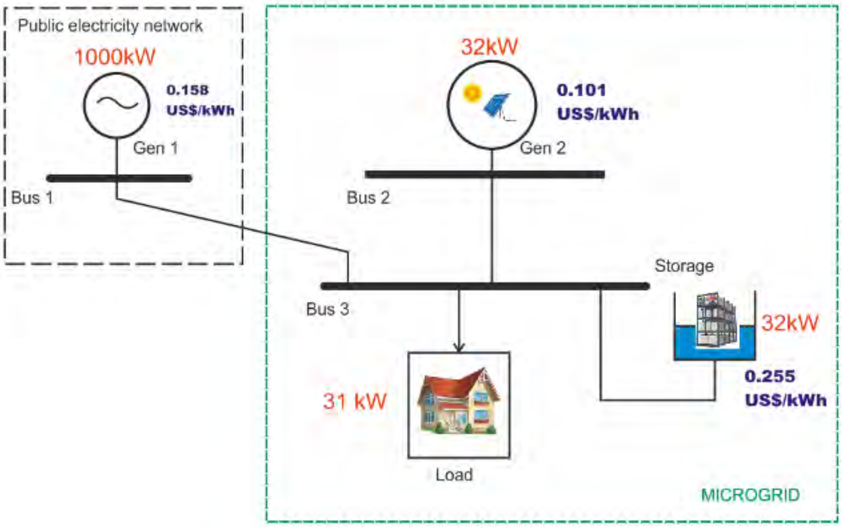

Fig. 4. Microgrid with renewable generation, storage and load

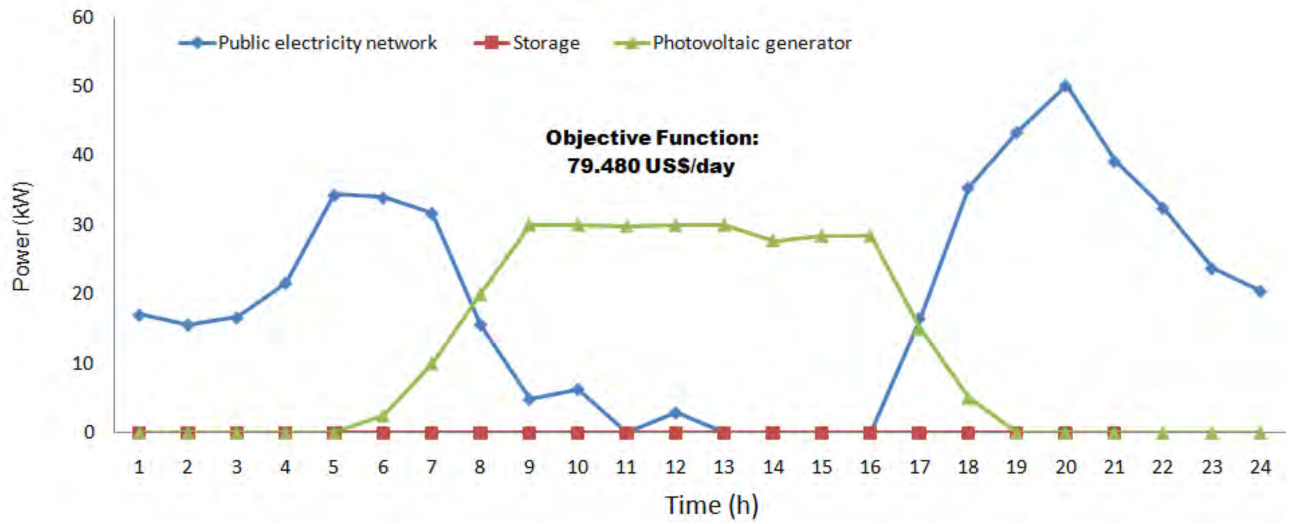

Fig. 5. Microgrid dispatching with power from the distribution network and the photovoltaic generator

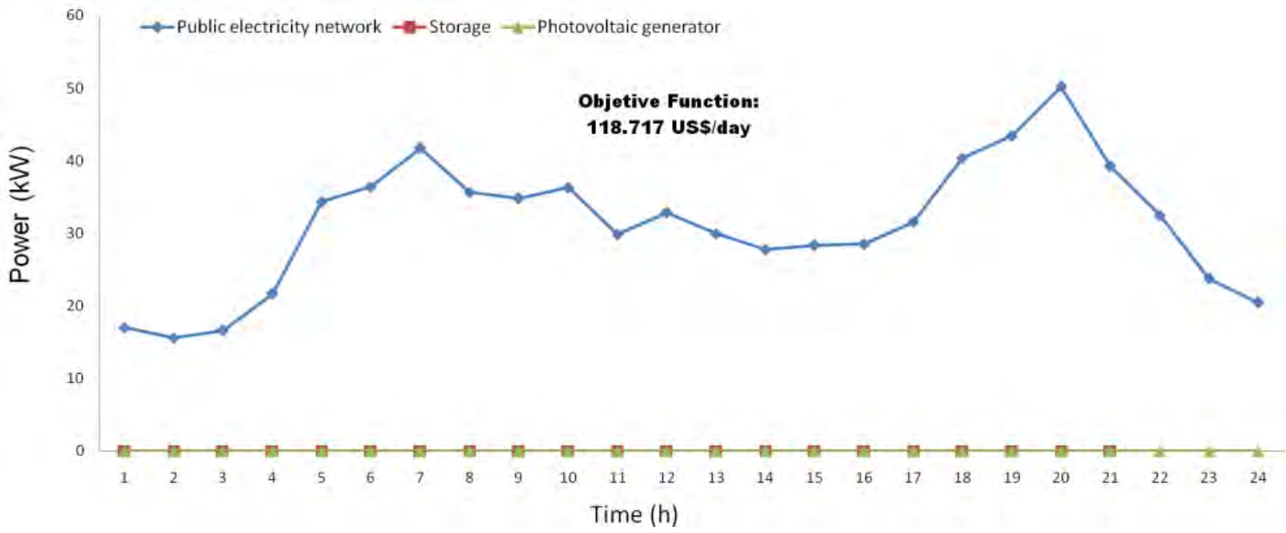

Fig. 6. Microgrid operating with power imported from the distribution network

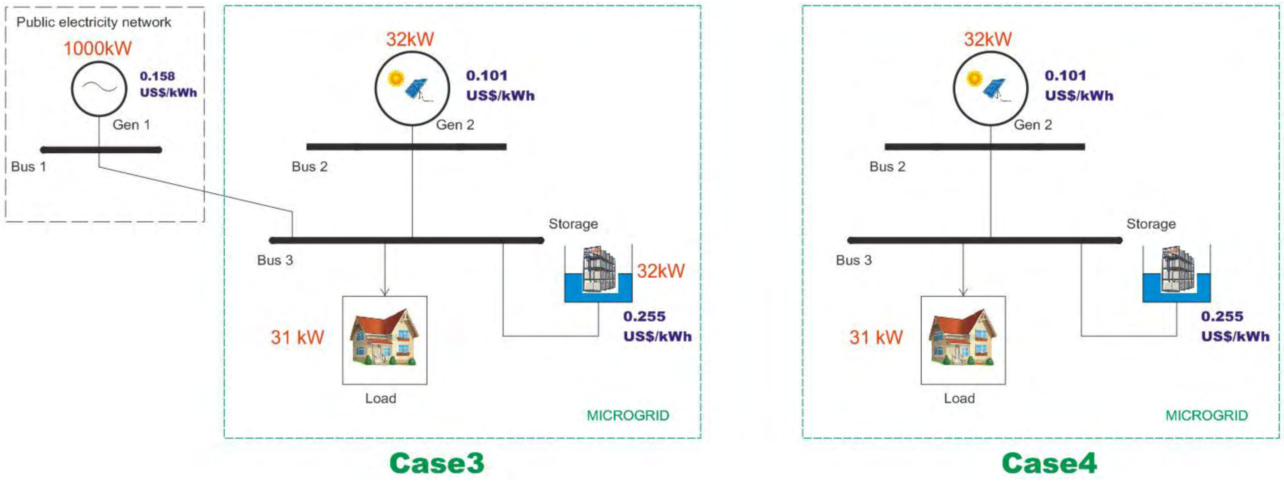

Fig. 7. Two cases of simulation with variation in the price of power from storage system

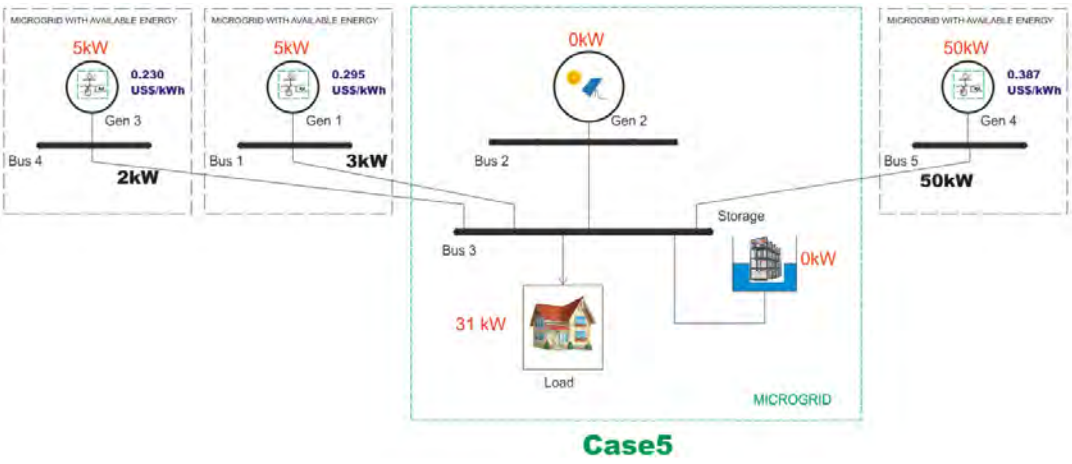

Fig. 8. Multiple microgrids interconnected with different prices

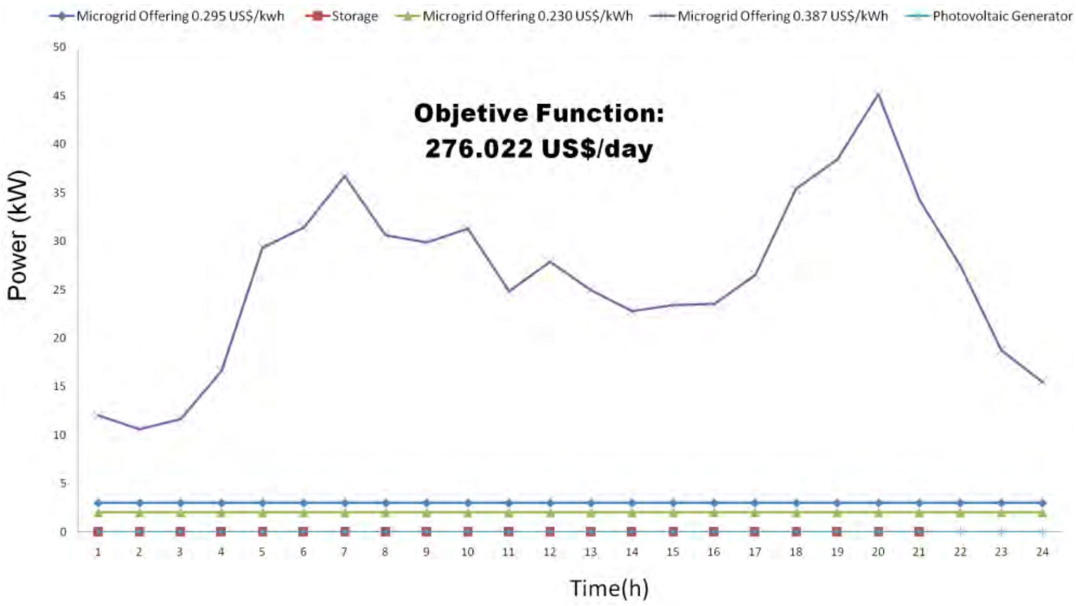

Fig. 9. Dispatching of multiple microgrids

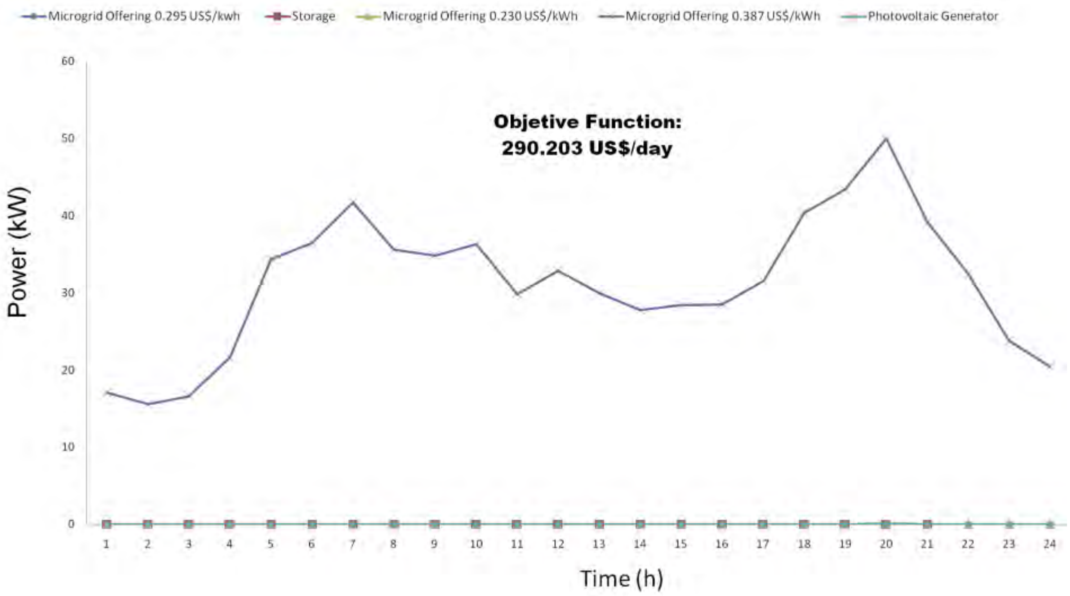

Fig. 10. Dispatching of multiple microgrids with power injected from the grid

V. Conclusion

This paper shows that the dispatching of a microgrid can be improved with an optimal power flow with benefits in the operation. This paper presents various cases of operation of a microgrid with storage. It has presented papers have presented a complete case of a microgrid connected to the distribution network with the alternative to operate in isolated mode. The results offer economic evidence between using dispatch programming under a constraint of minimum cost and without cost restrictions. This paper proposes a model of a microgrid for residential level. The methods presented in this paper can be used to do feasibility studies for the designing and operation of microgrids connected to the distribution network. This paper has presented simultaneously the design of a microgrid considering the topology of connection of the inverters and the photovoltaic system.

This design can be scaled up if a capacity increase is needed. As can be seen in the results, the electricity tariffs are major contributors to power interchanges between the distribution network and the microgrid.

Therefore, microgrid operators should place an increased emphasis in the operation and in the management of microgrids in order to get benefits from the operation. To this end, the findings of this paper can be highly useful for designing and operation of microgrids for different players in the energy sector such as distribution networks, retailers, and aggregators. This paper has presented an approach to dispatch power in microgrids considering photovoltaic systems and storage.

One of the main novelties in this paper has been the consideration of electricity tariffs in the model. This reflects a new way for microgrids to interchange power with the distribution network considering market opportunities. Given the integration of distributed energy resources, then the operation of microgrids will play an active role in future distribution networks. The work may be extended to account other power sources in the microgrid such as biogas, small wind turbines, and electric vehicles. Furthermore, since the growth of demand response may be important in the next years, the work may be extended to include demand response strategies according to electricity tariffs.

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Authors' information

[1]Universidad Autónoma de Occidente, Cali, Colombia.

[2]Department of Electrical Engineering, Universidad Distrital Francisco José de Caldas, Bogotá, Colombia.

Jairo Jamaica-Obregón received the B.S. degree in mechatronics engineering from Universidad Autónoma de Occidente (Autonomous University of the West), Colombia, in 2016. He will earn his master degree at 2020.
E-mail: jairo.jamaica@uao.edu.co

Ricardo Moreno-Chuquen is Professor of Electrical Engineering at the Universidad Autónoma de Occidente (Autonomous University of the West). His research and teaching activities are in the area of power system analysis, economics and planning. Ricardo Moreno earned his undergraduate degree at Universidad de Los Andes and he did his graduate studies (M.Sc. and PhD) at Universidad de Los Andes, Colombia.
E-mail: rmoreno@uao.edu.co

Oscar Flórez-Cediel is an associate professor of electrical and electronics engineering department at the Universidad Distrital Francisco José de Caldas in Bogota, Colombia. His research and his teaching activities are in the area of power system, smart grids, electric machinery and power electronics. Oscar Flórez is Electrical Engineer and he did his graduate studies M.Sc. in Eng of Electric Power at Universidad de Los Andes, Colombia. Investigator inside of a research group LASER (Laboratorio de Automatización, Sistemas Embebidos y Robótica) of the Universidad Distrital Francisco José de Caldas. He is the former chairman of the electrical engineering department of the Universidad Distrital Francisco José de Caldas.
E-mail: odflorez@udistrital.edu.co