Integration of electric vehicles in smart grids for optimization and support to distributed generation

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***Abstract*—The concept of microgrids configured as smart grids is becoming more widespread worldwide and is inevitable for future electrical systems. In addition, recently it has intensified the growth of distributed generation (DG), which are located with the consumers themselves. In this way, the complexity of the electric system is increasing in the presence of these new generating units carrying to several questions concerning supply problems, energy quality and generation intermittences. Moreover, the electric vehicles (EV) are increasingly present in the market and they may become an additional issue to deal with peak demands. On the other hand, the EV can be seen as a good alternative for electric energy storage since they can cooperate to improve the electrical system regulation. However, in order to make it possible it is necessary to develop methods to integrate the management of the DG and EV units. In this context, a new approach is proposed using the EV to mitigate DG intermittences and large demands common to the system profile. Therefore, this paper presents a management strategy for microgrids allowing the interaction of EV with photovoltaic generation (PV) and consumer loads using a configuration that employs a shared AC bus. The proposed management strategy includes economic and quality supply aspects. The paper also it is presented results of the management strategy analysis using real profiles of PV generation and consumer demand.**

***Index Terms*—Smart microgrids, distributed generation, electric vehicles, management**

I. Introduction

The power generation through renewable sources is increasingly growing and have been enabling the integration of distributed generation (DG) in the electrical scenario. Meanwhile, this cluster of DG can bring some issues related to overvoltages, islanding, generation intermittence, among others. Therefore, it is necessary a suitable management system to an acceptable smart grids operation [1], [2].

Smart grids have the purpose of resource integration to become the distributed and transmission energy systems more efficient and feasible. The concept of smart grids intend to approach supply, demand, quality and scheduling issues, develop efficient energy savings and reduced energy costs [1]. Smart grids are the future of efficient supply because they enable the integration of renewable sources with storage energy systems (ESS), thereby the random and intermittent characteristics of renewable energy can be mitigated [3]. These storage devices can provide power to the system in high demand periods, hence the energy costs and the use of generators are decreased, likewise ancillary services and voltage regulation [1]–[4].

Recently, the associate ESS devices in smart grids have become an outline to improve operational aspects of electrical systems. The ability to accumulate energy from the grid in lower demand periods and restore it to the grid in higher demand periods is something that has interested industries and the commercial sectors. Several US states have been developing incentives policies to install ESS, e.g. New York, California and Texas. Another factor that has been aiding the ESS spread is the price curtailment of lithium-ion. Along with the demand growth and increased incentives the ESS technology has achieved space in energy planning by providing support to electrical systems [5].

Furthermore, electric vehicles (EV) participation are constantly growing on the world market due to greenhouses gas emissions concern. Therefore, the daily demand profile would change considering the significant energy request from the grid for EV charging. Furthermore, the ESS cost depends of the grid capacity, the EV charging profile and the DG penetration, such that it is possible to reduce the generation costs [6]. Fig. 1(a) illustrates a conventional system without smart handling of DERs elements meanwhile Fig. 1(b) represents the EV charging distribution and energy support EV in high demand periods [8].

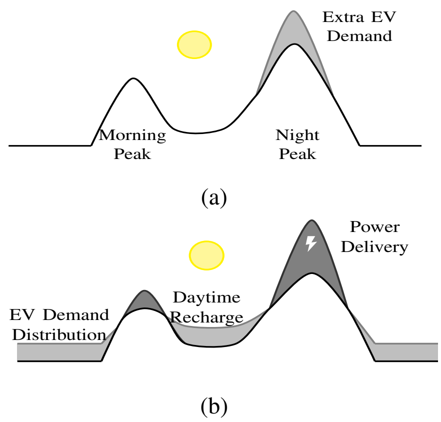

Fig. 1: Typical daily system demand: (a) conventional and (b) with smart energy management.

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Since most EVs include batteries as the ESS, they can be seen as an attractive alternative for ESS implementation in smart grids since they can optimize the demand profiles and also collaborate to reduce the DG intermittences. Many countries acknowledge EV as a good alternative for energy storage. As reported in [7], the Germany government stipulates that in future EVs will have a remarkable participation in its power grid. All ESS systems, DG sources and local loads are commonly considered Distributed Energy Resources (DER).

A large number of countries have been researching EV integration techniques with smart microgrids to improve energy efficiency and a better handling of the process. An example can be found in the Amsterdam government which accomplished an integration project called *AmsterdamV2G* [8] consisting of a EV charging station and photovoltaic (PV) units connection to the grid and local loads. The idea is to reduce demand peaks distributing EV energy request throughout the day.

The relationship between all of this elements makes the systems more complex. Therefore, an energy management scheme may be necessary for a suitable operation. Several recent researches [9]–[20] investigate strategies for energy management and optimization methods to obtain better results of supply quality, voltage regulation and costs saving. In [9] the voltage problems are approached with a two stages management control; [10] presents the voltage quality and economic aspects concerns adding a priority index for EV charging; [11] shows a smart charging station with 4 management modes; [12] uses the artificial bee colony method to process optimization; in [13] it is presented an economic charging based on real-time energy price market; [14] proposes an arrival and departure EV model; [15] devolves solutions for multi-agents microgrid management problems; in [16] it is proposed an online integration between measurement, forecast and optimization modules, for connected and island modes; [17] approaches an architecture to mitigate overloads and minimize solar irradiance intermittences; [18] proposes a colored-Petri nets management system; in [19] the author approaches challenges of local energy storage optimal size; and in [20] there are two charging options: a fast energy exchange and optimal energy exchange.

In Fig. 2 it is exemplified a microgrid where the General Management System (GMS) controls the power flows among DERs, in this case, the local loads are separated in Not-Controllable Loads (NCL) and Controllable Loads (CL). However, most of these works consider the microgrid power elements connected by a main DC bus. Meanwhile, most microgrids architectures are composed of power elements connected through AC buses.

This topology presents advantages due to direct EV supply from DG source throughout the DC bus, consequently a lower energy processing in the converters. Although it supplies only DC loads wherefore if there are AC loads connected to the microgrid they must contain an inverter, it increases the system spending and complexity. Moreover the typical architecture networks already have an AC bus to joint DG sources with the external grid, it becomes easier to include EV charging

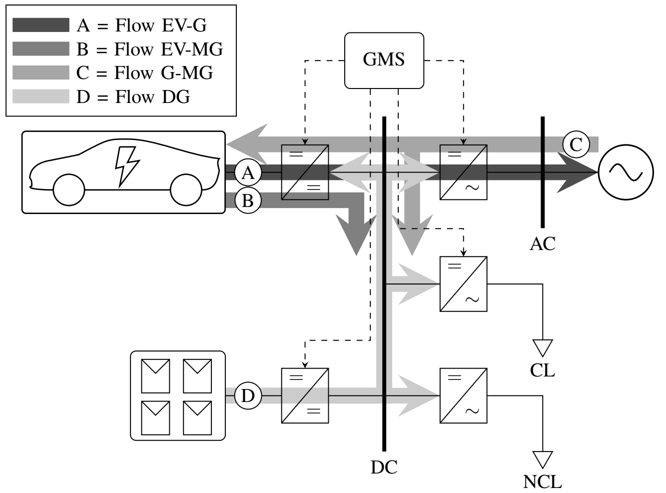

Fig. 2: Possible microgrid (MG) flow diagram among the EV, grid (G), local loads (CL and NCL) and the DG.

station in existent systems.

The main contribution of this paper is to propose a microgrid management strategy based on supply quality and energy cost (SQEC-MMS). The microgrid is considered as composed by AC loads connected to the grid through a local AC bus. Photovoltaic arrays (DG source) and vehicle chargers clusters (ESS systems) are also connected to the local AC bus. The proposed management strategy considers that the microgrid energy can be exchanged among DERs in a way that the energy cost from the grid is minimized. Also, the quality supply variables (voltage regulation, power factor, reactive power, ...) are controlled such that they can attend international standards as IEC 62898-1, IEC 60038.

This paper is organized as follows: Section II presents the proposed microgrid representation while Section III establishes the microgrid energy modeling, including EV model, PV model, AC loads and the AC grid. Section IV sets the operation restrictions and Section V presents the proposed algorithm. The analysis of the microgrid management strategy is carried out in Section VI, while Section VII concludes the work.

II. Proposed System Representation

Considering the system in Fig. 3 that shows a PV array, EV connected in charging stations and loads linked to the microgrid. The modular form of the system has the objective to allow a better bleeding of PV generation, as well as flexibly utilize the EV energy. Through this scheme are developed some equations to determine the circuit behavior.

Analyzing the Fig. 3, the variable P_n^{PV} represents the active power of the n^{th} group of panels of the system connected to an inverter; P_m^{PV} and Q_m^{PV} represent the active and reactive power, respectively, of n group of associated panels; P_e^{PV} is the active power of the individual EV; P_a^{PV} and Q_a^{PV} are respectively the active and reactive powers of the groups of charging stations. The variables S_x^L and S_G represent the apparent power of the connected loads and the resulting

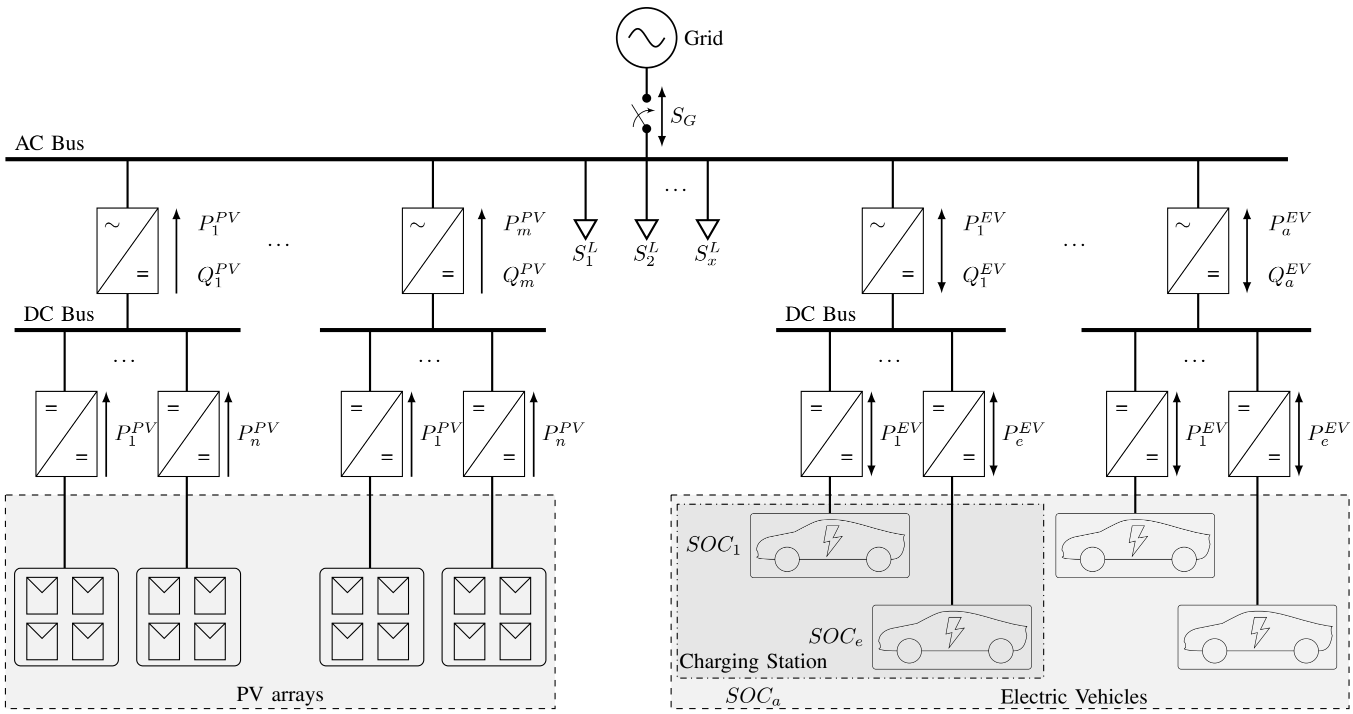

Fig. 3: Proposed microgrid diagram.

apparent power of the grid, respectively. It is assumed that the generic system contains N_a loading points, which are able to supply N_e vehicles [21].

For that related topology, the EVs are connected in a single DC bus forming charging stations. Unlike a few papers where all elements are connected to a DC bus, this topology option allows vehicles to be connected to the existing AC bus in current PV generation systems. This contribution differs from several papers presented in the literature.

III. Elements Modeling of the System

A. Modeling of EV

Each vehicle connected to the station can be in charge or discharge mode, so the state of charge (SOC) of each vehicle can be obtained through the following (1) and (2) for charge and discharge mode, respectively.

$$SOC_{e,t} = SOC_{e,t-1} + \eta_{ch} \frac{P_{e,t}^{ch}}{E_b} 100, \tag{1}$$

$$SOC_{e,t} = SOC_{e,t-1} - \eta_{dch} \frac{P_{e,t}^{dch}}{E_b} 100, \tag{2}$$

where $SOC_{e,t}$ represents the state of charge of the EV battery; η_{ch} and η_{dch} are the charge and discharge efficiencies, respectively; $P_{e,t}^{ch}$ and $P_{e,t}^{dch}$ are the power transfer rates for charging and discharging, respectively; and E_b is the total battery capacity [21].

To represent the equivalent state of charge of the EV group at each charging station, (3) can be used as

$$SOC_{a,t} = \frac{\sum_{e=1}^{N_e} SOC_{e,t}}{N_e}. \tag{3}$$

The variable $SOC_{a,t}$ represents the equivalent state of charge of all vehicles connected to a single DC bus. The resulting power demanded by the vehicles is the difference between the charge and discharge transfer rates, as can be seen in (4)

$$P_{e,t}^{EV} = P_{e,t}^{ch}(EV_{e,t}) - P_{e,t}^{dch}(EV_{e,t}), \tag{4}$$

wherein $EV_{e,t}$ represents a binary value indicating the presence of EV connected. It should be noted that charging and discharging processes must not occur simultaneous, thus (5) is formulated. Considering this restriction, it is possible to obtain the power resulting from all EV charging stations through (6) [21]. The chargers are connected to the AC bus via an inverter as shown in Fig. 3, therefore it is possible to compensate reactive power from the system.

$$P_{e,t}^{ch} P_{e,t}^{dch} = 0, \tag{5}$$

$$P_{res}^{EV} = \sum_{a=1}^{N_a} P_{a,t}^{EV}. \tag{6}$$

Here, in (7) S_{res}^{EV} represents the resulting apparent power for EV, as can be seen the active power obtained through (4) only will be present if there are vehicles connected to the system, otherwise, it is simply possible to inject reactive power

$${S_{res}^{EV}}^2 = {P_{res}^{EV}}^2 + {Q_{res}^{EV}}^2. \tag{7}$$

B. Modeling of PV

PV systems are configured to operate in maximum power point available (MPP), therefore methods for tracking these points (MPPT) are developed. Equation (8) represents the maximum power supplied based on the level of solar irradiance and size of the panel [21].

$$P_{PV_{m,t}}^{max} = \eta_{PV} A_m I_{PV}, \tag{8}$$

where η_{PV} is the panels efficiency, A_m is the surface area $\left(m^2\right)$ and I_{PV} is the solar irradiance denoted by kW/m^2.

Nevertheless, in some planning and optimization management scenario it may be preferred that the dispatch point is not in the MPP, so the planned active power is represented by the variable $P_{m,t}^{PV}$ [21].

Likewise the charging stations, PV panels are distributed in groups connected to the AC bus, according to Fig. 3. Therefore the active power from the DG is shown in (9)

$$P_{res}^{PV} = \sum_{m=1}^{N_m} P_{m,t}^{PV}, \tag{9}$$

here, N_m means the quantity of associated panel groups [21].

Reactive power can be also supplied by the inverter connected to the PV, in this way (10) presents the apparent power of DG

$$S_{res}^{PV^2} = P_{res}^{PV^2} + Q_{res}^{PV^2}, \tag{10}$$

wherein Q_{res}^{PV} the reactive power through the inverters of each PV group.

C. Modeling of grid

The resulting apparent power provided or requested from grid is presented by S_G and is composed by the sum of the power flow of the PV, chargers, EV and loads connected to AC bus. This relation can be seen in (11)

$$S_G = S_{res}^{EV} + S_{res}^{PV} - S_L, \tag{11}$$

that S_L is the apparent power from all connected loads S_x^L and x vary up to the maximum loads quantity N_x connected to the AC bus.

IV. Operating Restrictions

In this section some constraints and operating conditions are modeled for the purpose of being used in the process of planning the power flow between the devices of the system. Among the approach assumptions highlight the economic and energy quality aspects.

A. Economic aspects

Initially, the economic costs of the elements will be calculate. Dealing with the EV battery, degradation of the life cycle occurs according to the number of charging cycles and the depth of discharge (dod) as shown in [22]. Thus, to represent the cost of battery degradation C_{DB} is formulated the following (12)

$$C_{DB} = \frac{C_{CB}}{1000 L_b E_b dod}, \tag{12}$$

where C_{CB} is the investment costs, L_b is the life cycle of the battery and dod is the depth of discharge [21].

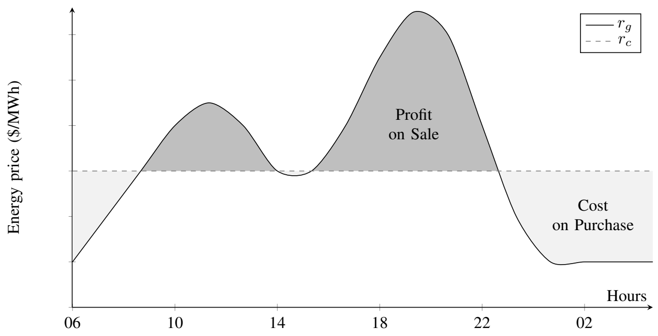

Fig. 4: Payment price representation requested by the charger and by the electricity grid.

Relating the battery degradation and the discharge EV power $P_{a,e,t}^{dch}$ the discharge cost can be obtained. Later, including the costs with the energy exchanges between the grid and the microgrid it is possible to define (13) as being a system spending function

$$F^{eco} = \sum_{t=1}^{T} \left[\left(r_t^P P_{G,t} + r_t^Q Q_{G,t} \right) + \sum_{a=1}^{N_a} \sum_{e=1}^{N_e} C_{DB} P_{e,a,t}^{dch} \right], \tag{13}$$

here, the variables r_t^P e r_t^Q refer to the costs of active and reactive power exchanges with the grid, respectively, and vary according to the daily hour [21]. Therefore, (13) can be divided into two main terms: one related to the power exchange spendings with the grid; and the other referent to battery degradation spending during the discharge process.

Some techniques of optimization methods can be applied in (13) in order to reduce costs by providing an appropriate management with a minimum economic spending.

Considering a fixed value, given by r_c, owed by charging station comparing with a daily energy value represented by r_g in this case. For convenience, the variable r_g is considered for the active and reactive powers. Thereby, the two variables are represented in Fig. 4, highlighting the probable proportion of prices between them.

Whereas that r_c is greater than r_g it means that the EV charging is profitable for the microgrid, allowing the purchase of power from the electric grid. If r_g is greater than r_c the profit is obtained when the energy produced in the microgrid is sold to the grid.

B. Bus voltage

The insertion of DG and EV causes disturbances in the system bus voltage, where the voltage level at the connection point of the generation units tends to rise and in the loads point tend to reduce the voltage [9]. Therefore, the voltage level control is necessary to maintain fitting operation of the microgrid. Equation (14) depicts the voltage drop throughout the system buses.

$$F^V = \sum_{t=1}^{T} \sum_{b=1}^{N_b} |1 - V_{b,t}|, \tag{14}$$

here, $V_{b,t}$ represents the voltage in the adjacent bus b at each instant t for a total N_b system buses [21].

The voltage $V_{b,t}$ must respect some active and reactive power balance conditions, respectively presented in (15) and (16)

$$P_G + P_{res}^{PV} - P_{res}^{EV} - P_x^L + \\ - V_{b,t} \sum_{b=1}^{N_b} V_{b-1,t} \left(G_b cos\theta_b + B_b sen\theta_b \right) = 0, \quad (15)$$

$$Q_G + Q_{res}^{EV} - Q_x^L - V_{b,t} \sum_{b=1}^{N_b} V_{b-1,t} \left(G_b sen\theta_b - B_b cos\theta_b \right) = 0, \quad (16)$$

being G_b the matrix conductance and B_b bus matrix susceptance, the voltage angle θ_b between the buses [21].

The voltage regulation must be carried out on the AC bus at the connection point (CP) to the grid. In this way the voltage ranges considered to formulate the operating conditions of the system are based on IEC 60038 which determines the suitable voltage levels for the operation of the system. The voltage levels 100 V to 1 kV are indicated based on IEC 60038 standard [23]. The supply voltage range must be within $\pm$ 10% at the CP [23].

C. State of charge

In the system two states of charge are considered: one represents the individual percentage of the battery of each vehicle (SOC_e); the other associates the individual percentages and represents an average for each vehicle group (SOC_a).

As a way of restricting the use of the energy contained in each car, a minimum state of charge of 60 % (SOC_{min}) was determined. Thereby, at the end of the process, there will still be enough energy in the battery for the user to leave the charging station. Therefore, for any car that has a percentage below this level, it will automatically be charged until it reaches this condition, regardless of other system variables. Based on depth of discharge and life cycle relation presented in [22] an ideal state of charge (SOC_{ideal}) of 80 % was determined for energy exchanges, since considerable deep discharges reduce the battery life cycle. In Fig. 5, it is illustrated the three main stages of the SOC considered.

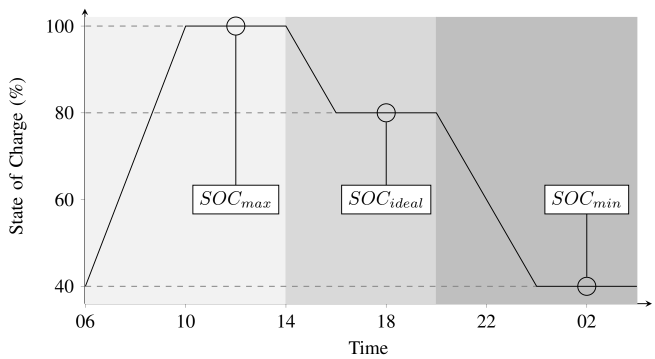

Fig. 5: Guidelines SOC representation.

Considering the elements of system representation previously presented in Fig. 3 and relating among the chosen operation conditions, the variables that affect each available flow between the elements , illustrate in Fig. 6, are depicted in Table I.

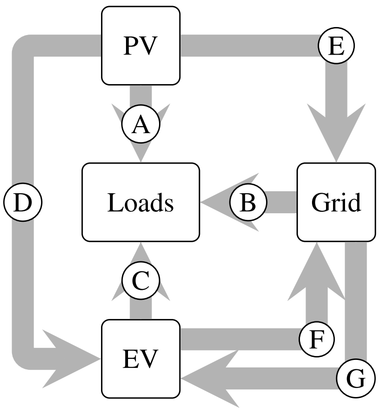

Fig. 6: Influence of restriction variables on power flow.

TABLE I: Restrictive variables for each power flow

Flows	Restrictions			
	Priority	V_b	\$	SOC
A	X			
B	X	X	X	
C	X		X	X
D			X	X
E		X	X	
F		X	X	X
G		X	X	X

Flows A, B, and C feed the loads of the microgrid, so the *Priority* column determines that loads must be supplied regardless of the system arrangement. The active and reactive powers have the objective of voltage regulation at the connection point and reactive compensation, so the flows connected to the grid and loads are influenced by the voltage quality variable V_b. Similarly, all flow associate to the vehicle charging/discharging hinge on the SOC variable. The flows B, C, D, E, F and G are related directly or indirectly to the profit obtained by the system.

V. Proposed Management Strategy Algorithm

Based on elements models previously developed, the simulation algorithm has been elaborated. Firstly P_C is calculated as a differ between PV generation and load demand, this term is important because its signal indicates the system status. Whether P_C is positive, the system has overbalance generation so it must sell the surplus to the external grid or charge vehicles; however if it is negative, the system has over load demand, therefore, the microgrid must purchase energy from external grid or discharge vehicles to support this deficit.

The management idea of this paper is to obtain profit for the owner of the charging station and reduce purchase spending from external grid. For that reason P_{EV} is calculated based on

r_c and r_g values. The vehicles charging occurs when $r_c > r_g$ and discharge whether $r_g > r_c$, always searching the profit and economic savings.

The charging/discharging rate is determined in sequence and the adjacent SOC ($SOC(t+1)$) is calculated for future calculation loop.

In the end of the loop the P_{grid} value is determined and verifies if P_C and P_{EV} are null, thus all loop is recalculated and repeat it until the end of time samples. In Fig. 7 is presented the elements models algorithm flowchart resuming the calculation process.

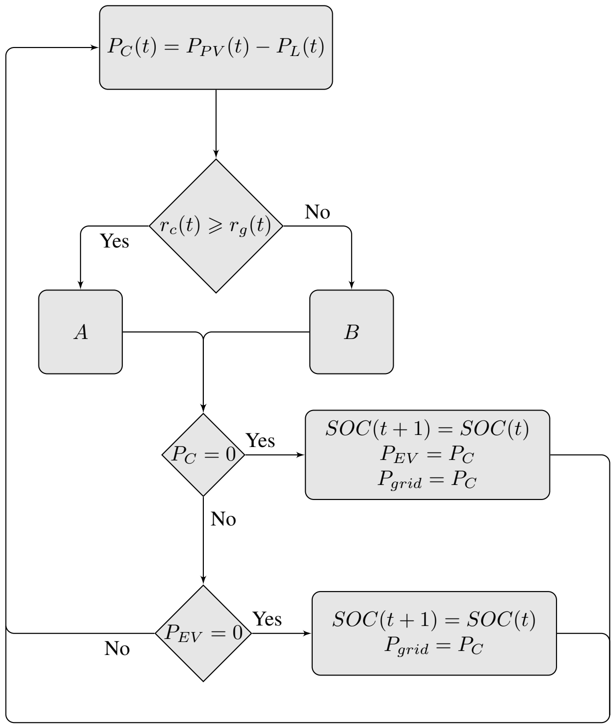

Fig. 7: Proposed microgrid operation flowchart.

The A and B block are composed by other blocks where are calculated P_{EV}, SOC and P_{grid} values. They are presented in Fig. 8.

The power flow management based on Fig. 6 is developed separately from elements model loop algorithm. After P_{grid} and P_{EV} terms have been calculated, the power is distributed to elements considering the management profit idea. The power flow management can be seen in Table II.

When the conditions are satisfied the energy is sent to the element microgrid based on management idea searching an economical profit. Analyzing Table II, $DSCH$ and CH correspond to discharging and charging periods, respectively, and OVB is when generation overbalance occurs.

VI. Application of Management Energy Strategy

As a form to validate the modeling described previously, simulations were performed analyzing the microgrid for a basic management strategy. The idea of this operation is to prioritize the handling of loads, taking into account economic

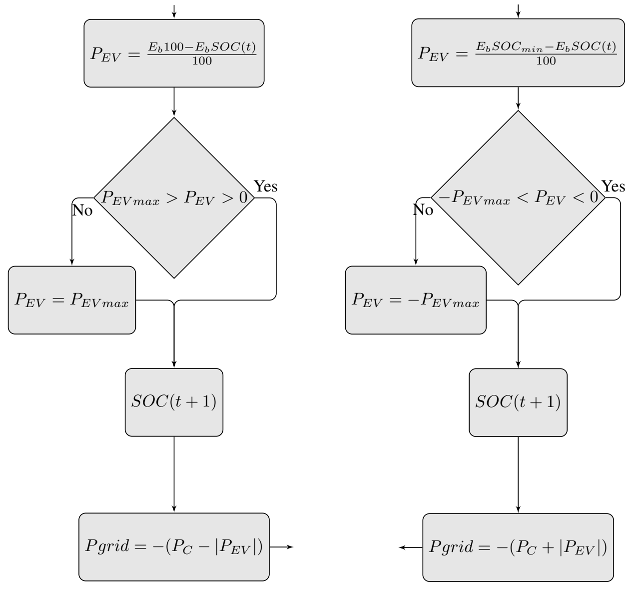

Fig. 8: Power rating determination for microgrid operation algorithm: (a) A and (b) B.

TABLE II: Management power flow algorithm

	$DSCH = find(P_{EV} < 0)$
	$CH = find(P_{EV} > 0)$
	$OVB = find(P_L < P_{PV})$
$\%A$	$Ppv2L = P_{PV}$
	$Ppv2L(OVB) = P_L(OVB)$
$\%C$	$When(P_{PV}(DSCH) < P_L(DSCH))$
	$Pev2L = P_{EV}$
$\%B$	$When(P_L > P_{PV})$
	$G2L = P_L$
$\%D$	$When(P_{PV}(CH) > P_L(CH))$
	$Ppv2EV = P_{EV}$
$\%E$	$Ppv2G(OVB) = P_{PV}(OVB) - P_L(OVB) - Ppv2EV(OVB)$
$\%F$	$When(P_{PV}(DSCH) > P_L(DSCH))$
	$Pev2G = P_{EV} - Pev2L$
$\%G$	$When(P_{PV}(CH) < P_L(CH))$
	$G2EV = P_{EV} - Pev2G$

aspects, but not measuring voltage regulation or energy supply quality. For this scenario, only one charging station containing 10 electric vehicles is considered.

In Fig. 9, the PV generation and the load demand profile are highlighted during three different days of solar irradiance, for a real profile of UTFPR, Brazil. Also the two price curves considered are illustrated, r_c is chosen by charging station and r_g is determined by daily energy price.

From the curves shown at Fig. 9, the proposed algorithm is utilized and the SOC solve could be obtained. The Fig. 10 shows the SOC of EV group response, with PV generation and load demand (L) profiles. The maximum power transfer from charging station is based on current 32 A used for Level 2 charging mode of SAE J1772, generally utilized in urban applications, resulting in a maximum power of 12 kW [24].

Comparing prices curves presented in Fig. 9 it can be seen that the EV charging occurs when $r_c > r_g$ and EV discharging

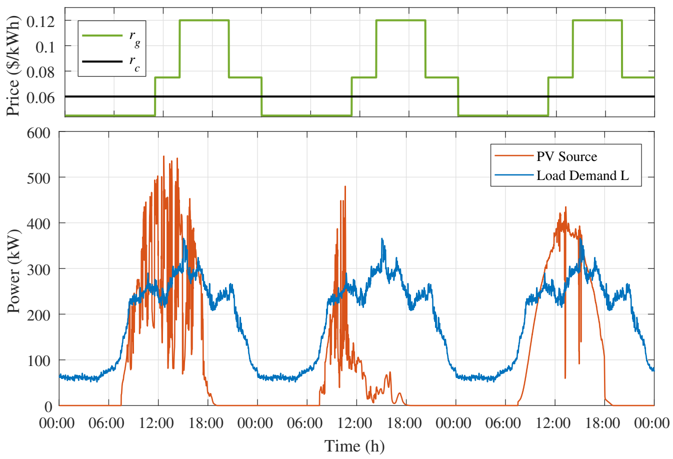

Fig. 9: Generation and demand profiles highlighting the price profiles considered.

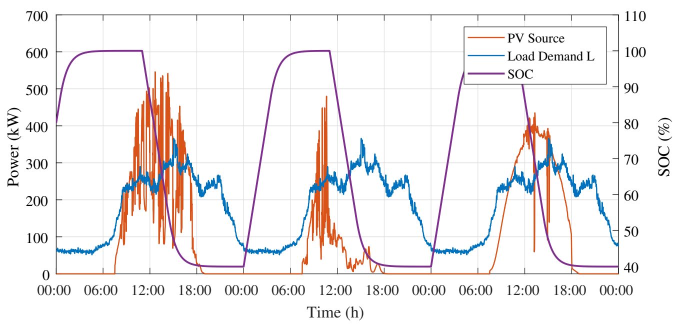

Fig. 10: PV generation and demand profiles considered for simulation and the state of charge of the EV group.

appears whether $r_g > r_c$, regardless of generation surplus or over load demand. Observing the SOC curve it can be noticed that simulation respects SOC_{min} consideration narrowing the minimal percentage in 40%.

In Fig. 11, the EV and grid energy are presented separately: when P_{res}^{EV} is positive, it means that EV group is charged and considered as a load; and, when P_{res}^{EV} is negative, the group is discharged and considered as a energy source. The resulting energy from EV and PV are combined as P_G. Thus, when $P_G > 0$, power flows from grid into the microgrid and when $P_G < 0$, power flows from the microgrid to the external grid.

Analyzing three simulated days it is possible to see a considerable EV participation in load supply, mostly noticed in higher solar irradiance days. The maximum power provided by EV group is 122 kW, approximately, that is because it is considered 10 vehicles recharging. The PV and EV cluster represents a great alleviate for energy purchase from grid decreasing peak load demand thereby reducing operation spendings.

For a better flow representation all power paths presented in Fig. 6 are associated in Fig. 12. It can be noticed that EV feed represents a significant part of load supply, therefore it is turned into profit for the installation. However in some periods

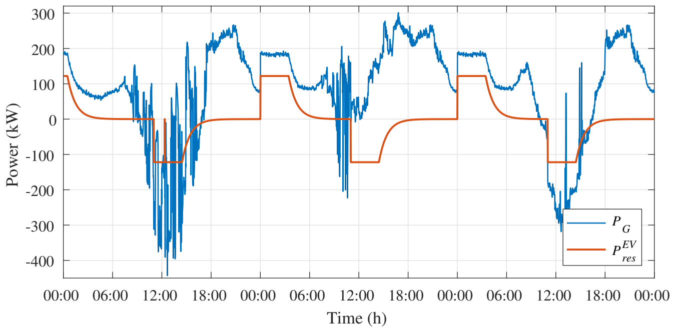

Fig. 11: Power transfer of VE and grid.

the EV portion means an increase of energy purchase, in Fig. 12 this is presented by G.

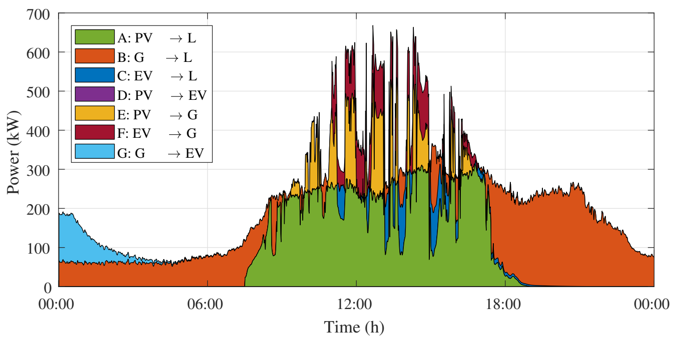

Fig. 12: Power flows between the elements of microgrid for the 1^{st} day.

It can be noticed that high solar irradiance days, the PV and EV has higher participation on load supply, in opposition, in low solar irradiance days, the system faces a small generation, relying therefore, on storage energy available on EVs. In Fig. 12, it can be seen the PV intermittence and EV assistance to transfer energy to the loads in a more uniform way. Moreover, it is noticed the PV and EV overbalance to grid separately.

To verify the economics benefits of this approach, the system costs to purchase energy from the grid are calculated. Furthermore, the EV station profit is highlighted as well the PV generation and load sale. The real case analysis results are presented in Table III.

TABLE III: Economic indicators for the EV-PV microgrid

Economic aspects (US$)	**1^{st} Day**	**2^{nd} Day**	**3^{th} Day**	**Total (3 days)**
PV Generation	224.98	52.86	239.11	516.94
EV Station Profit	27.54	8.50	8.50	44.55
Microgrid loads	362.20	362.30	362.30	1,086.60
Cost with EV-PV	**159.35**	**253.43**	**153.82**	**566.41**

It can be noticed that the EV station profit, after 3 simulation days, considering different DG profiles, is around 8% of the total energy purchase from grid to the microgrid. It is important to be emphasize that the purchase reduce from the grid with DG unit and EV station participating in microgrid is about 48% less than before.

VII. Conclusion

The increasing of DG and EV is a motivation to develop techniques and methods to improve energy efficiency, quality voltage supply and saving costs. This paper presented a micro-grid management strategy based on supply quality and energy cost (SQEC-MMS) that is able to improve grid efficiency and supply quality. A real data based analysis demonstrates the microgrid behavior using the strategy presented in this paper. It can be seen that PV and EV cluster alleviates the energy purchase from the grid in high demand periods. Also from the developed analysis, it can be noticed that the SOC restriction was met with chosen values and the voltage range quality will be considered in future work. An important aspect for management energy system is that the PV generation intermittence could be reduced by EV participation and it results in a smoother microgrid from/to grid operation.

From economic aspects results, it could be noticed that the cluster implementation of PV and EV station is a significant option to benefits the system, furthermore, the EV station owner can obtain promising economical results.

For future work it is intended to incorporate random profiles of EV participation and develop an optimal energy management, therefore, approximating to a more realistic behavior of the system.

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