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Energy Management System for Hybrid Microgrids

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Abstract

Energy management in grid-connected Micro-grids (MG) has undergone rapid evolution in recent times due to several factors such as environmental issues, increasing energy demand and the opening of the electricity market. The Energy Management System (EMS) allows the optimal scheduling of energy resources and energy storage systems in MG in order to maintain the balance between supply and demand at low cost. The aim is to minimize peaks and fluctuations in the load and production profile on the one hand, and, on the other hand, to make the most of renewable energy sources and energy exchanges with the utility grid. In this paper, our attention has been focused on a Rule-based energy management system (RB EMS) applied to a residential multi-source grid-connected MG. A Microgrid model has been implemented that combines distributed energy sources (PV, WT, BESS), a number of EVs equipped with the Vehicle to Grid technology (V2G) and variable load. Different operational scenarios were developed to see the behaviour of the implemented management system during the day, including the random demand profile of EV users, the variation in load and production, grid electricity price variation. The simulation results presented in this paper demonstrate the efficacy of the suggested EMS and confirm the strategy's feasibility as well as its ability to properly share power among different sources, loads and vehicles by obeying constraints on each element.

Keywords: Microgrids, Energy Management System, Rules-based methods, Energy Storage System, Electric Vehicle, Renewable Energy.

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1. Introduction

In recent decades, the development of renewable energies such as photovoltaic systems, wind turbines and energy storage systems has attracted much interest worldwide due to the increasing energy demand, fossil fuel depletion, climate change, and increasing energy prices.

In this respect, the multiplication of these energy resources and modern loads such as electric vehicles in power distribution systems has encouraged the deployment of a new concept of smart Microgrid [1].

This new paradigm appears to be an effective way to facilitate the insertion of RE (Renewable Energy) which are intermittent in nature into distribution systems and to satisfy the customer's demands. Generally, MGs can operate in both stand-alone and grid-connected configurations.

In the island mode, the MGs guarantee the reliability of the system in case of failure of the main grid on the one hand, and on the other hand they ensure the minimization of operating costs. While in grid-connected mode the aim is to maintain a smooth and robust exchange of energy between the system and the power utility while increasing system revenues and limiting the grid's use [2].

To achieve optimal operation of a grid-connected MG, energy management systems (EMS) are used to control energy flows in a system in real-time in terms of efficiency, reliability and power quality, while ensuring self-sufficient power generation that satisfies various operational and economic constraints.

The development of energy management systems (EMS) for MGs is one of the most important research areas due to the high deployment of renewable energies.

To ensure energy transfer between sources and loads, various energy management techniques have been suggested in the literature. For example, Luu proposed in [3] a dynamic programming method for designing the best EMS for an isolated microgrid.

Other papers such as in [2] have proposed a RIS-based EMS capable of managing in real-time, the energy flows of a grid connected MG.

In [4] Diego Arcos-Aviles proposed an FLC-based EMS design for smoothing the power profile of a grid-connected residential microgrid with renewable generators and battery storage.

Also, in vehicle applications, EV energy management systems are presented in [5], the rules-based energy management system (REMS) has been applied for recharging electric vehicles from a photovoltaic system (PV-grid) with the aim of recharging EVs at a constant price during working hours.

Recently, Mohammad Jafari and his collaborators proposed in [6] a fuzzy logic strategy to control energy, and this algorithm has been commonly used in the design and development of a residential microgrid energy management unit.

The paper [7] also proposes an energy management strategy based on a combination of fuzzy logic control, flatness control and rule-based control for a hybrid energy storage system applied to electric vehicles.

In reference [8] a rules-based energy management system has been proposed that operates to make the most of the energy from the battery-based energy storage system and to purchase as little energy from the grid as possible.

In paper [9], the authors proposed a dynamic energy management system (I-DEMS) capable of operating in grid-connected and island Microgrids based on an adaptive dynamic programming and reinforcement learning framework.

For the optimal sizing of renewable energy resources in microgrids, a method for generating wind speed, irradiation, and load scenarios was proposed in this study, which the researchers examined an energy management system to select the optimal configuration of the microgrid system using a teaching and learning based optimization (TLBO) method in [10].

The literature in [11] describes a new rule-based EMS for hybrid Microgrid (AC/DC) autonomy with higher quantum thermal loads and renewable energy sources.

A hierarchical energy management system based on a robust predictive control model (MPC) for a microgrid has been considered in reference [12] which takes into account the uncertainty of renewable energy supplies and electrical load consumption.

By reviewing the literature, it can also be observed that the (EMS) is applied in Microgrids where load flexibility is not explicitly considered. Therefore, the absence of these loads may reduce optimal management solutions on the one hand, and on the other hand, optimization algorithms applied for energy management using linear, dynamic, hybrid programming techniques and fuzzy logic result in high computational requirements and need relaxation techniques due to the presence of non-linear and integer variables and a wide range of operating modes. It can also be indicated that the smoothing of the power profile of the load to minimize the operating cost by using renewable energy is not addressed in all the mentioned previous work.

Therefore, by addressing these research gaps, rule set methods can be a very effective approach to integrate more intelligence into Microgrids as well as simplify the complexity of the fuzzy logic (FLC).

This rule-based management approach has been successfully applied to energy management in Electric Vehicles (charging/discharging) [6] and in stand-alone Microgrids [4]. In this respect, the main novelty of this paper consists in the energy management strategy, which is based on a rule-based energy management system (EMS) applied to a multi-source residential grid connected Microgrid that combines renewable energy sources (PV, wind, BESS), an EV station equipped with V2G technology as a flexible load and a dynamic load.

Under various unforeseen conditions, the algorithm is designed to prioritize the sale of additional electricity produced from renewable energy sources (RES) by using time-of-use rates for the purchase of electricity from the grid during off-peak hours and reselling it back to the grid during peak demand hours, as well as reduce peak load demand.

This algorithm generates a set of rules for efficient interaction between energy sources and loads using human knowledge and experience with the system. They are chosen for real-time energy management because of their computational efficiency and ability to provide an exact solution to the desired performance conditions. The algorithm is developed in the form of the if-then-else", which is responsible for implementing a real-time decision-making strategy. These modes execute the energy flow between the different components of the system. It has the advantages of low computational complexity, simple control, high robustness and reliability. The decision can be made if and only if the information on solar irradiation, wind speed, load profile and SOC of the BESS, and SOC of each EV at time t is known [5], [13].

The overall objective of energy management of a microgrid is to optimally program energy resources to achieve economical, sustainable and reliable operation at a possibly low cost.

2. Microgrid description

The study developed in this paper is designed for a residential MG connected to the grid.

Figure 1 shows the microgrid structure that will be studied in this paper.

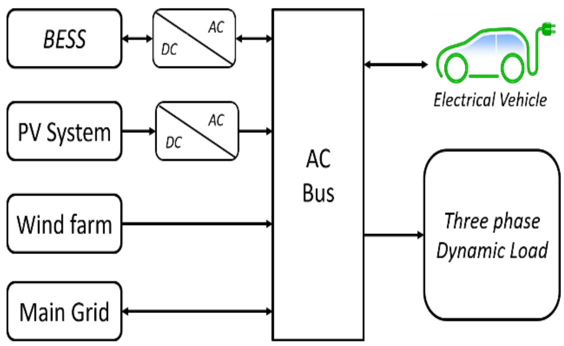

Figure 1. The architecture of the connected Microgrid system

The MG includes an uncontrollable variable load with a nominal power rating of 400 kW, a photovoltaic (PV) array of 235 kW, A 200 kW wind farm (WT) and a 750-battery energy storage system (BESS).

A bi-directional connection between the Microgrid and the main grid (i.e., energy can be bought or sold) is used to ensure voltage/frequency stability and an EV charging station that receives 8 cars of 60 kWh each with different charging profiles, these vehicles are equipped with V2G technology.

The entire system is controlled by an energy management system (EMS).

Table 1. Microgrid parameters

Symbole	Description	Value	Unit
Ppv	Photovoltaic rated power	235	KW
Pwt	Wind turbine rated power	200	KW
P_L	Load rated Power	400	KW
P_{BAT}	Battery rated power	750	KWh
SOCB-max	Maximum Battery SOC	95	%
SOCB-min	Minimum Battery SOC	20	%
SOCEV-max	Maximum EV SOC	100	%
PEV	EV rated power	60	KWh
Pgrid-max	Maximum power given by grid	260	KW
T	**Simulation time**	**24**	h

Table 1 presents the microgrid parameters that include the power of each distributed energy source and load, the maximum power allowed by the grid and the maximum/maximum state of charge for the storage system and EVs.

A detailed description of the system components is shown below:

2.1. Photovoltaic System (PV)

In the approach proposed by this paper, to make the most of renewable energies, the photovoltaic energy must be used as a priority to supply the load. The PV system includes a PV array, DC-AC converter and a control system contains (an MPPT regulator, a VDC voltage and current regulator, PLL (Phase locked Loop), and a PWM generator. The MPPT controls are directly implemented for the inverters [14].

PV production follows the variation of solar insolation during the day and reaches its maximum at midday.

2.2. Wind Turbine Power (WT)

In this paper wind energy is used as a second priority in the supply.

A variable speed wind turbine connected to the grid (PMSG) is used. The three-phase output of the generator is rectified using a diode rectifier and the voltage level is increased using a DC-DC step-up converter.

The MPPT (Maximum Power Point Tracking) controller is used to ensure the extraction of the maximum power [15], [16]. The energy recoverable by a wind turbine (WT) is proportional to the area covered by its rotor and to the cube of the wind speed. The maximum power delivered by the wind turbine is given by the equation (1).

$$P_{\max} = K.\rho.\mathrm{S}.\mathrm{V}^3 \tag{1}$$

Where: K is a constant, P_{max} is the power in (KW), S is the area covered by the blades in (m^2) and V is the wind speed in meters per second (m/s) [17].

2.3. Battery Energy Storage System (BESS)

The BESS plays a crucial role in the operation of micro-grids. Their main function is to facilitate the integration of renewable energies of an intermittent nature [18], [19].

The Storage system is connected to the grid via an electronic power interface where energy can be injected or extracted directly from the grid [5].

The charging and discharging of the BESS depend on the operating strategy of the hybrid system. The BESS will be charged when the electricity price is low and when production exceeds consumption. On the other hand, if the load demand is higher than the available production, the BESS will discharge to cover the deficit [20], [21].

The battery state of charge is described in equation (2).

$$SOC(t) = \frac{C(t)}{C_{ref}(t)} \tag{2}$$

$C_{ref}(t)$: Reference capacity.

$C(t)$: Battery capacity at all times.

The battery also operates in these two modes according to the energy constraints which are determined by [12], The battery must not be overcharged or over discharged, and the SOC limits of the battery can be specified as shown in the following constraint: [22], [23].

$$SOC_{Bmin}(t) \leq SOC_B(t) \leq SOC_{Bmax}(t) \tag{3}$$

SOC_{Bmax} and SOC_{Bmin} are the maximum and minimum state of charge respectively, to extend the battery's life [24].

The state of charge is calculated by considering the variation in the amount of charge in the process [20].

2.4 Electrical Vehicle (EV)

The development of electric vehicles has brought a new challenge to the smart grid. The development of the V2G system makes it possible to manage the EV " park " as a consumer or as an energy source of a distributed storage system. Electric vehicles are charged when the electricity price is low (i.e. during off-peak hours) or by excess energy from renewable sources, and inject part of their power at peak times.

In this paper, an EV model using a bidirectional infrastructure has been used. The charging station is composed of a bi-directional DC/AC converter with a control system, and a data processing unit. The distribution transformer is connected between the micro-grid and the power grid [23]-[26].

The station receives 8 EVs during the day according to different vehicle user profiles as shows in Figure 2.

The battery in each vehicle has an energy capacity of 60 kWh and a charge rate that is expected to be in the range of 20-100 %. This is an off-line study with known parameters.

This work takes into account charging EVs at the time of arrival at home or the workplace using excess renewable resources at a price below the average grid electricity price.

EVs can participate in power generation during peak grid hours, and it depends on the SOC of each EV and the vehicles that allow access at the time of fluctuation [27], [28].

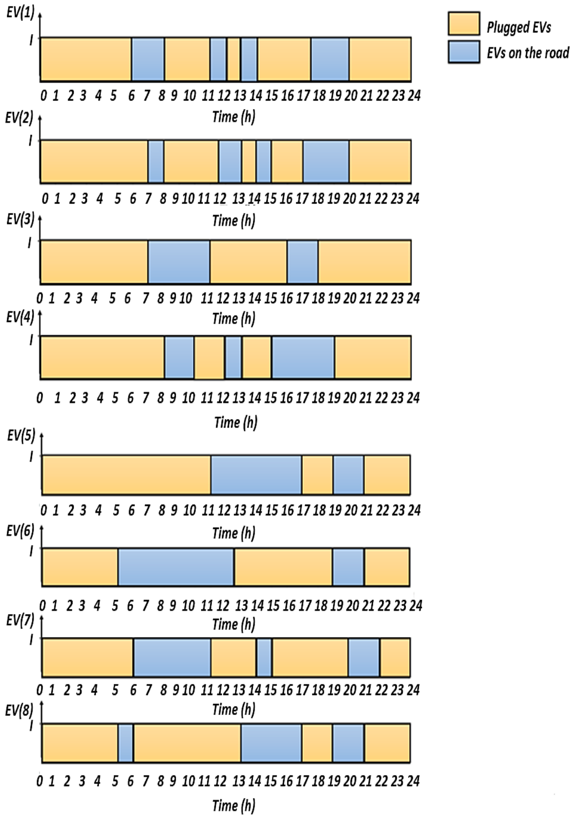

Figure 2. Electric vehicles profiles

Figure 2 shows the random distribution of EV user profiles during the day according to their lifestyle and the state of charge (SOC) of each vehicle.

Where the parked vehicles perform 2 operations either charging or injecting power, while the others are on the road.

The EV parameters, arrival time (when the EV is available to be charged), and departure time (when the consumer must use the EV) are known and shown in Figure 2 [29].

Electric vehicles data are given as a function of the variation of the state of charge SOC of each charging profile [5]. The state of charge SOC(t) is estimated by the previous value SOC(t-1) and the rejected /absorbed power.

The SOC at time t can be calculated by the equation (4):

$$SOC_B(\mathrm{t}) = SOC_B(\mathrm{t}-1) + \frac{P_{pv}(t)+P_{wt}(t)+P_{Grid}(t)-P_L(t)}{100}\Delta T \quad (4)$$

Where : $SOC_B(t)$ is the battery state of charge, P_L is the load power, P_{Grid} is the power delivered by the grid, P_{PV} is the photovoltaic power, P_{wt} is the power of the wind turbine , Δt is a unit time interval: Δt = 1 (1 hour).

2.5 Dynamic AC load

For simplicity, an AC dynamic load model is used, the load data used in this paper is based on the daily load curve. The load profile represents a community that contains homes and small industrial sites with a maximum power of 400 KW.

Also, many factors affect the load, such as time, weather, and economics.

3. Proposed Rules-Based Energy Management System (RB-EMS)

The Energy Management System (EMS) is used to optimally schedule energy resources, storage systems and EV in Microgrids to satisfy demand [20], [22], [30].

The algorithm is developed in the form of the if-then-else", responsible for implementing a real-time decision-making strategy. These modes execute the flow of energy between the different components of the system, i.e. the purchase and sale of energy.

The EMS in a microgrid is shown in the Figure 3.

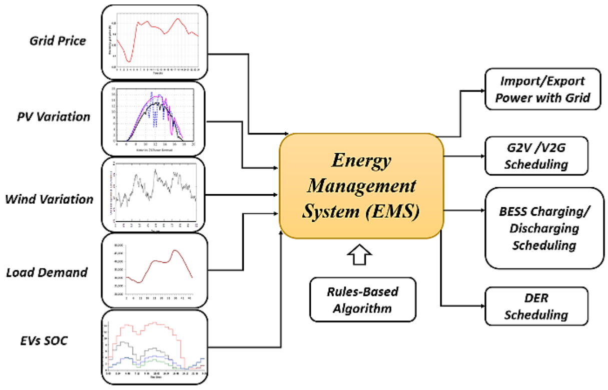

Figure 3. The proposed Rule-Based EMS

The energy management system receives forecasted load demand values, distributed energy resources (PV and WT) (irradiation, wind speed), the storage system state of charge (SOC) and data from EVs connected to the charging stations and their SOCs as well as the market price of electricity at each hour of the day to impose the programmed output power of the DERs, the import/export power with the main grid, power import/export time of EVs and the EVs that participate in the power generations and the others that are programmed to be charged (Figure 3) [20].

In this sub-section, a "constraints" management strategy is proposed on the basis of a pre-defined rule.

The system operation is determined according to PV power, WT, the storage system state of charge and load demand. This management method takes into account predefined rules.

The Rule-based energy management is based on the following main rules:

- Photovoltaic and wind energy are mainly used to supply the loads.
- The BESS is charged by the grid or surplus power from renewable energy when the price of electricity is low (when the production is higher than the loads).
- The BESS discharges when the PV system and WTs are not sufficient and the grid electricity price is high.
- EVs charge in times when the grid electricity price is low and by the excess of PV and WT energy.
- EVs inject a part of their power (V2G) when a consumption peak occurs or when there is a fluctuation in the renewable generation.
- The grid feeds load when PV, WT and BESS systems are not sufficient.

– When the BESS is charged and production is greater than consumption, excess renewable energy will be sent directly to the grid.

The constraints applied to the optimization system are described below:

The energy flow in the micro-grid system must always remain balanced as shown in the equation (5).

$$P_L(t) = P_{pv}(t) + P_{wt}(t) + P_{BAT}(t) + P_{Grid}(t) + P_{EV}(t) \quad (5)$$

The power surplus and deficit can be expressed as follows in equations (6) and (7).

$$P_{EX}(t) = [P_{pv}(t) + P_{wt}(t)] - P_L(t) \quad (6)$$

$$P_{Def}(t) = P_L(t) - [P_{pv}(t) + P_{wt}(t)] \quad (7)$$

$$P_{Grid}(\mathrm{t}) \leq P_{Grid\max} \quad (8)$$

Where : P_L is the load power, P_{BAT} is the battery power, P_{Grid} is the power delivered by the grid, P_{PV} is the photovoltaic power, P_{wt} is the wind turbine power, P_{EV} is the EV power, P_{EX} is the excess power and P_{Def} is the deficit power.

The load must always be supplied by solar, wind, grid or storage system or by EVs (V2G). Positive sign of P_{Grid} for the purchase of electricity from the grid, negative for the sale of electricity to the grid.

P_{BAT} and P_{EV} are negative for discharge and injection respectively, and positive for charging.

The start and end SOC of the battery are not identical.

– Battery state of charge constraint:

The SOC of the battery is limited within a pre-defined limit as shown in the following constraint:

$$SOC_{B\min}(t) \leq SOC_B(t) \leq SOC_{B\max}(t) \quad (9)$$

The state of charge of each EV is limited within a predefined limit as shown in the following constraint:

$$SOC_{EV\min}(t) \leq SOC_B(t) \leq SOC_{EV\max}(t) \quad (10)$$

Constraints (9) and (10) mean that the batteries of the storage system and EVs must not be charged or discharged when the SOC is out of limits.

Figure 4 depicts the RBA algorithm's flow in detail:

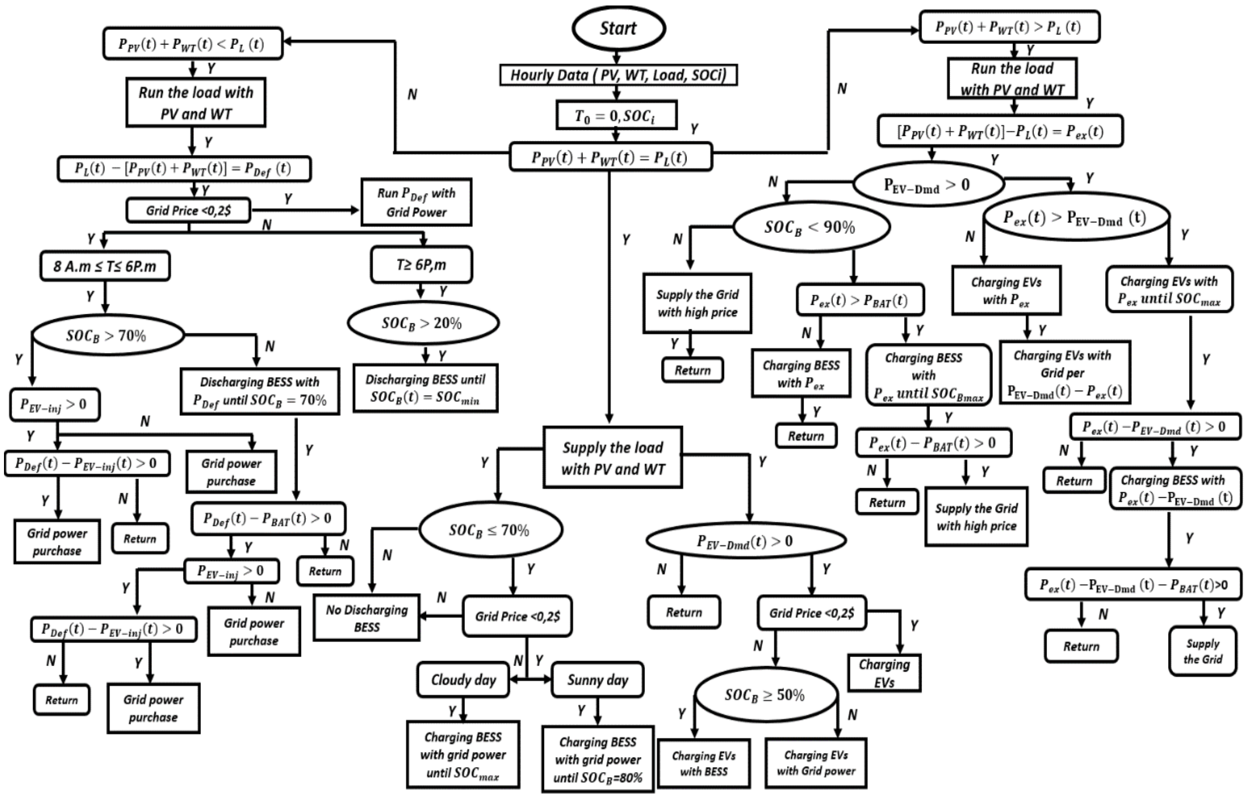

Figure 4. Proposed Rule-based algorithm flowchart

The hybrid system operating strategy is illustrated in Figure 4 and is described as follows:

$$P_{pv}(t) + P_{wt}(t) = P_L(t)$$

In the first case, photovoltaic and wind power are used to satisfy the load. And;

– If $P_{EV-Dmd} > 0$

The EMS ensures EV charging by the storage system when the $SOC_B(\mathrm{t}) \geq 50\ \%$ or by the grid when the price is low. And:

– if the $SOC_B(\mathrm{t}) \leq 70\ \%$ and the electricity price is low, the EMS schedules the charging of the batteries by the grid according to the weather conditions.

$$P_{pv}(t) + P_{wt}(t) > P_L(t)$$

When the production is higher than the consumption, the entire load is supplied by renewable energies (PV and WT).

The management of the surplus given by equation (6) is as follows:

- If $P_{EV-Dmd} > 0$ and $P_{ex}(t) > P_{EV-Dmd}$, The EMS decides to charge all of the EVs, and the remaining surplus is used to directly charge the BESS; if $P_{ex}(t)$ is still positive, the electricity is sold directly to the grid.
- If $P_{ex}(t) < P_{EV-Dmd}$, The surplus and the grid are used to charge the electric vehicles. If the EVs do not require any power and $SOC_B <$ 90 % and;

$P_{ex}(t) > P_{BAT}$(t) the batteries will be charged up to $SOC_{B\max}$ otherwise by the $P_{ex}(t)$ power.

- If $SOC_B > 90$ % and the electricity price is high the excess will be sold directly to the grid.

$P_{pv}(t) + P_{wt}(t) < P_L(t)$

Deficit management in this case given by equation (7) takes into account the time and the electricity price.

When the electricity price is high then:

- if (8a.m<T<6p.m) and $SOC_B(t) > 70$ % and some EVs can inject part of their power then the deficit will be fed by the EVs and the rest is covered by the grid.
- if (8a.m<T<6p.m) and $SOC_B < 70$ % the deficit will be fed in priority by the BESS, VE and the grid as the last solution.

During the evening (T>6.pm), if the $SOC_B > 20$ % the storage system covers the demand.

If the electricity price is low, the grid makes up the deficit.

4. Results and Discussion

The simulation is performed on MATLAB/Simulink to evaluate the efficacy of the proposed control system of a microgrid in connected mode integrating renewable energy sources photovoltaic, wind turbines, battery storage systems, electric vehicles and the main grid. To obtain accurate results for each scenario, simulations were performed in discrete mode.

The simulation takes into account typical residential tariffs for grid electricity as seen in Figure 5.

The price of the selling and buying energy is considered equal.

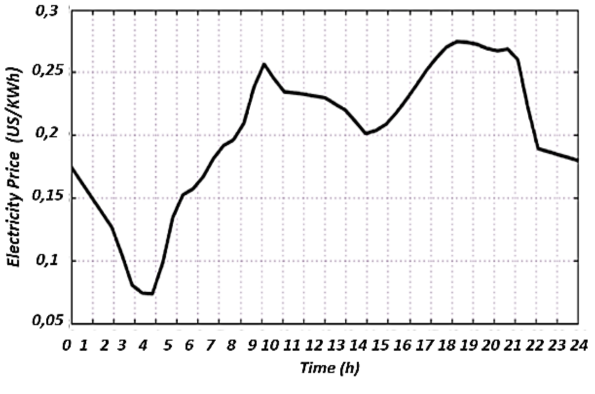

Figure 5. Electricity Price curve [20]

Figure 5 presents the electricity grid price for one day.

It can be seen that the price varies throughout the day in the form of peaks and valleys.

During the peak periods (afternoon and early evening, i.e. from (5 pm to 9:30 pm) and at (9 pm) when electricity consumption is above average, the output of power plants must be increased to meet demand, and operators need more production capacity, including expensive peaking plants. This leads to higher prices.

During the off-peak period, when demand is low from (1 am to 7 am) and (10 pm to midnight) the price decreases, in this case consumers can take advantage of low tariffs.

At the same time, in periods of high demand (midday and evening), the selling price of electricity is high, allowing consumers to sell part of their power to limit the use of the grid.

This study takes into account the fluctuation in the price of electricity given by the Figure 5 to allow the EMS to optimize the power sharing in the Microgrid at low-cost.

Different scenarios are implemented to see the behaviour of the energy management system (EMS) in power-sharing between different sources in all operating modes (electricity price, BESS SOC, load, charging and injection times of the electric vehicle).

The simulation was carried out for 24 hours to test the different operating modes.

The operation of the system is divided into two main scenarios:

Mode 1 - The BESS is disconnected from the Microgrid and the V2G technology is disabled.

Mode 2 - Normal operation: two scenarios are executed for a sunny day:

- **Scenario-1**: The initial SOC of the BESS SOCi = 20 %.
- **Scenario-2**: The initial SOC of the BESS SOCi = 95 %.

In the second modes, EVs staying in the parking lot have the option of selling their battery power to the grid based on the behaviours of each consumer and the SOC of each connected EV.

Note that the V2G is only activated during:

- The peak hours of the grid;
- The electricity price bought from the grid is high;
- The fluctuation of renewable production.

In all scenarios, the photovoltaic system follows a normal distribution during the day which depends on the insolation and reaches its maximum power at midday as shown in the Figures 6, 7 and 9.

The wind production follows a random variation that depends on the wind speed which presents peaks and valleys during the day.

The daily load curve shows a residential community with a maximum power output of 400 kW, the load profile varies throughout the day and shows periods of high demand in the evening and morning and lows during the night.

The simulation result is shown in following figures.

Mode 1:

The BESS is disconnected from the Microgrid and the V2G technology is disabled.

The variation of the active power of PV-WT-Grid for one day is shown in Figure 6.

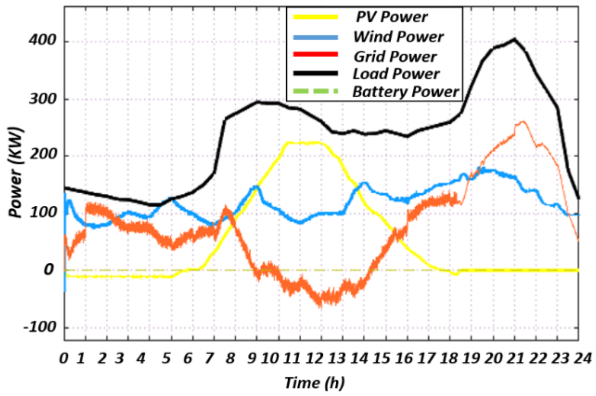

Figure 6. Power variation in load, PV, grid and wind power during a day

In **Mode 1** when the Microgrid operates without BESS and V2G (Figure 6), At the beginning of the day, when the energy price is low (7 am), demand loads are supplied by the main grid and wind turbines as shown in Figure 5. Then the PV system starts to produce energy to satisfy the demand at the same time the power produced by the grid decreases. From (10 am to 2:30 pm) the (PV and WT) feeds the entire load and the excess power will be sold directly to the grid at a high price to also gain economic benefits.

From (2:30 pm to 6 pm) when production PV starts to decrease, the grid provides power in collaboration with the WT.

During the evening from (6 pm to midnight), the energy demand reaches its maximum value at (8 pm to 9 pm), the wind turbines feed the load and all the energy is purchased from the grid to cover the power demand which results in very high purchase costs.

In this scenario, the EVs are programmed to be charged at the beginning and end of the day when the electricity price is low, to this effect the energy is purchased from the grid at a low price to meet the demand of the EVs.

The implemented management system suggests to parked customers to recharge their EVs with excess energy when production exceeds consumption from (9 am to 10 am) and (midday to 7 pm). At a time of high demand, charging EVs during the day results in slightly higher costs when the consumer is obliged to charge his vehicle at that time. We can see that the grid assumes all of the power demanded by the load at the begin and end of the day, which raises the cost and decreases the optimal management solution. Figure 6 shows that the grid is stopped for 4 hours per day and the maximum power called by the grid reaches 250 KW.

In this mode of operation, the absence of storage means (stationary (BESS) and mobile (V2G)) results in additional energy costs and makes the system less economical outside of renewable production periods when the entire demand is purchased from the grid.

Mode 2- Normal operation.

During normal operation, (Mode 2) i.e. when the load profile follows the daily consumption, the following figures show the results for different SOC values. In this section the battery storage system (BESS) and V2G technology are implemented.

– **Scenario-1**: The initial SOC of the BESS SOCi = 20 %.

The variation of the active power of PV-WT-BESS-Grid for one day is shown in Figure 7.

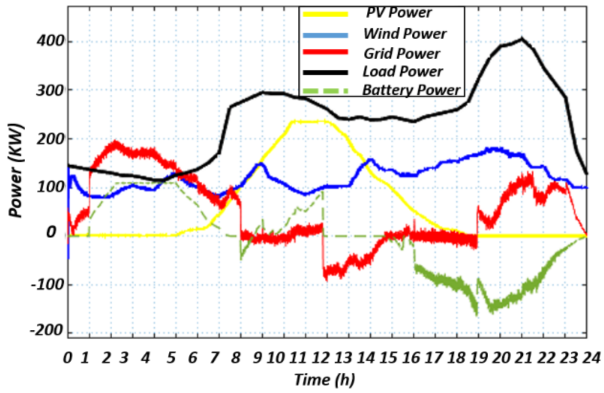

Figure 7. Power variation in load, PV, grid, wind and BESS power during a day in scenario-1

At the beginning of the day, the grid and WTs cooperate to ensure the demand and cover the battery charging before sunrise at a SOC of 80 % when the SOCi is below 70 % to take advantage of the low energy cost at that time as shown in Figures 7.

At (8a.m) the production exceeds the consumption, the demand is supplied by the PV and WT systems until (4 pm) and the excess power coming from the renewable energy is used in priority, in this case the surplus is used to increase the BESS SOC up to its final SOCf limit from (9a.m to midday) at a low cost, the rest of the surplus will be destined to the recharging of the EVs presented in the stations as a second priority at (9:30 am) and (3 pm) as shown in Figure 8 and at the end as a last step the additional energy will be sent directly to the grid from (midday to 2:30 pm).

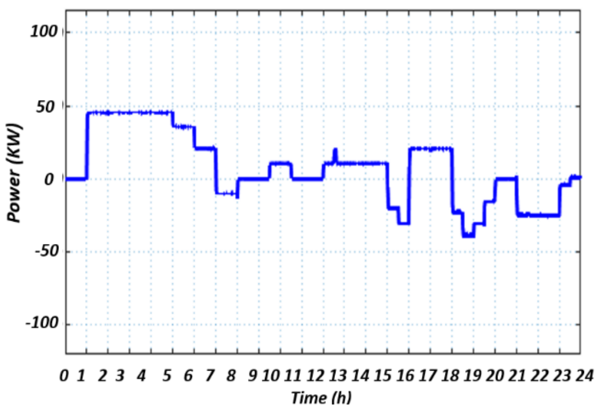

Figure 8. Charging and V2G operations in scenario-1

From 2:30 pm to 6 pm, the demand is higher than the consumption, the BESS starts discharging to make up the power deficit. at the end of the day, after sunset, the BESS and the WT feed the load to its final SOC limit to reduce the load on the grid, which brings a considerable economic gain. We can see that the grid stops operating for 11 hours per day from 8 am to 7 pm, estimated using the rule-based method and the power supplied by the grid decreases to a value of 190 KW compared to the previous example. This results in improved operating conditions and a simultaneous reduction in fuel costs, purchase of electricity from the grid, and CO_2 emissions. The active power variation of the EV station for one day is shown in Figure 8. Figure 8 presents the total charging and injection power of the vehicles parked during the day.

It can be seen that the parked EVs at (7 am to 8 am) at the time of the start-up of industrial sites which present peaks and from (3 pm to 4 pm) contribute to the injection of power for selling to the grid at high prices, and in the evening when people enter their homes to reduce the peak at that time. It can also be seen in Figure 8 that electricity is purchased from the grid at the beginning of the day to charge the electric vehicle from 1:00 am to 7:00 am and by excess renewables in the middle of the day (from 9:00 am to noon) to take advantage of the low price at that time.

This curve demonstrates the role of EVs thanks to V2G technology in smoothing the load curve and removing peaks.

– **Scenario 2:** The initial SOC of the BESS SOCi = 95 %.

The active power variation of the PV-WT-BESS-Grid for one day is shown in Figure 9.

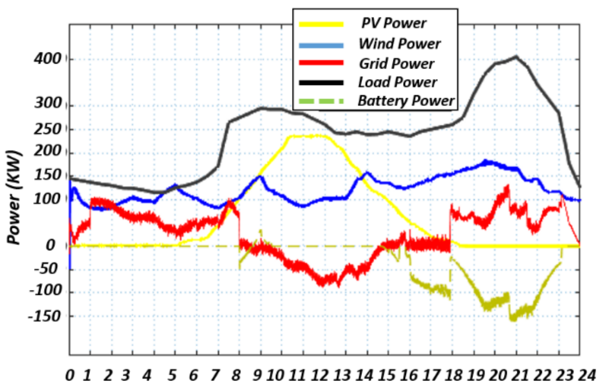

Figure 9. Power variation in load, PV, grid, wind and BESS power during a day in scenario-2

When the BESS is fully charged as seen in the Figure 9 (i.e., initially charged), The beginning of the day is reserved for charging the EVs and feeding the load.

When renewable production equals consumption between 6 am and 9:30 am, no electricity is called by the grid, and renewable sources meet demand; when renewable production exceeds consumption between 9:30 am and 2:30 pm, the surplus of energy is sent directly to the grid at a high price.

From 4:00 pm to 7:00 pm, the BESS begins to discharge in order to provide some of its power to meet the load demand in cooperation with the EVs and WTs and avoid buying energy from the grid at a very high price as shown in Figure 5. At the end of the day, when consumers return home, the BESS provides load up to its final SOC limit in cooperation with the WTs to minimize the amount of energy provided by the grid (peak shaving) which brings a considerable economic gain. At 10 pm, when the price drops, demand is met by the WTs and the grid.

Figure 9 shows that the grid is stopped for 10 hours per day and the maximum power called by the grid reaches 110 KW.The variation of the active power of EV station for one day is shown in Figure 10.

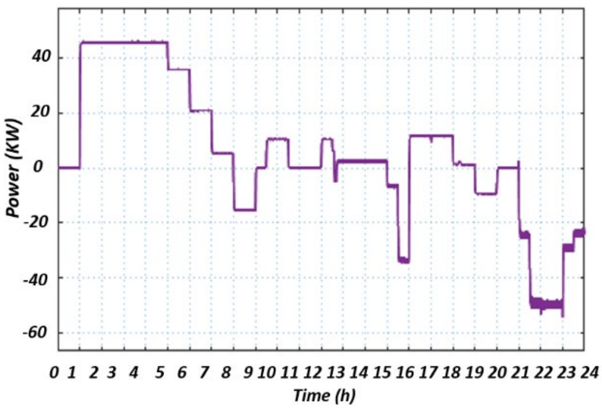

Figure 10. Charging and V2G operations in scenario-2

Figure 10 describes the total charging and injection power of the vehicles parked during the day.

In this scenario, the vehicles stationed from (8 am to 9 am), (3 pm to 4 pm), (7 pm to 8 pm) and at the end of the day allow part of their power to participate in the generation of energy at intermittent and peak times in order to avoid the peak load on the grid (Figures 10).

From (9 pm to 11 pm) the majority of the vehicles participate in the reduction of the peak with a large part of their power. The management system allows charging the electric vehicles parked at the beginning of the day (1 am to 7 am) when the energy price is low and in priority by the excess power when the renewable energy production is higher than the consumption from (9 am and midday) as described in Figure 10.

It can be seen that after the integration of the storage systems (BESS and V2G), the EMS optimizes power sharing between the different energy sources and load in a cost-efficient manner, and this reduces the purchase of energy from the grid (peak shaving), and energy expenses at peak times and it can also be seen that the EMS with these storage systems reduces unexpected energy fluctuations due to variations in weather conditions. The results obtained in the different scenarios demonstrated that using the RB approach to assess energy management for a connected microgrid produces the best results. Furthermore, among the RB process scenarios, scenario 2 (SOC=95%) produces the best results.

5. Conclusions

In this paper, our attention has been focused on an energy management system (EMS) applied to a grid connected microgrid that includes a PV system, a wind farm, a battery storage system and EVs with V2G technology and variable loads. A rule-based technique has been developed to find the optimal configuration of energy sources taking into account forecasts for renewable resources in order to minimize operating costs, dependence on the grid and maximize the use of renewable energy and the exchange of electricity with the grid. The simulation results demonstrated the capacity of the systems involved in power generation during fluctuating periods according to the needs of the power system and provide a more flexible and efficient service. Also, the energy exchange mechanism between the load and a different sources demonstrates the performance offered by smart grids in optimizing energy management and reducing consumption costs, maximizing energy exchanges with the main grid and optimizing the use of green resources.

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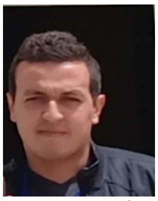

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