Marouane Lagouir[1,*], Abdelmajid Badri[1], Yassine Sayouti[1]

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Development of an Intelligent Energy Management System with Economic Dispatch of a Standalone Microgrid

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Microgrid concept has been widely used for grid connected distributed energy resources. That can operate either connected or disconnected from the main grid during grid failures. Such integration presents new challenges to microgird operations. Therefore, an energy management system is an essential factor for optimal energy scheduling of these distributed energy resources. This paper presents a new control approach for optimal energy management and economic dispatch of a standalone microgrid. Typical results are presented with initial state of charge, load profile and meteorological conditions as variables parameters, and the performance of the proposed system is evaluated in three case studies considering power balancing, maximizing the utilization of renewable energy, monitoring the battery state of charge, fuel cost optimization, real time information exchanges and satisfying the system objective constraints.

Keywords: Microgrid; distributed energy resources; energy management system; ecocnomic dispatch; fuel cost optimization; real time information exchanges; objectives constraints.

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1. Introduction

The need for more flexibility in the electric power system, the intermittent generation of renewable energy sources, with a growing energy consumption and the environmental issues, especially the global warming from excessive energy dependency on fossil resources are the main reasons for the emergence of Microgrid (MG) concept, which is predicted to play a promising power scenario for the electric power system of the near future [1]. The concept of MG is demonstrated as a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries, which act as a single controllable entity with respect to the grid [2]. A MG can operate in both grid-connected mode and islanded mode.

However, the rapidly increasing trend of MG integration into the existing electricity grid presents some technical and economic challenges. An energy management system (EMS) is the key factor in ensuring an efficient, reliable, and secure decisions for the MG operations.

Significant research has been conducted in the areas of MG technologies and operation. The studies of Wang [3,4] propose an energy management modelling based on interpreted Petri Nets (PN) for a multi-source power generation into a grid connected PV array with an energy storage system. In [5-8] the design and simulation of a fuzzy logic energy management system has been proposed, since the fuzzy logic approach is suitable for complex nonlinear system and it is a promising solution for its robustness and good real-time performance. In [9], the authors have discussed two power management strategies Petri Nets and Fuzzy logic approaches and compared their performance. The studied MG

[*] Corresponding author: M. Lagouir, Faculty of Science and Technology, E-mail: lagouir.mar1@gmail.com
[1] Department of Electrical Engineering, EEA&TI Laboratory, Faculty of Science and Technology –FSTM–, Hassan II University of Casablanca, BP 146 Mohammedia 20650, Morocco

includes wind and photovoltaic units associated with an energy storage system and connected to the grid through a Point of Common Coupling (PCC). The results have shown that the use of fuzzy logic approach for energy management has technical and economic advantages considering system objectives constraints, power penalty cost when the battery SoC is less than 20% and the total cost energy of exchanging the power with the main grid.

Marzband et al. [10] proposed an optimal energy management system for islanded microgrids based on a multi-period artificial bee colony (MABC) algorithm and an artificial neural network combined with a Markov chain (ANN-MC) approach to predict non-dispatchable power generation and load demand, while taking uncertainties into account. In [11], Riffonneau et al. propose a predictive control system based on a dynamic programming (DP) approach, that optimizes the power flow management into a grid connected PV system with storage and the performance is compared with a simple ruled-based management system. Nemati et al. propose in [12] two improved methods to schedule the unit commitment (U.C) and economic dispatch (E.D) of microgrids units. The functionality of the developed real-coded genetic algorithm (G.A) and the enhanced mixed integer linear programming (MILP) based method have been evaluated and compared based on cost-benefit under different operation policies, such as connected and islanded operations, cost-optimized, emission-optimized and combined modes.

An overview of MG energy management and control is done in [13-16]. Other studies like [17-18] propose Multi-Agent based control structures for microgrid power management.

The purpose of this work is to design, and implement a multi-layer control structure to schedule the power delivery of a hybrid ac/dc microgrid (HMG). Each layer with a different function and they collaborate to ensure more flexible energy management control. The proposed system handles together power balancing, energetic cost optimization, renewable energy sources constrained production and intermittency, load shedding option, supply limitation of conventional energy sources and real time information exchanges within the HMG.

The paper is organized as follows. The global system overview is shown in Section 2. Section 3 details the problem formulation. Section 4 describes the proposed energy management approach. In Section 5, the simulation results are presented and discussed in details. Finally, Section 6 concludes this paper.

2. Global system overview

The HMG architecture under study in islanded mode is shown in figure 1. It is an agglomeration of power generation resources (PGRs), energy storage system (ESS) [19] and variable demands (VDs). All those units are connected to a control system dedicated to solve the problem of the energy management. The PGRs combine renewable energy sources (RESs) which are represented by photovoltaics panels (PVs) and wind turbine (WT), with conventional energy sources (CESs) consisting of a diesel generator (DG), a fuel cell (FC), and a microturbine (MT). Moreover, because of the random nature of RESs a support energy source is required to improve the controllability and operability of the HMG. Traditionally, this function is performed by an ESS [20] and mainly refers to batteries. The mathematical modelling of the consisting components is described in the following subsections.

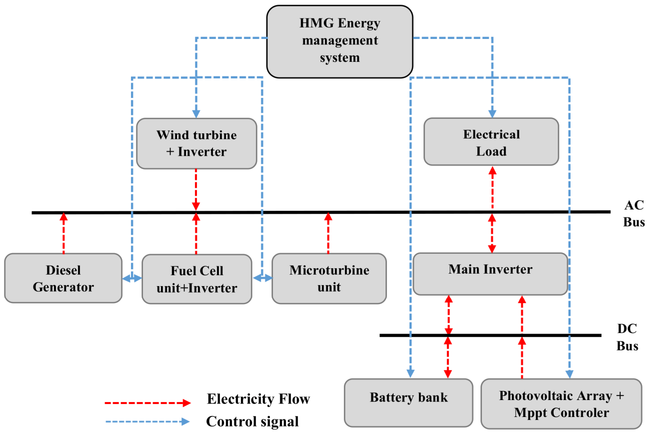

Figure 1. Hybrid AC/DC microgrid architecture

2.1. Power generation resources

a) Solar energy system

Assuming that the PV panel is equipped with an MPPT controller, the power output is expressed as a function of irradiance and temperature using the following formula [21,22]:

$$P_{PV} = F_{PV} \times P_{PV,R} \times \frac{G}{G_{STC}} \left[1 + \alpha_T \left(T - T_{STC} \right) \right] \tag{1}$$

Where F_{PV} is the factor reflecting shading, and wiring losses. α_T represent the temperature coefficient, G_{STC} and T_{STC} are the solar irradiation and the PV cell temperature under standard test conditions, respectively. Finally G and T are the solar irradiation and temperature, respectively.

b) Wind energy system

The power output of the WT unit can be approximated as follows (2) given as [1,21,23]:

$$\begin{cases} P_{WT} = 0 \;;\; V < V_{CI} \text{ or } V > V_{CO} \\ P_{WT} = P_{WT,R} \left(\dfrac{V^3 - V_{CI}^3}{V_R^3 - V_{CI}^3} \right) \;;\; V_{CI} < V < V_R \\ P_{WT} = P_{WT,R} \;;\; V_R < V < V_{CO} \end{cases} \tag{2}$$

Where $P_{WT}, P_{WT,R}, V_{CI}$ and V_{CO} are the produced power, rated power, cut-in and cut-out wind speed respectively. Furthermore, V_R and V are the rated and actual wind speed.

The real electrical power is given by:

$$P_{e,WT} = P_{WT} \times A_{Wind} \times eff_{Wind} \tag{3}$$

Where A_{Wind} is the total swept area and eff_{Wind} is the efficiency of the wind turbine generator.

c) Diesel generator cost

The fuel cost function of a DG system is approximated to be a quadratic function of the active power from the generator [1,22,24]:

$$C_1(P_{DG}(t)) = \alpha_{DG} + \beta_{DG} P_{DG}(t) + \gamma_{DG} P_{DG}^2(t) \tag{4}$$

Where $\alpha_{DG}, \beta_{DG}, \gamma_{DG}$ are cost coefficients of DGs, P_{DG} is the power generation of the DGs and C_1 is the total fuel cost of DGs .

d) Fuel cell cost

Similarly, with the DG system. The economic model of FC is also denoted by a quadratic polynomial with regard to its power output [12,22]:

$$C_2(P_{FC}(t)) = \alpha_{FC} + \beta_{FC} P_{FC}(t) + \gamma_{FC} P_{FC}^2(t) \tag{5}$$

Where $\alpha_{FC}, \beta_{FC}, \gamma_{FC}$ are cost coefficients of FCs, P_{FC} is the power generation of the FCs and C_2 is the fuel cost of FCs.

e) Microturbine cost

Many researches used second-order polynomial functions to express the fuel cost function of a MT unit [22]:

$$C_3(P_{MT}(t)) = \alpha_{MT} + \beta_{MT} P_{MT}(t) + \gamma_{MT} P_{MT}^2(t) \tag{6}$$

Where $\alpha_{MT}, \beta_{MT}, \gamma_{MT}$ are cost coefficients of MTs, P_{MT} is the power generation of the MTs and C_3 is the fuel cost of MTs.

The cost coefficients of CESs have been used in this study are provided in Table 1 as specified in [22].

Table 1. Cost coefficients of conventional energy sources

i[th] generator	Cost coefficients of conventional energy sources		
	α_i (\$/h)	β_i (\$/kwh)	γ_i (\$/(kw)^{2}h)
DG	0.4333	0.2333	0.0074
FC	3	0.1	0.0003
MT	5	0.3	0.0004

2.2. Energy Storage System

For MG system, bank of lead-acid battery is commonly used. It is employed as a backup to store the excess of power when the supply from RESs exceeds load demand. On the other hand, battery will provide energy to the system when the supply from RESs cannot meet the load demand. The State of Charge (SoC) for battery is considered as one of the important parameter to be controlled. To express the variation of the battery SoC the following formula is used:

$$SoC_t = SoC_0 + \frac{1}{Q}\int_{t_0}^{t_f} i\,dt \tag{7}$$

Where $\int idt$ and Q are the battery bank instantaneous and maximal capacity in Ah respectively.

To maintain a longer life time for battery, monitoring its SoC is essential to prevent it from any overcharging or undercharging. The associated inequality constraint is given as follow [21,24]:

$$SoC_{Min} \le SoC_t \le SoC_{Max} \tag{8}$$

3. Problem statement

In the proposed HMG the three dispatchable sources represented by DG, FC and MT are used as a backup to supply the system when the load demand exceeds each of RESs and battery power supply limitation. The problem is about minimizing the fuel cost of those generating units for a specific period of operation with the aim of satisfying the system load demand and the power system operational constraints to be maintained [25].

Therefore, a new energy management system (EMS) is developed. This optimization approach is designed in multi-layer structure combines a fuzzy logic system as the main controller with real-time cost optimization layer dedicated to minimize the total cost of the CESs in case of use.

3.1. Objective function

The main objective of the economic load dispatch (ELD) problem is about minimizing the fuel cost of CESs while meeting the mismatch between the total power supplied by RESs including the power generated by ESS (in case of discharging mode) and the total load demand including the ESS power needed (in case of charging mode).

Mathematically the problem is defined by equation (9) given as [25,26].

Minimize:

$$F_T = \sum_{i=1}^{n_g} (\alpha_i + \beta_i P_i + \gamma_i P_i^2) = \sum_{i=1}^{n_g} F_i(P_i) \tag{9}$$

Where $\alpha_i, \beta_i, \gamma_i$ are cost coefficients, P_i is real power generation, n_g is the number of CESs.

Neglecting transmission losses, total generation of CESs should meet the mismatch ΔP. Hence, the equality constraint is given by equation (10):

$$\Delta P = \sum_{i=1}^{n_g} P_i \tag{10}$$

This problem is solved using Lagrange multiplier [27,28], So the augmented function is given by:

$$L(P_i, \lambda) = F_T + \lambda \left(\Delta P - \sum_{i=1}^{n_g} P_i \right) \tag{11}$$

Where λ is the Lagrangian multiplier. The necessary conditions for the optimization problem are:

$$\frac{\partial L(P_i,\lambda)}{\partial P_i}=\frac{\partial}{\partial P_i}\left\{\sum_{i=1}^{n_g}F_i(P_i)+\lambda\left(\Delta P-\sum_{i=1}^{n_g}P_i\right)\right\}$$
$$\frac{\partial F_i(P_i)}{\partial P_i}-\lambda=0,(i=1,...n_g) \tag{12}$$

Furthermore,

$$\frac{\partial L(P_i,\lambda)}{\partial \lambda}=\Delta P-\sum_{i=1}^{n_g}P_i=0 \tag{13}$$

By arranging equation (12):

$$\frac{\partial F_i(P_i)}{\partial P_i}=\lambda,(i=1,...n_g) \tag{14}$$

Where, $\frac{\partial F_i(P_i)}{\partial P_i}$: Incremental cost of the ith generator (\$/KWh)

By deriving equation (9) with respect to Pi, the incremental cost can be obtained as:

$$\frac{\partial F_i(P_i)}{\partial P_i}=2\gamma_i P_i+\beta_i,(i=1,...n_g) \tag{15}$$

Rewriting (14)

$$2\gamma_i P_i+\beta_i=\lambda,(i=1,...n_g) \tag{16}$$

Or,

$$P_i=\frac{\lambda-\beta_i}{2\gamma_i},(i=1,...n_g) \tag{17}$$

Substituting P_i from above in (10),

$$\Delta P=\sum_{i=1}^{n_g}\frac{\lambda-\beta_i}{2\gamma_i},(i=1,...n_g) \tag{18}$$

Or,

$$\lambda=\frac{\Delta P+\sum_{i=1}^{n_g}\frac{\beta_i}{2\gamma_i}}{\sum_{i=1}^{n_g}\frac{1}{2\gamma_i}},(i=1,...n_g) \tag{19}$$

3.2. System constraints

To ensure steady operating system, the HMG's components are subjects to several constraints.

During the whole simulation time, the output power of all generating units including the ESS should be equal to the total of load demand. This power balance is given by:

$$P_D=P_{DG}+P_{FC}+P_{MT}+P_{ESS}+P_{PV}+P_{WT} \tag{20}$$

The inequality constraints of PGRs is specified as the following:

$$\begin{aligned} P_{DG_{\mathrm{Min}}} \leq P_{DG} \leq P_{DG_{\mathrm{Max}}} \\ P_{FC_{\mathrm{Min}}} \leq P_{FC} \leq P_{FC_{\mathrm{Max}}} \\ P_{MT_{\mathrm{Min}}} \leq P_{MT} \leq P_{MT_{\mathrm{Max}}} \\ 0 \leq P_{PV} \leq P_{PV_{Mppt}} \\ 0 \leq P_{WT} \leq P_{WT_{Mppt}} \\ P_{ESS_{\min}} \leq P_{ESS} \leq P_{ESS_{\max}} \end{aligned} \tag{21}$$

4. Energy management system

To increase the reliability of the energy management system, it is designed to operate in a two-level control structure as presented in figure 2. The highest level contains a fuzzy logic system (FLS) as the main controller, implemented in order to define the participation of each RESs, monitoring the battery SoC, load shedding option and the decision to switching on or off the CESs. In this strategy the CESs are dispatched only when the available power from the RESs and the battery are unable to meet the required demand. In each step, the FLS acquires current SoC data, RESs power generation and the load demand, then for each combination of inputs the FLS decides to activate or not the CESs, This FL control system has three inputs, the battery SoC, the last operating state of the battery (charging or discharging mode) and the net power, it has one output which represents a special situation of each combination of inputs. The operating modes of the FLS are summarized in Table 2. And Table 3 shows the FLS rule base.

As regards the lower layer is implemented to solve the ELD problem, due to the use of the CESs. Lambda iteration method is selected to take care of the ELD issue. This method is characterized by its simplicity of implementation, furthermore it converges rapidly [28] and allows real time resolution. The detailed algorithm of this solution is summarized in the flowchart of figure 3.

The multi-layer structure implemented provides more flexibility, each layer is designed to run independently and they collaborate to ensure an optimal energy management with cost minimization.

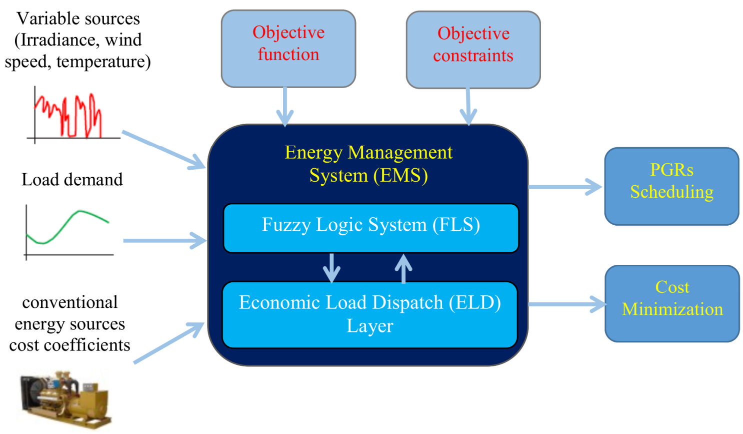

Figure 2. The EMS in the Hybrid microgrid

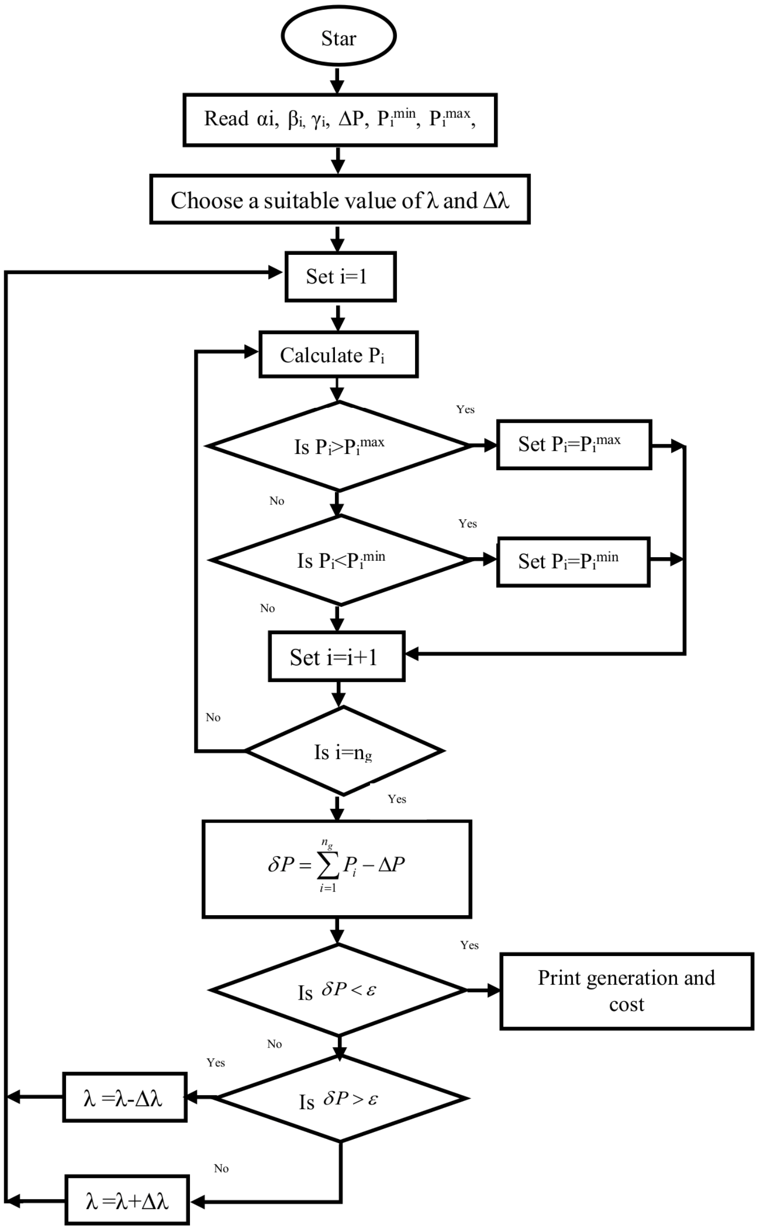

Figure 3. Flowchart of lambda iteration method for ELD

Table 2: Modes of fuzzy logic system operating conditions

Modes	Operating conditions
Mode1	The available power from the two RESs in Mppt mode exceeds the load demand. So, the system switch the RESs to the limited mode when their combined output power is sufficient to meet the required demand.
Mode2	The load demand is greater than the produced power from PV and WT, but the inclusion of the battery can overcome the problem. Therefore, the storage system has to supply the remaining loads.
Mode3	The combined output power of the RESs and the battery is less than the load demand. Thus, the CESs subscribe in the energy management to ensure power balancing in an optimization cost.
Mode4	The load demand exceeds each of RESs and CESs supply limitation, so to ensure system stability the load switch to the constrained mode where all power generation resources satisfy the power demand of the critical load.

Table 3: The rule base of the FLS

ΔP / SoC	NB		ZO		PB	
	Charging Mode	Discharging Mode	Charging Mode	Discharging Mode	Charging Mode	Discharging Mode
Low SoC	-CESs ON -RESs Mppt - P_{ESS} Ch - P_D Max	-CESs ON -RESs Mppt -Stop SoC $_{Min}$ - P_D Max	-CESs ON -RESs Mppt - P_{ESS} Ch - P_D Max	-CESs ON -RESs Mppt -Stop SoC $_{Min}$ - P_D Max	-CESs ON -RESs Mppt - P_{ESS} Ch - P_D Limit	-CESs ON -RESs Mppt -Stop SoC $_{Min}$ - P_D Limit
Medium Low	-CESs OFF -RESs Mppt -P_{ESS} Ch - P_D Max	-CESs OFF -RESs Limit - P_{ESS} Disc - P_D Max	-CESs ON -RESs Mppt - P_{ESS} Ch - P_D Max	-CESs ON -RESs Mppt - P_{ESS} Disc - P_D Max	-CESs ON -RESs Mppt -P_{ESS} Ch - P_D Limit	-CESs ON -RESs Mppt - P_{ESS} Disc - P_D Limit
Medium	-CESs OFF -RESs Mppt - P_{ESS} Ch - P_D Max	-CESs OFF -RESs Limit -PB Disc - P_D Max	-CESs ON -RESs Mppt - P_{ESS} Ch - P_D Max	-CESs ON -RESs Mppt - P_{ESS} Disc - P_D Max	-CESs ON -RESs Mppt - P_{ESS} Ch - P_D Limit	-CESs ON -RESs Mppt - P_{ESS} Disc - P_D Limit
Medium High	-CESs OFF -RESs Mppt - P_{ESS} Ch - P_D Max	-CESs OFF -RESs Limit - P_{ESS} Disc - P_D Max	-CESs ON -RESs Mppt - P_{ESS} Ch - P_D Max	-CESs ON -RESs Mppt - P_{ESS} Disc - P_D Max	-CESs ON -RESs Mppt - P_{ESS} Ch - P_D Limit	-CESs ON -RESs Mppt - P_{ESS} Disc - P_D Limit
High	-CESs OFF -RESs Limit -Stop SoC $_{Max}$ -P_D Max	-CESs OFF -RESs Limit -Stop SoC $_{Max}$ - P_D Max	-CESs ON -RESs Mppt -Stop SoC $_{Max}$ - P_D Max	-CESs ON -RESs Mppt - P_{ESS} Disc - P_D Max	-CESs ON -RESs Mppt -Stop SoC $_{Max}$ - P_D Limit	-CESs ON -RESs Mppt - P_{ESS} Disc - P_D Limit

5. Results and discussions

The application of the multi-layer EMS to the HMG under study is evaluated in this section. The EMS was evaluated with a time step of ΔT=15 min during 24h time interval and using MATLAB/Simulink environment. The purpose of this intelligent strategy is to ensure an optimal energy management with high penetration of RESs, real-time fuel cost minimization in case of using CESs and the previous constraints mentioned above to be taken into account. To validate the developed strategy three different scenarios are investigated for different load profile and initial SoC. The simulation results obtained is described hereafter:

5.1. Scenario 1 with SoCin=20%

Figure 4 shows the optimal output power from the RESs and the SoC variation during the 24h system operation, as it is observed the battery is initially discharged, therefore, the two RESs controls unites operate in Mppt Mode to meet power balance while keep charging the ESS. Once the battery reaches a maximum value the two RESs switch to the limited mode while their combined output power is sufficient to supply the required demand. During the phase where the demand exceeds the RESs and the battery power supply limitation, the EMS decides to start up the CESs. Figure 5, 6 and 7 show the optimal output power of DG, FC and MT respectively. From the figure 6, it can be seen that the best choice to reduce cost is to make use of FC unit. And Figure 8 describes a real time optimal cost due to the use of CESs.

5.2. Scenario 2 with SoCin=20%

For this case study, the demand slightly becomes greater than the combined output power of the RESs and the battery, but the inclusion of CESs can overcome the problem. As shown in figure 9 the two RESs control units almost operate in MPPT mode over the time. Figure 10, 11 and 12 show the optimal output power of DG, FC and MT respectively. It can be seen that the optimal combination of those CESs leads to cost optimization. Figure 13 describes a real time optimal cost of using CESs. And Figure 14 reveals the total system power balance.

5.3. Scenario 3 with SoCin=80%

For this case study, the load demand exceeds each of RESs and CESs supply limitation, so to ensure steady operating system the FLS switch the load to the constrained mode (load shedding option) where all power sources (RESs, CESs and battery in case of discharging) meet the power demand of the critical load (Figure 15, Figure 16, Figure 17 and Figure 18). As may be seen during (4h-6h) p.m and (17h30min-21h) a.m, respectively, a load shedding option is introduced, turning the non-critical load off while keep supplying the critical one as shown in figure 19. Table 4 summarizes the data obtained of each scenario.

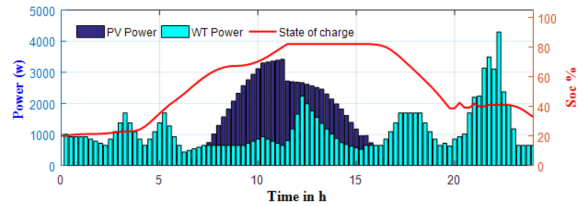

Figure 4. Optimal power RESs delivery in islanded mode under scheduling policy 1

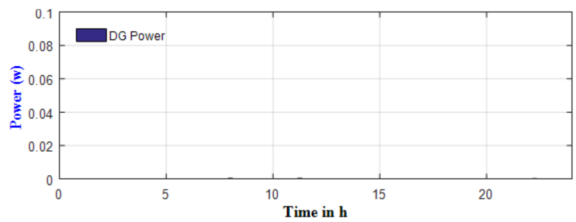

Figure 5. Optimal power product from Diesel Generator unit under scheduling policy 1

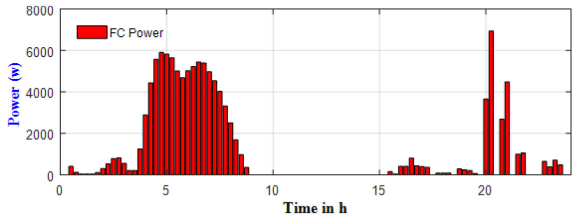

Figure 6. Optimal power product from Fuel Cell unit under scheduling policy 1

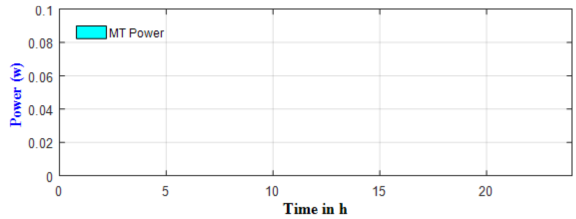

Figure 7. Optimal power product from Microturbine unit under scheduling policy 1

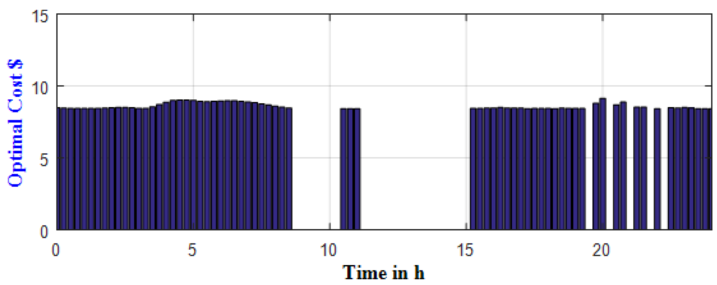

Figure 8. Optimal cost of using the CESs for each time interval under scheduling policy 1

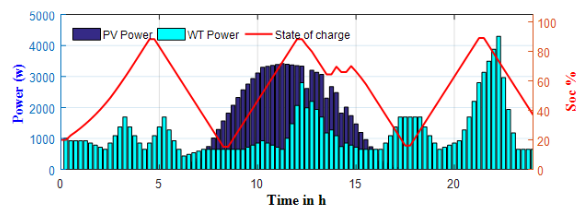

Figure 9. Optimal power RESs delivery in islanded mode under scheduling policy 2

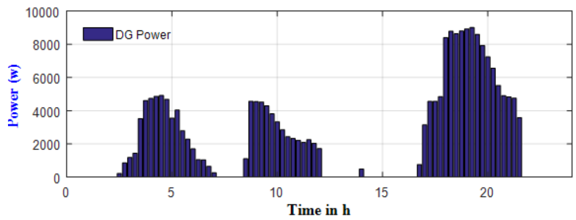

Figure 10. Optimal power product from Diesel Generator unit under scheduling policy 2

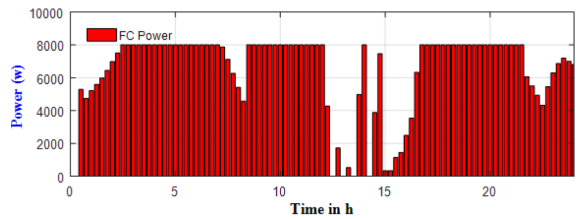

Figure 11. Optimal power product from Fuel Cell unit under scheduling policy 2

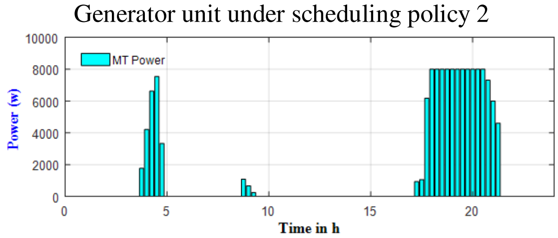

Figure 12. Optimal power product from Microturbine unit under scheduling policy 2

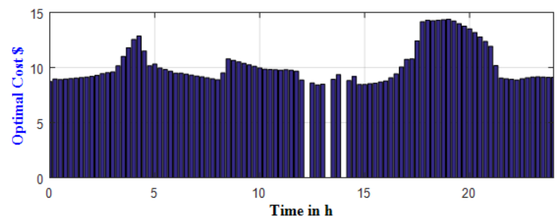

Figure 13. Optimal cost of using the CESs for each time interval under scheduling policy 2

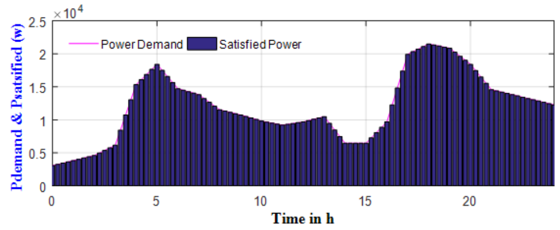

Figure 14. Total system power balance under scheduling policy 2

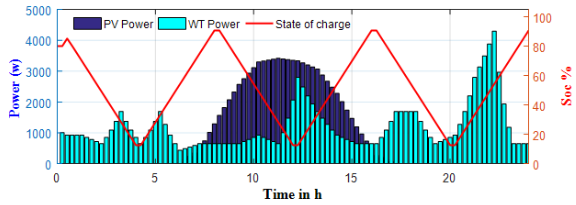

Figure 15. Optimal power RESs delivery in islanded mode under scheduling policy 3

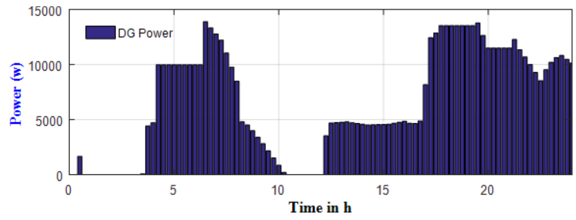

Figure 16. Optimal power product from Diesel Generator unit under scheduling policy 3

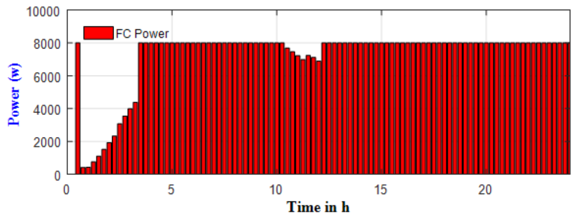

Figure 17. Optimal power product from Fuel Cell unit under scheduling policy 3

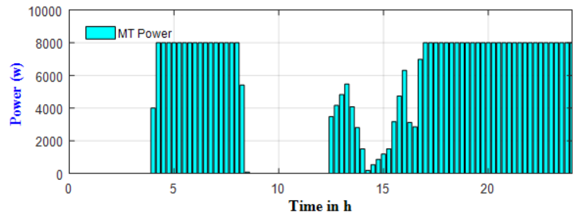

Figure 18. Optimal power product from Microturbine unit under scheduling policy 3

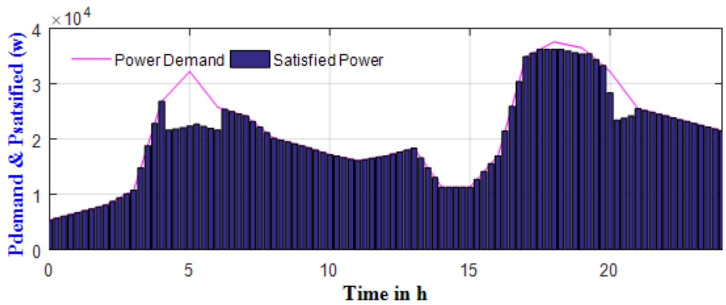

Figure 19. Total system power balance under scheduling policy 3

Table 4. Detail of daily simulation results for the three scenarios

		Total Generation Cost ($/day)	Total Power Generated by DG (kw)	Total Power Generated by FC (kw)	Total Power Generated by MT (kw)	Total Power Generated by RESs (kw)
Scenario 1	SoC_{in}= 20%	593.6270	0.0000	$1.1511\ 10^2$	0.0000	$1.8571\ 10^2$
	SoC_{in}= 80%	548.9348	0.0000	85.972	0.0000	$1.7976\ 10^2$
Scenario 2	SoC_{in}= 20%	958.7509	$2.1723\ 10^2$	$6.1791\ 10^2$	$1.3957\ 10^2$	$1.9865\ 10^2$
	SoC_{in}= 80%	982.7282	$2.4384\ 10^2$	$5.5826\ 10^2$	$1.6208\ 10^2$	$2.0023\ 10^2$
Scenario 3	SoC_{in}= 20%	$1.2139\ 10^3$	$5.7591\ 10^2$	$7.3000\ 10^2$	$4.6791\ 10^2$	$2.0131\ 10^2$
	SoC_{in}= 80%	$1.2176\ 10^3$	$6.3076\ 10^2$	$6.9005\ 10^2$	$4.2728\ 10^2$	$2.0131\ 10^2$

6. Conclusion

This paper has presented and evaluated a novel EMS for a standalone HMG, composed by PV panels and WT as RESs, battery as ESS, and DG, FC, MT as CESs. The EMS is designed to operate in two levels structure, combines fuzzy logic system as the main controller with lambda iteration algorithm dedicated to solve the economic load dispatch of the conventional energy sources in case of use. The main objectives of the energy management system include maximizing the utilization of renewable energy from wind and solar units, fuel cost minimization, monitoring battery SoC, limiting the load (load shedding) for stability, and satisfying the system objective constraints. It can be summarized that the proposed system is appropriate to solve both technical and economic problems in a microgrid and can be consequently used for real time optimal power management with fuel cost optimization.

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