

Energy Scheduling in a Hybrid DC/AC Micro-Grid Considering Battery/Wind/Photovoltaic Power Sources using Heuristic Optimization Algorithm

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ABSTRACT:

This paper is treated with optimum energy management in a DC/AC Microgrid (MG) containing hybrid power sources to supply the load within cost minimization. In this hybrid electrical networks, energy sources are exploited as DC and AC manner, in which the Independent System Operator (ISO) should provide a practical coordination between them in order to procure the demand load optimally. This paper presents a framework that all available resources are formulated mathematically in hybrid microgrid with full constraints along with Demand Response (DR) programs implementation. The network under consideration can operate both in grid-tied and autonomous modes to manage power exchanging. Uncertainty and intermittent of Photovoltaic (PV) with Maximum Power Point Tracker (MPPT) equipped, Wind Turbine (WT), Energy Storage Systems (ESS) and DR programs are also considered to achieve the optimal control and operation. The ESSs are capable to connect both DC and AC links and the State of Charge (SOC) is maintained within permissible range. The proposed DG control framework and operation scheduling has facilitated the energy management of renewables using dynamic programming approach. A 24-hour time horizon simulation and discussion through three scenarios verified on a IEEE 33 bus distribution network, is done to represent the effectiveness of proposed energy management strategy to keep the whole hybrid grid stable.

KEYWORDS: Distributed Generation, Energy Management, Hybrid Micro-Grid, Optimization.

1. INTRODUCTION

Nowadays, due to the completion of fossil fuels and the struggle to reduce the use of these resources, the attention of countries is focused on the use of Renewable Energy Sources (RESs). A typical (MG) is such a conventional electrical network in which renewable sources have been used to supply the load [1], as shown in Fig. 1. The MG, consisting of a set of small and medium-sized products in low and medium voltage systems, includes a set of energy sources such as Distributed Generation (DG), renewable sources of energy like wind, Photovoltaic (PV) and Energy Storage Systems (ESS).

The MGs are utilized to provide energy for consumers such as households, industrial and agricultural, and their cost estimation is based on pricing policies on the electricity market. Due to the use of new technologies such as wind turbines and photovoltaic in the microgrid, the stochastic nature of RESs such as wind and sun, optimal management and operation of these platforms has become one of the research priorities of researchers in this regard.

Predicting the behavior of these resources and the optimal use of them will increase the efficiency of the system in the optimum operation with different targets such as economic, environmental and reducing pollutions [2-5].

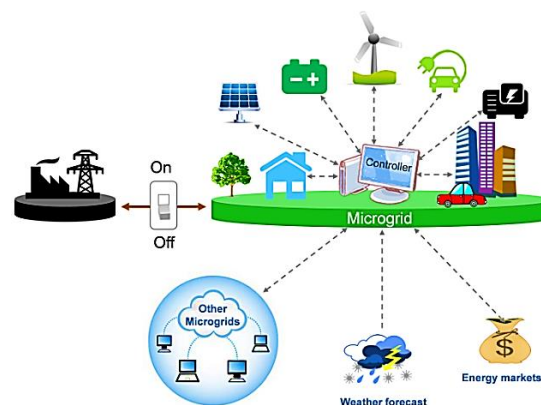


Fig. 1. A typical MG with DGs and islanded mode capability.

In [6], a study has been carried out in which with the aim of lowering environmental viability, photovoltaic and wind turbine blades are used as main sources of energy supply and beside them DGs are modeled as backup generators. In [7], to solve the problem of Unit Commitment (UC) and Economic Load Dispatch (ELD) for the next 24 hours within 5 minute intervals from local marginal prices, the optimization is conducted out and resulting model is examined on a medium sized system. In [8], a MG with the existence of RES, Fuel Cell (FC) and a battery is exploited by the multi-objective algorithm called (AMPSON) and used in the formulation of the nonlinear model, in which the target consists the cost and emissions of greenhouse gases reduction at the same time. In [9], the solution of the unit commitment problem in the microgrid, which includes controllable loads, is developed by the improved Genetic Algorithm (GA) by adopting Simulated Annealing (SA) method to accelerate the convergence. Objective functions defined at the simulation level and desired results include reducing the operation cost of the MG in an independent state and the revenue maximization when connected to the upstream power grid.

The economic benefits of DR programs and the development of various methods to reduce the cost of customers have been investigated in many studies [10-26]. Many of these researches have provided optimization methods for economically exploiting smart home appliances by implementing a cost-based DR program. Another important advantage of deploying DR programs is the benefit of their ancillary services [10-12]. Due to the development of smart communication infrastructure, DR applications play a significant role in improving the efficiency of future smart networks by providing different demand side services. Likewise, with the increasing development of renewable energy source technologies, it is anticipated that the level of penetration of these generation resources into future power grids is far greater than it is today [13]. In situations where uncertain resources account for a high volume of network power generation, responsive loads play an important role in power balancing. This is of great importance due to the limitations of Energy Storage System (ESS) as well as the low efficiency and high cost of their operations [14]. Therefore, many researches have been conducted and reported on the capability of DR programs as the sources of system capacity building. Among these studies, some authors have examined the impact of the DR program on the provision of ancillary services in standalone micro-networks that utilize renewable resources such as wind and solar units to supply noteworthy recharge [15-17]. Increasing the penetration of renewables due to a mistake in predicting their

production capacity has a significant impact on the reliability and safe operation of independent micro-networks [18]. In these circumstances, implementation of DR programs plays a significant role in energy planning and storage. Because with demand-side partnerships, DR procedures increase/decrease their consumption if production is reduced or increased. However, precise determination of the amount of spin and non-spin reserve required for the safety of standalone MG in the face of uncertainties arising from renewable resources and DR is vital. In [19-21], an energy management system is proposed for an islanded MG with capability of estimating system rotation storage under uncertainties caused by renewable resources and demand loads. However, in the proposed model, the impact of the response of DR on spinning reserve allocation for the system is not considered. In [22-26], the other probabilistic models for simultaneous scheduling of energy resources and storage of a microcontroller are presented. In these researches, uncertainties arising from load demand, renewable energy production capacity, and electricity market price uncertainties are considered. But the role of Demand-Side Management (DSM) in system and ESS allocation have been overlooked.

As the traditional power systems require some deregulations such as flexibility, altering the regulatory and financial situations, this paper presents a framework to optimize the operation scheduling in a MG in which all DC and AC power sources supply the loads, together. DR programs are also designed to further increase the efficiency and flexibility of the MG to compensate the probable power shortage at peak load intervals or at high electricity tariff periods. Modeling of all the DGs used in this framework is presented mathematically with high precision constraints that can be used as a complete reference for operating a mixture MG. The PV is considered to be capable to connect to the MG or be disconnected according to the low market price or protection procedures.

The SOC of ESSs is then kept in 20% to 80% of their nominal power. Briefly the paper novelties can be written in bullets:

- A complete framework in hybrid MG optimization considering several DG types.
- The grid-tied of autonomous operation modes effects on energy management, since the uncertainty in wind and solar generation is modeled by Monte Carlo approach.
- The high-reliability capability of proposed method on different case studies.
- Low Expected Energy Not Supplied (EENS) and Loss of Energy (LOE) in all scenarios.

This paper is structured as follows: Section 2 describes the problem concepts and statement, the

hybrid MG and the DGs formulations. The optimization algorithm using Dynamic Programming (DP) is presented in Section 3. Confirmation of the performance of the proposed approach based on IEEE 33 bus system simulations and real-time verifications are presented in Section 4. Discussions and conclusion are stated in Sections 5 and 6, respectively.

2. PROBLEM FORMULATION & STATEMENT

In a hybrid micro-grid, in order to minimize the whole operation cost, both DC constraints and AC constraints must be considered. Therefore, the objective function formed to be optimized is expressed in (1). The decision vector, input vector and, active power vector and price vectors have also been investigated in (1).

$$\min \sum_{t=1}^T \left\{ \begin{array}{l} \pi_{grid}(t) \cdot P_{grid}(t) \\ + \sum_{j=1}^{N_{DG}} [CE_{DG}(j, t) + CS_{DG}(j, t) + CR_{DG}(j, t)] \\ + \sum_{k=1}^{N_L} [CE_L(k, t) + CR_L(k, t)] \\ + \sum_{d=1}^{N_{DR}} [CE_{DR}(d, t) + CR_{DR}(d, t)] \end{array} \right\} \quad (1)$$

decision vector: $X = [P_{grid} \ P_{DGs} \ P_{DR}]^T$

input vector: $U = [\pi_{grid} \ \pi_{DGs} \ \pi_{DR}]^T$

$P_{DGs} = [P_{WT} \ P_{PV} \ P_{ch} \ P_{disch} \ P_{conv}]$

$\pi_{DGs} = [\pi_{WT} \ \pi_{PV} \ \pi_{ch} \ \pi_{disch} \ \pi_{conv}]$

$P_{DR} = [P_{Controlabal \ Load} \ P_{load}]$

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Where, $P_{grid}(t)$ represents the power purchased from upstream network regarding $\pi_{grid}(t)$ price, $CE_{DG}(j, t)$ shows the AC operating cost of DGs at the time t , $CR_{DG}(j, t)$ represents the cost of scheduled reserve capacity reduction of DGs at the time t , $CE_L(k, t)$ and $CR_L(k, t)$ are the load shedding cost and reserve decreasing cost, respectively, $CE_{DR}(d, t)$ is load reduction in DR scheduling and $CR_{DR}(d, t)$ shows the DR reserve programming. Here in AC areas of MG, there are some constraints which should be considered to ensure the best power balance in active and reactive generation. These power balances are discussed in (2) and (3) [27]. The authors in [27] only discuss about the complete formulation precisely and investigate the voltage profile, however they did not show the effectiveness of this energy management framework properly, that will be completed in this manuscript.

$$\sum_{k=1}^{N_{bus}} \left\{ \begin{array}{l} P_{grid}(k, t) + P_{DG}(k, t) + P_{WT}(k, t) \\ + P_{PV}(k, t) + P_{ch}(k, t) - P_{disch}(k, t) \\ + P_{DR}(k, t) + P_L(k, t) - P_D(k, t) \\ + P_{DC-AC}(k, t) \cdot \eta_{DC-AC} \end{array} \right\} \quad (2)$$

$$= \sum_{j=1}^{N_{bus}} \{V_k(t) \cdot V_j(t) \cdot Y_{bus}(k, j) \cdot \cos(\delta_k(t) - \delta_j(t) + \theta_{kj})\} + P_{AC-DC}(t)$$

$$\sum_{k=1}^{N_{bus}} P_{grid}(k, t) - P_D(k, t)$$

$$= \sum_{j=1}^{N_{bus}} \{V_k(t) \cdot V_j(t) \cdot Y_{bus}(k, j) \cdot \sin(\delta_k(t) - \delta_j(t) + \theta_{kj})\} \quad (3)$$

Where, $P_{DC-AC}(k, t)$ is the active power sold to the AC grid from DC parts with η_{DC-AC} efficiency of DC-AC inverters. $P_{AC-DC}(t)$ represents the injected active power from AC sides to DC grids. Indices k and t are the bus numbers and 24 hours of operation, respectively.

Similarly, in DC areas, there are some constraints written in (4) to (19). The total operation costs and DC power balance, are formulated in (4) and (5), respectively.

$$OpCost_{DC} = \sum_{t=1}^T \sum_{k=1}^{N_{DG}} C_{DG}(k, t) \cdot P_{DG}(k, t) \quad (4)$$

$$P_{AC-DC}(t) \cdot \eta_{AC-DC} + P_{DG}(t) + P_{PV}(t) + P_{wind}(t) \cdot \eta_{AC-DC} + P_{disch}(t) = P_{load}^{DR}(t) + P_{ch}(t) + P_{DC-AC}(t) \quad (5)$$

The DR constraints are written in (6) to (8) as below.

$$P_{load}^{DR}(t) = P_{load}(t) + DR(t) \quad (6)$$

$$-DR^{max} \cdot P_{load}(t) \leq DR(t) \leq DR^{max} \cdot P_{load}(t) \quad (7)$$

$$\sum_{t=1}^T DR(t) = 0 \quad (8)$$

The battery charging and discharging constraints are formulated in (9) to (13) mathematically.

$$P_{ch}^{DC}(t) \leq X_{ch}^{DC}(t) \cdot P_{ch}^{DCmax} \quad (9)$$

$$P_{disch}^{DC}(t) \leq X_{disch}^{DC}(t) \cdot P_{disch}^{DCmax} \quad (10)$$

$$X_{ch}^{DC}(t) + X_{disch}^{DC}(t) \leq 1 \quad (11)$$

$$SOC_{DC}(t) = SOC_{DC}(t-1) + P_{ch}^{DC}(t) \cdot \eta_{ch}^{DC} - \frac{P_{disch}(t)}{\eta_{disch}^{DC}} \quad (12)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (13)$$

The DG power generation limitations are represented in (14) and (15).

$$P_{DG}^{DC}(t) \leq P_{DG}^{DCmax} \cdot u_{DG}^{DC}(t) \quad (14)$$

$$P_{DG}^{DCmin} \cdot u_{DG}^{DC}(t) \leq P_{DG}^{DC}(t) \quad (15)$$

The wind turbine power generation constrains are shown in (16) and (17).

$$P_{wind}^{DC}(t) = \begin{cases} 0 & ; \quad 0 < v < v_{min} \quad \text{or} \quad v > v_{limit} \\ P_{rated} \cdot \frac{(v - v_{min})}{v_{max} - v_{min}} & ; \quad v_{min} < v < v_{max} \\ P_{rated} & ; \quad v_{max} < v < v_{limit} \end{cases} \quad (16)$$

$$P_{wind}^{DC}(t) \leq P_{wind}^{DC,max}(t) \quad (17)$$

For PV operation scheduling, the power generation limitations are described in (18) and (19).

$$P_{PV}^{DC,max}(t) = \frac{G_a(t)}{G_{a0}} \left[+\mu_{P_{max}} \left(\frac{P_{max,0}^{DC,max}(t)}{T_a(t)} + \frac{G_a(t)(NOCT - 20)}{800} - T_{M0} \right) \right] \quad (18)$$

$$P_{PV}^{DC}(t) \leq P_{PV}^{DC,max}(t) \quad (19)$$

The converter modeling and power exchange platform are discussed in (20)-(22).

$$P_{DC-AC}(t) \leq X_{DC-AC}(t) \cdot P_{conv}^{max}(t) \quad (20)$$

$$P_{AC-DC}(t) \leq X_{AC-DC}(t) \cdot P_{conv}^{max}(t) \quad (21)$$

$$X_{DC-AC}(t) + X_{AC-DC}(t) \leq 1 \quad (22)$$

Where, X is a binary variable to determine the power exchange between AC and DC networks. The maximum power conversion is shown with $P_{conv}^{max}(t)$ to represent the capacity of power electronics interfaces. All the system constrains including DR rating, AC grid, equipment capacities, DG sizing and etc., are described in (23) to (55) mathematically. The voltage and current flowing the lines constrains are written in (23)-(26).

$$I(k, j, t) \leq I_{max}(k, j, t) \quad (23)$$

$$V_{min}(t) \leq V(t) \leq V_{max}(t) \quad (24)$$

$$V(n, t) = 1 = \text{constant}, n = \text{subs, bus} \quad (25)$$

$$I(k, j, t) \leq I_{max}^{sub} = 1, n = \text{subs, bus} \quad (26)$$

The DR program and capacity constraints are:

$$R_L(k, t) + R_{DR}(k, t) + R_{DG}(k, t) = 0.02 P_{WT}(k, t) + 0.1 P_D(k, t) \quad (27)$$

$$O_{min}^d \leq o_1^d \leq O_1^d \quad (28)$$

$$0 \leq o_k^d \leq (O_{k+1}^d - O_k^d) \quad (29)$$

$$P_{DR}(d, t) = \sum_k O_k^d \quad (30)$$

$$CE_{DR}(d, t) = \sum_k o_k^d \cdot \pi_k^d \quad (31)$$

$$P_{DR}(d, t) + R_{DR}(d, t) \leq P_{DR}^{Max}(d, t) \quad (32)$$

$$CR_{DR}(d, t) = R_{DR}(d, t) \cdot KR_{DR}(d, t) \quad (33)$$

Where, $R_L(k, t)$ is the scheduled reserve capacity of L category and O_{min}^d is the minimum amount of load reduction offered by DRPs. The reserve constrains are shown in (34)-(36).

$$P_L(k, t) + R_L(k, t) \leq P_L^{Max}(k, t) \quad (34)$$

$$CE_L(d, t) = P_L(d, t) \cdot KE_L(d, t) \quad (35)$$

$$CR_L(d, t) = R_L(d, t) \cdot K \cdot R_L(d, t) \quad (36)$$

The other DG and renewable resources constrains are represented in (37) to (55), briefly [27].

$$P_{wind}(t)^{min} \leq P_{wind}(t) \leq P_{wind}(t)^{max} \quad (37)$$

$$P_{wind}(t) \leq P_W(v_{cut}(t)) \quad (38)$$

$$B_{Sc}(b, t) + B_{Sd}(b, t) \leq 1; \quad B_{Sc}(b, t), B_{Sd}(b, t) \in \{0, 1\} \quad (39)$$

$$SOC(b, t) = SOC(b, t-1) + \eta^c \cdot P_{Sc}(b, t) - \eta^d \cdot P_{Sd}(b, t) \quad (40)$$

$$SOC_{min}(b) \leq SOC(b, t) \leq SOC_{max}(b) \quad (41)$$

$$0 < P_{Sc}(b, t) \leq P_{Sc}(b, t)^{Max} \cdot B_{Sc}(b, t) \quad (42)$$

$$0 < P_{Sd}(b, t) \leq P_{Sd}(b, t)^{Max} \cdot B_{Sd}(b, t) \quad (43)$$

$$CE_{DG}(k, t) = a_k \cdot u(k, t) + b_k P_{DG}(k, t) + c_k P_{DG}^2(k, t) \quad (44)$$

$$CS_{DG}(k, t) = SUC(k) \cdot (u(k, t) - u(k, t - 1)) \quad (45)$$

$$CS_{DG}(k, t) \geq 0 \quad (46)$$

$$CR_{DG}(k, t) = KR_{DG} \cdot (b_k + 2 c_k P_{DG}(k, t)^{max}) \cdot R_{DG}(k, t) \quad (47)$$

$$P_{DG}(k, t)^{min} \cdot u(k, t) \leq P_{DG}(k, t) \leq P_{DG}(k, t)^{max} \cdot u(k, t) \quad (48)$$

$$P_{DG}(k, t) + R_{DG}(k, t) \leq P_{DG}(k, t)^{max} \cdot u(k, t) \quad (49)$$

$$P_{DG}(k, t) - P_{DG}(k, t - 1) \leq P_{DG}(k, t)^{min} \cdot \gamma(k, t) + UR(k) \cdot (1 - \gamma(k, t)) \quad (50)$$

$$P_{DG}(k, t - 1) - P_{DG}(k, t) \leq DR(k) \cdot (1 - \zeta(k, t)) + P_{DG}(k, t)^{min} \cdot \zeta(k, t) \quad (51)$$

$$\sum_{h=t}^{t+DT(j)-1} (1 - u(k, h)) \geq DT(k) \cdot \zeta(k, t) \quad (52)$$

$$\sum_{h=t}^{t+UT(j)-1} u(k, h) \geq UT(k) \cdot \gamma(k, t) \quad (53)$$

$$\gamma(k, t) - \zeta(k, t) = u(k, t) - u(k, t - 1) \quad (54)$$

$$\gamma(k, t) + \zeta(k, t) \leq 1 \quad (55)$$

3. OPTIMIZATION ALGORITHM

Hybrid Micro-Grid System (HMGS) offers an optimal, reliable, and cost-effective solution for utilizing localized renewable energy resources over individual DC or AC micro grid. Generally, production, distribution, and demand subsystems are joined together to form an HMGS, that vary greatly depending on availability of renewable resources, desired services to provide, and demand subsystem parameters. These parameters together have a high impact on decision taking, reduction of the cost and reliability improvement of the system. The Multi-Stage Decision Based Dynamic Programing (MSD-DP) optimization approach is used to minimize the operation costs of the proposed MG. In this method, for each decision stage, there are numerous system states determining the current cost. Thus, the outputs of current stage, will be input states of next stage as shown in Fig. 2.

A set of MSD formulation with the equality and non-equality constrains are formulated as below:

$$x^{k+1} = f^k(x^k, u^k) ; \quad (56)$$

$$x^k \in X ; \quad u^k \in U ; \quad k \in \{0, 1, \dots, N-1\}$$

$$V^N(x^N) = \min \left\{ g^N(x^N) + \sum_{k=0}^{N-1} g^k(x^k, u^k) \right\} \quad (57)$$

Where, k donates the number of time intervals, x^k is the state vector at stage k , u^k represents the decision vector at stage k , f^k is the state transition functions.

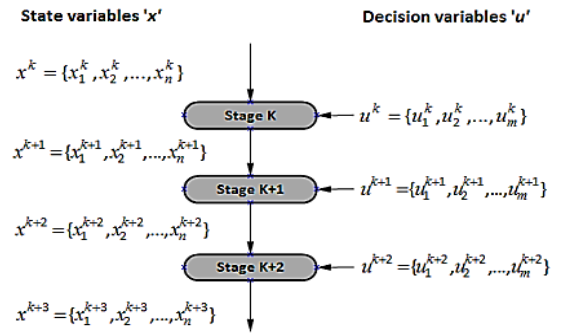


Fig. 2. The MSD problem tree.

g^k is the cost function of the state and decision variables at stage k and V^N shows the summation of costs of all N stages. At stage k , the objective function and constraints are written in (58) and (59).

$$V^k(x^k) = \min \{ g^k(x^k, u^k) + V^{k-1}(x^{k-1}) \} \quad (58)$$

$$u_{min}^{k-1} < u^{k-1} < u_{max}^{k-1}$$

$$x_{min}^k < x^k < x_{max}^k \quad (59)$$

$$x^k = f^{k-1}(x^{k-1}, u^{k-1})$$

Where u_{min}^{k-1} and u_{max}^{k-1} are decision variables possible range, and states limitation are represented by x_{min}^k and x_{max}^k . The MSD problem could not be solved by itself, therefore the DP approach described in [28-29] is used to minimize the problem formulations. So, let X_i considered as a state vector including the power exchanged of DGs, DR and upstream network, and U_i be an input vector determining the real time price for operation. Briefly, the objective functions considered to be minimized in (1), are simplified as (60)-(61).

$$Z = \min \left\{ \sum_{k=1}^{N-1} f_k(X_k, U_k) + f_N(X_N) \right\} \quad (60)$$

$$\text{decision vector: } X = [P_{grid} \ P_{DGs} \ P_{DR}]^T$$

input vector: $U = [\pi_{grid} \ \pi_{DGs} \ \pi_{DR}]^T$

Subject to:

Iterative problem solving principle:

$$x_{k+1} = g_k(x_k, u_k) \tag{61}$$

Equality constraints: $h_k(x_k, u_k) = 0$

Non-equality constraints: $g_k(x_k, u_k) < 0$

The eq. (61) implies on the all equality and non-equality relations written in (2)-(55).

4. SIMULATION AND DISCUSSION

The MG under study is considered as IEEE 33 bus distribution system, shown in Fig. 3. This power network is capable to operate both in grid connected and islanded modes. The DERs described in previous sections are located in several buses of this power network to supply the load. The Time of Use (TOU) electricity tariff represented in Fig. 4 is applied to the MG energy management. This implies on instantaneous DG unit commitment regarding the total operation costs is minimized. Table 1 represents the DGs power rating. The simulation results are obtained under three different case studies as listed below:

1. Operating MG without ESS in grid-tied mode;
2. Operating MG with all DGs in autonomous mode;
3. Operating MG with all capacity of minimizing costs;

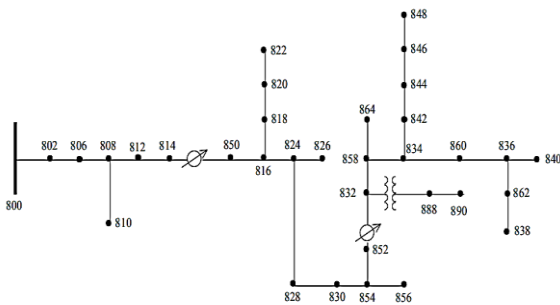


Fig. 3. IEEE 33 bus system.

Table 1. DGs power rating.

DG	Power rating
PV	60 × 2 kW
ESS	20 × 6 kW
Wind	60 × 2 kW
Converter	130 × 4 kW
DR	Up to 20 % of total load

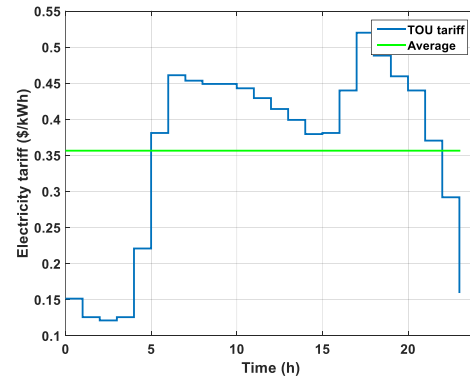


Fig. 4. TOU electricity tariff.

4.1. Scenario 1

The first case study outputs are shown in Figs. 5 and 6. In this simulation platform, it is assumed that customers are divided into 10 groups (H1 to H10) with different power level and the demand power of each group with the adjacent group can vary due to their different user, shown in Fig. 5. These changes in power and categorization are due to the variety of commercial, domestic and industrial loads in the micro-grid. The sum of all these required loads now constitutes the same dimensional load profile that must be provided by the DG resources presented in the framework. In this scenario, the wind power supplies the load at high-wind power existing periods, resulting in decrease of the other DG generation power pressure. The converter loss is also being negligible, while the PV generates the electrical power in high-irradiance power received. The ESS is not contributed at the MG energy management as it is supposed to be charged in cheap hours and discharged in high electricity tariff especially in peak hours (16:00 to 19:00). The remained load power is considered to be supplied by the upstream network as plotted in Fig. 6 in dash style. The total operation costs in this scenario are calculated as 75608.12 \$.

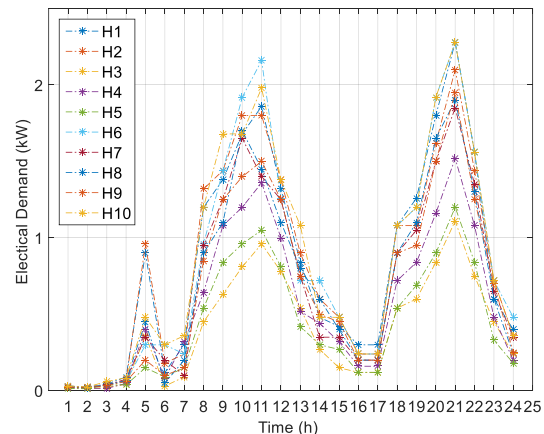


Fig. 5. Electrical demand by the 10 categorized consumers.

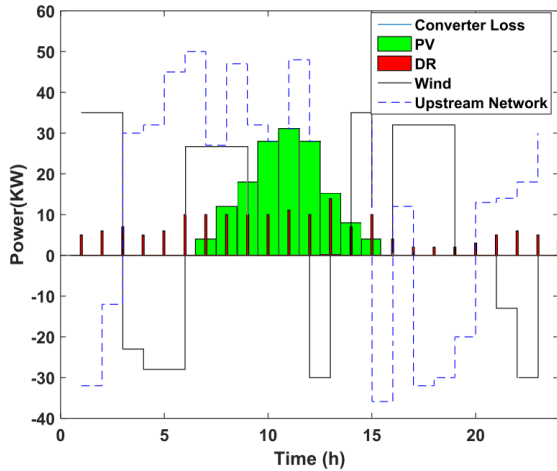


Fig. 6. Power exchange between DERs and upstream network in scenario 1.

These DGs unit commitments are directly subordinated to the electricity tariff shown in Fig. 4. The DR resources play an important role in supplying loads at low power hours, significantly.

4.2. Scenario 2

This scenario investigates the operating MG with all DGs in autonomous mode. Likewise, the previous scenario, first the DERs power exchange is shown in Fig. 7. As in the scenario 2, the distributed generation resources do not exchange any power with the upstream network, thus the network is in autonomous mode and all requested loads are supplied by the network's own resources. In this case, ESS plays the most important role in providing power, especially in periods where the wind turbines and the solar powers are off. Fig. 8 illustrates the battery charge and discharge power diagram, and Fig. 3 also shows the battery SOC, which is kept at least 20% constant. The total loss is calculated as 7.41 kW and the mean voltage profile of all buses are 0.986 pu. Totally the operation costs of autonomous hybrid MG is calculated as 68452.95 \$, which is lower than the first case study.

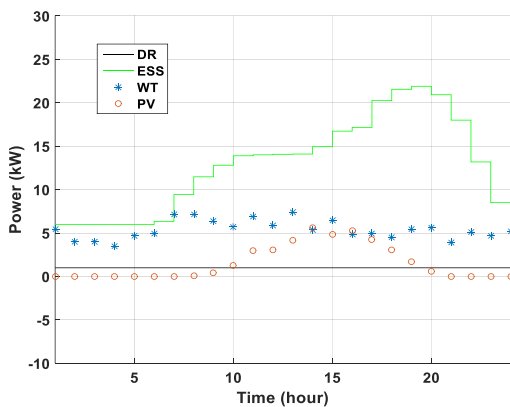


Fig. 7. Power exchange of DERs in scenario 2.

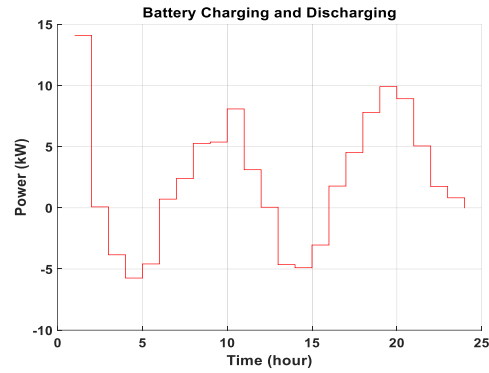


Fig. 8. ESS charging and discharging in scenario 2.

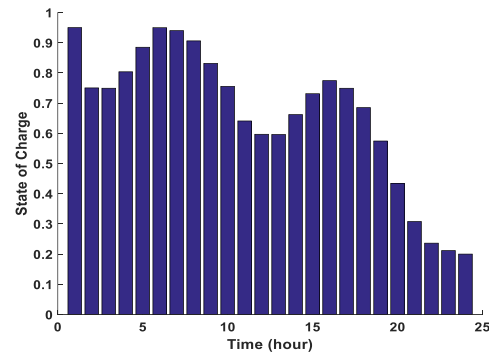


Fig. 9. The SOC of ESS in scenario 2.

4.3. Scenario 3

In this case study, all DERs and upstream network participate to supply the load in case of cost minimization. The total operation costs are 62562.89 \$ which implies that this is the lower price in all scenarios. By the way, the active power loss is calculated as 5.12 kW which approximately is 31% lower than case study 2. The voltage profiles are also improved with 1.007 pu as mean amount. The ESS variation is considered to be limited rather than the scenario 2 to (20 % , 72 %), due to the power injected to the MG from upstream network.

The output results of second and third scenarios are gathered in table 2 briefly. As it is observed, the DGs generated power are decreased in grid connected mode regarding in much power injected to the MG at low electricity price in upstream network. In this case, the reliability is increased and the Expected Energy Not Supplied (EENS) in this simulation time horizon is decreased, correspondingly.

$$EENS = \sum_{j=1}^{N_{contingencies}} E[LOE(j)] \tag{62}$$

$$LOE = \sum_r Q_r \cdot P(t)$$

Where, Q_r is the amount of lost load in position r .

Table 2. Output results of grid connected and islanded modes of operation states.

Operation modes	Grid connected mode			Islanded mode		
	Mean output power	Mean time off	Converter loss	Mean output power	Mean time off	Converter loss
PV	5.2 kW	11 hours	0.21 kW	10.6 kW	7 hours	0.35 kW
ESS	7.6 kW	6 hours	0.32 kW	11.4 kW	3 hours	0.52 kW
Converter	29.3 kW	0	2.2 kW	32.5 kW	0	3.13 kW
Wind	9.3 kW	13 hours	0.47 kW	11.9 kW	13 hours	0.76 kW
Upstream network	7.7 kW	8 hours	0	0	0	0
EENS	6.53 %			9.36 %		
Mean voltage profile	1.007 pu			0.986 pu		
Total loss	5.12 kW			7.41 kW		
SOC (min, max)	(20 % , 95 %)			(20 % , 72 %)		
Operation costs	62562.89 \$			68452.95 \$		

5. CONCLUSION

In this paper, the framework formulation of DC and AC kinds of DERs is expressed in a hybrid MG and the optimized simultaneous operation of DGs were carried out. The simulation results of the models and the proposed method show that the micro grid is stable in all case studies and the voltage profile is improved, consequently. The use of DR applications under the TOU electricity tariff will smooth the load profile, which significantly reduces the power generation pressure of the electricity distribution companies.

Evaluation and assessment of different case studies have shown that hybrid networks, whether in grid-connected or islanded mode, will optimally perform power exchange between loads and DERs, and reduce operating costs. In this paper, the losses of AC-DC and DC-AC converters are also considered, which increases the accuracy of the output responses. The comparisons show that the DP optimization algorithm is capable of improving the performance of the MG and will also increase battery life.

Table 3. The parameters used in this paper.

Parameter	Definition
π_{grid}	Grid price
P_{grid}	Grid power
CE_{DG}	AC operating cost of DGs
CR_{DG}	Cost of scheduled reserve capacity reduction of DGs
CE_L	Load shedding cost
CR_L	Reserve decreasing cost
CE_{DR}	Load reduction in DR scheduling
CR_{DR}	DR reserve programming
$X = [P_{grid} P_{DGs} P_{DR}]^T$	Decision vector
$U = [\pi_{grid} \pi_{DGs} \pi_{DR}]^T$	Input vector
$P_{DGs} = [P_{WT} P_{PV} P_{ch} P_{disch} P_{conv}]$	DGs powers

$\pi_{DGs} = [\pi_{WT} \ \pi_{PV} \ \pi_{ch} \ \pi_{disch} \ \pi_{conv}]$	DGs prices
$P_{DR} = [P_{Controlabal Load} \ P_{load}]$	DR powers
$\pi_{DR} = [\pi_{Controlabal Load} \ \pi_{load}]$	DR prices
V_k	Voltage of node k
Y_{bus}	Admittance matrix
δ_k	Phase angle of voltage at node k
θ_{kj}	Phase angle of each admittance matrix arrays
P_{ch}^{DC}	Charging power
P_{ch}^{DCmax}	Discharging power
SOC_{DC}	State of charge
u, γ, ζ	Binary variables
P_{wind}^{DC}	Wind power
v	Wind speed
P_{rated}	Nominal power of wind
$G_a(t)$	Ambient irradiation for PV
μ_{Pmax}	PV efficiency at maximum power
$NOCT$	Normal operating cell
T_{M0}	Ambient temperature
P_{conv}^{max}	Maximum power transmitted by the converter
I	Branch current
O_k^d	Amount of load reduction by DR
B_{S_C}, B_{S_D}	Binary variable for charging/discharging of the battery
η	Efficiency

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