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Mathematical modeling of electrochemical storage for incorporation in methods to optimize the operational planning of an interconnected micro grid

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Abstract: We extract a mathematical model to simulate the steady-state charging and discharging behaviors of an electrochemical storage over a 24-hour time interval. Moreover, we develop a model for optimizing the daily operational planning of an interconnected micro grid considering electrochemical storage. The optimization model is formulated to maximize the total benefit of the micro grid via selling power to its end consumers and also exchanging power with the wholesale energy market so that the constraints of distributed energy resources (DERs) and low-voltage grid are met. The optimization problem is solved by a genetic algorithm, and applied on two micro grids operating under different scenarios containing the absence or presence of electrochemical storages. Comparison of the results of the optimization model for this micro grid, with and without electrochemical storage, shows that the electrochemical storage can improve the economical efficiency of the interconnected micro grids by up to 10.16%.

Key words: Electrochemical storage, Micro grid, Operational planning, Distributed energy resources
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1 Introduction

Due to many economical, political, and environmental factors, the share of distributed energy resources (DERs) in the power system has increased worldwide. DER contains distributed generators (DGs), controllable loads, and storage devices. As the penetration of DER in the distribution network increases, several issues related to technical, commercial, and regulatory barriers of reliance of these units remain to be solved (Dondi *et al.*, 2002; Djapic *et al.*, 2007; Pecas Lopes *et al.*, 2007). Pudjianto *et al.* (2005) investigated some of these subjects in micro grids. A micro grid comprises a low-voltage distribution network with DER that can operate either interconnected or isolated from the main distribution grid as a controlled entity. The operation of DER in a micro grid can be performed through either a centralized or a decentralized supervisory control approach (Hatziargyrious *et al.*, 2004; 2005; Jiang and Dougal, 2008; Katiraei *et al.*, 2008). Optimizing the operation of a micro grid requires a knowledge of the models of its components, regardless of its control strategy. A storage device is a component of the micro grid; it enhances the overall performance of the micro grid in three ways. First, it stabilizes and permits DG units to run at a constant and stable output, despite load fluctuations. Second, it provides the ride-through capability when there are dynamic variations of primary energy (e.g., sun, wind). Third, it permits DG to operate as a dispatchable unit (Kroposki *et al.*, 2008). Furthermore, in this work, the storage device is used and operated for improving the economical efficiency of an interconnected micro grid.

Because the direct storage of electricity is not very practical, the storage of energy by other methods (e.g., electrochemical storage, superconducting energy storage when cost is not an issue, or flywheel over short time periods) is employed for later use in electricity generation (Abu-Sharkh *et al.*, 2006).

It is likely that a micro grid relies on chemical energy in the form of batteries (Abu-Sharkh *et al.*, 2006). These devices use electrochemical reaction to store electricity in the form of chemical potential during charging. This process can be reversed during discharging to provide electricity to loads. These devices may be rechargeable or not. The major types of rechargeable electrochemical storages are lead acid, nickel-cadmium, lithium-ion, sodium sulfur, and so forth (Oshima *et al.*, 2005; Paloheimo and Omidiora, 2009; Robalino *et al.*, 2009). A literature review on battery energy storage technologies was provided in Divya and Østergaard (2009). All electrochemical storages can be described by certain characteristics such as battery capacity as a function of discharge rate or discharge current (Peukert's equation), temperature effects on the charge and discharge voltage of battery, and so forth. These subjects are not discussed in this paper since they are well addressed elsewhere (Biradar *et al.*, 1998; Medora and Kusko, 2006; Sun *et al.*, 2008; Erdinc *et al.*, 2009). According to the relevant literature, many studies have been performed to determine the dynamic battery models, especially concerning the above characteristics (Giglioli *et al.*, 1990; Ceraolo *et al.*, 1992; Ceraolo, 2000; Medora and Kusko, 2006; Rong and Pedram, 2006; Erdinc *et al.*, 2009).

The aim of this paper, however, is to extract a mathematical static model for simulating charging and discharging behaviors of electrochemical storages over a 24-hour time interval, while providing charging and discharging rates of the storages. This general model is applicable for decision making on scheduling charge and discharge of the storage on a daily basis. The model is incorporated in optimizing the 24-hour operational planning of an interconnected micro grid including electrochemical storages. Note that a real time (hourly) optimization model can be considered for the operation of a micro grid to cover any deviation from daily decisions and also to take dynamic characteristics of the electrochemical storages into account. The real time optimization model and also dynamic modeling of the storage, however, are beyond the scope of this paper. It is assumed that the micro grid is centrally controlled and the optimization problem is formulated to maximize the benefit of the micro grid by determining the operation decisions on the grid purchase, scheduling of dispatchable DGs and electrochemical storages, and also using interrupting options. In this respect, the micro grid steady-state security issues, i.e., voltage constraints and power flow thermal limits, and also the capacity limit of interconnection, which have been neglected in other research (Agovic *et al.*, 2005; Hernandez-Aramburo *et al.*, 2005; Mohamed and Koivo, 2007; Tsikalakis and Hatziargyriou, 2008), are taken into account. The problem is solved by a genetic algorithm (GA) and the above constraints are checked in power flow calculations. The optimization model is applied on two micro grids operating under different scenarios containing the absence or presence of electrochemical storages, and the results are analyzed.

2 Electrochemical storage modeling

In this section a set of formulas are extracted to simulate the charge and discharge states of an electrochemical storage over a 24-hour time interval. The capacity of electrochemical storage is measured in either W·h, kW·h, or A·h. The charge/discharge rate of the electrochemical storage is given by its capacity divided by the number of hours it takes to charge or discharge. Therefore, the charge/discharge rate of the electrochemical storage can be measured in W, kW, or A. For example, a 12-V electrochemical storage with a capacity of 500 A·h that is theoretically discharged in 20 h will have a discharge rate of 25 A or 300 W. Although measuring the battery capacity in A·h is more common, in this paper, the capacity of electrochemical storage is defined in kW·h and its charge/discharge rate in kW. This is for consistency between the measurements of the battery and the measurements of loads and productions of DG units which are in kW.

Suppose $P_{\text{str}}^{\max}$ is the installed capacity of electrochemical storage in kW·h, and $R_{\text{str-ch}}$ and $R_{\text{str-dch}}$ the maximum charge and discharge rates in kW, respectively. In many types of electrochemical storage, particularly lead acid batteries, the full energy stored in the electrochemical storage cannot be withdrawn (in other words, the electrochemical storage cannot be fully discharged). This occurs because extracting the full capacity of electrochemical storage dramatically reduces its lifetime. Therefore, the minimum state of charge of the battery is assumed to be $P_{\text{str}}^{\min}$. Suppose cap_{t-1} is the state of charge of the storage at hour $t-1$. We have $P_{\text{str}}^{\min} \le \text{cap}_{t-1} \le P_{\text{str}}^{\max}$. Then, at hour t, the maximum power generation capability of the storage is equal to $\text{cap}_{t-1} - P_{\text{str}}^{\min}$, and its maximum charging capability is equal to $P_{\text{str}}^{\max} - \text{cap}_{t-1}$ (Fig. 1).

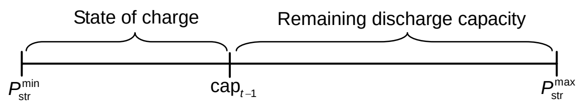

Fig. 1 The status of storage at time *t*−1

Suppose $P_{\text{str},t}$ is a variable that denotes the amount of charge/discharge capacity of storage at hour t (negative and positive values indicate discharge and charge states respectively). Then, $\forall t$=1, 2, …, 24, the following relations are established:

$$-\text{cap}_{t-1} - P_{\text{str}}^{\min} \le P_{\text{str},t} \le P_{\text{str}}^{\max} - \text{cap}_{t-1}, \tag{1}$$

$$\text{cap}_t - \text{cap}_{t-1} \le R_{\text{str-ch}}, \text{ if storage is charged,} \tag{2}$$

$$\text{cap}_{t-1} - \text{cap}_t \le R_{\text{str-dch}}, \text{ if storage is discharged,} \tag{3}$$

$$\begin{bmatrix} \text{cap}_0 \\ \text{cap}_1 \\ \vdots \\ \text{cap}_{t-2} \\ \text{cap}_{t-1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 1 & 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & 1 & 1 & \cdots & 0 \\ 1 & 1 & 1 & \cdots & 1 \end{bmatrix} \begin{bmatrix} \text{cap}_0 \\ P_{\text{str},1} \\ \vdots \\ P_{\text{str},t-2} \\ P_{\text{str},t-1} \end{bmatrix}. \tag{4}$$

The given value of cap_0 is the state of charge of the storage at the beginning of the scheduling period. By substituting Eq. (4) in Eq. (1), the following is derived:

$$\begin{cases} -(\text{cap}_0 - P_{\text{str}}^{\min}) \le P_{\text{str},1} \le P_{\text{str}}^{\max} - \text{cap}_0, \\ -(\text{cap}_0 - P_{\text{str}}^{\min}) \le P_{\text{str},1} + P_{\text{str},2} \le P_{\text{str}}^{\max} - \text{cap}_0, \\ -(\text{cap}_0 - P_{\text{str}}^{\min}) \le P_{\text{str},1} + P_{\text{str},2} + P_{\text{str},3} \le P_{\text{str}}^{\max} - \text{cap}_0, \\ \qquad\qquad\vdots \\ -(\text{cap}_0 - P_{\text{str}}^{\min}) \le P_{\text{str},1} + P_{\text{str},2} + \ldots + P_{\text{str},24} \le P_{\text{str}}^{\max} - \text{cap}_0. \end{cases} \tag{5}$$

Eq. (5) can be summarized as follows:

$$-(\text{cap}_0 - P_{\text{str}}^{\min}) \le \sum_{k=1}^{t} P_{\text{str},k} \le P_{\text{str}}^{\max} - \text{cap}_0, \ \forall t = 1, 2, ..., 24. \tag{6}$$

By substituting Eq. (4) in Eqs. (2) and (3), $\forall t$=1, 2, …, 24, the following relations are derived:

$$P_{\text{str},t} \le R_{\text{str-ch}}, \text{ if storage is charged.} \tag{7}$$

$$-P_{\text{str},t} \le R_{\text{str-dch}}, \text{ if storage is discharged.} \tag{8}$$

Eqs. (6)–(8) are used to simulate the behavior of electrochemical storage over a 24-hour time interval.

3 Optimization problem

Based on a case in Iran, it is assumed that a private entity is the owner of DG units, electrochemical storages, and low voltage grid. The entity has bilateral contracts with the end consumers in the micro grid for supplying them. Moreover, it signs a contract with interruptible consumers in which the upper limit of curtailing ($P_{\text{curt}}^{\max}$), the cost of curtailing, and the permitted number of hours for curtailing (S_{hour}) are determined. It is assumed based on work done elsewhere (Fahrioglu and Alvearado, 2001; Li *et al.*, 2007) that, the cost of curtailing is a function of unserved load (P_{curt}) and modeled as a quadratic polynomial function ($C(P_{\text{curt}})=\alpha_{\text{int}} P_{\text{curt}}^2 + \beta_{\text{int}} P_{\text{curt}}$), in which given coefficients α_{int} and β_{int} quantify the cost of unserved load. This micro grid is centrally controlled and the optimization problem is formulated to maximize the total benefits of the micro grid via selling power to its consumers as well as exchanging power with the main grid/wholesale energy market so that the technical constraints of DER and low voltage grid are met. The outputs of the optimization model determine the amount of exchanged power with the upstream grid, scheduling of DGs and electrochemical storages, as well as the amount of the load that should be interrupted. The price of exchanging is assumed to be the price of the wholesale market plus the usage cost of the medium voltage distribution grid.

The cost function of each DG is assumed based on Li *et al.* (2007) to be a function of its real power output (P_{dg}) and modeled as $C(P_{dg})=\alpha_{dg} P_{dg}^2+\beta_{dg}P_{dg}$, in which α_{dg} and β_{dg} are positive coefficients of the quadratic cost function. The start up and shut down costs of DG can be considered if they are not negligible. Renewable DGs are uncertain, non-dispatchable resources and thus are not included in this paper.

The operational cost of electrochemical storage is generally concerned with maintenance costs and here it is assumed to be a linear function of the absolute value of its charged or discharged capacity each hour. That is, $C_{str}(P_{str})=\alpha_{str}|P_{str}|+\beta_{str}$, in which α_{str} and β_{str} are positive coefficients of the linear cost function of electrochemical storage.

This study develops the model of Tsikalakis and Hatziargyriou (2008) from a single period to a multi-period optimization problem. The steady-state security issues of the micro grid contain bus voltage limits, power flow thermal limits, and also the capacity constraint of interconnection, which were neglected in Tsikalakis and Hatziargyriou (2008). Moreover, the electrochemical storage is incorporated in optimizing the operation of the micro grid.

3.1 Objective function

$$\begin{aligned}\text{Benefit}\\ &=-\sum_{t=1:24}\rho_{E,t}\cdot E_t+\sum_{t=1:24}\rho_{L,t}\cdot(\text{LOAD}_t-\sum_{i\in S_{int}}P_{curt,i,t})\\ &-\sum_{\substack{i\in S_{dg}\\ t=1:24}}\left(C_{dg,i,t}(P_{dg,i,t})\cdot I_{i,t}+\text{SC}_{dg,i,t}\cdot J_{i,t}+\text{SHC}_{dg,i,t}\cdot K_{i,t}\right)\\ &-\sum_{\substack{i\in S_{str}\\ t=1:24}}C_{str,i,t}(P_{str,i,t})\cdot U_{i,t}-\sum_{\substack{i\in S_{int}\\ t\in S_{hour,i}}}C_{int,i,t}(P_{curt,i,t}). \qquad (9)\end{aligned}$$

Herein, i is the index for bus; t is the index for hour; S_{dg}, S_{str}, and S_{int} are the sets of DG buses, electrochemical storages, and interruptible loads, respectively; $S_{hour,i}$ is the set of the permitted number of hours in which interruptible load may be curtailed, if necessary; $P_{dg,i,t}$ is the generation of DG in kW; $P_{str,i,t}$ is the amount of charge/discharge capacity of electrochemical storage at hour t in kW (negative and positive values indicate discharge and charge states, respectively); $P_{curt,i,t}$ is the un-served load; E_t is the amount of exchanged power between the micro grid and the main grid (positive and negative values indicate purchasing from and selling to the main grid, respectively); LOAD_t is the total forecasted load of the micro grid; $C_{dg,i,t}(P_{dg,i,t})$ is the generation cost function of a DG; $\text{SC}_{dg,i}$ and $\text{SHC}_{dg,i}$ are the start-up and shut-down costs of a DG, respectively; $C_{str}(P_{str,i,t})$ is the operational cost of an electrochemical storage; $C_{int,i,t}(P_{curt,i,t})$ is the cost curve of an interruptible consumer to curtail its load; $\rho_{E,t}$ is the price of the wholesale market plus the usage cost of the distribution network; $\rho_{L,t}$ is the contracted price for end consumers of the micro grid; $I_{i,t}$, $J_{i,t}$, and $K_{i,t}$ are the binary variables denoting the commitment status, start-up decision, and shut-down decision for a DG, respectively; $U_{i,t}$ is the binary variables denoting the commitment status of storage for charge and discharge.

3.2 Constraints

1. The supply-demand balancing constraint is

$$E_t+\sum_{i\in S_{dg}}P_{dg,i,t}-\eta_{str,i}\sum_{i\in S_{str}}P_{str,i,t}=\text{LOAD}_t-\sum_{i\in S_{int}}P_{curt,i,t},\quad \forall t=1:24, \qquad (10)$$

where $\eta_{str,i}$ is the round-trip efficiency of the battery and converter.

2. DG constraints:

$$P_{dg,i}^{\min}\le P_{dg,i,t}\cdot I_{i,t}\le P_{dg,i}^{\max},\ \forall i\in S_{dg},\ \forall t=1:24, \qquad (11)$$

$$(T_{i,t-1}^{\text{on}}-\text{MUT}_i)\times(I_{i,t-1}-I_{i,t})\ge 0,\ \forall i\in S_{dg},\ \forall t=1:24, \qquad (12)$$

$$(T_{i,t-1}^{\text{off}}-\text{MDT}_i)\times(I_{i,t-1}-I_{i,t})\ge 0,\ \forall i\in S_{dg},\ \forall t=1:24, \qquad (13)$$

$$\begin{cases}I_{i,t}-I_{i,t-1}\le J_{i,t},\\ I_{i,t-1}-I_{i,t}\le K_{i,t},\\ I_{i,t}-I_{i,t-1}\le J_{i,t}-K_{i,t}.\end{cases} \qquad (14)$$

Herein, $P_{dg,i}^{\min}$ and $P_{dg,i}^{\max}$ are the lower and upper limits on the generation of a DG, respectively; MUT_i and MDT_i are the integer parameters denoting minimum up and down time limits of a DG in hour, respectively; $T_{i,t}^{\text{on}}$ and $T_{i,t}^{\text{off}}$ are the numbers of hours for which the DG unit has been on and off at hour t, respectively.

3. Electrochemical storage constraints:

$$-(\text{cap}_{0,i}-P_{str,i}^{\min})\le\sum_{k=1}^{t}P_{str,i,k}\le P_{str,i}^{\max}-\text{cap}_{0,i},\quad \forall i\in S_{str},\ \forall t=1:24, \qquad (15)$$

$$P_{\text{str},i,t} \le R_{\text{str-ch},i}, \text{ if the storage is charged, } \forall i \in S_{\text{str}}, \forall t = 1:24, \quad (16)$$

$$-P_{\text{str},i,t} \le R_{\text{str-dch},i}, \text{ if the storage is discharged, } \forall i \in S_{\text{str}}, \forall t = 1:24, \quad (17)$$

where $\text{cap}_{0,i}$ is the given value of the state of charge of storage at the beginning of the scheduling period, and $R_{\text{str-ch},i}$ and $R_{\text{str-dch},i}$ are the maximum charge and discharge rates of electrochemical storage in kW, respectively.

4. Constraint of interruptible load:

$$0 \le P_{\text{curt},i,t} \le P_{\text{curt},i}^{\max}, \ \forall i \in S_{\text{int}}, \forall t \in S_{\text{hour},i}, \quad (18)$$

where $P_{\text{curt},i}^{\max}$ is the upper limit for curtailing on interruptible load.

5. Steady-state security constraints of the micro grid:

$$S_{i-j,t} \le S_{i-j}^{\max}, \ \forall i-j \in S_{\text{b}}, \ t = 1:24, \quad (19)$$

$$V_i^{\min} \le V_{i,t} \le V_i^{\max}, \ \forall i \in S_{\text{n}}, \ t = 1:24, \quad (20)$$

where S_{b} and S_{n} are the sets of branches and nodes of the micro grid respectively, $S_{i-j,t}$ is the power flow between nodes i and j, $S_{i-j}^{\max}$ is the thermal limit of line $i-j$, $V_{i,t}$ is the voltage magnitude at node i, and $V_i^{\min}$ and $V_i^{\max}$ are limits of voltage magnitudes.

6. The capacity of interconnection:

$$|E_t| \le E_{\text{exch}}^{\max}, \quad (21)$$

where $E_{\text{exch}}^{\max}$ refers to the thermal rating of the interconnection, the transformer, or the contracted capacity for exchanging power with the main grid.

3.3 Solving the model

The optimization problem is a nonlinear mixed-integer programming with hard inter-temporal constraints, i.e., Eq. (15). Mathematical techniques are not suitable for solving this problem, since they are model-based and the precise model of a system is needed for derivation. Moreover, they start from one point and the probability of being involved in local optima is high for these types of method. The major difficulty in Bender's decomposition approach is the determination of the solution of the master problem, which is still regarded as a large-scale integer optimization problem (Yamin, 2004). Some of the constraints, such as nonlinear minimum up and down time constraints, are difficult to handle in this method (Habibollahzadeh and Bubenko, 1986).

The genetic algorithm (GA) is a population-based, data-based, and free-derivative method; it takes advantages of genetic operators so that the chance of being involved in a local optimum is less in comparison with mathematical methods. Therefore, GA has the potential of obtaining a near global solution while including the constraints. GA has been employed in power system solutions for generation scheduling in electric power systems (Yang *et al.*, 1996; Christiansen *et al.*, 2000; Swarup and Yamashiro, 2002). Therefore, in this study GA is used to solve the optimization problem. In what follows, the applied GA is briefly discussed.

Each chromosome includes the outputs of DGs, charge and discharge capacities of storages, and load curtailment values. Based on the above values, 24 backward/forward power flows (Moghaddas-Tafreshi and Mashhour, 2009) are run for each chromosome to determine the power exchange between micro grid and main grid at each hour. The steady-state security constraints are checked in power flow calculations. After checking all constraints, the objective function is calculated and a penalty term is applied when the constraints are violated. The penalty function can be in two forms: (1) constant penalty and (2) variable penalty. The constant penalty approach is known to be less effective for complex problems than the variable penalty approach (Gen and Cheng, 2000). In this study, the variable penalty is employed as a function of the distance from the feasible area. For each infeasible chromosome, the summation of absolute distances of violated constraints is determined. Then this summation is subtracted from the objective function value of the worst feasible chromosome in current population; the result is considered as the value of the objective function of the infeasible chromosome. By this approach, infeasible chromosomes are not discarded and their information can be used for improving the algorithm search.

In reproduction processes, roulette-wheel selection is used for creating children for the next generation. Moreover, by a set-and-test approach it is found that two-point crossover, with a fraction of 0.7, provides good results. The mutation rate is also found by the set-and-test approach to be 0.1. The algorithm stops if there is no improvement in the objective function for a certain number of consecutive generations. In this work, the stop criterion is set for each test system by the set-and-test approach.

4 Numerical results

In this section, first a small micro grid MG1 is used to evaluate the proposed models. Then micro grid MG2 is used to show the effectiveness of the proposed models for larger micro grids with multiple DERs.

4.1 Micro grid MG1

The single-line diagram of MG1 is shown in Fig. 2a. It contains a DG at node 121 and an electrochemical storage at node 122. The forecasted load of MG1 is shown in Fig. 2b. A part of the load (up to 25 kW) may be curtailed during hours 7–8 and 11–18, if necessary. The cost of curtailing is assumed to be calculated by a quadratic polynomial function as $C(P_{\text{curt}})=0.01P_{\text{curt}}^2+P_{\text{curt}}$. The contracted price for the end consumers of the micro grid is as shown in Fig. 2c. Three scenarios are considered for the price of the wholesale market regarding the usage cost of the distribution network (Fig. 2d).

It is assumed that at the beginning of the scheduling period, DG has been off for 2 h. Different cases are considered below and the results are each analyzed.

4.1.1 Evaluating the optimization model

Case 1-A1 (Removing electrochemical storage) The electrochemical storage is removed and the price of the wholesale energy market regarding the usage cost of the distribution network is assumed to be curve (1) in Fig. 2d. The results of the optimization model are shown in Figs. 3a and 3b. During hours 1–15 and 22–24, the market price is greater than the production cost of DG; therefore, DG is on, and its generation reaches the upper level. During hours 16–21, DG is off (Fig. 3a). Comparison of Fig. 2b with curve (3) in Fig. 3b shows that the load is curtailed during hours 7–8 and 11–15. This is because during hours 7–8 and 11–15, the contracted price for the end

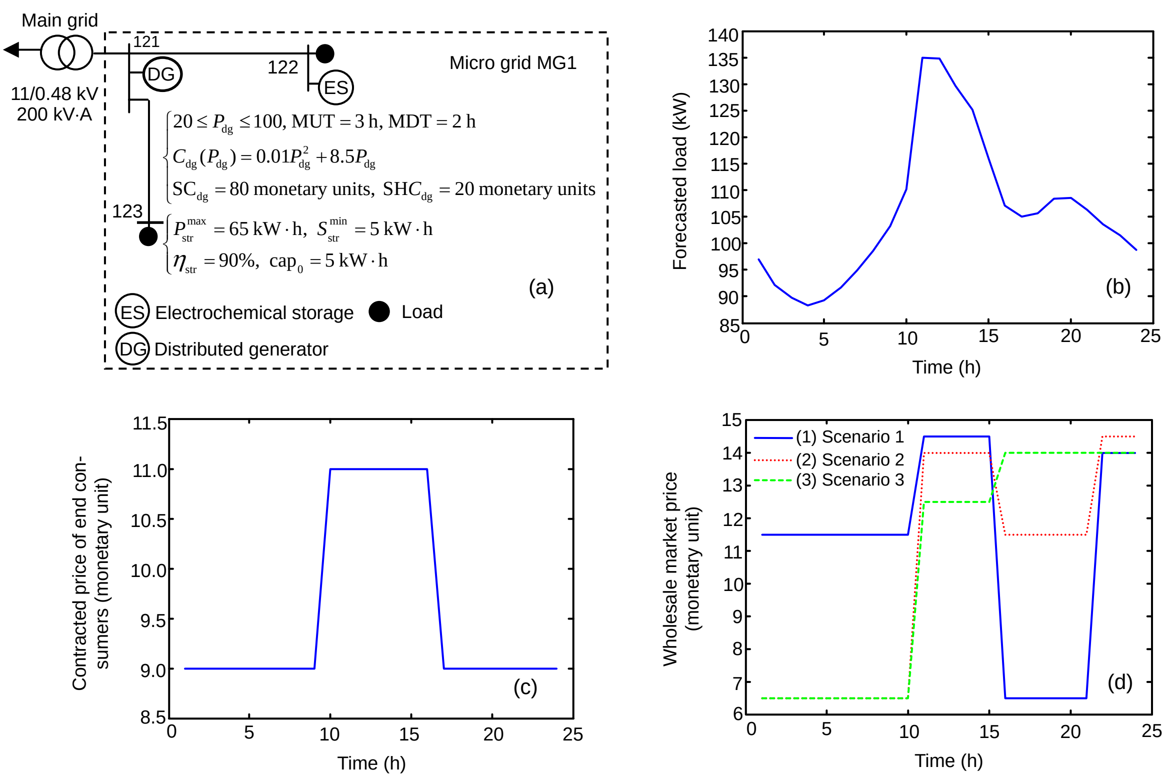

Fig. 2 MG1: (a) single-line diagram; (b) forecasted daily load curve of the micro grid; (c) contracted price for the end consumers of the micro grid; (d) different scenarios for the price of the wholesale market regarding the usage cost of the distribution network

consumers of the micro grid is lower than the price of the wholesale market; therefore, during hours 7–8, more profit is made by curtailing the load and selling power to the market (see curve (1) in Fig. 3b). Moreover, during hours 11–15, the power purchased from the market at a high price is reduced by curtailing the load. During hours 16–18, DG is off and the total consumption of the micro grid is purchased from the main grid (wholesale market) at a low price (lower than the contracted price for the end consumers of the micro grid), for which curtailing the load is unnecessary. In this case, the maximum benefit of the micro grid, as given by Eq. (9), is 1829.30 monetary units.

Case 1-A2 (Considering electrochemical storage) The electrochemical storage is considered and its maximum charge and discharge rates are assumed to be 12 kW. The cost function of electrochemical storage is assumed to be $C_{\text{str}}(P_{\text{str},t})=0.1\times|P_{\text{str}}|+0.35$. The results of the optimization model are shown in Figs. 3c and 3d. Fig. 3c shows the optimal generation and consumption of the micro grid as well as the power exchanged with the main grid. Generation of the micro grid includes the generation of DG and discharged capacity of storage. The micro grid consumption includes its supplied load and charge capacity of storage. The sign of power exchanged with the main grid shows the direction of exchanged power. Fig. 3d shows that the storage is charged during hours 1–8, in which the load is low (see curve (3) in Fig. 3c) and the market price is 11.5. Then, it is discharged during hours 11–14, in which the market price is 14.5. The storage is again charged during hours 16–21, in which the market price is low, and it is discharged during hours 21–24. In this case, the maximum benefit of the micro grid is increased to 2015.20 monetary units.

4.1.2 Sensitivity analysis

Case 1-B1 (Considering different values for maximum charge and discharge rates of storage) The price of the wholesale market is as shown by curve (1) in Fig. 2d. Three different sets are assumed for maximum charge and discharge rates of the electrochemical storage as follows and the optimization problem is solved.

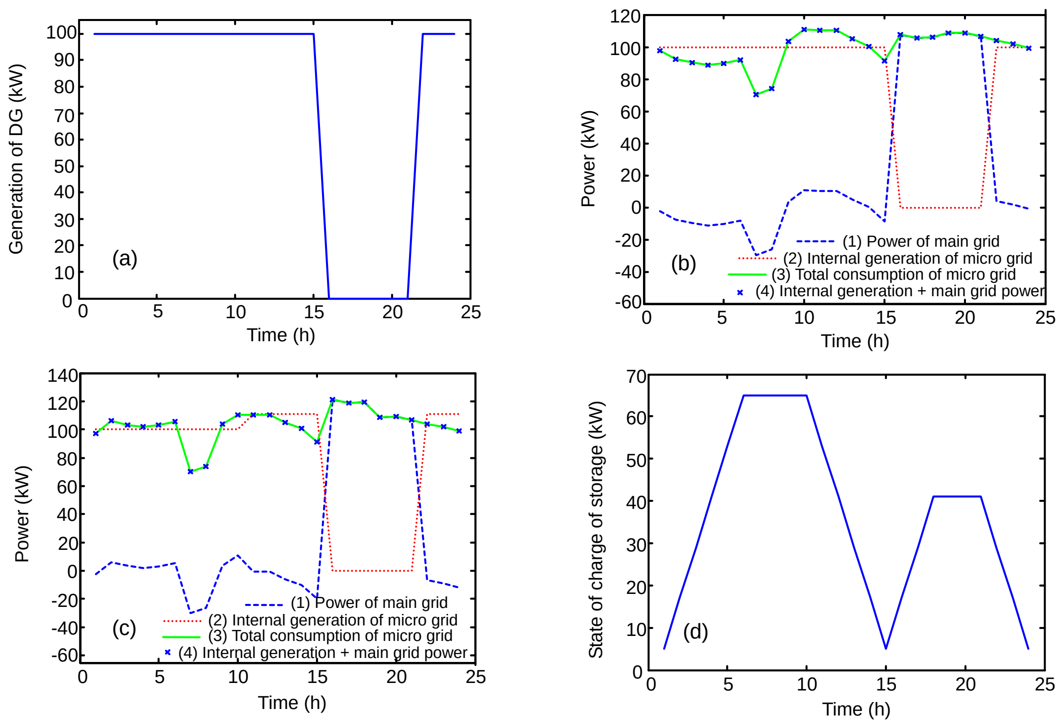

Fig. 3 MG1: evaluating the optimization problem

(a) Generation of DG (case 1-A1); (b) Total generation, consumption, and exchanging power of the micro grid (case 1-A1); (c) Total generation, consumption, and exchanging power of the micro grid (case 1-A2); (d) Charging and discharging behaviors of storage (case 1-A2). In (b) and (c), the positive value indicates that the power is absorbed by the micro grid and the negative value means that the power of the micro grid is injected into the main grid

S1: $R_{\text{str-ch}}$=12 kW, $R_{\text{str-dch}}$=12 kW;
S2: $R_{\text{str-ch}}$=10 kW, $R_{\text{str-dch}}$=10 kW;
S3: $R_{\text{str-ch}}$=11 kW, $R_{\text{str-dch}}$=8 kW.

Fig. 4 shows the charging and discharging behaviors of the storage to maximize the micro grid benefit when these assumptions are applied. For S1, the constraints of maximum charge and discharge rates of the storage are not activated and the full capacity of storage is used, so that the maximum benefit of the micro grid reaches 2015.20 monetary units. For S2, the maximum discharging capability of storage is 50 kW and 30 kW during hours 11–15 and 22–24, respectively. These capabilities are 40 kW and 24 kW respectively for S3. Therefore, the full capacity of storage is not used for sets S2 and S3. In comparison with S1, the maximum benefit of the micro grid is decreased. For all these sets, however, the maximum benefit of the micro grid is better than in case 1-A1, in which the storage is removed (Fig. 5).

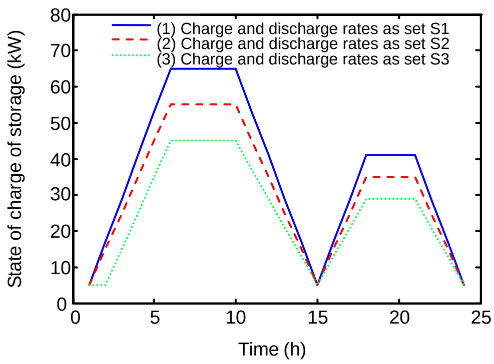

Fig. 4 MG1: comparison of charging and discharging behaviors of storage for different charge and discharge rates (case 1-B1)

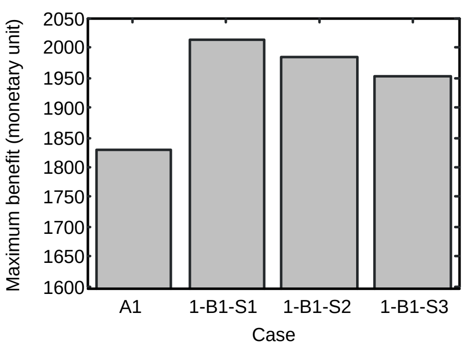

Fig. 5 MG1: comparison of the maximum benefit of the micro grid without and with electrochemical storage considering different charge and discharge rates

S1: $R_{\text{str-ch}}$=12 kW, $R_{\text{str-dch}}$=12 kW; S2: $R_{\text{str-ch}}$=10 kW, $R_{\text{str-dch}}$=10 kW; S3: $R_{\text{str-ch}}$=11 kW, $R_{\text{str-dch}}$=8 kW

Case 1-B2 (Considering different scenarios for the price of the wholesale market) The maximum charge and discharge rates of storage are considered as the set S2 defined in case 1-B1 and also three different scenarios as shown in Fig. 2d for the price of the wholesale market are taken into account. Fig. 6 compares the charging and discharging behaviors of storage for these scenarios. Curve (1) in Fig. 6 is the same as curve (2) in Fig. 4. For the second and third scenarios, the storage is fully charged during hours 1–8 in which the load and the price of the wholesale market are low. For the second scenario, 50 kW of storage is discharged during hours 11–15, and then it is again charged during hours 16–18 so that it can provide 30 kW, considering the maximum discharge rate of storage during hours 22–24. For the third scenario, full capacity of storage is discharged during hours 16–24 in which the price of the wholesale market is very high.

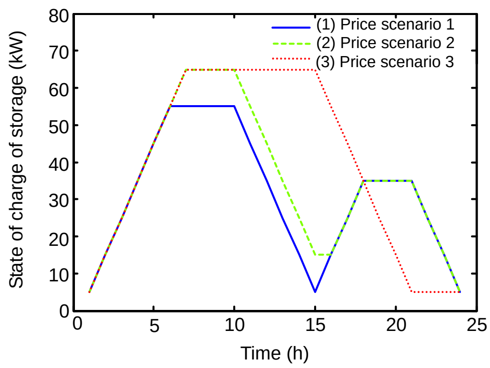

Fig. 6 MG1: comparison of charging and discharging behaviors of storage for different scenarios of market prices (case 1-B2)

Case 1-B3 (Considering different parameters for the cost function of storage) The price of the wholesale market is assumed to be curve (1) in Fig. 2d, and different values are considered for the parameters of the cost function of storage as follows:

C1: $C_{\text{str}}(P_{\text{str},t})=0.05|P_{\text{str},t}|+1$;
C2: $C_{\text{str}}(P_{\text{str},t})=0.3|P_{\text{str},t}|+2$;
C3: $C_{\text{str}}(P_{\text{str},t})=2.5|P_{\text{str},t}|+3.5$.

The charging and discharging behaviors of storage are compared in Fig. 7. For C1, the storage is charged and discharged twice during hours 1–15 and 16–24. The maximum benefit of the micro grid is 2063.68 monetary units. For C2, the storage is charged and discharged once during hours 16–24. This is because the operation cost of storage is greater than the cost reduction during hours 1–15. In this situation, the maximum benefit of the micro grid is 2032.43 monetary units. For C3, the storage is not used because the operation cost of storage is greater than the cost reduction over the scheduling period. In this situation, the maximum benefit of the micro grid is 1829.30 monetary units, which is the same as in case 1-A1.

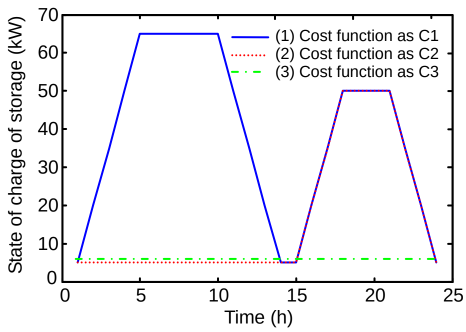

Fig. 7 MG1: comparison of charging and discharging behaviors of storage considering different parameters for the cost function of storage (case 1-B3)

4.2 Micro grid MG2

The single-line diagram of MG2 and its forecasted load are shown in Figs. 8a and 8b, respectively. The load of nodes 4 and 7 can be curtailed up to 30 kW and 40 kW, respectively, during hours 7–22 if necessary. The costs of curtailing paid to consumers are assumed to be $C(P_{\text{curt},t})=0.01P_{\text{curt},t}^2+3.5P_{\text{curt},t}$ for node 4 and $C(P_{\text{curt},t})=0.01P_{\text{curt},t}^2+1.5P_{\text{curt},t}$ for node 7. The contracted price for the end consumers of MG2 is as shown in Fig. 8c. The price of the wholesale market regarding the usage cost of the distribution network is illustrated in Fig. 8d.

Case 2-A (Base case) The results of the optimization model in this case are shown in Figs. 9a–9c. Fig. 9a shows that during hours 1–6, the productions of DG units are zero and the total demand of the micro grid is supplied by the main grid. During hours 7–18, the total demand of the micro grid is supplied by a combination of DG productions and the main grid power. During hours 19–24, the micro grid injects power to the main grid. The dispatch of DG

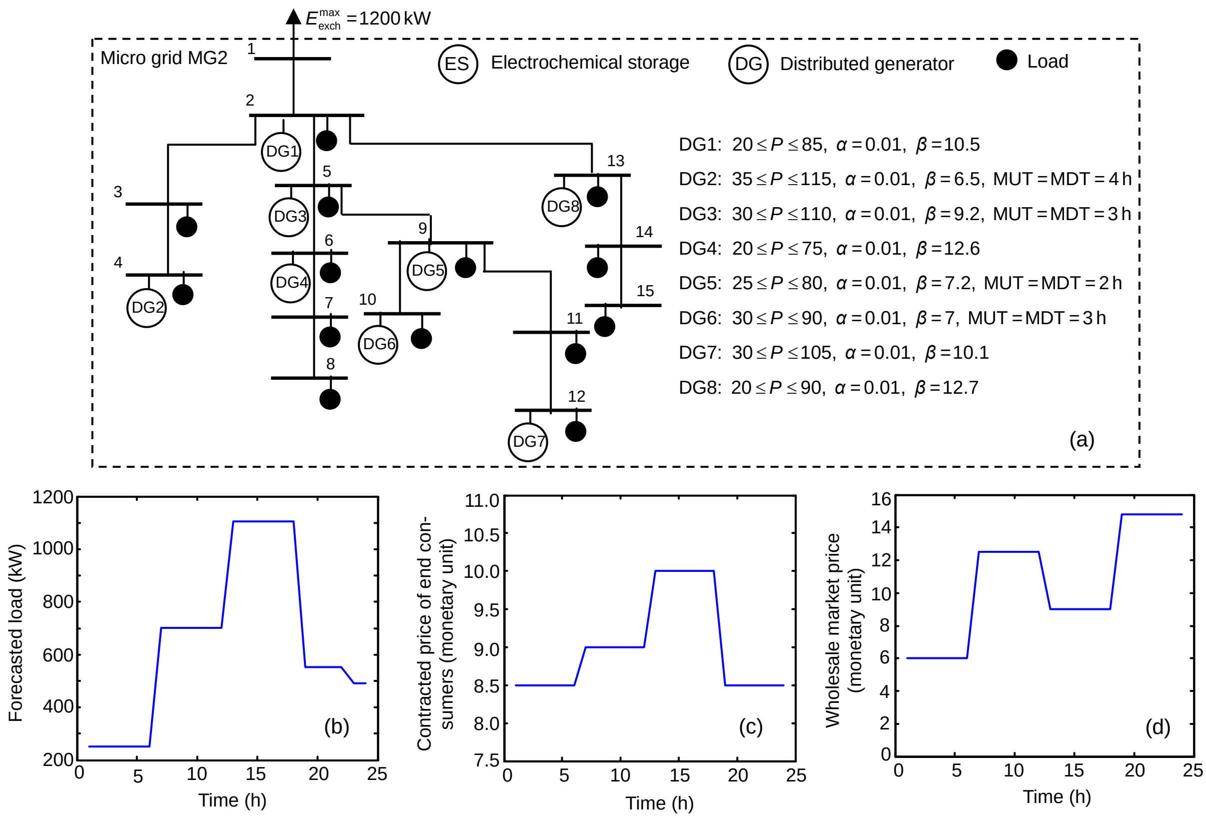

Fig. 8 MG2: (a) single-line diagram; (b) forecasted daily load of the micro grid; (c) contracted price for the end consumers of the micro grid; (d) price of the wholesale market regarding the usage cost of the distribution network

units is shown in Fig. 9b. As expected, during hours 1–6, in which the market price is very low, all DG units are off. During hours 7–12, in which the market price is relatively high, all DG units operate at their maximum level unless DG4 and DG8, which are expensive units, and they remain off. During hours 13–18, the market price is falling and the DG units whose production costs are greater than the market price (i.e., DG1, DG3, DG4, DG7, and DG8) are off. During hours 19–24, in which the market price is high, all DGs are on. Fig. 9c shows the interrupting options. As expected, the interruptible load at node 7 is interrupted during hours 8–12 and 19–22, while the interruptible load at node 4 is interrupted only during hours 19–22. This is because the cost of curtailing for node 4 is high, so that the decreased revenue from curtailing the load during hours 7–12 plus the cost of curtailing is greater than the benefit obtained via curtailing. During hours 13–18, the contracted price of end consumers of the micro grid is high (greater than the market price) and the loads are not curtailed. The best value of the objective function in this case is 5722.80 monetary units.

Case 2-B (Restricting the interconnection capacity) The capacity of interconnection ($E_{\text{exch}}^{\max}$) is limited to 700 kW and the optimization problem is solved. Figs. 9d–9f show the results. Fig. 9d shows that the amount of exchanged power (the power injected from the main grid to the micro grid) during hours 13–18 is limited to 700 kW. The dispatch of DGs (Fig. 9e) shows that during hours 13–18, DG1, DG3, and DG7 are on while they are off in Fig. 9b. In this case, the constraint of interconnection capacity is active and a part of the demand of the micro grid is inevitably supplied by DG units while production costs are greater than the market price. Fig. 9f shows the interrupting options, which are the same as in Fig. 9c. Despite restricting the capacity of interconnection, the load is not interrupted during hours 13–18. This is because during hours 13–18, the internal price for end consumers of the micro grid is higher than the production cost of DG units; therefore, the load is not curtailed. The best value of the objective function in this case is decreased to 4343.02 monetary units.

Case 2-C (Adding electrochemical storages to the micro grid) Two electrochemical storages, ES1 and ES2, are added to nodes 11 and 3, respectively.

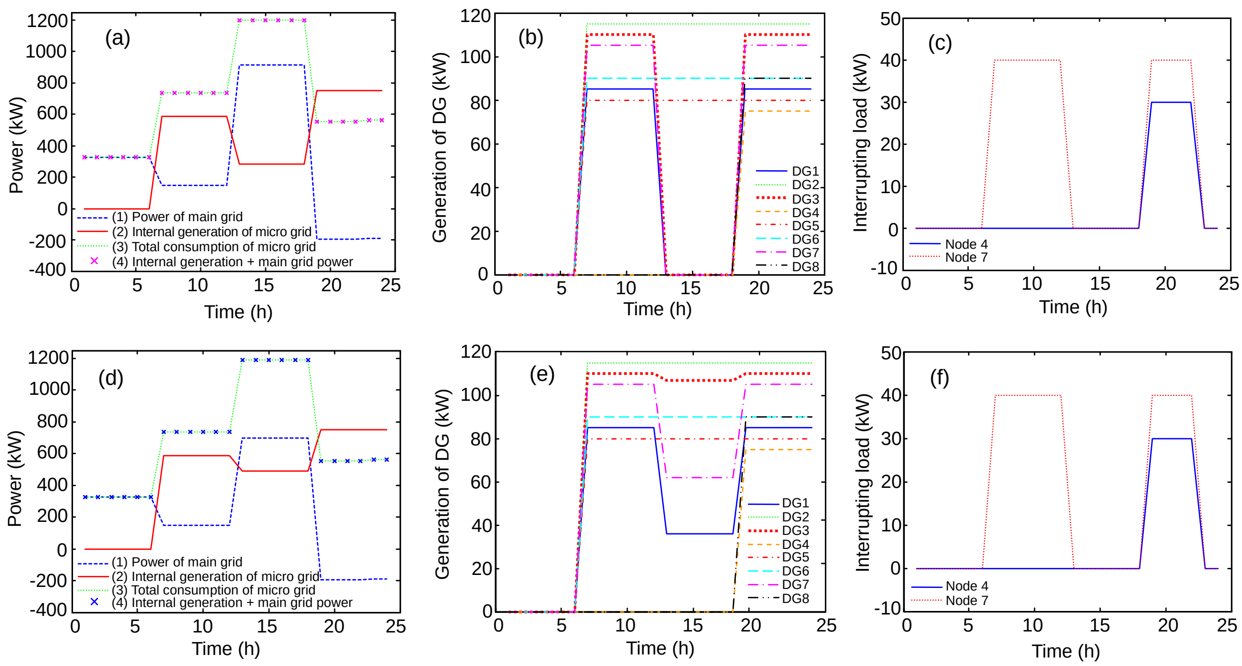

Fig. 9 MG2: cases 2-A and 2-B: (a) total generation, consumption, and exchanging power of the micro grid (case 2-A); (b) dispatch of DG units (case 2-A); (c) load interrupting (case 2-A); (d) total generation, consumption, and exchanging power of the micro grid (case 2-B); (e) dispatch of DG units (case 2-B); (f) load interrupting (case 2-B)

The characteristics of the storages are as follows:

$$\text{ES1}:\begin{cases} P^{\max}=40\ \text{kW}\cdot\text{h},\ \ P^{\min}=10\ \text{kW}\cdot\text{h},\ \ \eta_{\text{str}}=90\%,\\ R_{\text{str-ch}}=R_{\text{str-dch}}=10\ \text{kW},\ \ \alpha=0.25,\ \ \beta=1,\\ \text{cap}_0=40\ \text{kW}\cdot\text{h}; \end{cases}$$

$$\text{ES2}:\begin{cases} P^{\max}=58\ \text{kW}\cdot\text{h},\ \ P^{\min}=10\ \text{kW}\cdot\text{h},\ \ \eta_{\text{str}}=80\%,\\ R_{\text{str-ch}}=R_{\text{str-dch}}=8\ \text{kW},\ \ \alpha=0.1,\ \ \beta=0.4,\\ \text{cap}_0=10\ \text{kW}\cdot\text{h}. \end{cases}$$

The optimization problem is solved and the charging and discharging behaviors of electrochemical storages are shown in Fig. 10a. ES1 is fully charged at the beginning of the scheduling period. During hours 7–12, in which the market price is relatively high, it is discharged, and then it is charged during hours 13–18, in which the market price is relatively low. Afterward, it is discharged during hours 19–24, in which the market price is high. Although the operational cost of ES2 is less than that of ES1, it is charged and discharged only once throughout the scheduling period. This is because the efficiency of ES2 is low so that the imposed cost due to its discharging and charging during hours 7–18 is greater than the resulting cost saving in relation to market prices. Assuming η_{str}=85% for ES2, the optimization problem is solved and the charging and discharging behaviors of electrochemical storages are shown in Fig. 10b. ES2 is charged and discharged twice throughout the scheduling period. Afterward, the efficiency of ES1 is assumed to be decreased to 85% (η_{str}=85%). Fig. 10c illustrates the charging and discharging behaviors of electrochemical storages. In this case, ES1 remains charged until hour 18 and then it is discharged. Fig. 11 compares the maximum benefit of the micro grid for these scenarios.

4.3 Execution time and convergence

The presented optimization model was simulated in Matlab (Gilat, 2007) and tested on a laptop computer with a 2.5 GHz processor. For MG1, the average execution time of 10 executions of the algorithm for each case is less than 6 min. Fig. 12a shows the GA trace for maximizing the benefit of MG2 in case 2-A. The GA reaches the optimal solution after 348 generations. The average execution time in this case is 1410 s.

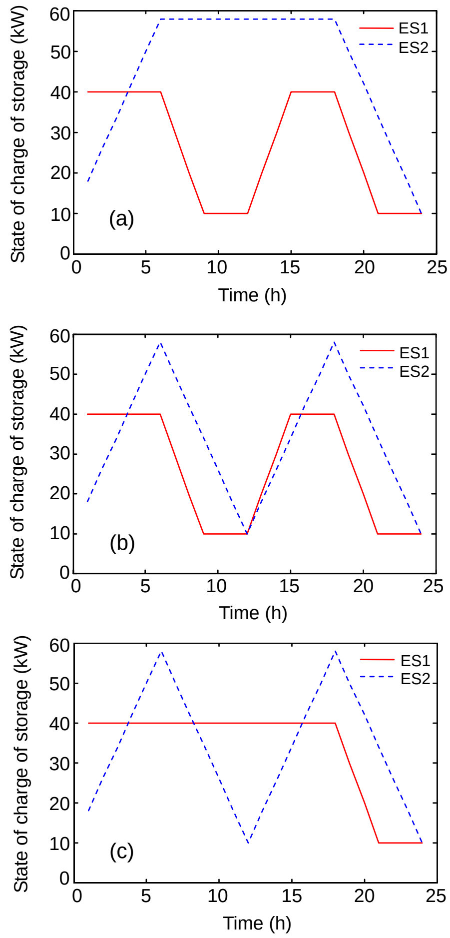

Fig. 10 MG2: evaluating behaviors of storages when efficiency of ES1 is 90% and efficiency of ES2 is 80% (a), efficiency of ES1 is 90% and efficiency of ES2 is 85% (b), and efficiencies of ES1 and ES2 are both 85% (c)

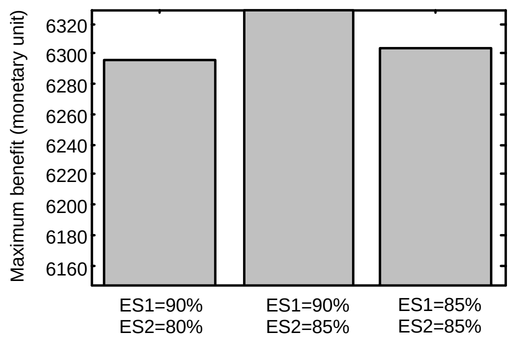

Fig. 11 MG2: comparison of the maximum benefit of the micro grid considering different values for efficiency of storages (case 2-C)

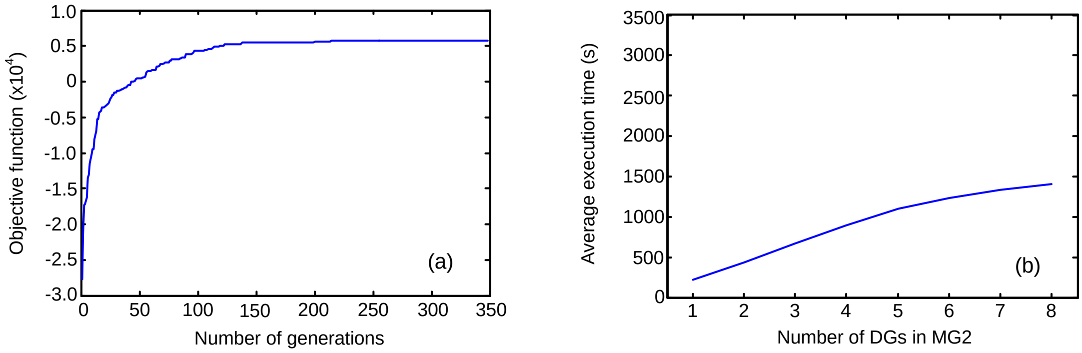

Fig. 12 MG2: (a) genetic algorithm (GA) trace for maximizing the benefit in case 2-A (base case); (b) change of execution time of the algorithm for the presence of different numbers of DGs in MG2

To evaluate the variation of simulation time with respect to the number of DG units, the optimization problem is solved for different scenarios of DG units in the micro grid, i.e., presence of 1–8 DG(s). Fig. 12b shows the average execution time for these scenarios. When the number of DG units in the micro grid is increased, the average execution time is increased. The slope of the increment of average execution time, however, is decreased by increasing the number of DG units. The average execution time is acceptable for day-ahead decision making of the micro grid, which is an off-line program with limited time.

Matlab is a high level language and it is supported by many functions which help it to be efficiently and simply applied in academic research. This is the reason why the authors used Matlab for evaluating their models. Its computational speed, however, is very low in comparison with the languages that are closer to the machine language, such as C++/C# and also JAVA. Although the calculated average execution time is satisfactory, in practical applications, it can be considerably decreased by using C++/C# or Java software for simulating the program and also applying multi-trading programming.

5 Conclusions

This paper extracts a set of mathematical formulas to simulate the steady-state charging and discharging behaviors of an electrochemical storage over a 24-hour time interval. Moreover, it develops an optimization model for 24-hour operational planning of an interconnected micro grid including electrochemical storages. The objective function is maximizing the benefit of the micro grid by optimizing the production/consumption of local distributed emergy resource (DER), and the power exchange with the upstream distribution grid. The constraints of the optimization problem include technical constraints of both DER and the micro grid. First, a small micro grid MG1 containing a distributed generator (DG), an electrochemical storage, and an interruptible load is used to evaluate the presented models. Comparison of the results of the optimization model for this micro grid, with and without electrochemical storage, shows that the electrochemical storage can improve the economical efficiency of the interconnected micro grid by up to 10.16%. The optimization problem is solved in different scenarios for the maximum charge and discharge rates of the storage, the price of the wholesale market, and also for the coefficients of the cost function of storage. Then a micro grid MG2 with 15 nodes, 8 DG units, 2 electrochemical storages, and 2 interruptible loads, is used to show the effectiveness of the presented models for larger micro grids with multiple DERs.

The average excecution time calculated for different cases of the two micro grids is acceptable for day-ahead decision making of a micro grid, which is an off-line program with limited time.

In all cases, the results show the effectiveness and quality of the procedure and validate the proposed models.

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