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Optimal droop gains assignment for real-time energy management in an islanding microgrid: a two-layer techno-economic approach

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Abstract: Real-time energy management is an important challenge in today's microgrids. In this study, a two-layer techno-economic energy management framework is proposed for an islanding microgrid. The minimisation of operation and emission costs are considered in the first layer procedure. Dynamic performance of dispatchable distributed energy resources is taken into account to improve the load following performance. Optimal operation of the microgrid is considered as an optimisation problem which is solved using modified particle swarm optimisation algorithm. In the second layer, optimal droop gains of micro-resources are assigned based on the combination of gradient descent method and minimum mean square frequency error algorithm. The proposed methodology is applied to a typical microgrid and its performance is evaluated. The simulation results show that using the proposed methodology, the frequency deviation of microgrid is reduced properly so that the results are better than the results of conventional methodology. Moreover, the microgrid energy management and power sharing between micro-sources are more economical in comparison with conventional methods.

Nomenclature

Indices

i	set of distributed generation (DG) numbers
k	set of time intervals
m	set of wind turbine numbers
n	set of photovoltaic (PV) panel numbers
s	set of iteration numbers in gradient descent methodology
y	set of bus numbers
z	set of feeder numbers

Parameters and variables

P^{PV}	output power of PV panel (W)
N_{s}^{PV}	number of series PV module cells
N_{P}^{PV}	number of parallel PV module cells
$P_{\text{ST}}^{\text{PV}}$	PV output power in standard test condition (W)
G^{T}	solar radiation (W/m^2)
G_{ST}^{T}	solar radiation in standard test condition (W/m^2)
k_{PT}	power temperature coefficient (1/°C)
T_j	cell temperature (°C)
T_j^{ST}	reference cell temperature (°C)
T_{amb}	ambient temperature (°C)
NOCT	normal operating cell temperature (°C)
P^{WT}	output power of wind turbine (W)
P_{n}^{WT}	nominal power of wind turbine (W)
v	wind speed (m/s)
v_{r}	rated speed of wind (m/s)
v_{ci}	cut-in speed of wind (m/s)
v_{co}	cut-off speed of wind (m/s)
$P_{\text{ref}}^{\text{FC}}$	fuel cell (FC) reference power (W)
V_{FC}	FC voltage (v)
P^{FC}	FC output power (W)
q_{H2}	input flow of hydrogen (kmol/s)
P_{H2}	hydrogen pressure (atm)
K_{H2}	hydrogen valve constant (kmol/atm.s)
T_{H2}	hydrogen time constant (s)
K_{r}	modelling constant (kmol/s.A)
q_{O2}	input flow of oxygen (kmol/s)
P_{O2}	oxygen pressure (atm)
K_{O2}	oxygen valve constant (kmol/atm.s)
T_{O2}	oxygen time constant (s)
$P_{\text{ref}}^{\text{MT}}$	microturbine (MT) reference power (W)
P^{MT}	MT output power (W)
K_{c}	constant gain of control system transfer function in MT model
T_{T}	time constant of turbine transfer function in MT model
K_{T}	constant gain of turbine transfer function in MT model
$f_{i,k}$	frequency of ith DG during time interval k (Hz)
$P_{i,k}$	steady-state output power of ith DG during time interval k (kW)
f_{N}	nominal frequency (Hz)
$m_{i,k}$	droop gain of ith DG during time interval k (Hz/kW)
f_k^{MG}	frequency of microgrid during time interval k (Hz)
$ct_{i,k}^{\text{op}}$	operation cost of ith DG during time interval k (cents/h)
$ct_{i,k}^{\text{em}}$	emission cost of ith DG during time interval k (cents/h)
$ct_{i,k}^{\text{esu}}$	energy storage utilisation cost for ith DG during time interval k (cents/h)
$\text{FC}_{i,k}$	fixed cost of ith DG during time interval k (cents/h)
$\text{GC}_{i,k}$	generation cost of ith DG during time interval k (cents/kWh)
$\text{EC}_{i,k}$	emission cost of ith DG during time interval k (cents/kg)
$\text{ER}_{i,k}$	emission rate of ith DG during time interval k (kg/kWh)
ESC_k	cost of energy from energy storage system (ESS) during time interval k (cents/kWh)
$P_{i,k}^{\text{sch}}(t)$	scheduled power for ith DG during time interval k (kW)
$P_{i,k}^{\text{rt}}(t)$	real-time output power of ith DG during time interval k (kW)
$t_{i,k}^{\text{ch}}$	time of change in generation for ith DG during time interval k

$t_{i,k}^{\mathrm{d}}$	time of delay in load following for ith DG during time interval k
$P_{m,k}^{\mathrm{WT}}$	output power of mth wind turbine, during time interval k (kW)
$P_{n,k}^{\mathrm{PV}}$	output power of nth PV panel, during time interval k (kW)
P_k^{load}	load power demand during time interval k (kW)
$P_i^{\min}$	lower limit of power generation for ith DG (kW)
$P_i^{\max}$	upper limit of power generation for ith DG (kW)
$P_k^{\mathrm{ch(disch)}}$	charging (discharging) power of ESS during time interval k (kW)
$P_{\max}^{\mathrm{ch(disch)}}$	power limitation of ESS (kW)
$E_k^{\mathrm{ch(disch)}}$	energy stored in (consumed from) ESS during time interval k (kWh)
$E_{\max}^{\mathrm{ch(disch)}}$	energy limitation of ESS (kWh)
η_{ESS}	efficiency of ESS
$\eta_{\mathrm{ch(disch)}}$	charge (discharge) efficiency of ESS
V_y^l	minimum allowed operation voltage of yth bus (p.u.)
V_y^u	maximum allowed operation voltage of yth bus (p.u.)
V_y	voltage of yth bus (p.u.)
I_z^{u}	upper limit of zth feeder current (A)
I_z	zth feeder current (A)
$\omega_{k,s}$	weighting coefficient for sth iteration during time interval k
$m_{k,s}^{\mathrm{ref}}$	reference droop gain for sth iteration during time interval k (Hz/kW)
$f_{k,s}^{\mathrm{ref}}$	reference frequency for sth iteration during time interval k (Hz)
$m_{k,s}$	droop gain for sth iteration during time interval k (Hz/kW)
ε	error between reference and current value of droop gain
ε_{d}	desired error between reference and current value of droop gain
R_{mf}	cross-correlation of reference droop gain and reference frequency
R_{ff}	autocorrelation of reference frequency
ζ	convergence factor
T_i	time constant for first-order equivalent model of ith DG
$i_{i,k}^{\mathrm{rms}}$	rms value of ith DG current during time interval k (A)
$I_{i,k}^{\mathrm{rms}}$	averaged rms value of ith DG current during time interval k (A)
i_l	limitation for current deviation from its average value (A)
ct^{ESS}	annual cost of the ESS ($)
C^{ESS}	capital cost of the ESS ($/kW)
O^{ESS}	operating and maintenance costs of the ESS ($/kW)
$P_{\max}^{\mathrm{ESS}_i}$	maximum power capability for the ESS of the ith DG (kW)

1 Introduction

Due to several economic and environmental considerations, energy management in today's power system, mainly in distribution networks, is very important. The various energy management strategies have been proposed for optimisation of operation cost [1, 2]. The energy management strategies proposed for microgrids control the distributed generations (DGs) output power to supply the predetermined active/reactive power demands. In [3], online power management is proposed for a microgrid using measured or short-term forecasted data of renewable energy and loads. It improves dynamic performance of microgrid along with participating customers with demand response programs for cost minimisation. Additional benefits of proposed method such as reduction in fuel and emission costs and improved nodal voltages are also taken into account. Real-time energy management system for microgrid is proposed in [4]. Minimising the cost of energy and total emissions is achieved as well as maximising the available power supplied by renewable energy resources. The cost-mitigation problem is solved by binary particle swarm optimisation.

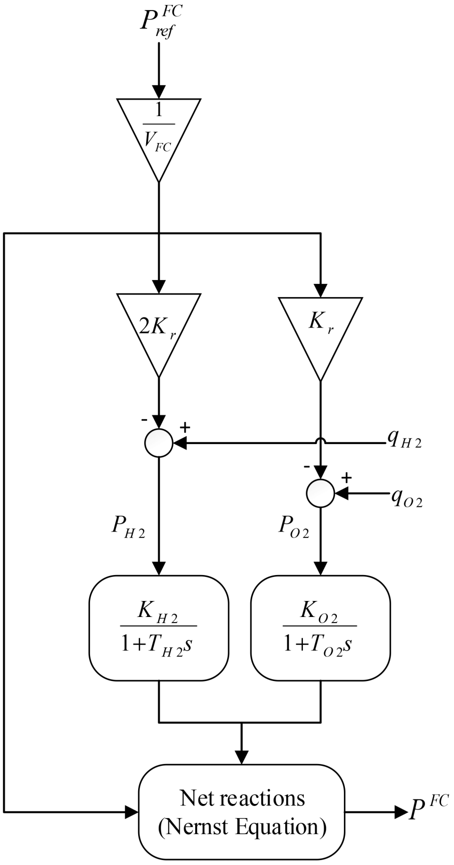
The objectives of energy management for grid-connected microgrids, generally, include peak shaving, power loss reduction, voltage and frequency control and so on. The difference between the power produced by DGs and load demand is accommodated by absorption/injection to the main grid or demand response programs [5–7]. While, in an islanding microgrid the generation of DGs cannot be predetermined and must achieve real-time response to ensure the supply-demand equality satisfaction [8]. Moreover, the system voltage and frequency should be controlled by appropriate power sharing of DGs [9].

Generally, an islanding microgrid contains several DGs such as microturbine (MT) and fuel cell (FC) with output dc voltage which is connected to the grid by voltage source converter. Due to the mechanical structure of the primary energy source (PES) of these DGs, they have low dynamic in load following. As a conventional method, the dynamic response is improved by adding energy storage systems (ESSs) like battery or supercapacitor to meet the load transients [10–13]. Based on this assumption, therefore, FC and MT are considered as ideal dispatchable power sources in previous research studies.

In islanding microgrids, the output power of inverter-based dispatchable DGs are commonly determined by conventional droop control method. Inspired from traditional power systems, droop method facilitates the power sharing between DGs and mimics the operation of governor and exciter in synchronous generators [14]. However, the droop gains should be assigned optimally. In [15], a new optimisation method is proposed to optimal operation of a microgrid with wind turbine (WT) generators. A hybrid harmonic search–genetic algorithm (GA) is developed to find optimal droop gain of DGs. Minimising the fuel consumption, voltage profile improvement and stability of the microgrid subject to operational and security constraints are the main goals which have been achieved. An optimal power flow methodology is proposed in [16] for maximum loadability in microgrid. The system constraints including DG capabilities, power flow constraints, frequency and voltage regulation are taken into account. The authors in [17, 18] have developed economic choosing of droop parameters. To find the optimum result, proposed method formulates the power flow, voltage and frequency regulation and line and generation capacity constraints. This algorithm adopts a probabilistic analytical method to deal with the stochastic nature of renewable energy sources (RES) and load demand in the absence of microgrid central controller.

In the above-mentioned works, there is not a comprehensive study considering load following performance of dispatchable DGs in microgrid energy management. In other words, no alternative solution has been proposed instead of combined utilisation of ESS and PES in each low dynamic generator. Hence, this paper proposes an energy management framework to handle both short-term optimisation and real-time scheduling of an islanding microgrid. Instead of using an ESS for each installed DG, a single ESS is considered to operate for reliable operation of the microgrid and its operation constraints are considered in the optimisation problem. Using the optimisation results and considering frequency deviation of the microgrid, optimal droop gain assignment to each micro-source is outperformed. The proposed approach is based on a two-layer techno-economic energy management framework which intensifies the reliable operation of the microgrid. The combination of gradient descent method and minimum mean square frequency error algorithm is used to determine the optimal droop gains of micro-sources. Using the proposed power sharing algorithm, the frequency deviation of the microgrid is reduced properly in comparison with conventional methodology. In addition to accelerated particle swarm optimisation (APSO) algorithm, the energy management problem is solved using GA. The simulation results show that the proposed APSO algorithm has better performance in comparison with GA.

The rest of the paper is organised as follows. In Section 2, power generation characteristic of DERs are modelled and power sharing strategy in microgrid is discussed. The proposed methodology for optimal energy management (OEM) of microgrid



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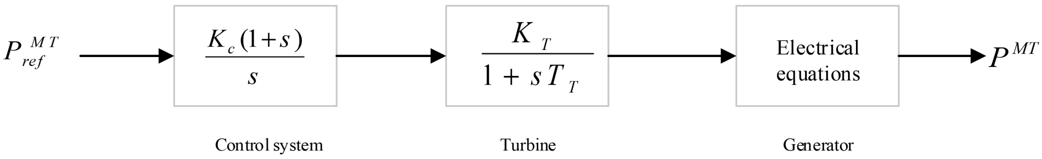


b

Fig. 1 *Dynamic model of dispatchable DGs*
(a) FC, ***(b)*** MT

is presented in Section 3. Section 4 evaluates the proposed methodology on a typical microgrid and gives the results. Finally, Section 5 consists of the conclusion remarks.

2 Problem statement

Energy management strategies depend on characteristics of the microgrid components. In this section, all of the components are modelled mathematically.

2.1 Photovoltaic (PV) panel

The output power of PV panel depends on solar irradiation. Based on maximum power point tracking techniques, the achieved solar power can be obtained according to the following equation [19]:

$$P^{\rm PV} = N_{\rm s}^{\rm PV} \times N_{\rm P}^{\rm PV} \times P_{\rm ST}^{\rm PV} \times \frac{G^T}{G_{\rm ST}^T} \times \left[1 - k_{\rm PT} \times (T_j - T_j^{\rm ST})\right] \quad (1a)$$

where

$$T_j = T_{\rm amb} + \frac{G^T}{G_{\rm ST}^T} \times ({\rm NOCT} - 20) \quad (1b)$$

2.2 Wind turbine

The WT output power depends on wind speed and can be derived according to the following equation [20]:

$$P^{\rm WT} = \begin{cases} 0, & v < v_{\rm ci} \\ P_{\rm n}^{\rm WT}(A + B \times v^3), & v_{\rm ci} \le v \le v_{\rm r} \\ P_{\rm n}^{\rm WT}, & v_{\rm r} < v \le v_{\rm co} \\ 0, & v_{\rm co} < v \end{cases} \quad (2a)$$

where

$$A = \frac{v_{\rm ci}^3}{v_{\rm ci}^3 - v_{\rm r}^3} \quad (2b)$$

$$B = \frac{1}{v_{\rm r}^3 - v_{\rm ci}^3} \quad (2c)$$

2.3 Fuel cell

The FC dynamic model is proposed in [21, 22]. A simplified representation of FC model is shown in Fig. 1*a*. It is worth to mention that FC response time depends on oxygen and hydrogen flow rate.

2.4 Microturbine

The MT comprehensive model is presented in [23]. As presented in [23], the mechanical components of MT have low dynamic in comparison of the electrical parts. Hence, a simplified model of

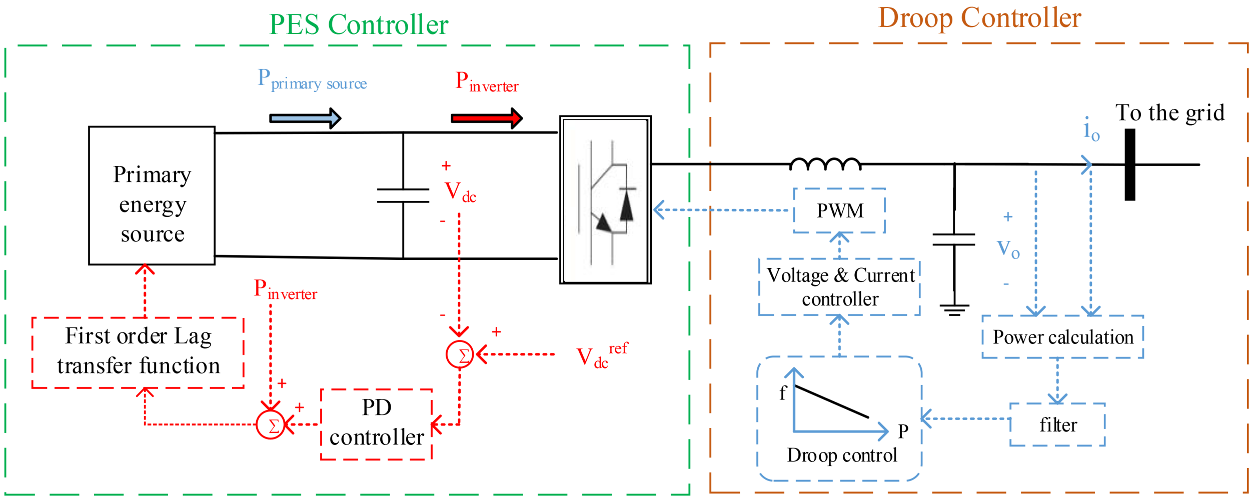


Fig. 2 *PES and droop controller of inverter-based dispatchable DGs*

MT, as shown in Fig. 1*b*, is considered for evaluation of its load following performance.

2.5 Power sharing control strategy in an islanding microgrid

Slow response of dispatchable DGs is due to their PES. According to dynamic model of FC and MT, time delay of these micro-sources can be approximated by a first-order lag transfer function [24, 25]. Control mechanism of PES is shown in Fig. 2 for an inverter-based DG. Whenever the received power from primary source is not equal to the inverter power, output dc voltage will deviate from its reference value. In PES controller, output dc voltage (V_{dc}) of primary source is compared with its reference value and the error is compensated by a proportional derivative controller.

The energy delivered to the grid is determined by droop control method which is shown in Fig. 2. Based on a mathematical relation between power and frequency of each DG, this method shares the demand power between the generators autonomously. Voltage and current controllers and pulse width modulation module are embedded subsequently to create inverter switching pulses properly.

Droop characteristic for *i*th DG in time interval *k* is formulated as follows:

$$f_{i,k} = f_{\text{N}} - m_{i,k}P_{i,k} \tag{3}$$

Worth to be noted, any power deviation would cause the frequency violation from the nominal value. Droop control guarantees that all of dispatchable DGs are producing voltages with the same steady state angular frequency [26]. Hence, the microgrid frequency can be obtained as

$$f_k^{\text{MG}} = f_{\text{N}} - m_{1,k}P_{1,k} = f_{\text{N}} - m_{2,k}P_{2,k} = \dots = f_{\text{N}} - m_{i,k}P_{i,k} \tag{4}$$

The main contribution of this paper is determining the output power and optimal droop gain for dispatchable DGs of the microgrid. A metaheuristic optimisation algorithm is applied to enhance the power sharing between DGs considering their techno-economic aspects and load following performance.

3 Proposed approach

The proposed OEM method in this paper is economic power sharing between different energy resources in an islanding microgrid considering dynamic performance of dispatchable DGs. The objective function is considered to minimise the operation cost subject to technical and environmental constraints of energy resources. The forecasted data of renewable power generation and load demand are utilised. Based on the proposed methodology, the optimal operation of microgrid is carried out using the APSO algorithm in first layer and then, in second layer the droop gain of dispatchable DGs is assigned using the iterative gradient descent methodology.

3.1 First layer optimisation approach

In this section, a mathematical representation of microgrid optimal operation is proposed to determine the output power of DGs. It consists of an objective function with equality and inequality constraints. It is assumed that FC and MT are low dynamic dispatchable DGs installed in the microgrid.

3.1.1 Objective function: RES are locally controlled in order to track their maximum power point and therefore not considered in the objective function. The main goal is minimising the cost of microgrid due to the fuel consumption and dynamic performance improvement of dispatchable DGs. Concurrently alleviation of emissions can be ensured by applying the pollution cost as a penalty factor in the cost function. Objective function for each time interval *k* can be obtained and formulated as follows:

$$\min\left\{\sum_i (ct_{i,k}^{\text{op}} + ct_{i,k}^{\text{em}} + ct_{i,k}^{\text{esu}})\right\} \tag{5}$$

The operation cost consists of fixed cost and fuel cost and is calculated as follows:

$$ct_{i,k}^{\text{op}} = \text{FC}_{i,k} + \text{GC}_{i,k} \times P_{i,k} \tag{6}$$

The emission cost depends on pollution rate of DGs and is obtained according to the following equation:

$$ct_{i,k}^{\text{em}} = \text{ER}_{i,k} \times \text{EC}_{i,k} \times P_{i,k} \tag{7}$$

The difference between scheduled (steady state) power and real-time output power of dispatchable DGs over the transient time indicates the required energy for dynamic performance improvement. This energy is supplied by a centralised ESS in the microgrid. Equation (8) calculates the cost of energy that should be generated by the ESS

$$ct_{i,k}^{\text{esu}} = \text{ESC}_k \times \left(\int_{t_{i,k}^{\text{ch}}}^{t_{i,k}^{\text{ch}} + t_{i,k}^{\text{d}}} (P_{i,k}^{\text{sch}}(t) - P_{i,k}^{\text{rt}}(t))\,\text{d}t\right) \tag{8}$$

Real-time output power of dispatchable DGs can be obtained considering the dynamic model given in Fig. 1.

3.1.2 Optimisation constraints: The microgrid should operate under technical constraints as presented in the following.

Power balance constraint: Total scheduled power for dispatchable DGs and forecasted power of RES (PV and WT) should be equal to the forecasted load demand in each time interval. In other words, microgrid power balance constraint must be satisfied. As it can be seen in (9), the ESS is not participated in unit commitment because the main role of ESS is dynamic performance improvement of dispatchable DGs

$$\sum_{i} P_{i,k} + \sum_{m} P_{m,k}^{\mathrm{WT}} + \sum_{n} P_{n,k}^{\mathrm{PV}} = P_{k}^{\mathrm{load}} \tag{9}$$

Power generation constraint: The produced power of each DG in every time interval should be in allowable boundary. Accordingly, the following constraint is enforced:

$$P_i^{\min} \le P_{i,k} \le P_i^{\max} \tag{10}$$

ESS constraints: In optimal power sharing between dispatchable DGs, the rate of power and energy from ESS is taken into account. This relates to the role of ESS in dynamic performance improvement of DGs. Hence, inequality constraint of (11a) is applied regarding the power limitation of the ESS

$$P_k^{\mathrm{ch(disch)}} \le P_{\max}^{\mathrm{ch(disch)}} \tag{11a}$$

where

$$P_k^{\mathrm{ch(disch)}} = \left| \sum_{i} (P_{i,k} - P_{i,k-1}) \right| \tag{11b}$$

Also the energy inequality constraint can be represented as

$$E_k^{\mathrm{ch(disch)}} \le E_{\max}^{\mathrm{ch(disch)}} \tag{12a}$$

where

$$E_k^{\mathrm{ch(disch)}} = \left| \sum_{i} (\eta_{\mathrm{ESS}} \times (\int_{t_{i,k}^{\mathrm{ch}}}^{t_{i,k}^{\mathrm{ch}} + t_{i,k}^{\mathrm{d}}} (P_{i,k}^{\mathrm{sch}}(t) - P_{i,k}^{\mathrm{rt}}(t))\, \mathrm{d}t)) \right| \tag{12b}$$

and

$$\eta_{\mathrm{ESS}} = \begin{cases} \eta_{\mathrm{ch}} & \text{for charging state} \\ \dfrac{1}{\eta_{\mathrm{disch}}} & \text{for discharging state} \end{cases} \tag{12c}$$

Grid operation constraints: The microgrid busses voltage and feeders current should not exceed their specified limits. Hence, the following constraints are enforced:

$$V_y^l \le V_y \le V_y^u \tag{13a}$$

$$I_z \le I_z^{\mathrm{u}} \tag{13b}$$

3.1.3 Accelerated particle swarm optimisation: Due to their exceptional ability, the metaheuristic algorithms have been used in many researches in power system studies. A comprehensive review on several optimisation algorithms is carried out in [27], where it is found that PSO algorithm is more suitable in distribution network studies. Hence, in this paper the optimal operation problem is solved using PSO algorithm. For intensification of conventional PSO algorithm, it is developed as APSO that is proposed by Yang [28, 29]. APSO uses random solutions (particles) to solve the optimisation problem. By modifying particle positions, it reaches the optimum point (fitness). To choose the new position, each particle considers the current position and the distance to current global best. Unlike the conventional PSO, the distance to particle own best location is not used. Therefore, APSO converges to optimum solution sooner.

The modified position of particle l in iteration $u + 1$ is obtained by (14), where β is typically chosen in the range of 0.1–0.7 and γ is drawn from $N(0, 1)$. g is the global best and $\alpha = 0.7^u$

$$X_l^{u+1} = (1 - \beta) \times X_l^u + \alpha \times \gamma + \beta \times g \tag{14}$$

Particles adjust their position and velocity according to the best position of all particles. Subsequently, all particles readjust their positions until being closed to an optimum point of the fitness function. The output of APSO is optimal scheduling of dispatchable DGs in operation period.

3.2 Second layer optimisation approach

After determining the optimal output power of dispatchable DGs, their droop gain is scheduled considering allowable frequency deviation of the microgrid. Finally, real-time droop characteristic is proposed.

3.2.1 Droop gain assignment: In this paper, the droop gain is assigned based on the allowable frequency deviation of the microgrid. Mathematical principle of the proposed methodology is based on minimum mean square frequency error and gradient descent algorithm [30]. Higher droop gains might lead the microgrid to instability while improving the accuracy of load sharing [31]. Therefore, scheduling of DGs output power for power sharing must be followed by optimal droop gain assignment.

Determining the droop gain has an iterative process until being converged to the desired result. In iteration s, reference droop gain and reference frequency of DG are obtained by (15) and (16). As high droop gain ensures proper load sharing [32], $\omega_{k,s}$ is initialised with high values in each time interval

$$m_{k,s}^{\mathrm{ref}} = \omega_{k,s} \times f_{\mathrm{N}} \tag{15}$$

$$f_{k,s}^{\mathrm{ref}} = f_{\mathrm{N}} - m_{k,s}^{\mathrm{ref}} \times P_{i,k} \tag{16}$$

where f_{N} is the nominal frequency of DGs and the microgrid. The estimation of current iteration droop gain is calculated as

$$m_{k,s} = \omega_{k,s} \times f_{k,s}^{\mathrm{ref}} \tag{17}$$

To adjust the droop gain, the error between its reference and current value should be lower than a desired ε_{d} as declared in (18). Allowable frequency deviation is determined according to the IEEE standards [33]

$$\varepsilon = \Delta m_{k,s} = \left| m_{k,s}^{\mathrm{ref}} - m_{k,s} \right| < \varepsilon_{\mathrm{d}} \tag{18}$$

ε_{d} is determined based on allowable frequency deviation of the microgrid. If the error does not satisfy the inequality condition, the weighting coefficient should be modified for the next iteration. In this case, the mean square error (MSE) is defined as

$$\begin{aligned} \mathrm{MSE} = E[\varepsilon^2] = E\left[(m_{k,s}^{\mathrm{ref}})^2\right] - 2 \times E\left[m_{k,s}^{\mathrm{ref}} \times f_{k,s}^{\mathrm{ref}}\right] \\ \times \omega_{k,s} + \omega_{k,s}^2 \times E\left[(f_{k,s}^{\mathrm{ref}})^2\right] \end{aligned} \tag{19}$$

Cross-correlation of reference droop gain and reference frequency and the autocorrelation of reference frequency can be written as

$$R_{\mathrm{mf}} = E\left[m_{k,s}^{\mathrm{ref}} \times f_{k,s}^{\mathrm{ref}}\right] \tag{20}$$

$$R_{\mathrm{ff}} = E\left[(f_{k,s}^{\mathrm{ref}})^2\right] \tag{21}$$

It is worth mentioning that MSE is an ascending parabolic function of weighting coefficient and has a global minimum. The gradient function of MSE can be achieved by differentiating (19) with respect to $\omega_{k,s}$ and rearranging as follows:

$$\nabla_{\rm MSE} = \frac{\partial E[\varepsilon^2]}{\partial \omega_{k,s}} = -2 \times R_{\rm mf} + 2 \times R_{\rm ff} \times \omega_{k,s} \quad (22)$$

By estimating MSE as ε^2, the gradient function can be represented as

$$\nabla_{\rm MSE} = \nabla[\varepsilon^2] = 2 \times \varepsilon \times \nabla[\varepsilon] = 2 \times \varepsilon \times \nabla \times \left[m_{k,s}^{\rm ref} - \omega_{k,s} \times f_{k,s}^{\rm ref}\right] = -2 \times \varepsilon \times f_{k,s}^{\rm ref} \quad (23)$$

Using gradient descent method which is a first-order iterative optimisation algorithm [34], the next iteration value for weighting coefficient is obtained by

$$\omega_{k,s+1} = \omega_{k,s} - 2 \times \varepsilon \times f_{k,s}^{\rm ref} \times \zeta \quad (24a)$$

where

$$0 < \zeta < \frac{1}{f_{\rm N}^2} \quad (24b)$$

The iterative process will continue until the inequality condition of (18) is satisfied. According to (4), by choosing the optimal droop gain of each micro-source, droop gain of other DGs can be obtained.

3.2.2 Time-variant droop characteristic: In previous sections, the techno-economic microgeneration dispatch was provided for steady-state operation of microgrid in each time interval as well as optimal droop gain assignment. For real-time operation of microgrid it is mandatory to schedule the droop gains considering dynamic performance of DGs. Hence, a time-variant droop characteristic is proposed in this paper in accordance with dynamic response of PES.

For determining time-variant droop characteristic, DG model is estimated with an equivalent first-order transfer function with T_i as time constant. Optimal steady-state droop gain for ith DG during time interval k is also determined as $m_{i,k}$ by gradient descent method. By these assumptions, proposed time-variant droop gain ($m_{i,k}(t)$) is formulated as follows:

$$m_{i,k}(t) = m_{i,k} + (m_{i,k-1} - m_{i,k}) \times {\rm e}^{-((t - t_{i,k}^{\rm ch})/T_i)} \quad (25)$$

In real-time operation, this droop characteristic should be applied in exact scheduled time. Hence, a mechanism is provided to determine the new time interval. In this method, $t_{i,k}^{\rm ch}$ is the time when the output current of ith DG is changed. It should be considered that this change is new in comparison to few previous seconds (Δt). These conditions are formulated as follows:

$$\left|i_{i,k}^{\rm rms}(t_{i,k}^{\rm ch}) - I_{i,k}^{\rm rms}(t_{i,k}^{\rm ch})\right| > i_l \quad (26a)$$

$$\left|i_{i,k}^{\rm rms}(t_{i,k}^{\rm ch} - \Delta t) - I_{i,k}^{\rm rms}(t_{i,k}^{\rm ch} - \Delta t)\right| \leq i_l \quad (26b)$$

In (26a) and (26b), i_l is the limitation for current deviation from its average value and $I_{i,k}^{\rm rms}$ is averaged current over few previous seconds and is calculated by trapezoidal rule [35].

The overall flowchart of proposed methodology is shown in Fig. 3.

4 Results and discussion

To verify the proposed power sharing methodology, a typical microgrid is studied and the simulation results are analysed. The microgrid operates in islanding mode and its topology is shown in Fig. 4. The microgrid contains two WTs installed at buses 6 and 16, two PV units installed at buses 5 and 10, two FCs installed at buses 7 and 14, two MTs installed at buses 3 and 12 and an ESS installed at bus 8. The parameters and data of studied microgrid are presented in Table 1.

Hourly forecasted renewable generation (WT and PV) and load demand are shown in Fig. 5.

The results of first layer, which is optimised by APSO algorithm, are presented in Table 2 including total operation costs and power sharing between energy resources. To validate APSO results, the first layer is optimised using GA as well and the results are presented in Table 3. More details about GA can be found in [27, 37]. The comparison of Tables 2 and 3 shows that the proposed algorithm has better results. The total operation costs at every hour is lower in Table 2 that is computed by APSO.

Table 4 presents the second layer optimisation results. These results indicate the values of obtained optimal droop gain for DGs and microgrid frequency regulation. It can be seen that the proper frequency regulation is achieved for all time intervals. In order to validate the proposed algorithm in the second layer optimisation, droop gains are determined based on conventional method [18] and the results are given in Table 5. The comparison of Tables 4 and 5 shows that the proposed method has better performance in reducing the frequency deviation of the microgrid.

Scheduled power of DGs according to Table 2 is applied when the conditions of (26a) and (26b) are satisfied. To evaluate the real-time performance of proposed energy management algorithm, a step change in load demand is considered in the microgrid and simulation results are shown.

The change in output power of DGs in time interval of hour 19–20 is considered. Fig. 6*a* shows the output power of dispatchable DGs. These figures are plotted from an arbitrary zero point of time. It can be seen that the output power of each DG is changed in accordance with its time-variant droop gain ((25)). Fig. 6*b* illustrates the output power of ESS for dynamic performance improvement of DGs.

Figs. 6*a* and *b* show that by means of proposed real-time energy management framework, the change in load demand is detected at exact occurrence time. By applying time-variant droop gain, output power of dispatchable DGs are increased in accordance with their primary source power. Also the lack of energy in transient time is supplied by the ESS.

As discussed in section 1, microgrid conventional structure uses an ESS in hybrid operation with each low dynamic DG. In order to compare the proposed OEM framework with the conventional structure, a cost-benefit analysis is performed. The investment and operation costs of ESS for the test microgrid are considered in both cases.

In Fig. 7*a*, the output energy of ESS for improving DGs dynamic performance is shown for the proposed method. Meanwhile, the energy consumption for each DG can be observed in each time interval. Fig. 7*b* illustrates the cumulative change in output power of DGs ($\sum_i (P_{i,k} - P_{i,k-1})$) for 24 h. In conventional method, the specific ESS for ith DG should be designed for the highest probable change in its output power. Therefore, based on Fig. 7*b*, the boxplot of changes in DGs output power is shown in Fig. 7*c* for a sample day. The maximum value of data given in Fig. 7*c* is used to choose the ESS power capacity for the DG.

The annual cost for ESS is calculated by (27) regarding the parameters given in [38]

$$ct^{\rm ESS} = \eta_{\rm ESS} \times (C^{\rm ESS} + O^{\rm ESS}) \times \sum_i P_{\max}^{{\rm ESS}_i} \quad (27)$$

For the studied microgrid, total required ESS power capacity ($\sum_i P_{\max}^{{\rm ESS}_i}$) is 88 kW in conventional power sharing structure. Meanwhile, in the proposed method, the capacity of utilised ESS is 50 kW. Calculating the annual cost shows that the proposed method costs 14,753 dollars less than the conventional structure. It can be concluded that by means of a single ESS and the proposed energy management framework, the cost of microgrid is reduced while the power sharing is properly achieved.

According to the simulation and numerical results, it can be concluded that the proposed energy management framework has some advantages in comparison with previous studies. From

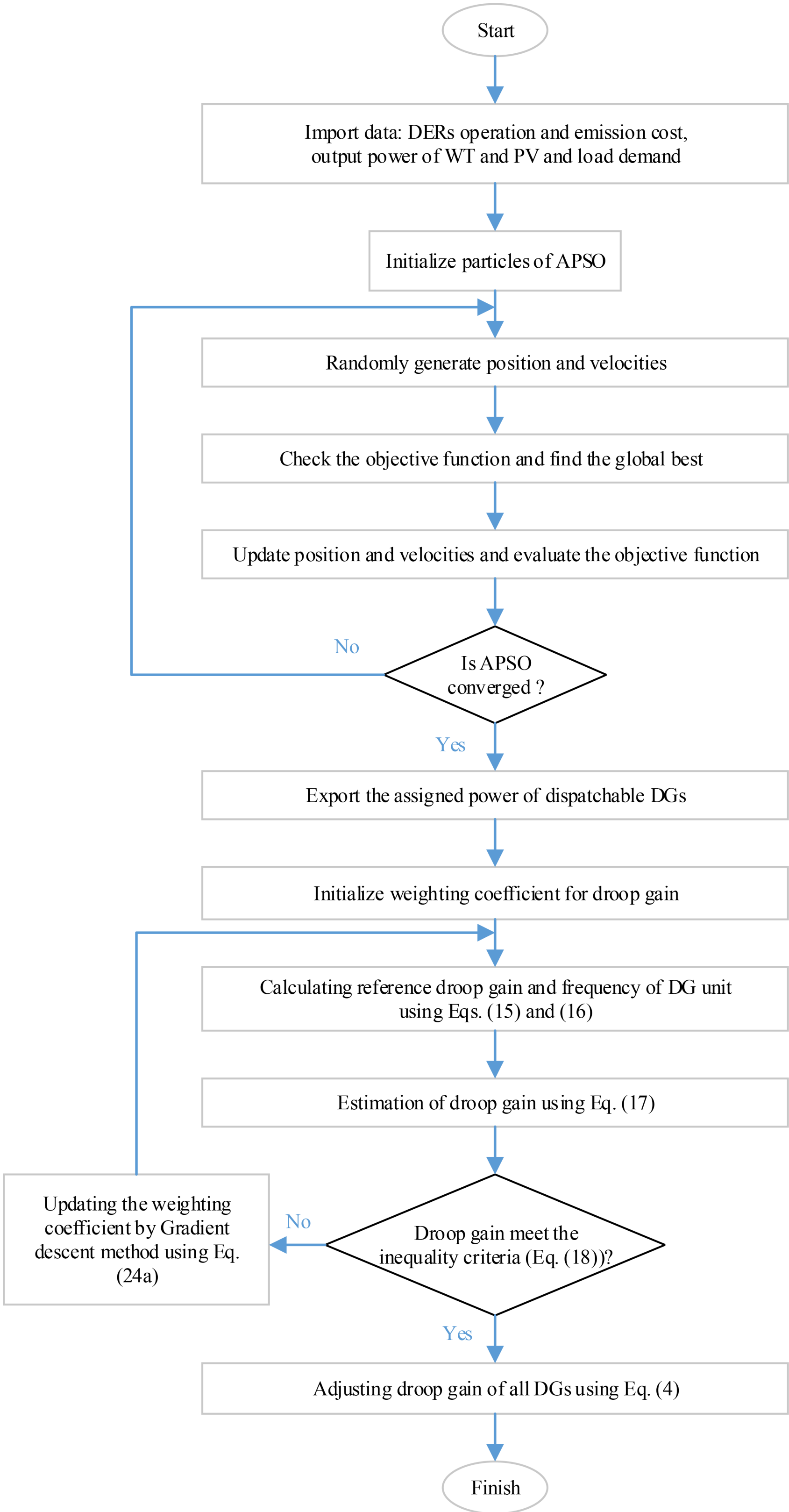


Fig. 3 *Proposed microgrid energy management algorithm*

technical point of view, optimal droop gains of dispatchable DGs are determined and a time-variant droop characteristic is proposed based on gradient descent method and least mean square algorithm. It was shown that the assigned power of dispatchable DGs are in accordance with their capability in load following. Meanwhile, the microgrid frequency regulation is improved in comparison with the conventional power sharing methods.

As a new trend, a centralised ESS is scheduled for dynamic performance improvement of dispatchable DGs in the microgrid while its power and energy limitations are taken into account. An optimisation problem is formulated to optimal scheduling of the ESS as well as minimising the microgrid operation and emission costs which is solved using the APSO. The advantage of APSO with respect to GA in microgrid cost minimisation is outperformed using numerical results. Also, the presented cost-benefit analysis proves that the scheduling cost of a single ESS is drastically lower than the conventional methods.

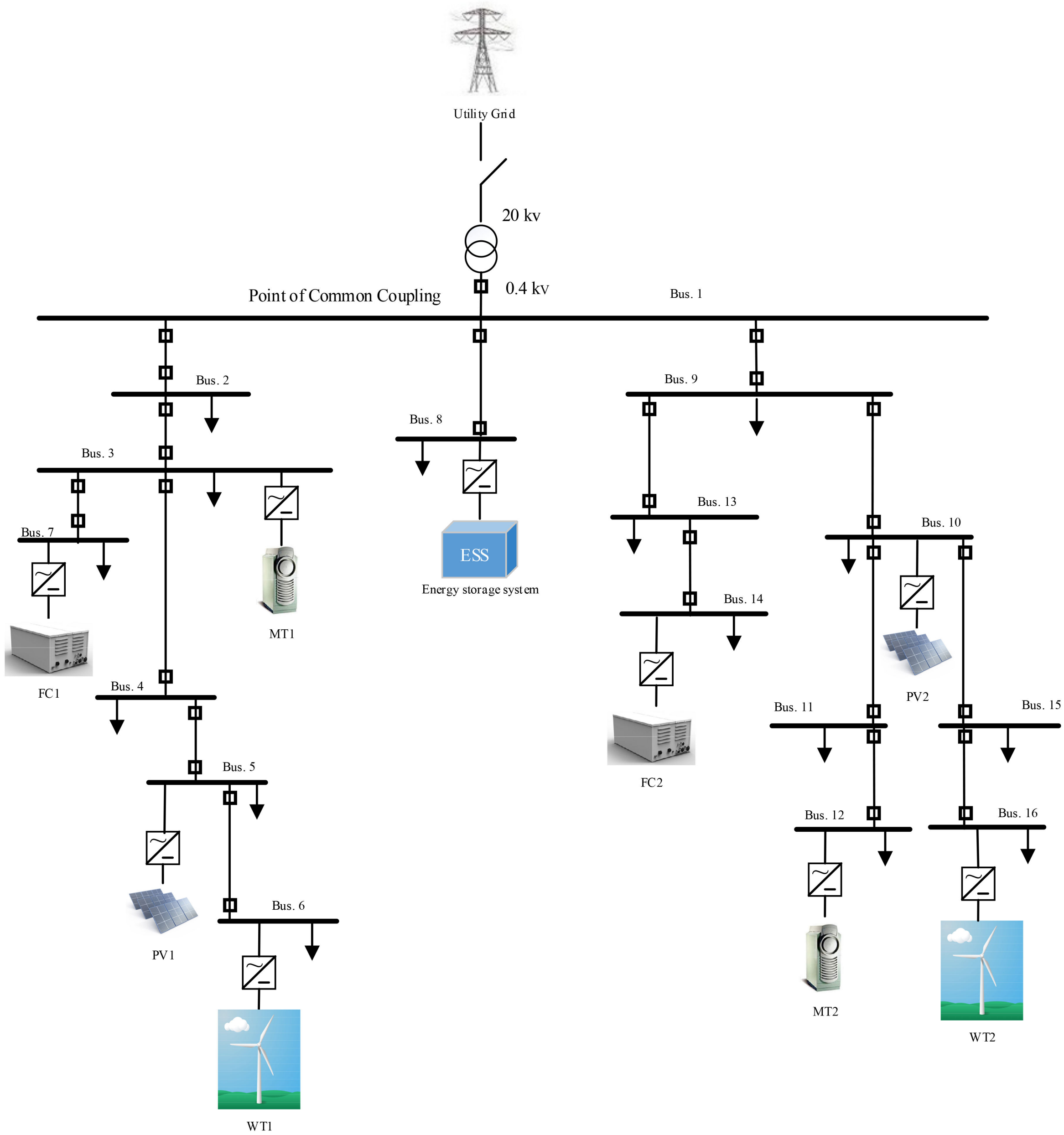


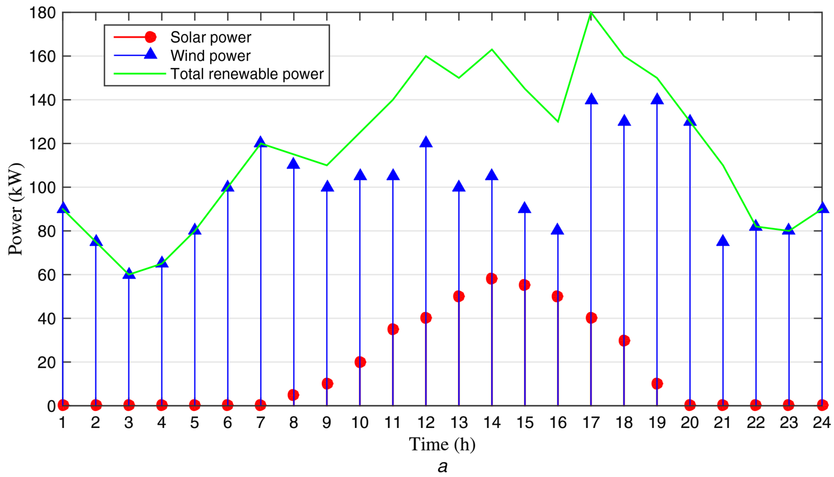
Fig. 4 *Topology of studied microgrid*

Table 1 Installed DERs of the microgrid [36]

DG	Minimum power, kW	Maximum power, kW	Fixed operation cost, cents/h	Generation cost, cents/kWh	Start-up cost, cents	Shut down cost, cents	Emission rate, kg/kWh	Emission cost, cents/kg
FC	20	100	255	2.84	16	9	0.38	4.07
MT	25	150	85	4.37	9	8	0.55	4.07
PV	0	70	—	55	—	—	—	—
WT	0	80	—	11	—	—	—	—
ESS	−50	50	—	5	—	—	—	—

5 Conclusion

In this paper, a comprehensive energy management framework was proposed considering load following performance of dispatchable DGs. A two-layer optimisation approach was presented for optimal operation of the microgrid. In first layer, DERs operation and emission cost and the cost of using the ESS for DGs dynamic performance improvement was minimised by APSO. In second layer, optimal droop gains of dispatchable DGs were scheduled based on the least frequency deviation for the microgrid. A time-variant droop characteristic was proposed for each micro-source to enhance the power sharing among the generators. A sample microgrid was considered to evaluate the proposed energy management method and simulation results were given for the real-time operation. It was shown that the demand power is properly shared between DGs while the minimum operation cost is achieved.



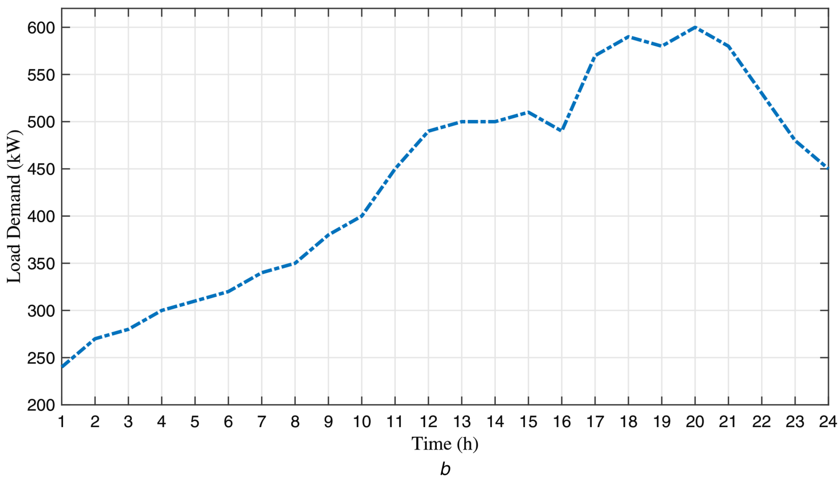


Fig. 5 *Day ahead forecasted data*
(a) Renewable power generation, ***(b)*** Load demand

Table 2 Day ahead scheduled power of dispatchable DG units and total microgrid operation cost using proposed method

Hour	Output power of dispatchable DGs, kW				Total cost, cents
	FC1	FC2	MT1	MT2	
1	45.24	41.19	27.44	36.12	2468.6
2	44.63	48.88	45.36	56.12	2585.3
3	58.55	41.19	52.43	67.81	2571.6
4	67.79	50.42	56.69	60.07	2684.4
5	75.28	57.96	45.53	51.21	2782.8
6	52.90	60.57	49.62	56.89	2980.6
7	54.39	73.73	46.72	45.14	3168.2
8	64.51	62.98	56.03	51.46	3433.6
9	75.60	70.16	68.00	56.22	3789.2
10	63.84	70.95	66.45	73.74	4451.6
11	74.39	69.39	81.00	85.20	5488.0
12	79.29	69.99	85.69	95.01	6047.8
13	72.13	63.64	102.72	111.48	6540.1
14	65.07	51.05	106.63	114.23	6993.0
15	72.07	53.52	122.19	117.20	6827.0
16	54.55	48.48	136.36	120.59	6459.2
17	59.50	49.99	133.91	146.58	6753.2
18	72.67	64.49	143.10	149.73	6295.9
19	74.06	86.42	139.22	130.28	5253.7
20	86.90	91.60	143.32	148.16	4817.8
21	91.73	99.61	132.28	146.35	4184.0
22	79.69	87.36	131.91	149.02	4169.7
23	67.80	75.01	125.39	131.78	3884.6
24	55.21	73.34	119.23	112.20	3762.2

Table 3 Day ahead scheduled power of dispatchable DG units and total microgrid operation cost using GA

Hour	Output power of dispatchable DGs, kW				Total cost, cents
	FC1	FC2	MT1	MT2	
1	41.55	58.42	25.00	25.01	2609.1
2	53.80	73.56	33.66	33.96	2680.3
3	73.73	77.59	43.35	25.31	2627
4	66.46	83.84	41.42	43.27	2783.4
5	76.05	76.49	28.84	48.61	2910.4
6	80.41	64.13	37.43	38.01	3082.2
7	74.37	77.11	26.34	42.16	3286.6
8	82.15	82.80	44.96	25.07	3520.7
9	82.51	82.15	43.66	61.66	3917.6
10	83.19	84.14	63.61	44.04	4549.7
11	95.73	97.89	48.92	67.44	5547.3
12	100	100	74.50	55.92	6106.2
13	100	100	83.62	66.45	6567.6
14	100	100	63.36	73.70	6996.6
15	100	100	90.15	75.54	6833.1
16	100	100	88.13	72.21	6464.3
17	100	100	93.45	96.57	6761.8
18	100	100	115.70	114.29	6326.1
19	100	100	114.45	115.54	5336.1
20	100	100	135.99	134.12	4940.4
21	100	100	135.83	134.16	4335.4
22	100	100	124.04	123.95	4267
23	100	100	100.25	99.74	3927.8
24	100	100	87.16	72.84	3773.5

Table 4 Optimal droop gains of dispatchable generators and microgrid frequency regulation in the proposed method

Hour	Optimal droop gain of DGs, mHz/kW				Frequency regulation, %
	FC1	FC2	MT1	MT2	
1	20.0000	21.9676	32.9753	25.0519	0.30
2	20.0049	18.2645	19.6807	15.9091	0.02
3	19.8885	28.2715	22.2082	17.1737	0.55
4	19.9260	26.7902	23.8268	22.4866	0.36
5	19.9400	25.9008	32.9674	29.3152	0.29
6	20.1790	17.6252	21.5117	18.7653	0.90
7	19.9880	14.7463	23.2718	24.0825	0.05
8	19.9190	20.4013	22.9337	24.9686	0.40
9	19.9112	21.4545	22.1366	26.7754	0.44
10	20.0940	18.0801	19.3045	17.3956	0.47
11	19.9155	21.3498	18.2908	17.3880	0.42
12	19.9607	22.6140	18.4703	16.6598	0.19
13	20.0572	22.7335	14.0846	12.9781	0.28
14	20.0564	25.5646	12.2409	11.4261	0.28
15	19.9440	26.8553	11.7637	12.2645	0.27
16	20.1401	22.6624	8.0583	9.1120	0.70
17	19.9604	23.7566	8.8699	8.1033	0.19
18	19.8946	22.4188	10.1032	9.6559	0.52
19	19.9888	17.1305	10.6334	11.3632	0.05
20	19.8972	18.8757	12.0647	11.6708	0.51
21	19.9613	18.3834	13.8428	12.5119	0.19
22	20.0963	18.3336	12.1420	10.7473	0.48
23	20.0951	18.1620	10.8653	10.3385	0.47
24	20.1007	15.1312	9.3078	9.8906	0.50

Table 5 Optimal droop gains of dispatchable generators and microgrid frequency regulation in conventional method

Hour	Optimal droop gain of DGs, mHz/kW				Frequency regulation, %
	FC1	FC2	MT1	MT2	
1	15.4944	11.0201	25.7517	25.7415	0.55
2	18.4615	13.5023	29.5077	29.2470	0.52
3	16.6566	15.8279	28.3297	48.5221	0.84
4	15.2190	12.0641	24.4195	23.3755	0.84
5	28.9249	28.7585	76.2740	45.2529	0.48
6	15.4241	19.3397	33.1353	32.6297	0.69
7	20.9670	20.2219	59.1995	36.9857	0.30
8	8.1738	8.1096	14.9350	26.7841	0.91
9	5.2824	5.3055	9.9829	7.0686	0.52
10	7.9127	7.8234	10.3484	14.9469	0.53
11	11.5133	11.2592	22.5300	16.3429	0.76
12	20.2800	20.2800	27.2216	36.2662	0.83
13	15.8978	15.8978	19.0119	23.9244	0.50
14	35.1578	35.1578	55.4890	47.7039	0.69
15	34.8391	34.8391	38.6457	46.1201	0.17
16	24.0621	24.0621	27.3030	33.3225	0.22
17	16.7171	16.7171	17.8888	17.3108	0.84
18	25.6213	25.6213	22.1446	22.4178	0.79
19	46.5078	46.5078	40.6359	40.2526	0.10
20	33.3164	33.3164	24.4991	24.8407	0.92
21	25.7021	25.7021	18.9222	19.1578	0.01
22	33.1412	33.1412	26.7182	26.7376	0.54
23	17.0344	17.0344	16.9919	17.0788	0.82
24	9.5856	9.5856	10.9977	13.1598	0.70

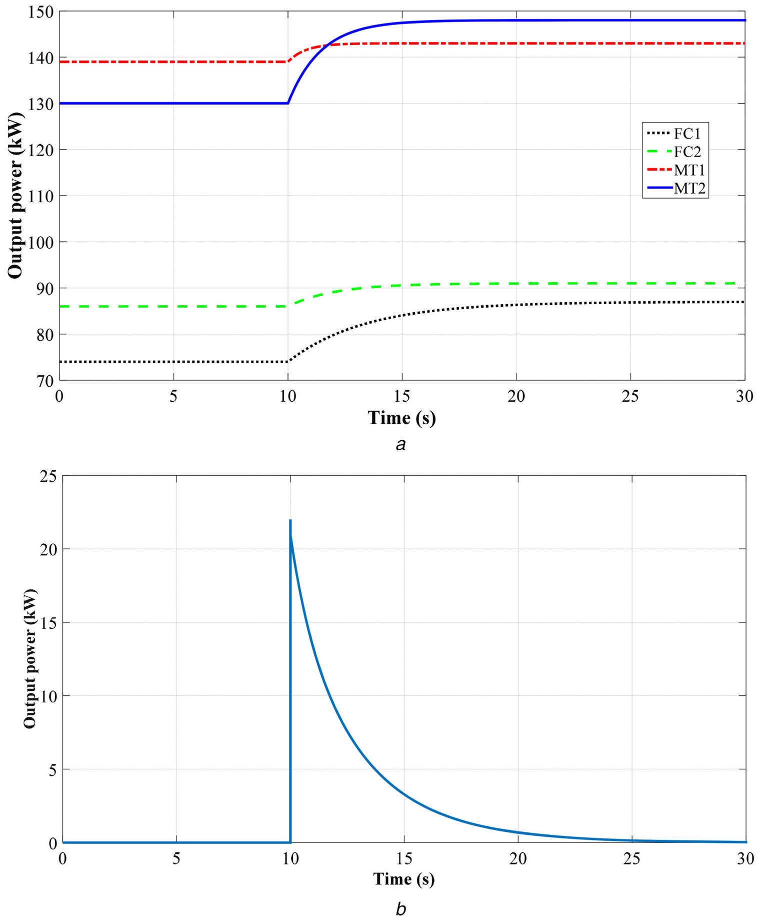


Fig. 6 *Real-time operation of power sharing mechanism*
(a) Output power of DGs, ***(b)*** Output power of ESS

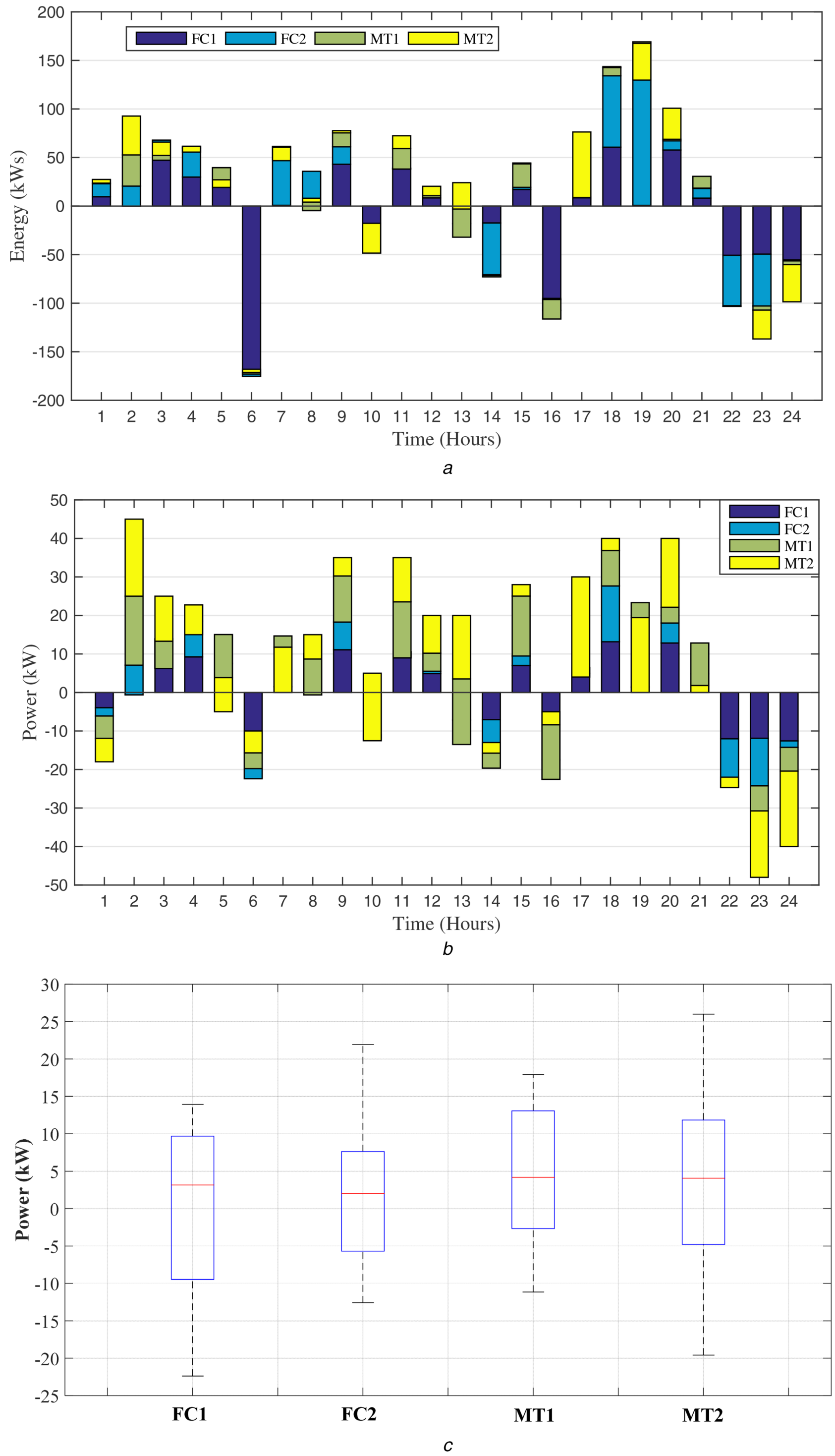


Fig. 7 *Day ahead operation of the typical microgrid*
(a) Output energy of ESS for improving DGs dynamic performance, ***(b)*** Cumulative change in output power of DGs, ***(c)*** Boxplot of changes in output power of DGs

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