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Optimal integration of renewable energy sources, diesel generators, and demand response program from pollution, financial, and reliability viewpoints: A multi-objective approach

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A B S T R A C T

In electric power systems, operators should account for the optimal operation of generation units to accommodate an efficient system with cleaner productions. In this paper, annual simultaneous planning and scheduling of generation resources are considered to determine the optimal capacity and type of the generation resources for microgrids (MGs). In the proposed approach, renewable energy sources (RESs), including wind turbines (WT) and photovoltaic systems (PVs), are incorporated in addition to diesel generators in each bus of the MG. The power loss of the MG is calculated by applying the Kron's loss formula. Three different categories of loads are considered. The impact of consumer's role on the performance of the demand response program (DRP) is also analyzed. Because of the stochastic nature of RESs, which influences the reliability, the impact of DRP on the energy not supplied (ENS) is studied. The proposed multi-objective model includes several conflicting objective functions including ENS, pollution, DRP, and operational costs. This model is solved by the ε-constraints method and optimized employing the exchange market algorithm (EMA). Simulation results highlight the impact of the generation resources' types on the cost of operation, pollution, reliability, and power loss in the MG. The proposed approach will result in a system with cleaner production and improved financial condition.

1. Introduction

Microgrids (MGs) have gained much attention recently due to their impacts on the power grid reliability, voltage profile, power loss, etc. MGs facilitate the integration of distributed generators (DGs) (Hajar et al., 2015). Diesel generators, as one of the common type of DGs, can act as controllable and reliable sources of energy with low investment cost (Deb et al., 2016). However, the utilization of diesel generators is decreasing due to the high cost of fuel and adverse environmental impacts (Askarzadeh, 2017). To this end, renewable energy sources (RES) such as photovoltaic systems (PVs) and wind turbines (WTs) have emerged as clean energy resources and widely utilized in power grids (Sheng et al., 2015). Not relying on the fossil fuels and consequently minimal environmental impacts are the most important advantages of PVs and WTs.

Due to the intermittent nature of sun's radiation and the wind speed, PVs and WTs generations are associated with some uncertainties. The integration challenges of RESs been addressed in (Mirzaei et al., 2019; Tarafdar Hagh and Khalili, 2019). Moreover, RESs are usually associated with higher investment costs (Cingoz et al., 2016; Zhang et al., 2017). Economical, technical, and environmental impacts of DGs are investigated in (Pazouki et al., 2015). A reliability assessment in an independent network which its sources are PVs and WTs is performed by (Paliwal et al., 2014). The impacts of renewable and nonrenewable generation resources from a economical point of view is analyzed in (Ruggiero and Lehkonen, 2017; Zafar et al., 2019). RESs' role in reducing the pollution is analyzed in (Shamshirband et al., 2018).

To address the challenges associated with RESs, several methods have been presented by the scholars (Li et al., 2019). One approach to reduce the operation costs, increase the reliability, and obtain the consumers' satisfaction is the demand response program (DRP) (Mahboubi-Moghaddam et al., 2016; Soares et al., 2017). The optimal probabilistic operation of the PVs in the presence of DRP is

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Nomenclature

Parameters

a, b, c	Fuel cost function's coefficients
$B_{n,n'}, B_{0,n}, B_{00}$	B matrix coefficients
C_{dsl}	Investment price rate of diesel generators
C_{ENS}	Price rate of unsupplied energy
C_{PV}	Investment price rate of PVs
C_w	Investment price rate of WTs
c_1	Scale parameter of Weibull distribution
C'_{dsl}	Installation price rate of diesel generators
C'_{PV}	Installation price rate of PVs
C'_w	Installation price rate of WTs
C''_{dsl}	Maintenance price rate of diesel generators
C''_{PV}	Maintenance price rate of PVs
C''_w	Maintenance price rate of WTs
em	Price rate of emissions
E_n	Elasticity of the consumers demand
ER_n	Emission rate
k_1	Shape parameter of Weibull distribution
$P^0_{\mathrm{LD},n,m,d,h}$	Initial demanded load by applying the DRP connected to the nth bus, in the mth month, the dth day and the hth hour
$P'_{PV,n,m,d,h}$	Maximum production capacity of the PVs connected to the nth bus, mth month, the dth day and the hth hour
$P'_{w,n,m,d,h}$	Maximum production capacity of the WTs connected to the nth bus, mth month, the dth day and the hth hour
s	Random variable of distribution function
ρ	Incentive price rate paid to consumers in the DRP
α, β	Shape parameters of Beta distribution
μ	Expectation of the normal distribution
σ	Standard deviation of Normal distribution
λ	Rate of incentive cost in the hth hour

Decision variables

B	Beta distribution function
$Cost_{DRP}$	Annual cost of DRP
$Cost_{ENS}$	Annual cost of ENS
ENS	Energy not supplied of the MG
FC	Fuel cost
f	Weibull distribution function
F_1	First objective function
F_2	Second objective function
F_3	Multi-objective function
g	Probability density function of Beat distribution function
h	Normal distribution function
$InvC$	Cost of investment of power sources
$InsC$	Cost of installation of power sources
MC	Maintenance cost
$P_{dsl,n}$	Rated power diesel generators connected to the nth bus
$P_{\mathrm{PV},n}$	Rated power of PVs connected to the nth bus
$P_{w,n}$	Rated power of WTs connected to the nth bus
$P_{D,n,m,d,h}$	Participatory power by applying the DRP connected to the nth bus, in the mth month, the dth day and the hth hour
$P_{D,total\max}$	Maximum of total acceptable participatory power in DRP
$P_{\mathrm{LD},n,m,d,h}$	Demanded load by applying the DRP connected to the nth bus, in the mth month, the dth day and the hth hour
$P_{loss,m,d,h}$	Total loss of MG in the mth month, the dth day and the hth hour
$P_{L,n,m,d,h}$	Required load by applying the DRP connected to the nth bus, in the mth month, the dth day and the hth hour
$P^1_{\mathrm{LD},n,m,d,h}$	Secondary demanded load by applying the DRP connected to the nth bus, in the mth month, the dth day and the hth hour
$P_{ns,n,m,d,h}$	Unsupplied power of the MG in the nth bus in the mth month, dth day, and hth hour
$P_{\mathrm{nu},n,m,d,h}$	Unused power of the PVs and the WTs connected to the nth bus, in the mth month, the dth day and the hth hour
$P_n, P_{n'}$	Power generation in the nth and n$'^{\mathrm{th}}$ bus
$P'_{dsl,n,m,d,h}$	Generated of diesel generators connected to the nth bus in the mth month, dth day, and hth hour
$P'_{D,n,m,h}$	Amount of reduced load connected to the nth bus in the mth month, dth day, and hth hour
$P''_{D,n,m,h}$	Amount of increased load connected to the nth bus in the mth month, dth day, and hth hour

investigated in (Majidi et al., 2017a, 2017b). In (Nojavan et al., 2017), a cost-emission model for PVs is proposed in the presence of DRP. Optimal scheduling of a renewable-based MG considering DRP is proposed in (Aliasghari et al., 2018). Due to the proven advantages in utilizing diverse DG types, selection of the optimal type and capacity of the DGs in MG is of particular importance (Mitra et al., 2016).

This paper presents an optimization approach for annual planning of DGs in a MG to ensure the reliable supply of MG loads while reducing the costs of the installation, investment, and maintenance. PVs, WTs, and diesel generators are considered as three different DG types. The proposed multi-objective model includes the DG installation costs, costs associated with pollution, DRP, and energy not supplied (ENS). By using the ε-constraints method and Exchange market algorithm (EMA), the optimal capacity of the resources connected to each bus of MG are selected. EMA (Ghorbani and Babaei, 2014) is an effective, powerful, fast, and trustable algorithm for optimizing the real world's problems. In several papers, the performance of the EMA is confirmed and validated (Khalili et al., 2018, 2019b). For instance, optimal utilization of DGs for increasing the reliability of the power systems is studied in (Khalili et al., 2019a) by EMA. In addition (Khalili et al., 2019c), presents a stochastic multi-objective model for the RES-based MGs in the presence of DRP which is also solved by the EMA.

The simulation results demonstrate the impact of the capacity selection, optimal power source type, and the DRP on the costs, reliability, and pollution of the MG. The proposed approach will result in a MG with clean production and minimal costs. This paper makes the following contributions:

1. A multi-objective optimization approach for investigating the integration of RESs accompanied by the conventional diesel generators is proposed. In addition, DRP impact on the presented model is analyzed.
2. The proposed approach incorporates the stochastic nature of RESs.

3. Environmental impacts, financial, and reliability aspects of the MG's operation are proposed as the objectives.
4. The utilized RESs, i.e., PVs and WTs, are considered as popular sources of the clean energy. The proposed approach maximizes the utilization of these resources to incorporate cleaner production and less pollution. On the other hand, the economic and reliability viewpoints are taken into consideration.

The rest of this paper is organized as follows: Section 2 discusses the proposed case study. Section 3 elaborates the formulation of the proposed model. The results and discussion of the optimization problem are presented in Section 4. Section 5 concludes the paper.

2. Case study

In the following, the utilized MG, generation resources', and loads' models in the proposed multi-objective optimization approach is elaborated.

2.1. MG model

A 6-bus MG, shown in Fig. 1, is used to examine the proposed multi-objective optimization approach. As seen, a load, PV, WT, and diesel generator is connected to each bus of the MG. The MG loss can be calculated using Kron's loss formula as

$$P_{loss} = \sum_{n=1}^{6}\sum_{n'=1}^{6} P_n B_{n,n'} P_{n'} + \sum_{n=1}^{6} P_n B_{0,n} + B_{00} \tag{1}$$

where $B_{nn'}$ matrix is provided in Table 1. This matrix renders the active power loss using the connected active power to each bus, P_n, without requiring the details of network and power flow calculations. The advantage of this method is its high computational speed and non-iterative procedure that helps with reducing the optimization time.

2.2. Sources' models

Due to the intermittent nature of sun's radiation and wind speed, the PV and WT power generation is accompanied by some uncertainties. To model the probabilistic behavior of PV and WT, Beta and Weibull functions are used, respectively. These models are built up on the data presented in (Mitra et al., 2016; Padhee et al., 2017). The Beta and Weibull distribution functions can be formulated as

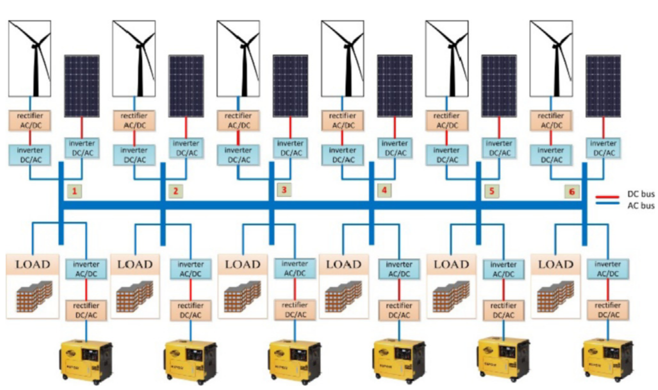

Fig. 1. Scheme of the MG

Table 1
B matrix data.

#	$B_{n,n'}(\times 10^3)$						$B_{0,n}(\times 10^3)$	$B_{00}(\times 10^3)$
	1	2	3	4	5	6		
1	1.7	1.2	0.7	−0.1	−0.5	−0.2	−0.39	56
2	1.2	1.4	0.9	0.1	−0.6	−0.1	−0.13	
3	0.7	0.9	3.1	0	−1	−0.6	−0.7	
4	−0.1	0.1	0	2.4	−0.6	−0.8	−0.059	
5	−0.5	−0.6	−0.6	−0.6	12.9	−0.2	0.216	
6	−0.2	−0.1	−0.6	−0.8	−0.2	15	−0.66	

$$g(s) = \frac{(1-s)^{\beta-1} s^{\alpha-1}}{B(\alpha,\beta)} \tag{2}$$

$$B(\alpha,\beta) = \int_0^1 s^{\alpha-1}(1-s)^{\beta-1} ds \tag{3}$$

$$f(s) = \frac{k_1}{c_1}\left(\frac{s}{c_1}\right)^{k_1-1} \times \exp\left\{-\left(\frac{s}{c_1}\right)^{k_1}\right\} \tag{4}$$

The yearly average and variance of the historical real data extracted from (Mitra et al., 2016; Padhee et al., 2017) are computed for PVs and WTs. Then, using Beta and Weibull distribution functions, intermittent RES generations are obtained. The obtained results are considered as the generation capacity limit of the RESs in each hour. It should be noted that to better estimate the PV generation, the possibility of cloudy weather and the variability of the duration of sunlight throughout the year are also considered. This is accommodated by considering a specific probability value for cloudy days and hours.

The second group of energy resources in the MG model are diesel generators. Diesel generators' model includes the cost of investment, fuel, and pollution that will be explained in Section 3.

2.3. Load model

Due to different types of consumers and their various energy consumption behaviors, the MG loads are categorized into three categories, namely, constant loads, non-responsive variable loads, and responsive variable loads that will be explained in the following subsections.

2.3.1. Constant loads

Some types of loads have constant demand; in the other words, these loads are constant all day long and cannot change their demand or participate in DRPs during the day. It is assumed that loads connected to Bus 1 to 3 are constant with the fluctuation of 5%.

2.3.2. Non-responsive variable loads

These models are modelled using the normal distribution function as (Mitra et al., 2016)

$$h(s;\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-(s-\mu)^2}{2\sigma^2}\right), \quad s \in \mathbb{R} \tag{5}$$

It is assumed that the load connected to Bus 4 is of this type. These loads are considered as critical loads and cannot participate in DRP.

2.3.3. Responsive variable loads

The probabilistic behavior of these loads is similar to nonresponsive variable loads and can be modelled using (5). However, these loads are not critical and are able to participate in DRP. These loads can transfer their unnecessary consumptions to off-peak load hours and have a willing to take part in different DRPs in order to decrease their electricity price. These loads change thorough the day according to energy price and incentive payments, and by transferring unnecessary loads from peak load hours to off-peak load hours, attempt to reduce total cost of energy consumption. In the MG model, loads connected to Buses 5 and 6 are of this type.

3. Formulation

The goal of this paper is to optimize the operation of MG in presence of renewable and conventional generation resources. Two considered groups of objective functions are converted to a single objective function. This problem is optimized by assuming that one of them is a constraint and the other is the objective, and vice versa. Then, the combined objective function is solved. Moreover, this paper investigates the impact of optimal DRP implementation on the optimal combination of resources and system costs.

The optimization algorithm, cost and objective functions, desired scenarios, and the constraints of optimization problem are discussed as follows:

3.1. EMA

EMA is an intelligent evolutionary algorithm which is inspired by the behavior of the shareholders in the stock market (Ghorbani and Babaei, 2014). In the stock market, members do their best by taking intelligent risks in order to reach the top-ranked members and achieve a better financial situation. Therefore, EMA divides the shareholders into three categories. Low-ranked, middle-ranked, and top-ranked are three considered groups which are competing to be the final best member. This goal is obtained by trading the shares. Additionally, EMA has two operators in order to find the optimal answers and cover a wide range of solutions. These operators are oscillation and not-oscillation operators which are working in the balanced and imbalanced modes, respectively.

3.1.1. Not-oscillation state in the stock market

In the balanced state of market, shareholders change their shares without considering any risk. In this state, the members with best rank in the market hold their shares intact. The members with average rank select new share values by combining the shares of best shareholders. In addition, the members with low rank in the market act similar to mid-ranked members; the difference is that these members change their shares in a wider range than members of the second group.

3.1.2. Oscillation state in the stock market

In the unbalanced state, unlike the balanced state, members take smart risks in changing their share values. Like balanced state, the members of first group do not change their share values in order to preserve their rank. The members of second and third group select new share values by combining the shares of first group members. They also take smart risks in their decisions. In both second and third groups, the less the rank of a member is, more risks are taken by that member. In the second group, the total shares of each member remain constant, but in the third group, it is possible to change the total shares of each member after combination.

3.2. Costs

In the proposed optimization problem, different cost components are considered as the objective functions that will be explained in the following subsections.

3.2.1. Costs of investment and installation of sources

The cost of investment and installation of generation sources such as PV, WT, and diesel generators are calculated using (6) and (7), respectively:

$$InvC = \sum_{n=1}^{6} P_{w,n}C_w + \sum_{n=1}^{6} P_{\mathrm{PV},n}C_{PV} + \sum_{n=1}^{6} P_{dsl,n}C_{dsl} \tag{6}$$

$$InsC = \sum_{n=1}^{6} P_{w,n}C'_w + \sum_{n=1}^{6} P_{\mathrm{PV},n}C'_{PV} + \sum_{n=1}^{6} P_{dsl,n}C'_{dsl} \tag{7}$$

3.2.2. Operation cost

The operation cost of MG includes maintenance costs for PV, WT, and diesel generators, as well as the annual fuel cost of the diesel generator and costs related to pollution, which is calculated using (8)–(10), respectively:

$$MC = \sum_{n=1}^{6} P_{w,n}C''_w + \sum_{n=1}^{6} P_{\mathrm{PV},n}C''_{PV} + \sum_{n=1}^{6} P_{dsl,n}C''_{dsl} \tag{8}$$

$$FC = \sum_{n=1}^{6}\sum_{m=1}^{12}\sum_{d=1}^{30}\sum_{h=1}^{24}\left(aP'^2 + bP' + c\right) \tag{9}$$

$$EC = \sum_{n=1}^{6}\sum_{m=1}^{12}\sum_{d=1}^{30}\sum_{h=1}^{24} em\, P'_{dsl,n,m,d,h}\, ER \tag{10}$$

The investment rate, installation, and maintenance of MG resources (Atia and Yamada, 2016), coefficients of fuel cost function (Moshi et al., 2014), pollution of diesel generator (Zangeneh et al., 2011; Pazouki et al., 2015), and investment rate, installation, and maintenance of the diesel generator (Zangeneh et al., 2011) are provided in Table 2.

3.2.3. DRP cost

This program is implemented by the incentive-based approach only for two available loads in Buses 5 and 6 which are ready to run the DRP. The annual cost of DRP is calculated using

$$Cost_{DRP} = 30\sum_{n=5}^{6}\left(\sum_{m=1}^{12}\sum_{h=1}^{24}\left(P'_{D,n,m,h} \times \lambda_h\right)\right) \qquad \mathrm{n} = 5,6 \tag{11}$$

where λ_h is set equal to 0.4 ($/kW).

In the implementation procedure of the desired incentive-based DRP, the incentive payment is considered for participants in DRP at the specific hours of day, especially peak load hours. By considering these incentive payments, the consumers are motivated to participate in DRP, and transfer unnecessary loads from peak load hours to off-peak load hours. The general mathematical equation of considered DRP is defined as follows:

Table 2
Coefficients of the fuel's cost function, pollution of diesel generator, investment rate, installation, and maintenance of diesel generator.

$C''_{PV} = 60\left(\frac{\$}{kw}\right)$	$C'_{PV} = 150\left(\frac{\$}{kw}\right)$	$C_{PV} = 3000\left(\frac{\$}{kw}\right)$	PV
$C''_{w} = 50\left(\frac{\$}{kw}\right)$	$C'_{W} = 750\left(\frac{\$}{kw}\right)$	$C_{W} = 2500\left(\frac{\$}{kw}\right)$	WT
$C''_{dsl} = 2\left(\frac{\$}{kw}\right)$	$C'_{dsl} = 0\left(\frac{\$}{kw}\right)$	$C_{dsl} = 500\left(\frac{\$}{kw}\right)$	Diesel generator
$c = 1(\$)$	$b = 0.2\left(\frac{\$}{kw}\right)$	$a = 0.00987\left(\frac{\$}{kw^2}\right)$	
$ER_{NO_x} = 4.483\left(\frac{kg}{kwh}\right)$	$ER_{CO_2} = 0.65\left(\frac{kg}{kwh}\right)$	$em = 30\left(\frac{\$}{ton}\right)$	
$ER_{CO} = 1.275\left(\frac{kg}{kwh}\right)$	$ER_{SO_2} = 0.093\left(\frac{kg}{kwh}\right)$		
$ER_{PM_{10}} = 0.16\left(\frac{kg}{kwh}\right)$			

$$P^1_{\mathrm{LD},n,m,d,h} = P^0_{\mathrm{LD},n,m,d,h} \times \left[1 + E_n(h)\frac{\lambda_h}{\rho_{\mathrm{h}}} + \sum_{\substack{t=1 \\ h\neq t}}^{24} E_n(h,t)\frac{\lambda_t}{\rho_t}\right] \tag{12}$$

$$P'_{D,n,m,h} = \begin{cases} P^0_{\mathrm{LD},n,m,d,h} - P^1_{\mathrm{LD},n,m,d,h} & \text{if} \quad P^0_{\mathrm{LD},n,m,d,h} > P^1_{\mathrm{LD},n,m,d,h} \\ 0 \quad \text{if} \quad P^0_{\mathrm{LD},n,m,d,h} < P^1_{\mathrm{LD},n,m,d,h} \end{cases} \tag{13}$$

In order to implement the proposed DRP, the loads are categorized into three levels of peak, mean, and off-peak loads. In this paper, the loads lower than 20 kW, loads between 20 and 30 kW, and higher than 30 kW are considered as off-peak, mean, and peak loads, respectively. The electricity price in the MG is considered equal to 0.35 ($/kWh). The self and cross elasticity values in the intended DRP are shown in Table 3.

3.2.4. ENS cost

If MG operator cannot supply required power of the consumer, a huge amount of money must be paid to the consumer due to the reduction of consumer reliability and lower quality of service. The cost of consumer's energy not supplied from the operator point of view is defined as

$$Cost_{ENS} = \sum_{n=1}^{6}\sum_{m=1}^{12}\sum_{d=1}^{30}\sum_{h=1}^{24}\left(P_{ns,n,m,d,h} \times C_{ENS}\right) \tag{14}$$

where C_{ENS} is set equal to 3 ($/kWh).

3.3. Objective functions

To evaluate the proposed model, three different scenarios are investigated.

3.3.1. Scenario 1

In the first scenario, despite financial constraints, the objective function is the cost of ENS according to (15), which is obtained by applying ε-constraints method as

$$\min F_1 = Cost_{ENS} \tag{15}$$

3.3.2. Scenario 2

In the second scenario, despite limitations related to ENS, the cost of operation and maintenance (O&M), which includes the cost of the MG equipment maintenance and generation resources' fuel and pollution, is calculated according to the (16) as the objective function using the ε-constraints method as

$$\min F_2 = InvC + InsC + MC + FC + EC + Cost_{DRP} \tag{16}$$

3.3.3. Scenario 3

In this scenario, the sum of the objective functions of the two previous scenarios, which have a conflicting behavior, are considered as the objective function as

$$\min F_3 = F_1 + F_2 \tag{17}$$

3.4. Constraints

The limitation of the power balance for MG is shown in (18) and (19).

$$\sum_{n=1}^{6} P'_{dsl,n,m,d,h} + \sum_{n=1}^{6} P'_{PV,n,m,d,h} + \sum_{n=1}^{6} P'_{w,n,m,d,h} + \sum_{n=1}^{6} P_{ns,n,m,d,h} - \sum_{n=1}^{6} P_{nu,n,m,d,h} = \sum_{n=1}^{6} P_{LD,n,m,d,h} + P_{loss,m,d,h} \tag{18}$$

$$P_{\mathrm{LD},n,m,d,h} = P_{L,n,m,d,h} + P_{D,n,m,d,h} \tag{19}$$

The constraint below shows the generation range of diesel generators of the MG.

$$0 \leq P'_{\mathrm{dsl},n,m,d,h} \leq P_{dsl,n} \tag{20}$$

Constraints (21) and (22) show the maximum and minimum power produced by PV and WT, respectively.

Table 3
The self and cross elasticity values of participants in the DRP.

	Peak load	Mean load	Off-peak load
Peak load	−0.1	0.16	0.12
Mean load	0.16	−0.1	0.1
Off-peak load	0.12	0.1	−0.1

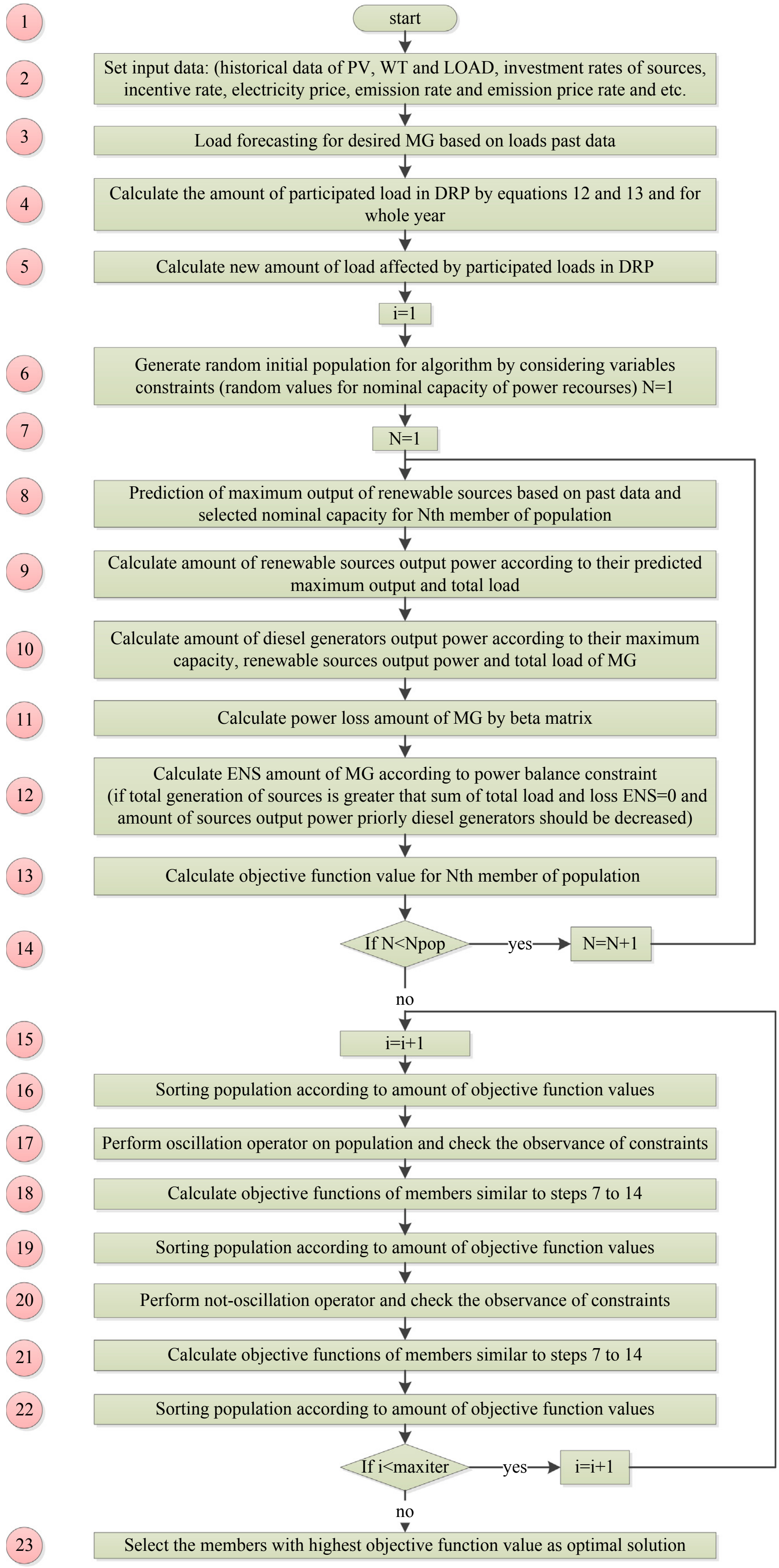

Fig. 2. The proposed multiobjective optimization algorithm using EMA.

$$0 \le P'_{PV,n,m,d,h} \le P_{PV,n} \tag{21}$$

$$0 \le P'_{w,n,m,d,h} \le P_{w,n} \tag{22}$$

Constraints related to the DRP are defined as follows.

$$-0.2\, P_{L,n,m,d,h} \le P_{D,n,m,d,h} \le 0.2\, P_{L,n,m,d,h} \;\; n = 5,6 \tag{23}$$

$$\sum_{h=1}^{24} P'_{D,n,m,h} \le P_{D,total\max} \quad n = 5,6 \tag{24}$$

$$\sum_{h=1}^{24} P'_{D,n,m,h} = \sum_{h=1}^{24} P'_{D,n,m,h} \quad n = 5,6 \tag{25}$$

The range of participatory power for Buses 5 and 6 is shown in (23). In addition, the maximum of total acceptable participatory powers in DRP is equal to ($P_{D,total\ max} = 20$ (kW)) that are shown in (24). Equation (25) expresses the equality of decreased and increased participatory power in load related to the nth bus. The maximum permissible limit of ENS in the first scenario follows from (26). In addition, the limitation for the maximum annual budget of the beneficiary in the second scenario is according to (27).

$$ENS \le 120 \text{ (MWh)} \tag{26}$$

$$InvC + InsC + MC + FC + EC + Cost_{DRP} \le 550000 \text{ (\$)} \tag{27}$$

3.5. Optimization algorithm

Fig. 2 shows the general procedure of solving the proposed optimization problem using EMA.

4. Results and discussion

The proposed optimization problem is solved in MATLAB. The number of iterations in EMA algorithm is set to 200. The average running time for one iteration is around 10 s. The total computational time average for 200 iterations is around 30 min.

By implementing the simulations and considering the objective functions and constraints of each scenario, values of the optimal nominal capacity for PV, WT, and diesel generators connected to each bus of the MG without applying and applying the DRP are shown in Tables 4 and 5, respectively.

The optimization results show that implementing DRP reduces the required generation capacity to supply the required load of MG. DRP implementation transfers load from peak load hours to off-peak load hours which in turn reduces the peak power needed in the MG. Because of the high cost of solar cells, as well as the limitation of hours of power generation that reduces the reliability of the system, their optimal selective capacity is low. Table 6 shows ENS and total MG cost expect ENS cost for all three scenarios. Table 7 demonstrates the total annual investment, O&M, and ENS costs of MG for all three scenarios.

As seen in Table 6, in the third scenario, implementing DRP results in a higher ENS. The main reason is that the objective function is the sum of ENS cost, O&M cost, and investment cost. Therefore, the implementation of DRP tries to transfer loads from hours with low renewable capacity to hours with high renewable capacity. This performance results in selecting more renewable capacity in optimal combination. As a result, the fuel and emission costs decrease which decreases the objective function value. Despite the ENS increase, implementing DRP improves the overall objective function. It should be noted that the mentioned procedure for DRP is not in line with transferring loads from peak load hours to off-peak load hours. Thus, the optimal implementation of DRP in this paper does not lead to improve the ENS value.

In the first scenario, since the objective function is ENS cost, the use of DRP reduces the ENS cost and simultaneously makes other costs approach the maximum financial constraint. In the second scenario, the use of DRP reduces the overall cost of MG, except for the ENS cost. Nevertheless, the amount of ENS is close to the maximum allowable value. Scenario 3 results in lower ENS and ENS cost (See Tables 6 and 7). This scenario also reduces the overall cost of MG. Costs of investment and installation of MG resources, as well as cost of O&M including cost of the maintenance, fuel, and pollution, are shown in Tables 8 and 9, in different scenarios, respectively.

Table 8 summarizes the investment and installation costs for the generation resources. Table 9 lists the MG O&M costs for all three scenarios. As seen in Tables 8 and 9, in Scenario 1, purchase, installation, and O&M costs are lower, and the fuel and pollution costs are higher compared to the second scenario. In Scenario 1, since the MG's costs are constrained, the mix of resources should be chosen in such a way to minimize the unnecessary costs considering the other constraints. On the other hand, since the fuel and pollution costs are more decisive than investment costs during the operating period, in Scenario 1, more RESs are used to meet the allowable cost limit which increases the costs of investment and installation and decreases the cost of fuel and pollution compared to Scenario 2. In Scenario 3, there is no limitation on the costs of investment and MG O&M, and the total costs are selected as the objective function. As a result, in order to minimize the ENS cost, which is the main objective of this scenario, more diesel generators are used which increases the fuel and pollution costs and reduces the cost of investment and installation of RESs. On the other hand, the optimal implementation of the DRP will shift the responsive variable loads from the peak load hours to the hours with higher RESs' generation; this results in reducing the dependence to the diesel generators for minimizing the ENS. Hence, implementation of DRP increases the initial investment costs and reduces the fuel and pollution costs. Among the studied scenarios, the second scenario, in which the investment and O&M costs are optimized, has the lowest pollution and fuel consumption. It can be concluded that Scenario 2, which has less fossil fuel consumption and far lower pollution, can be used to select the optimal combination of sources in the MG if only the energy supply is important to the operator.

The annual loss of MG for all three scenarios is listed in Table 10. The simulation results confirm the reduction of the loss by applying DRP. Scenario 3 has more loss than other scenarios. The reason is that this scenario does not consider the constraints of first and second scenarios; to decrease ENS which plays a significant role in the objective function, more generation capacity has been selected in the optimal combination; this results in the higher power flow in the MG which in turn increases the active power loss.

The annual average 24-h MG loads along with the effect of DRP on loads of Buses 5 and 6 are shown in Fig. 3. The results show that implementation of the DRP reduces the power needed for loads at peak hours and shifts it to low-load hours.

The annual average 24-h generations of PV and WT are shown in Fig. 4. The annual average 24-h generation of diesel generator is shown in Fig. 5. In the early hours of the day, due to MG low load, the low generation of PVs, and the large generation of WTs, less power from the diesel generators is required. On the other hand, in the evening, due to MG high load and shortage of PVs' and WTs' generation, diesel generators generate more power. In other words,

Table 4
Optimal capacity of resources without implementing the DRP (kW).

#	Selected Capacities in Scenario 1			Selected Capacities in Scenario 2			Selected Capacities in Scenario 3		
Number of bus	PV	WT	Diesel generator	PV	WT	Diesel generator	PV	WT	Diesel generator
1	0.115	26.040	7.349	0.113	6.450	9.596	0.140	11.990	19.710
2	0.159	25.086	7.182	0.110	0.386	8.180	0.163	0.477	18.520
3	0.108	1.515	9.331	0.095	4.531	7.180	0.210	0.250	21.326
4	0.145	1.148	7.614	0.250	26.038	7.638	0.483	5.450	22.387
5	0.082	0.120	7.905	0.120	11.534	8.577	0.108	8.094	18.868
6	0.095	0.108	7.377	0.080	5.962	8.278	0.115	2.295	21.576
Total capacity	0.704	54.017	46.758	0.768	54.901	49.369	1.219	28.556	122.387
Total generation capacity	101.479			105.038			152.162		

Table 5
Optimal capacity of resources by implementing the DRP (kW).

#	Selected Capacities in Scenario 1			Selected Capacities in Scenario 2			Selected Capacities in Scenario 3		
Number of bus	PV	WT	Diesel generator	PV	WT	Diesel generator	PV	WT	Diesel generator
1	0.169	0.110	9.182	0.110	0.900	7.645	0.128	5.764	18.276
2	0.110	9.307	13.395	0.105	26.810	7.945	0.122	23.485	15.486
3	0.147	13.073	9.095	0.085	0.105	7.982	0.117	11.750	13.015
4	0.095	7.074	9.175	0.130	9.690	8.685	0.105	13.639	12.446
5	0.165	3.248	8.886	0.105	0.103	8.520	0.095	0.115	12.475
6	0.115	0.317	9.419	0.080	0.113	7.770	0.180	0.296	12.340
Total capacity	0.801	33.129	59.152	0.615	37.851	48.547	0.747	55.049	84.038
Total generation capacity	93.082			87.013			139.834		

Table 6
ENS under different scenarios.

Scenarios	Without DRP		With DRP	
Objective functions and constraints	ENS (MWh)	Total cost except ENS cost ($)	ENS (MWh)	Total cost except ENS cost ($)
Scenario 1	108.68	549645	104.68	549670
Scenario 2	119.88	541988	119.998	525915
Scenario 3	7.278	711185	14.992	650170

Table 7
Annual costs of the MG ($).

Scenarios	Without DRP				With DRP				
	InvC ($)	O&M cost ($)	ENS cost ($)	Total cost ($)	InvC ($)	O&M cost ($)	DRP cost ($)	ENS cost ($)	Total cost ($)
Scenario 1	201095	348550	324040	873685	139711	406245	3714	314040	863710
Scenario 2	205573	336415	359640	901628	148772	373757	3386	359994	885909
Scenario 3	157850	553335	21834	733019	223273	457487	2410	77976	728146

Table 8
Investment and installation costs for generation resources ($).

Scenarios	Without DRP		With DRP	
	InvC	InsC	InvC	InsC
Scenario 1	160490	40605	114750	24961
Scenario 2	164280	41293	120390	28382
Scenario 3	136250	21600	181880	41393

Table 9
O&M costs ($).

Scenarios	Without DRP			With DRP		
	MC	FC	EC	MC	FC	EC
Scenario 1	3210	219600	125740	2295	251380	152570
Scenario 2	3285	211260	121870	2407	232720	138630
Scenario 3	2725	341670	207940	3637	282500	171350

Table 10
Annual power loss (MWh).

Scenarios	Total power loss without DRP	Total power loss with DRP
Scenario 1	19.884	19.552
Scenario 2	17.689	16.558
Scenario 3	37.418	26.309

because of the generation limit of RESs and their stochastic nature, by increasing the total load of MG, the optimal generation of the diesel generators increases. Comparing Figs. 3–5, one can see that, from hour 9, the total generation of the diesel generators increases as loads of Bus 1 to 3 increase. During these hours, RES units lack the enough generation capacity. The same pattern can be observed from hour 18.

The amount of annual spilled energy for each source is shown in Table 11. Because of the cost-free operation of the RESs, during most of the hours of day, except for hours that the generation capacity of

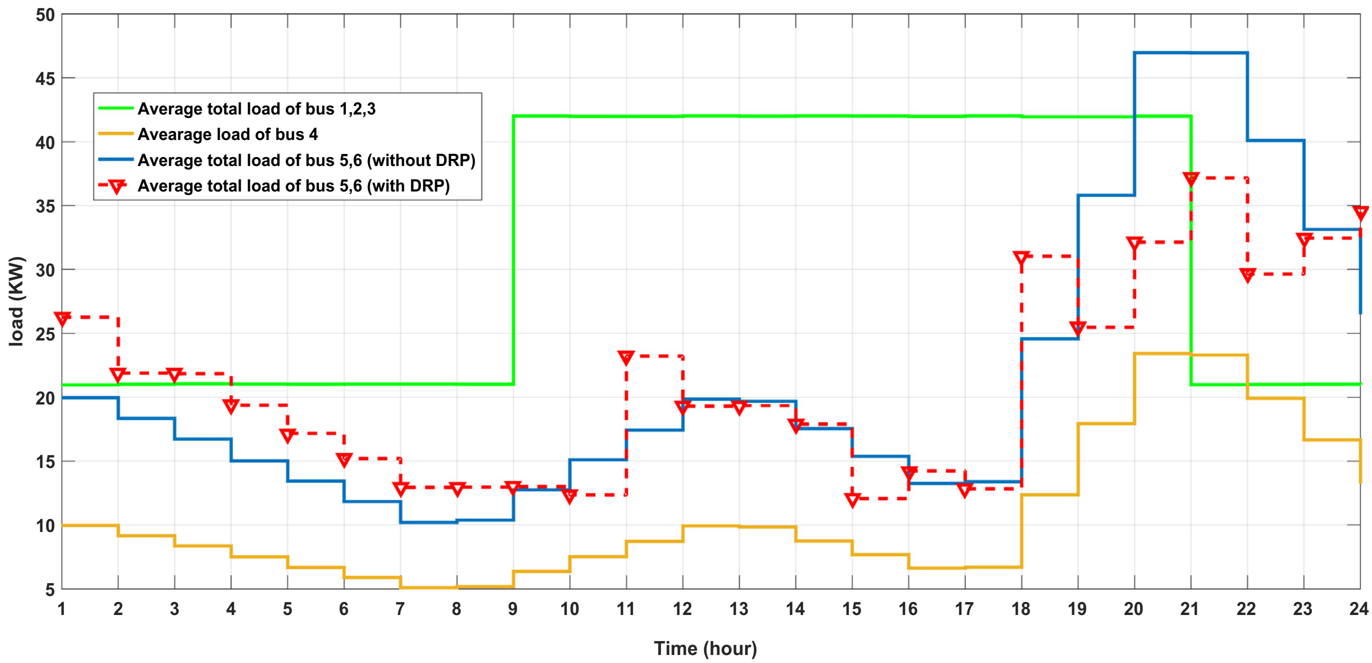

Fig. 3. Average load of the MG.

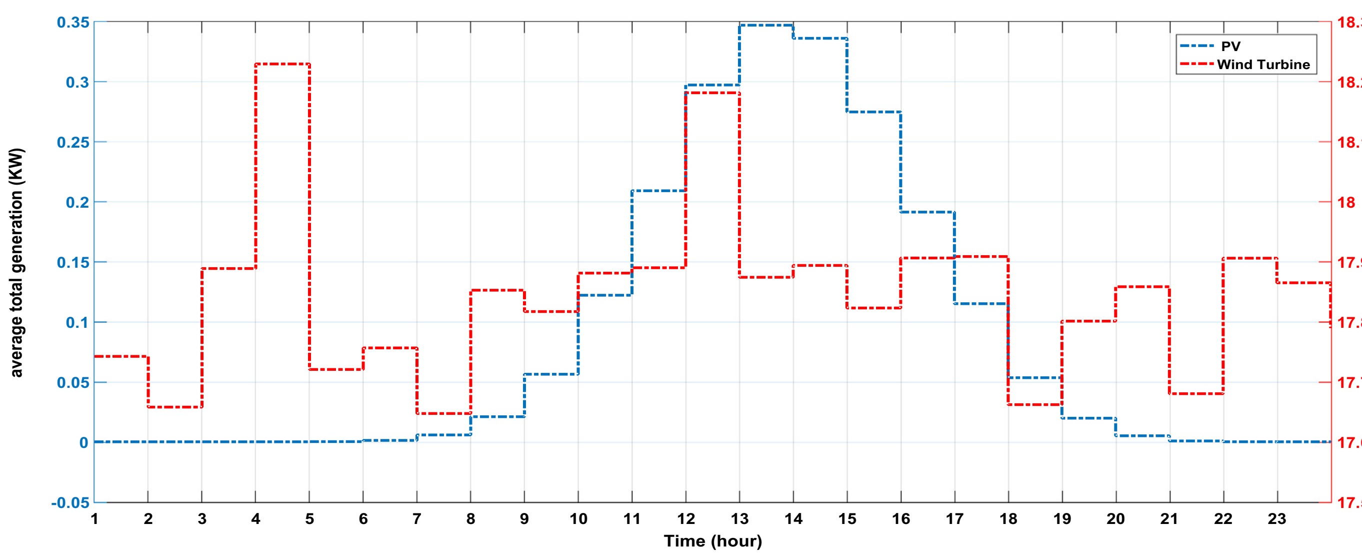

Fig. 4. Annual average generation for PV and WT.

RESs is higher than the total MG consumption, the whole generation capacity of these sources is used. Therefore, PVs and WTs from the point of spilled energy have the efficient performance, and usually their available capacity is not wasted. On the other hand, the generation capacity of the installed diesel generators during most of the hours are not used. Therefore, one can see that the invested capital on these generators during most of the hours is unusable. In the other words, the percentage of spilled energy to not supplied energy in these generators has a higher value, but their presence in the desired MG is essential in order to reach acceptable reliability.

Fig. 6 shows the impact factor of each type of generation resources on the ENS. The impact factor is defined as the ratio of the percentage of the unused energy over the percentage of the unsupplied energy. The low value of this factor is considered as an advantage for that type of generation resource because it shows that the specific generation type has utilized most of its available generation capacity towards minimizing the ENS. In other words, if most of the generated power of the generators are used, it means that source has the higher efficiency and the better impact on the ENS. In most of the hours of the day, RESs provide the needed energy of MG. Diesel generators only utilize their maximum power capacity at some hours of the day. Hence, once can conclude that in spite of the impact of diesel generators on reliability, their available capacity is not efficiently used toward minimizing the ENS. Moreover, due to the higher availability of wind rather than solar radiation in a day, WT has lower impact factor compared to PV. In addition, applying DRP improves the impact factor of each source on the ENS.

The power system operators should do their best to decrease the

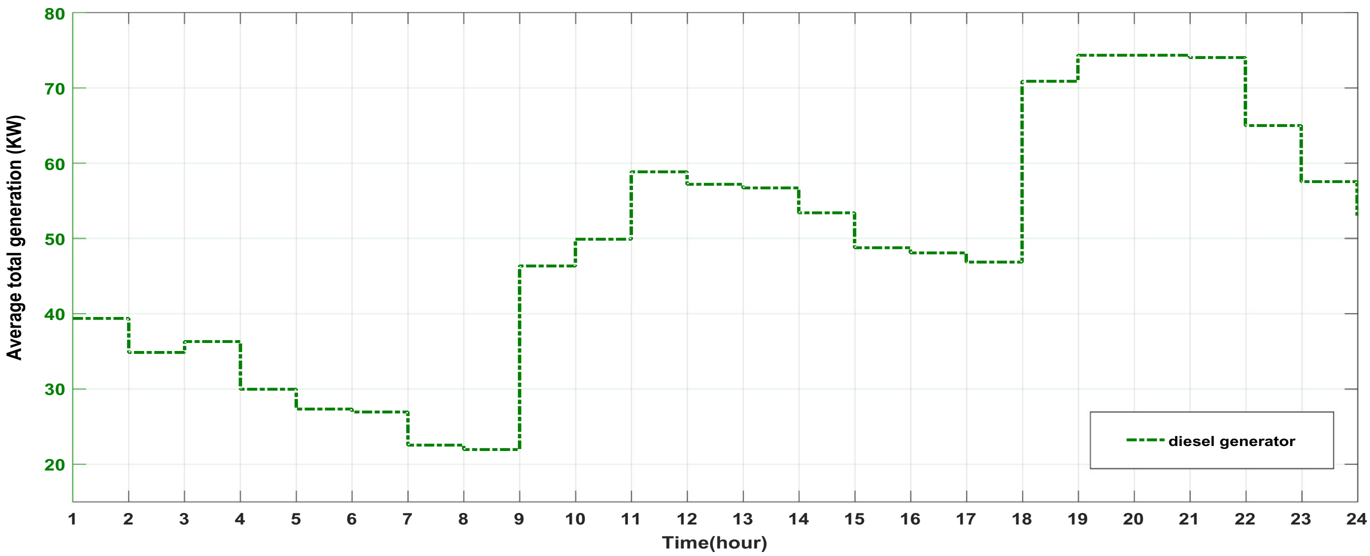

Fig. 5. Annual average generation for diesel generators.

Table 11
Spilled energy (%).

Source	Spilled energy without DRP	Spilled energy with DRP
PV	12.66	19.06
WT	12.52	7.58
Diesel Generator	51.47	41.8

pollution caused by the generation resources and increase the penetration of the RESs in their systems. Since RESs are more intermittent and less controllable than diesel generators, operators tend to utilize the conventional generators more than RESs which are environmentally friendly. However, it is of paramount value to increase the usage of RESs to have a cleaner production which is considered in this paper by maximizing the generation and benefits out of RESs.

5. Conclusions and future work

Due to the ever-increasing trend of using RESs, proper utilization of these generation resources to maximize the reliability of power system while minimizing the system costs is a significant topic. To this end, this paper presents a multi-objective optimization approach to select the suitable type and capacity of the generation resources. The performance of a six-bus MG integrating RESs and diesel generators is investigated. Demanded loads of the MG are divided into three categories of constant loads, non-responsive variable loads, and responsive variable loads. The

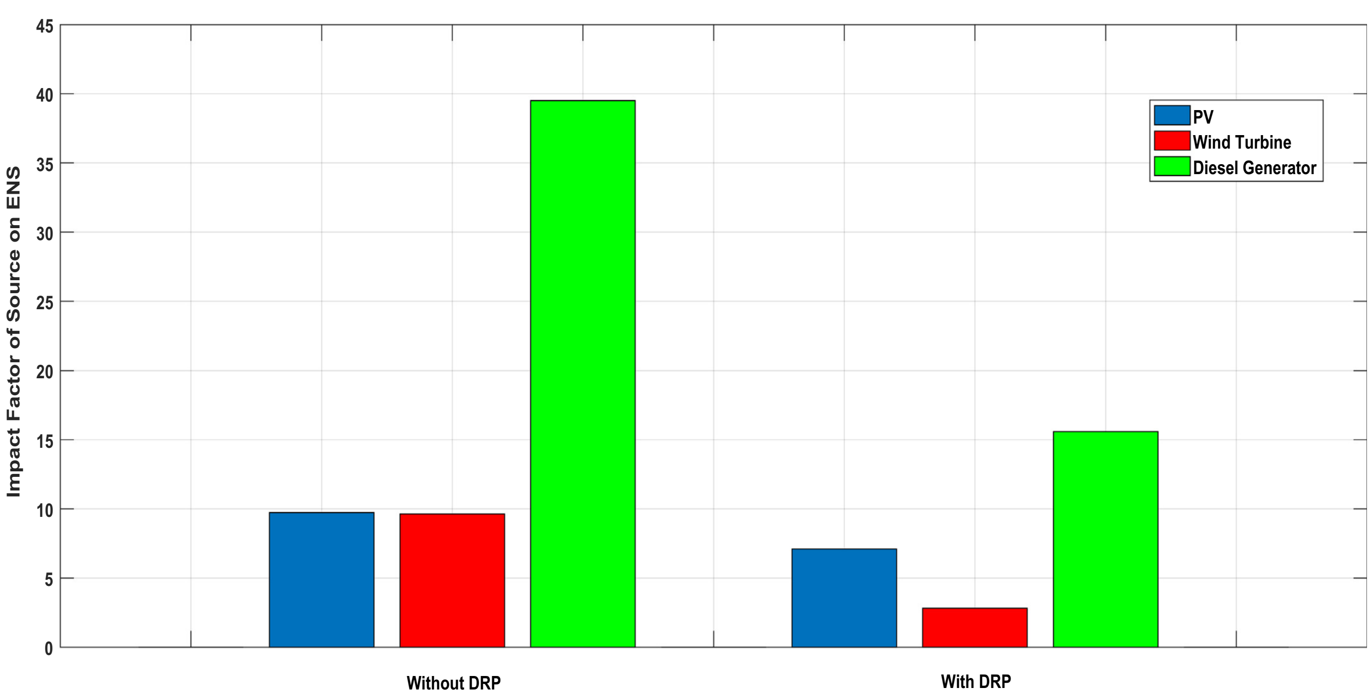

Fig. 6. Impact factor of each type of generation sources on the ENS.

generation resources are of RES and diesel generator types. Diesel generator disadvantages are emission of air pollutants and the high generation cost due to their fuel consumption. The positive features of diesel generators are their high reliability, availability, and controllability. On the other hand, PVs and WTs are emission-free and do not require any fuel for power generation. However, their intermittent nature can negatively impact the reliability of MG. By EMA and using ε-constraints method, costs of operation, pollution, DRP, and ENS is optimized. The simulation results demonstrate that how the proper allocation of different generation resources can mitigate their negative impacts. Additionally, the impact of DRP on the selection of the optimal type and capacity of the resources and ENS of the MG is studied.

The proposed multi-objective optimization approach provides the following contributions:

1. It smooths out a path for the reliable integration of RESs which promotes a cleaner production pattern in electric power systems.
2. Accounting for the pollution costs in the proposed multi-objective model, the presented approach minimizes the emissions from generation resources while tackling the challenges associated with the stochastic nature of RESs. Moreover, MG's costs and reliability and DRP are simultaneously considered in the proposed model to accommodate an acceptable economical and reliable MG operation.
3. An impact factor is defined to show the contribution of each type of generation resources toward minimizing ENS. The simulation results highlight the higher efficiency and impact of RESs for ENS minimization. It is shown that despite of the impact of diesel generators on reliability, their available capacity is not efficiently used toward minimizing the ENS.

In the future work, researchers can study the effect of the other types of generation resources on this proposed model. In addition, this model could be examined on the other MGs in order to be investigated. Moreover, some economic and facility-related limitations can be considered in the proposed approach.

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