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# A novel severity performance index for optimal allocation and sizing of photovoltaic distributed generations

Hassan M.H. Farh [a,*], Abdullah M. Al-Shaalan [a], Ali M. Eltamaly [b,c], Abdullrahman A. Al-Shamma'a [a,d]

[a] Electrical Engineering Department, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia
[b] Sustainable Energy Technologies Center, King Saud University, Riyadh 11421, Saudi Arabia
[c] Electrical Engineering Department, Mansoura University, Mansoura 35516, Egypt
[d] Department of Mechatronics Engineering, College of Engineering, Taiz University, Taiz 6803, Yemen

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ABSTRACT

Optimal allocation and sizing of the distributed generations (DGs) attract great attention of many researchers all over the world. In this study, the problems associated to optimal DGs allocation and sizing are divided into two sub-problems. One of them deals with the DGs allocation at the critical buses and the other aims to select the optimal size of these DGs. A novel severity performance index (*SPI*) is introduced to evaluate both the power system reliability and quality. The crow search (CS) is integrated with PSO not only to collect the merits of both CS and PSO but also to solve the optimal power flow problem including multi-DGs allocated at the critical buses for the IEEE 30-bus test system. Detailed comparisons of four distinct DGs allocation cases are presented, discussed, and analyzed. The simulation findings proved that the DGs allocated based on the multi-objectives (*SPI*, total fuel costs; $F_C$; and power losses; $P_L$) have a superior performance compared to other cases in terms of voltage profile, branches loading, power losses, and total costs. Therefore, the multi DGs is preferred to be allocated based on these multi-objectives (*SPI*, $F_C$, and $P_L$) in order to attain additional techno-economic benefits to the power system.



## 1. Introduction

The distributed generations (DGs) with appropriate allocation and sizing attract a great attention of many researchers all over the world. It becomes inevitable not only to overcome the conventional distribution system shortcomings but also to attain additional technical, and economical benefits with low investment. The appropriate allocation and sizing of the DGs into the existing distributed system participate in minimizing both the power losses and the power generation cost, fuel saving, voltage profile improvement, network reinforcement, and power system reliability and quality enhancement. In addition, installation of the DG units closer to load centers will, effectively, reduce the transmission and distribution costs and, in the meantime, will improve the reliability of the connected supply continuity to the connected loads (Rao et al., 2013; Viral and Khatod, 2012; Hung and Mithulananthan, 2013; Hung et al., 2013).

Although, the incorporation of the DGs into the existing distribution system avails great advantages and recompenses, it may involve some challenges and obstacles that confront the designers/planners during power system planning, installing and operations. The major challenges during DGs planning process are stemmed in optimal allocation, sizes, specific objectives and constraints needed to be considered. Therefore, the appropriate allocation and sizing of DGs based on specific objectives indices has become an essential issue during the power system planning stage. The majority of researches (Hung et al., 2013; Aman et al., 2014; Borges and Falcao, 2006; El-Zonkoly, 2011; Moradi and Abedini, 2012; Poornazaryan et al., 2016; Shin et al., 2007; Moradi and Abedini, 2016; Mohanty and Tripathy, 2016; Gampa and Das, 2015; Acharya et al., 2006; Hung et al., 2010; Gözel and Hocaoglu, 2009; Kayal and Chanda, 2013; Viral and Khatod, 2015; Aman et al., 2012; Rambabu and Prasad, 2014) divided the DGs allocation and sizing into two problems. The first one is the DGs allocation while the second one is the sizing of these DGs. With respect to the DGs allocation, the most sensitive bus-bars are predetermined or ranked based on certain objectives or performance indices in order to, properly, allocate DGs. For example, the critical bus-bars are specified for allocating DGs based on smallest voltage profile (Hung et al., 2013; Aman et al., 2014; Borges and Falcao, 2006; El-Zonkoly, 2011; Ullah et al., 2019; Khaled et al., 2017), voltage stability index (Moradi and Abedini, 2012; Poornazaryan et al., 2016; Shin et al., 2007; Kayal and Chanda,

* Corresponding author.
*E-mail address:* hfarh1@ksu.edu.sa (H.M.H. Farh).

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2013), both smallest voltage stability index (VSI) and voltage profile (Moradi and Abedini, 2016; Mohanty and Tripathy, 2016) and power losses (Acharya et al., 2006; Hung et al., 2010; Gözel and Hocaoglu, 2009). In Gampa and Das (2015), a sensitivity index has been used to specify the 10 weakest bus-bars to allocate DGs on it. Whereas, the loss saving has been used to specify the most severe bus-bar for the first DG allocation (Viral and Khatod, 2015). Similarly, with the presence of the first DG, the second DG is allocated at the bus-bar which has the highest loss saving and so on until no remaining variation in the loss saving. In Aman et al. (2012), Rambabu and Prasad (2014) the power stability index (PSI) is calculated for all lines and the first DG allocated at the receiving bus-bar of the line that has the highest PSI. For multi DGs allocation, in the presence of the first DG, the second DG will be allocated at the receiving bus-bar of the line that having the highest PSI value. With respect to the DGs sizing, the optimal power flow (OPF) with DGs allocated at the most severe buses is solved using analytical or soft computing optimization algorithms in order to determine the size of the pre-specified DGs allocated. Numerous optimization algorithms are proposed to solve and deal with this non-linear OPF optimization problem without and with multiple DGs. These OPF optimization algorithms can be divided into analytical and metaheuristic optimization algorithms. Analytical algorithms are efficient, non-iterative, accurate and less computational time but they are not adequate for multiple DGs (Hung et al., 2013; Acharya et al., 2006; Hung et al., 2010; Gözel and Hocaoglu, 2009; Viral and Khatod, 2015; Hung and Mithulananthan, 2014). To overcome this limitation, numerous researches (El-Zonkoly, 2011; Moradi and Abedini, 2012, 2016; Mohanty and Tripathy, 2016; Gampa and Das, 2015; Nayeripour et al., 2013; Mena and García, 2015; Liu et al., 2015; Farh et al., 2020) used the metaheuristic optimization techniques to solve the OPF problem including multiple DGs based on technical objectives (El-Zonkoly, 2011; Moradi and Abedini, 2012, 2016; Mohanty and Tripathy, 2016; Nayeripour et al., 2013) or economic objectives (Mena and García, 2015) or techno-economic objectives (Gampa and Das, 2015; Liu et al., 2015; Farh et al., 2020). These metaheuristic optimization techniques include particle swarm optimization (El-Zonkoly, 2011; Manafi et al., 2013; Eltamaly and Al-Saud, 2018; Eltamaly et al., 2019), gray wolf optimization (Siavash et al., 2017), teach learning based optimization (Mohanty and Tripathy, 2016), crow search optimization (Meddeb et al., 2018), ant colony optimization, artificial bee colony (Adaryani and Karami, 2013; Prakash and Khatod, 2016), and flower pollination algorithm etc. (Eltamaly and Al-Saud, 2018; Eltamaly et al., 2019; Sakti and Hadi, 2018; Farh and Eltamaly, 2020).

On the basis of the literature review, this study proposes a novel severity performance index (*SPI*) to rank the load buses and specify the most severe buses to allocate DGs on them. This index has two weighted indices which are the overloading index (*OLI*) and the voltage deviation index (*VDI*). The *OLI* provides an indication about the power system reliability while, the *VDI* provides an indication about the power system quality. Therefore, it can be said that the *SPI* provides an indications about both power system reliability and quality. On the other hand, the load buses are ranked with three other DGs allocation cases based on total fuel cost ($F_C$), transmission power losses ($P_L$), and a multi-function including all the three previous functions; *SPI*, $F_C$, and $P_L$. The purpose of ranking the load buses is to specify the most severe five buses in order to allocate the DG units on them. A detailed comparison between the four distinct DGs allocation cases based on *SPI*, $F_C$, $P_L$, and (*SPI*, $F_C$, and $P_L$) are discussed, analyzed and introduced. The reason behind this is to pick up the best case for multiple DGs allocation in terms of voltage profile improvement, branches loading alleviation, power losses reduction and total costs minimization. The OPF problem is solved using the crow search (CS) integrated with particle swarm optimization (PSO) technique in order to determine the optimal size of these DG units based on a multi-objective function including the total costs, power losses and voltage deviation. Detailed comparisons of four different DGs allocation and sizing cases have been attained in terms of total costs, power losses, voltage profile, and branches loading percent.

The rest of this paper is organized as follow; in Section 2, a novel *SPI* for DGs allocation is proposed. Section 3 shows the multi-Objectives for OPF Solution including photovoltaic DGs (PVDGs). Section 4 shows IEEE 30-bus system with five PVDGs at the most severe five buses. Section 5 presents the procedures of Crow Search Integrated with PSO Algorithm for OPF with the five PVDGs. Section 6 demonstrates, analyzes and discusses the simulation results. Section 7 shows the conclusions.

## 2. Allocation of the distributed generations

The distributed generations (DGs) allocation has been achieved based on ranking strategy. The load buses are ranked with four distinct objectives which are a novel severity performance index (*SPI*), total fuel cost ($F_C$), transmission power losses ($P_L$), and a multi-function including all the three previous functions; *SPI*, $F_C$, and $P_L$, respectively. The purpose of ranking the load buses is to specify the most severe five buses in order to allocate the DG units on them. The four distinct objectives used for ranking the load buses are introduced below.

### 2.1. A novel severity performance index

A novel severity performance index (*SPI*) is proposed to rank the most severe five buses to allocate the distributed generation units on them. This index contains two weighted indices which are the overloading index (*OLI*) and the voltage deviation index (*VDI*). The overloading index provides an indication about the power system reliability while the voltage deviation index provides an indication about the power system quality. Therefore, it can be said that the *SPI* evaluates both power system reliability and quality and it can be expressed as follows:

$$SPI = w_l \cdot OLI + w_v \cdot VDI \tag{1}$$

where $w_l$ and $w_v$ are the weights of both *OLI* and *VDI* where the summation of both $w_l$ and $w_v$ equals to unity. Therefore, $w_l = w_v = 0.5$ is assumed in this study. The *OLI* and *VDI* can be calculated as follow (El-Zonkoly, 2011; Banu and Devaraj, 2012):

$$OLI = \sum_{N=1}^{NBr} \left( \frac{S_{li}^{N}}{S_{li}^{max}} \right) \tag{2}$$

$$VDI = \sum_{N=1}^{Nbus} \left( \frac{V_i - V_i^{ref}}{V_i^{ref}} \right) \tag{3}$$

where $S_{li}^{N}$ and $S_{li}^{max}$ are the actual and maximum apparent power flow limit values in line *i*. Whereas, $V_i$ and $V_i^{ref}$ are the actual and reference values of the voltage magnitudes at load bus *i*, and *NBr* is the branches number.

### 2.2. Total fuel costs

The thermal generators fuel costs ($F_C$) can be expressed as follows:

$$F_C = \sum_{i=1}^{NG} a_i P_i^2 + b_i P_i + c_i \quad (\$/\mathrm{h}) \tag{4}$$

### 2.3. Total power losses

In this case, ranking the load buses has been achieved based on the total power losses ($P_L$) in the power distribution system which can be calculated using the following equation (Bouhouras et al., 2016; Biswas et al., 2017; Elattar, 2019):

$$P_L = \sum_{\substack{ij=1 \\ i\neq 1}}^{NBr} g_{ij}\left[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)\right] \tag{5}$$

where $V_i$ is the sending bus voltage; $V_j$ is receiving bus voltage; $g_{ij}$ is the conductance between sending bus and receiving bus; $\delta_i$ is the voltage angle at bus $i$; $\delta_j$ is the voltage angle at bus $j$; $NBr$ is the number of branches.

### 2.4. Multi-objective function including SPI, fuel costs and power losses

In this case, ranking the load buses based on a multi-objective function including all the three previous functions ($SPI$, $F_C$, and $P_L$) as follows:

$$F_{obj} = w_1 \cdot F_C + w_2 \cdot P_L + w_3 \cdot SPI \tag{6}$$

where $w_1$, $w_2$, and$w_3$are the weights of the three functions $F_C$, $P_L$, and $SPI$, respectively. The values of the weights; $w_1$, $w_2$, and$w_3$; are assumed to be 1, 19.5, and 200; respectively.

## 3. Sizing of the five PVDGs allocated at the most severe five buses

To determine the size of the five PVDGs allocated at the most severe five buses, the OPF including these five PVDGs is solved using the CS integrated with PSO based on a multi-objective function. This multi-objective function includes three main functions which are the total costs ($C_{Tot}$), power losses ($P_L$) and voltage deviation ($VD$) as follows:

$$F_{obj} = Min\left(w_1 \cdot C_{Tot} + w_2 \cdot P_L + w_3 \cdot VD + Penalty\right) \tag{7}$$

where $w_1$, $w_2$, and $w_3$ are the weights of the three functions $C_{Tot}$, $P_L$, and $VD$, respectively. The values of the weights; $w_1$, $w_2$, and $w_3$; are selected also to be 1, 19.5, and 200; respectively.

### 3.1. Total generation costs

The total generation costs ($C_{Tot}$) include the thermal generators fuel costs ($F_C$) shown above in Eq. (4) and the DGs costs ($C_{DGs}$) as follow:

$$C_{Tot} = F_C + C_{PVDGs} \tag{8}$$

where the $C_{PVDGs}$ can be expressed as follows (Biswas et al., 2017; Elattar, 2019):

$$C_{PVDGs} = w_j \cdot P_{PVDGsS,j} \tag{9}$$

where, $w_j$ is cost coefficient of the photovoltaic DGs (PVDGs) at bus $j$, $P_{PVDGsS,j}$ is the scheduled power from the PVDGs.

### 3.2. Voltage deviation

The voltage profile at all buses represent one of the most significant variables that provides an indication about power system quality. The voltage deviations ($VD$) of load buses is required to be minimized. Hence, it can be formulated as follows:

$$VD = \sum_{i=1}^{NB}\left|V_i - V_i^{ref}\right| \tag{10}$$

where $V_i$ and $V_i^{ref}$ are the actual and reference values of the voltage magnitudes at load bus $i$. $V_i^{ref}$ is taken as 1 p.u.

### 3.3. Constraints of penalty

The penalty for the independent and dependent variables can be expressed using the below equation (Elattar, 2019; El-Hana Bouchekara et al., 2016).

$$\begin{aligned} Penalty = {} & \lambda_P(P_{G1} - P_{G1}^{Lim})^2 + \lambda_V\sum_{i=1}^{NL}(V_{Li} - V_{Li}^{Lim})^2 \\ & + \lambda_Q\sum_{i=1}^{NG}(Q_{Gi} - Q_{Gi}^{Lim})^2 + \lambda_S\sum_{i=1}^{NTL}(S_{li} - S_{li}^{max})^2 \end{aligned} \tag{11}$$

where $P_{G1}$ is the real power generated of swing bus, $V_L$ is the load-bus voltage, $Q_G$ is the reactive power generated, and $S_l$ is the apparent power. The penalty of the dependent variable are $\lambda_P$, $\lambda_V$, $\lambda_Q$ and $\lambda_S$.

On the other hand, the equality power flow equations can be calculated using the following equations (Biswas et al., 2017; Elattar, 2019):

$$P_{Gi} - P_{Di} - V_i\sum_{j=1}^{NB}V_j\left[G_{ij}\cos\left(\delta_{ij}\right) + B_{ij}\sin(\delta_{ij})\right] = 0 \quad \forall\, i \in NB \tag{12}$$

$$Q_{Gi} - Q_{Di} - V_i\sum_{j=1}^{NB}V_j\left[G_{ij}\sin\left(\delta_{ij}\right) - B_{ij}\cos(\delta_{ij})\right] = 0 \quad \forall\, i \in NB \tag{13}$$

Whereas, the inequality constraints are described as follow:

$$V_{Gi}^{min} \le V_{Gi} \le V_{Gi}^{max}, \quad i = 1, \ldots, NG \tag{14}$$

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max}, \quad i = 1, \ldots, NG \tag{15}$$

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi}^{max}, \quad i = 1, \ldots, NG \tag{16}$$

$$TS_i^{min} \le TS_i \le TS_i^{max}, \quad i = 1, \ldots, NT \tag{17}$$

$$Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max}, \quad i = 1, \ldots, NC \tag{18}$$

$$V_{Li}^{min} \le V_{Li} \le V_{Li}^{max}, \quad i = 1, \ldots, NL \tag{19}$$

$$S_{li} \le S_{li}^{max}, \quad i = 1, \ldots, NTL \tag{20}$$

where $V_G$ and $P_G$ are the voltage and real power at the generation buses, $V_L$ is the load-bus voltage, $Q_G$ is the reactive power generated, and $S_l$ is the apparent power.

## 4. IEEE 30-bus system with five PVDGs at the most severe five buses

The CS integrated with PSO is used to solve the OPF with five PVDGs allocated at the most severe five buses for the IEEE 30-bus benchmark system. The main data of the IEEE-30 bus standard system are taken from Ullah et al. (2019). This system has 30 buses, 41 branches, 6 thermal generators at buses 1, 2, 5, 8, 11 and 13, 9 shunt VAR compensators at buses 10, 12, 15, 17, 20, 21, 23, 24 and 29 and 4 transformers between bus 6 and 9, bus 6 and 10, bus 4 and 12 and bus 28 and 27 as shown in Fig. 1. The most severe five buses are determined in order to allocate the photovoltaic DGs (PVDGs) through ranking the load buses based on four distinct cases. In Case 1, a novel severity index ($SPI$) which has two main weighted indices, overloading index ($OLI$) and the voltage deviation index ($VDI$), shown in Eq. (1) is used for ranking all load buses. The $SPI$ provides an indication about both power system reliability and quality. On the other hand, the load buses are ranked in Case 2, and in Case 3 based on the total fuel cost ($F_C$,) and the transmission power losses ($P_L$), respectively.

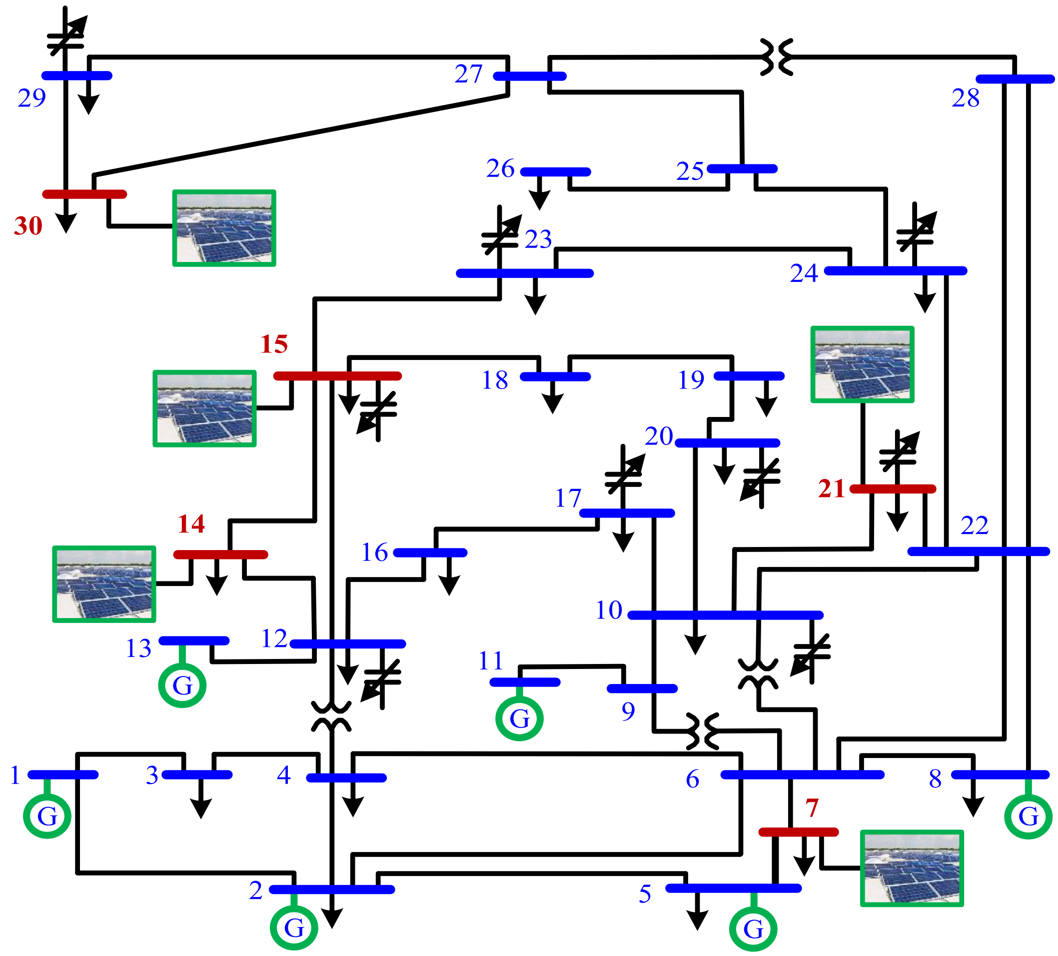


**Fig. 1.** The IEEE 30-bus test system with five PVDGs at the most severe five buses ranked.

Whereas, the load buses are ranked in Case 4 based on a multi-objective function including all the three previous functions; *SPI*, $F_C$, and $P_L$. The purpose of ranking the load buses is to specify the most severe five buses in order to allocate the PVDGs on them. On the other hand, the OPF problem including the prespecified five PVDGs of the IEEE 30-bus system is solved using the CS integrated with PSO in order to determine the sizing of these five PVDGs units. This OPF problem including these prespecified five PVDGs units is solved based on a multi-objective function including three main functions which are the total costs, power losses and voltage deviation as shown in Eq. (7). The detailed comparisons of the four PVDGs allocation and sizing cases have been discussed, analyzed and presented in the simulation results with respect to the total costs, power losses, voltage profile, and branches loading percent.

## 5. Crow search integrated with PSO algorithm

The crow search (CS) is efficient in global searching of DGs allocation and sizing while PSO is efficient in OPF local searching. Therefore, the CS is integrated with PSO not only to collect the merits of both CS and PSO algorithms but also to solve the OPF problem with multi-PVDGs allocated at the most severe five buses for the IEEE 30-bus test system. This OPF problem including these prespecified five PVDGs is solved in order to determine their sizing based on a multi-objective function including the total costs, power losses and voltage deviation as shown in Eq. (7) above. The flowchart of the CS is integrated with PSO as shown in Fig. 2 and the implementation procedures for this algorithm are introduced in the following part.

**Step 1: Initialize the OPF problem and adjust the initialization parameters of CS and PSO.**

- Define the input data of the IEEE 30-bus power system.
- Adjust the CS parameters which are flock size ($N$), flight length ($fl$), awareness probability ($AP$), and the number of iterations ($t_{max}$).
- Adjust the PSO parameters which include swarm size ($N_S$), total iterations ($Itr_{max}$), acceleration factors ($c_1$ and $c_2$), and inertia weight ($\omega$).

**Step 2: Initialize position and memory of crows.**

The initial positions (solution or sizing of DGs) are generated randomly for $N$ crows with a dimension $d$ as follows:

$$X = \begin{bmatrix} x_1^1 & x_2^1 & \dots & x_d^1 \\ x_1^2 & x_2^2 & \dots & x_d^2 \\ . & . & \dots & . \\ . & . & \dots & . \\ . & . & \dots & . \\ x_1^N & x_2^N & \dots & x_d^N \end{bmatrix} \tag{21}$$

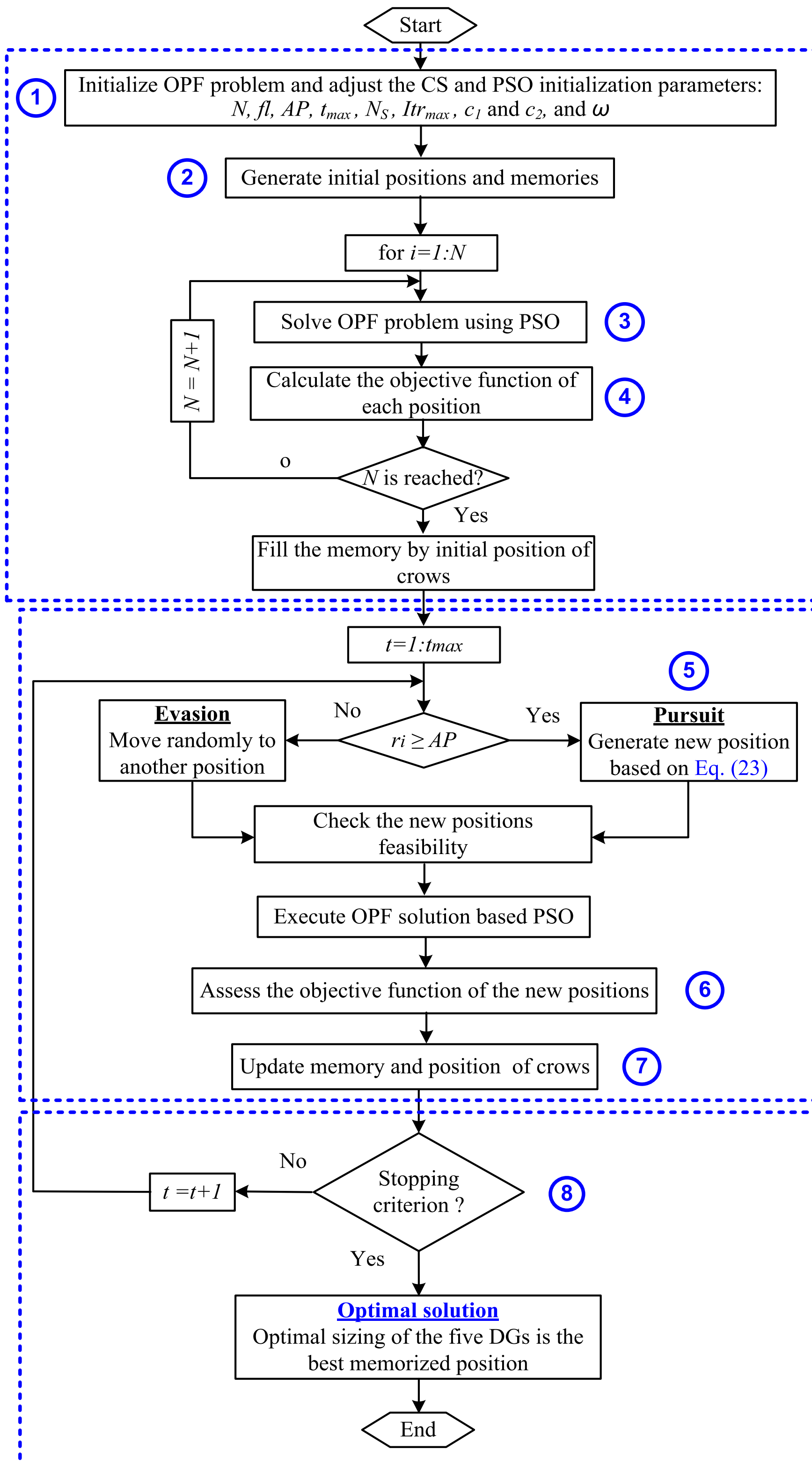


**Fig. 2.** The flowchart of CS integrated with PSO to solve OPF with five PVDGs at the critical five buses.

The memory of each crow ($M$) of all $N$ crows is initialized as in the following equation:

$$M = \begin{bmatrix} M_1^1 & M_2^1 & \cdots & M_d^1 \\ M_1^2 & M_2^2 & \cdots & M_d^2 \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot \\ M_1^N & M_2^N & \cdots & M_d^N \end{bmatrix} \tag{22}$$

**Step 3: OPF solution based on PSO.**

After generating the positions of crows (sizing of the five DGs) using CS in the outer loop, PSO is used to solve the OPF including these five DGs sizing based on the multi-objective function introduced above in Eq. (7). The optimal sizing of the five DGs is achieved at the minimum objective function value.

**Step 4: Assess the multi-objective objective function.**

For each crow, assess the multi-objective function to investigate its position quality.

**Step 5: Generate the new positions of all crows.**

Crows generate the new position in the searching area as follow:

- Assume crow $i$ wants to generate new position so crow $i$ follows crow $j$ to know its food hidden. Crow $i$ attains this goal if crow $j$ does not see it.
- If crow $j$ watches that crow $i$ follows it, so crow $j$ deceives crow $i$ through moving randomly to another position.

The new position of crow $i$ is generated at $t+1$ iteration based on the previous two states and can be formulated as shown below (Meddeb et al., 2018; Askarzadeh, 2016; Abdelaziz and Fathy, 2017).

$$x_i^{t+1} = \begin{cases} x_i^t + r_i * fl * \left(m_j^t - x_i^t\right) & if\ r_i \geq AP \\ Move\ to\ random\ position & if\ r_i < AP \end{cases} \tag{23}$$

where $x_i^{t+1}$ is the new position of crow $i$, and $x_i^t$ is the previous position.

The feasibility of the new position of each crow is checked. If its new position is feasible, the crow updates its position. Otherwise, the crow will stay in its position and does not move to the new position.

**Step 6: Assess the multi-objective objective function.**

For each new position, assess the multi-objective function to investigate its position quality.

**Step 7: Update memory of crow.**

The crows update their memory based on the following equation:

$$m_i^{t+1} = \begin{cases} x_i^{t+1} & if\ f_{obj}\left(x_i^{t+1}\right) > f_{obj}(m_i^t) \\ m_i^t & Otherwise \end{cases} \tag{24}$$

where $f_{obj}\left(x_i^{t+1}\right)$ is the multi-objective function value of the new position; $f_{obj}\left(m_i^t\right)$ is the previous multi-objective objectives function value.

**Step 8: Stopping criterion.**

The algorithm will be terminated after finishing all iterations ($t_{max}$) and the optimal sizing of the five DGs allocated at the most severe five buses are attained based on minimum multi-objective function value.

## 6. Simulation results and discussions

In this study, the optimal DGs allocation and sizing are divided into two sub-problem. The first one is allocating the DG units based on ranking strategy and the second one is sizing these DG units. To allocate the DG units, all load buses have been ranked based on four distinct objectives as shown in Table 1 in order to determine the most severe five buses to place five DG units at these buses. To determine the sizing of these DG units, the OPF problem including the prespecified five DG units of the IEEE 30-bus system is solved using the hybrid CS-PSO technique. The values of all parameters for the crow search integrated with PSO algorithm are summarized in Table 2. This OPF problem including these prespecified five DG units is solved based on the multi-objective function shown in Eq. (7). A detailed comparison of these four distinct DGs allocation and sizing cases are discussed, analyzed and introduced as follow:

*Case #1: Ranking buses based on SPI*

**Allocation:** In this case, all load buses are ranked based on a novel *SPI*. This index has two weighted indices as shown previously in Eq. (1). The first index is the overloading index (*OLI*) which can be calculated using Eq. (2) and it provides an indication about the power system reliability. Whereas, the second index is the voltage deviation index (*VDI*) which can be calculated using Eq. (3) and it provides an indication about the power system quality. Therefore, it can be said that the *SPI* provides an indications about both the power system reliability and quality. Fig. 3 shows the *SPI* for all load buses to rank and pick up the five most severe buses based on *SPI*. The most severe five buses ranked based on *SPI* are buses 7, 10, 14, 15, and 20 as shown in Fig. 3. These five buses are recommended to allocate the five DG units on them.

**Sizing:** The sizes of these five DG units is determined through solving the OPF problem including these five DG units using the crow search integrated with PSO based on the multi-objective function shown in Eq. (7). This multi-objective function contains the three weighted functions which are total costs, power losses and voltage deviation. As shown in Table 3, the optimal sizing of the five DGs; $DG_7$, $DG_{10}$, $DG_{14}$, $DG_{15}$, and $DG_{20}$; allocated based on *SPI* are 39.5669, 39.7810, 13.8780, 43.9508, and 43.7649 (MW), respectively. Also, the placement of the five DGs; $DG_7$, $DG_{10}$, $DG_{14}$, $DG_{15}$, and $DG_{20}$; allocated based on *SPI* improved the voltage deviation and reduced both the total costs and power losses compared to the base condition without DGs.

*Case#2: Ranking buses based on $F_C$*

**Allocation:** In this case, all load buses are ranked based on the total fuel costs ($F_C$) shown previously in Eq. (4). As shown previously in Table 1, all load buses have been ranked based on $F_C$ in order to specify the most severe five buses to allocate five DG units at these buses. Fig. 4 shows the total fuel costs for all load buses to rank and pick up the five most severe buses. The most severe five buses ranked based on $F_C$ are buses 7, 12, 19, 21, and 30 as shown in Fig. 4. These five buses are recommended to allocate the five DG units on them.

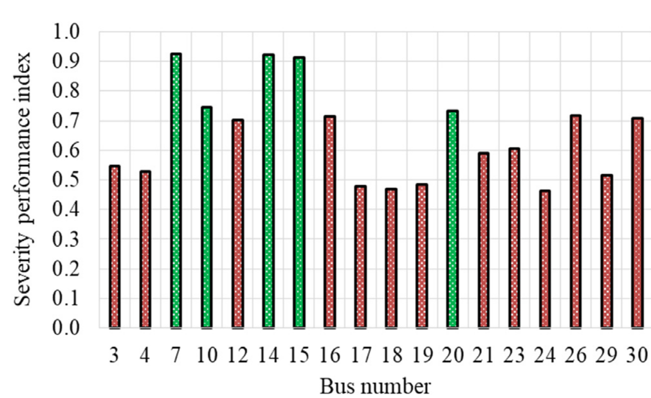


**Fig. 3.** The severity performance index for all load buses to rank and pick up the most severe five buses; 7, 10, 14, 15, and 20.

**Table 1**
Ranking buses to allocate five PVDGs at the most severe five buses based on four distinct objectives.

| Bus No. | $F_{obj}$ (SPI) Eq. (1) | | $F_{obj}$ ($F_C$) Eq. (4) | | $F_{obj}$ ($P_L$) Eq. (5) | | $F_{obj}$ (SPI, $F_C$, and $P_L$) Eq. (6) | |
|---|---|---|---|---|---|---|---|---|
| | Value | Ranking | Value ($/h) | Ranking | Value (MW) | Ranking | Value ($/h) | Ranking |
| 3 | 0.5478 | 12 | 804.68 | 17 | 8.8829 | 17 | 1087.46 | 17 |
| 4 | 0.5273 | 13 | 813.83 | 9 | 8.9629 | 15 | 1094.08 | 13 |
| 7 | 0.9247 | 1 | 842.04 | 1 | 9.6289 | 3 | 1214.74 | 1 |
| 10 | 0.7462 | 4 | 810.31 | 11 | 8.8386 | 18 | 1131.9 | 8 |
| 12 | 0.7015 | 9 | 819.99 | 4 | 8.9021 | 16 | 1133.87 | 7 |
| 14 | 0.9213 | 2 | 811.26 | 10 | 9.1216 | 11 | 1173.4 | 3 |
| 15 | 0.9115 | 3 | 814.85 | 8 | 9.2016 | 10 | 1176.59 | 2 |
| 16 | 0.7138 | 7 | 806.74 | 14 | 9.2151 | 9 | 1129.2 | 9 |
| 17 | 0.4793 | 16 | 816.71 | 6 | 9.3060 | 7 | 1094.03 | 14 |
| 18 | 0.4697 | 17 | 807.27 | 13 | 9.6299 | 2 | 1088.99 | 16 |
| 19 | 0.4857 | 15 | 817.94 | 5 | 9.4647 | 4 | 1099.64 | 12 |
| 20 | 0.7317 | 5 | 804.67 | 18 | 9.0717 | 14 | 1127.91 | 10 |
| 21 | 0.5915 | 11 | 833.48 | 2 | 9.7636 | 1 | 1142.16 | 5 |
| 23 | 0.6065 | 10 | 806.28 | 15 | 9.1174 | 12 | 1105.37 | 11 |
| 24 | 0.4635 | 18 | 816.26 | 7 | 9.2482 | 8 | 1089.29 | 15 |
| 26 | 0.7183 | 6 | 807.55 | 12 | 9.4084 | 6 | 1134.66 | 6 |
| 29 | 0.5157 | 14 | 805.11 | 16 | 9.0890 | 13 | 1085.47 | 18 |
| 30 | 0.7068 | 8 | 820.40 | 3 | 9.4226 | 5 | 1145.49 | 4 |

**Table 2**
The parameters of crow search and PSO algorithm used in this study.

| Crow search parameters | Value | PSO parameters | Value |
|---|---|---|---|
| Flock size ($N$) | 100 | Swarm size ($N_S$) | 40 |
| Number of iterations ($t_{max}$) | 150 | Iterations number ($Itr_{max}$) | 100 |
| Awareness probability ($AP$) | 0.1 | Acceleration factors ($c_1$ and $c_2$) | 1.89 and 2.12 |
| Flight length ($fl$) | 2 | Inertia weight ($\omega$) | −0.1618 |

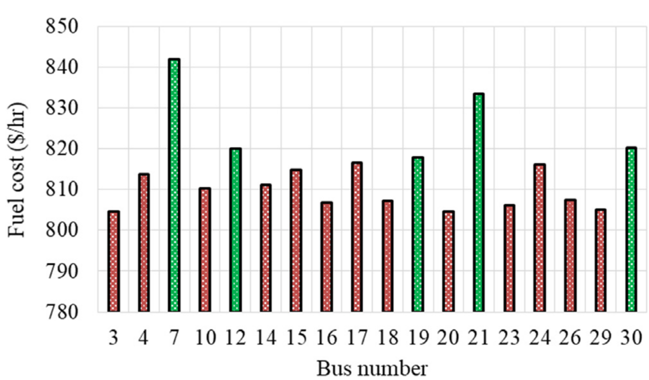


**Fig. 4.** The total fuel costs for all load buses to pick up the most severe five buses; 7, 12, 19, 21, and 30.

**Sizing:** The sizes of these five DG units is determined through solving the OPF problem including these five DG units using the crow search integrated with PSO based on the multi-objective function shown in Eq. (7). This multi-objective function contains the three weighted functions; total costs, power losses and voltage deviation. As shown previously in Table 3, the optimal sizing of the five DGs; $DG_7$, $DG_{12}$, $DG_{19}$, $DG_{21}$, and $DG_{30}$; allocated based on $F_C$ are 46.0012, 35.7528, 28.7758, 44.1811, and 17.3699 (MW); respectively. On the other hand, the placement of the five DGs; $DG_7$, $DG_{12}$, $DG_{19}$, $DG_{21}$, and $DG_{30}$; allocated at the most severe five buses ranked based on $F_C$ has a significant reduction in the total costs and power losses compared to both the base condition without DGs and Case 1 (five DGs allocated based on *SPI*).

*Case#3: Ranking buses based on $P_L$*

**Allocation:** In this case, all load buses are ranked based on the total power losses ($P_L$) shown previously in Eq. (5). As shown previously in Table 1, all load buses have been ranked based on $P_L$ in order to determine the most severe five buses to allocate five DG units at these buses. Fig. 5 shows the total power losses for all load buses to rank and pick up the most severe five buses. The most severe five buses ranked based on $P_L$ are buses 7, 18, 19, 21, and 30 as shown in Fig. 5. These five buses are recommended to allocate the five DG units on them.

**Sizing:** The sizes of these five DG units is determined through solving the OPF problem including these five DG units using the crow search integrated with PSO based on the multi-objective function shown in Eq. (7). This multi-objective function contains the three weighted functions; total costs, power losses and voltage deviation. As shown previously in Table 3, the optimal sizing of the five DGs; $DG_7$, $DG_{18}$, $DG_{19}$, $DG_{21}$, and $DG_{30}$; allocated based on $P_L$ are 41.6375, 16.8840, 30.2638, 34.9164, and 30.6107 (MW); respectively. On the other hand, the placement of the five DGs; $DG_7$, $DG_{12}$, $DG_{19}$, $DG_{21}$, and $DG_{30}$; allocated at the most severe five buses ranked based on $F_C$ has a significant improvement in voltage deviation and reduction in the total costs and power losses compared to all the previous cases without and with DGs based on *SPI* and $F_C$.

*Case #4: Ranking buses based on a multi-objective function including SPI, $F_C$, and $P_L$*

**Allocation:** In this case, all load buses are ranked based on a multi-objective function including all the three previous functions; *SPI*, $F_C$, and $P_L$ shown previously in Eq. (6). As shown previously in Table 1, all load buses have been ranked based on the multi-objective function; $F_{obj}$(*SPI*, $F_C$, and $P_L$) in order to determine the most severe five buses to allocate five DG units at these buses. Fig. 6 shows the multi-objective function value for

**Table 3**
Comparisons of the four distinct ranking cases without and with DGs.

| Cases | | Base condition **(Without DGs)** | Case 1: Ranking buses based *SPI* **(With DGs)** | Case 2: Ranking buses based $F_C$ **(With DGs)** | Case 3: Ranking buses based $P_L$ **(With DGs)** | Case 4: Ranking buses based *SPI*, $F_C$, and $P_L$ **(With DGs)** |
|---|---|---|---|---|---|---|
| Generated power (MW) | $P_1$ | 192.887 | 59.6285 | 123.2565 | 115.1972 | 145.2161 |
| | $P_2$ | 52.669 | 22.5634 | 35.5871 | 34.8415 | 40.8952 |
| | $P_5$ | 22.337 | 49.9989 | 17.7959 | 15.9337 | 19.4998 |
| | $P_8$ | 31.144 | 32.8823 | 10.0002 | 10.1842 | 12.9265 |
| | $P_{11}$ | 15.363 | 27.7362 | 10.0065 | 10.0046 | 10.0012 |
| | $P_{13}$ | 14.307 | 12.0120 | 12.0058 | 27.1143 | 12.0043 |
| | $\boldsymbol{DG_7}$ | – | **39.5669** | **46.0012** | **41.6375** | **36.5470** |
| | $\boldsymbol{DG_{10}}$ | – | **39.7810** | – | – | – |
| | $\boldsymbol{DG_{12}}$ | – | – | **35.7528** | – | – |
| | $\boldsymbol{DG_{14}}$ | – | **13.8780** | – | – | **23.6939** |
| | $\boldsymbol{DG_{15}}$ | – | **43.9508** | – | – | **34.5340** |
| | $\boldsymbol{DG_{18}}$ | – | – | – | **16.8840** | – |
| | $\boldsymbol{DG_{19}}$ | – | – | **28.7758** | **30.2638** | – |
| | $\boldsymbol{DG_{20}}$ | – | **43.7649** | – | – | – |
| | $\boldsymbol{DG_{21}}$ | – | – | **44.1811** | **34.9164** | **30.2442** |
| | $\boldsymbol{DG_{30}}$ | – | – | **17.3699** | **30.6107** | **26.7233** |
| Thermal generators Voltages (p. u) | $V_1$ | 1.1000 | 1.1000 | 1.1 | 1.1 | 1.1000 |
| | $V_2$ | 1.0649 | 1.0845 | 1.0891 | 0.9953 | 1.0917 |
| | $V_5$ | 1.0306 | 1.0788 | 1.0610 | 0.9514 | 1.0628 |
| | $V_8$ | 1.0340 | 1.0422 | 1.0794 | 1.0047 | 1.0752 |
| | $V_{11}$ | 1.1000 | 1.0999 | 1.1000 | 1.0983 | 1.0954 |
| | $V_{13}$ | 1.1000 | 1.0687 | 1.0776 | 1.0635 | 1.0688 |
| Tap-setting of transformers (p.u) | $TS_{6-9}$ | 0.9001 | 0.9437 | 0.9404 | 0.9639 | 0.9637 |
| | $TS_{6-10}$ | 1.0154 | 0.9561 | 1.1000 | 1.0868 | 1.0996 |
| | $TS_{4-12}$ | 0.9725 | 1.0318 | 1.0165 | 1.0006 | 0.9791 |
| | $TS_{28-27}$ | 0.9012 | 0.9004 | 1.0045 | 1.0046 | 1.0233 |
| Shunt VAR compensators (MVAr) | $Q_{10}$ | 5 | 4.9981 | 4.8243 | 0.1110 | 4.9996 |
| | $Q_{12}$ | 0 | 4.9218 | 4.9620 | 4.9688 | 4.0893 |
| | $Q_{15}$ | 3.7330 | 4.9414 | 2.4713 | 2.7107 | 2.2792 |
| | $Q_{17}$ | 1.2804e−06 | 0.0537 | 0.8427 | 0.2354 | 2.9500 |
| | $Q_{20}$ | 4.9943 | 0.0700 | 1.7408 | 4.6644 | 2.6480 |
| | $Q_{21}$ | 4.9993 | 0.1844 | 1.6427 | 1.9442 | 4.9322 |
| | $Q_{23}$ | 0 | 0.2065 | 0.0020 | 0.0022 | 1.7415 |
| | $Q_{24}$ | 4.4843 | 3.0199 | 4.9999 | 4.2772 | 3.1394 |
| | $Q_{29}$ | 0.7067 | 0.2334 | 1.6498 | 1.5216 | 3.7443 |
| Total cost ($/h) | | **928.87** | **456.30** | **468.50** | **447.82** | **430.99** |
| Power losses (MW) | | 10.9317 | 8.4236 | 4.904 | 3.6956 | **3.9301** |
| Voltage Deviation | | 1.51610 | 0.5171 | 0.7661 | 0.18478 | **0.22033** |
| **Objective function ($/h)** | | **1445.26** | **723.98** | **717.35** | **556.84** | **551.7** |

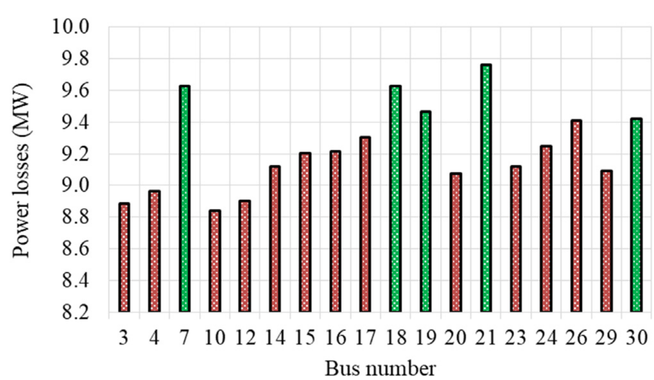


**Fig. 5.** The total power losses for all load buses all load buses to rank and pick up the most severe five buses; 7, 18, 19, 21, and 30.

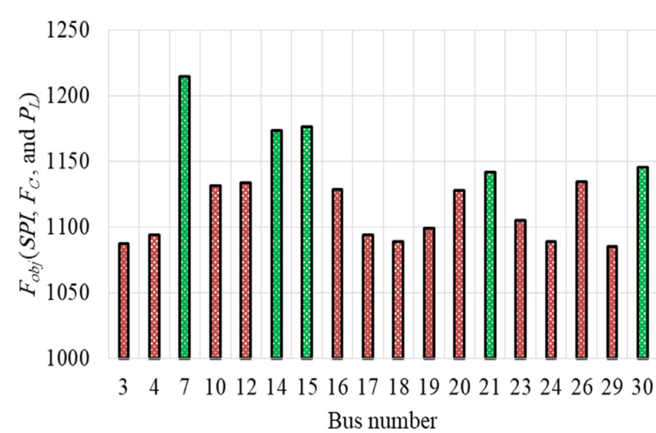


**Fig. 6.** The multi-objective function; $F_{obj}(SPI, F_C, \text{and } P_L)$; for all load buses all load buses to rank and pick up the most severe five buses; 7, 14, 15, 21, and 30.

all load buses to rank and pick up the most severe five buses. The most severe five buses ranked based on this multi-objective function are buses 7, 14, 15, 21, and 30 as shown in Fig. 6. These five buses ranked are recommended as a candidate buses to allocate the five DG units on them.

**Sizing:** The sizing of these five DG units is determined through solving the OPF problem including these five DG units using the crow search integrated with PSO based on the multi-objective function shown in Eq. (7). This multi-objective function contains the three weighted functions; total costs, power losses and voltage deviation. As shown previously in Table 3, the optimal sizing of the five DGs; $DG_7$, $DG_{14}$, $DG_{15}$, $DG_{21}$, and $DG_{30}$; allocated based on $F_{obj}(SPI, F_C$, and $P_L)$ are 36.5470, 23.6939, 34.5340, 30.2442, and 26.7233 (MW); respectively. On the other hand, the placement of the five DGs; $DG_7$, $DG_{14}$, $DG_{15}$, $DG_{21}$, and $DG_{30}$; allocated at the most severe five buses ranked based on $F_{obj}(SPI, F_C$, and $P_L)$ has a significant reduction in the multi-objective function value compared to both the base condition without DGs and all the three previous cases based on $SPI$, $F_C$, and $P_L$. Also, the three most common severe buses for all four cases are 7, 21 and 30 as shown in Table 3.

Fig. 7 shows the voltage profile of the 30 buses without and with five DGs allocated at the most severe five buses ranked based on the four distinct objectives; $F_{obj}(SPI)$, $F_{obj}(F_C)$, $F_{obj}(P_L)$, $F_{obj}(P_L)$ and $F_{obj}(SPI, F_C$, and $P_L)$. As shown in Fig. 7, the penetration of five DGs allocated at the most severe five buses ranked based on $F_{obj}(SPI, F_C$, and $P_L)$ has a significant improvement in the voltage profile compared to the base condition without DGs and all the three previous cases based on $SPI$ or $F_C$ or $P_L$. On the other hand, Fig. 8 shows the loading of all branches for the IEEE 30-bus system without and with five DGs allocated at the most severe five buses ranked based on the four distinct objectives; $F_{obj}(SPI)$, $F_{obj}(F_C)$, $F_{obj}(P_L)$, $F_{obj}(P_L)$ and $F_{obj}(SPI, F_C$, and $P_L)$. As shown in Fig. 8, the penetration of five DGs allocated at the most severe five buses ranked based on the multi-objectives including $SPI$, $F_C$, and $P_L$ alleviated the branches loading compared to the base condition without DGs and all the three previous cases based on $SPI$ or $F_C$ or $P_L$. As a result, the penetration of five DGs allocated based on the multi-objectives $F_{obj}(SPI, F_C$, and $P_L)$ outperformed the other three previous cases based on $SPI$ or $F_C$ or $P_L$ in terms of voltage profile improvement, branches loading alleviation, power losses reduction and total costs minimization. Therefore, it is preferred to rank the buses based on this multi-objectives including $SPI$, $F_C$, and $P_L$ in order to allocate the DGs at a potential buses and attain additional technical and economic benefits to the power system network.

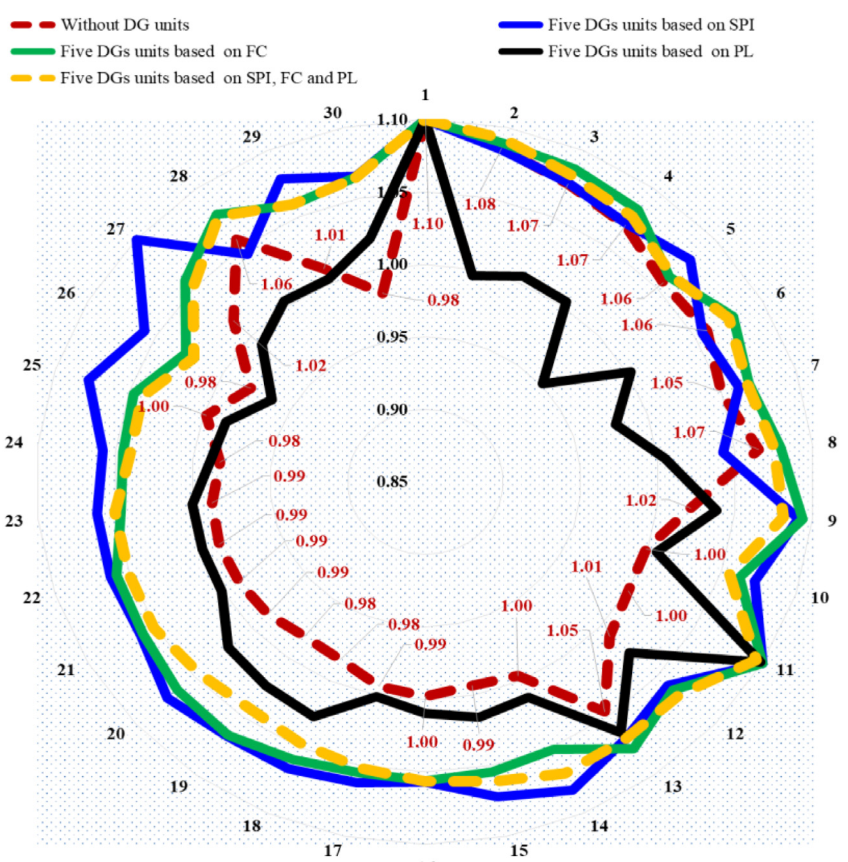


**Fig. 7.** Voltage profile of all 30 buses of the power system without and with five DG units allocated at the most severe five buses ranked based on the four distinct objectives.

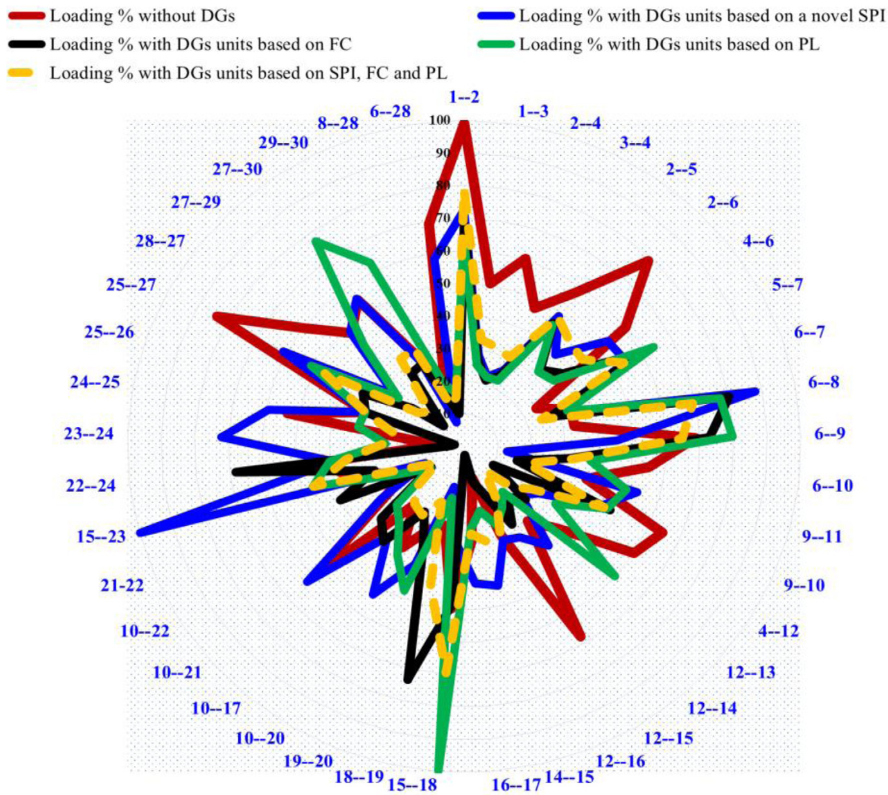


**Fig. 8.** The loading % for all branches of the power system without and with five DG units allocated at the most severe five buses ranked based on the four distinct objectives.

## 7. Conclusion

Optimal DGs allocation and sizing of the DGs can attain several technical, and economical benefits pertinent to the power system networks. The DGs allocation is specified through ranking all load buses based on four distinct objectives cases; a novel *SPI*, $F_C$, $P_L$ and a multi-objective function including all the three previous functions; *SPI*, $F_C$, and $P_L$. The purpose of ranking the load buses is to specify the five most severe buses to allocate five DGs on them. The most severe five buses ranked and recommended allocating five DGs based on *SPI* are buses 7, 10, 14, 15, and 20. Whereas, the DGs units are recommended to be allocated at buses 7, 12, 19, 21, and 30 based on $F_C$. Based on $P_L$, the most severe five buses ranked and recommended allocating five DGs are buses 7, 18, 19, 21, and 30. Finally, the most severe five buses recommended to allocate five DGs based on the multi-objective function including all the three previous functions; *SPI*, $F_C$, and $P_L$ are buses 7, 14, 15, 21, and 30. Sizing of these five DG units is determined through solving this OPF problem including these five DG units using the CS integrated with PSO based on a multi-objective function that includes total costs, power losses and voltage deviation. Although, the penetration of five DGs allocated based on *SPI* or $F_C$ or $P_L$ improved the power system performance, the penetration of five DGs allocated based on the multi-objectives $F_{obj}(SPI, F_C, \text{and } P_L)$ has a superior performance compared to all cases in terms of voltage profile improvement, branches loading alleviation, power losses reduction and total costs minimization. Therefore, the multi DGs allocation is preferred to be specified based on this multi-objectives including *SPI*, $F_C$, and $P_L$ in order to attain favorable technical and economic benefits to the power system network.

## CRediT authorship contribution statement

**Hassan M.H. Farh:** Conceptualization, Methodology, Software, Data curation, Writing - original draft, Visualization, Investigation, Software, Validation, Writing - review & editing. **Abdullah M. Al-Shaalan:** Supervision, Writing - review & editing. **Ali M. Eltamaly:** Supervision, Writing - review & editing. **Abdullrahman A. Al-Shamma'a:** Conceptualization, Methodology, Software, Visualization, Investigation, Software, Validation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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