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Research Article

Optimal Operation of Distributed Generations in Four-Wire Unbalanced Distribution Systems considering Different Models of Loads

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The distribution network is generally unbalanced due to the distribution of consumers in different phases and the different status of their energy consumption. Also, in recent years, the utilization of distributed generations (DGs) has flourished in the distribution network, thanks to their favorable operational and environmental benefits. Therefore, it is predicted that the optimal energy management of DGs in the unbalanced distribution network can improve the operation state of the network. Moreover, the consumer load model is generally a combination of constant impedance, constant current, and constant power conditions. Therefore, the current study focuses on the analysis of the operation of unbalanced four-wire distribution systems containing DGs, in which load models are also involved. An optimization structure is established to make the voltage deviation, power loss, neutral wire loss, and voltage unbalance minimized. Limitations of the problem include those related to the network and those concerning operating indices of the system like voltage magnitude and phase angle of buses, power flow through the distribution lines, constraints of operation of DGs, load model, and unbalanced conditions. The problem formed in this study is nonlinear and is solved using sequential quadratic programming (SQP) by implementing it in the GAMS simulation environment. To test the benefits of the introduced approach, a 13-bus distribution system has been adopted so that the optimal operation of DGs in the distribution network has been able to reduce the unbalanced situation of the network compared to the power flow studies. Also, this scheme has improved the operation of network, where energy losses and voltage drop have been reduced compared to power flow studies, and a smooth voltage profile has been extracted.

1. Introduction

The distribution network is generally three-phase four-wire, and its consumers are single-phase. Therefore, there is a possibility of unbalance in the distribution network [1]. In addition, it should be noted that in recent years, to reduce the environmental concerns caused by the uncontrolled consumption of fossil fuels, governments and organizations encourage customers to exploit renewable energy sources (RESs) such as wind and solar systems. Also, other distributed generations (DGs) such as microturbines and fuel cells have been encouraged [2]. Thanks to zero fuel consumption by wind and solar systems, they have attracted more customers and are therefore widely used in the power system, especially in the distribution network [3]. According to these cases, DGs such as wind and solar systems can be adopted to supply the consumers, in addition to enhancing the technical situation in the distribution network and affecting the performance of the network by their operating conditions [4]. Thus, it is expected that the optimal performance of DGs in the distribution network can play an effective role in minimizing network losses, reducing network unbalance, and reducing voltage deviation from the desired value (bus voltage of the distribution substation).

Various pieces of research have been conducted in the field of operation of DGs and unbalanced distribution networks. Energy management of an unbalanced AC microgrid has been realized in [5] by adopting a stochastic model that involves nodal load and generation, as well as voltage reference of the common coupling point. The aim is to propose solutions to energy management subject to contingency limits. The paper converts nonlinear programming to linear programming for which convex solvers can be employed. A new strategy to manage energy in unbalanced microgrids with active-reactive power generation units and active demand has also been proposed [6] so that different indices of the network, such as operation, reliability, pollution, and economic indices, are improved at the same time. Four different objects need to be optimized in this scheme, including the expected operating cost of the microgrids, expected pollutant amount, expected energy not-supplied, and voltage deviation. A new solution to AC optimal power flow in unbalanced networks is suggested in [7] so that the energy generation cost is minimized and the voltage and current of the network are maintained within the permissible limits. Reference [8] presents a two-stage optimal operation method for a network, in which various uncertain parameters related to demand are taken into account. Modeling of elements is provided and a thorough investigation is carried out concerning the energy conversion process and energy storage. The paper also develops optimal operation modeling to schedule the test network. The authors in [9] focus on the optimal operation of a network while taking into account the demand response, the horizontal complementary substitution, and the vertical time shift strategy of electricity-gas-heating-cooling. This is realized according to the demand response, and cooperative complementarity and flexible transformation of energy sources are considered so that a robust operation model is proposed for the network under study. The most proper waste-to-energy advancements used in DGs are discussed in [10], and various indices involving technical, economic, and environmental situations are also concerned to finally introduce a hybrid method with several different measures. To minimize the total operating cost and enhance user experience, Reference [11] models uncertainties associated with RESs and models optimal scheduling with several objective functions. The paper also adopts the sample average approximation to convert the model into mixed-integer linear programming with several objectives. Hosting capacity as an optimization problem with several objective functions subject to power quality status is improved in [12]. To this end, some operation indices including harmonic distortions of the currents and voltage of the common coupling point are investigated besides load power factor, the capacity of lines, and voltage profile. To take prediction uncertainties related to DG outputs and energy demand into account, Reference [13] presents a stochastic optimal operation model, and different scenarios are tested. To deal with the uncertainties in an approach with two stages, the paper adopts a scenario analysis approach for the optimization process. The first stage concerns operation scenarios and the second stage addresses reduce the number of generated scenarios using the K-means technique. The authors in [14] introduce an adaptive virtual impedance control method to control the voltage and frequency of microgrids. The method relies on particle swarm optimization so that power flow is appropriately managed.

In [15], we propose a safe deep reinforcement learning (SDRL)-based method to solve the problem of optimal operation of distribution networks (OODN). It formulates OODN as a constrained Markov decision process (CMDP). The objective is to achieve adaptive voltage regulation and energy cost minimization considering the uncertainty of renewable resources (RSs), nodal loads, and energy prices. Aiming to the more flexible operation of the active distribution network (ADN), an energy management method for ADN incorporating office buildings is proposed in [16] based on chance-constrained programming. In [17], a new implementation of artificial ecosystem optimizer (AEO) technique is developed for distributed generators (DGs) and capacitors allocation considering the reconfiguration of power distribution systems (RPDS). The AEO is inspired from three energy transfer mechanisms involving production, consumption, and decomposition in an ecosystem. In [18], the authors proposed a three-stage relaxation-weightsum-correction (TSRWC)-based probabilistic reactive power optimization method to deal with the uncertainty and correlation of wind generator in the distribution network.

Based on the presented background research, it can be seen that generally, the operation of DGs is performed in a balanced distribution network. Nonetheless, it should be noted that the distribution network generally has single-phase loads, especially the low-voltage distribution network. Therefore, a four-wire model is often necessary, considering single-phase and three-phase models. This network is considered unbalanced and requires the model of neutral wire current and zero-point voltage of star connection. Yet in a few studies, these cases have been included in the network unbalance indices model. Moreover, in the majority of studies, the constant power load model is generally considered for the loads. But in fact, the more realistic load model is in the form of constant power, constant current, and constant impedance, which is known as the ZIP model. Therefore, in this paper, the operation of the unbalanced four-wire distribution network in the presence of DGs is presented by taking into account the ZIP load model. The proposed scheme minimizes the normalized objective function of the sum of voltage deviations, power losses, and neutral wire losses. It is subject to the AC power flow equations in the unbalanced four-wire distribution network, operation limit, unbalance indices, and operation model of the load and DGs. The presented problem will be a constrained nonlinear problem (CNLP) and is solved using a mathematical rule. In this paper, the sequential quadratic programming (SQP) mathematical method is used. Finally, the contributions of the proposed scheme are as follows:

(i) Modeling the four-wire distribution network by considering unbalanced indices in the distribution network
(ii) Considering the neutral wire current model and the zero-point voltage of the distribution substation
(iii) Utilizing DGs to establish a balanced situation in the three-phase system
(iv) Considering the constant current, constant impedance, and constant power or the ZIP model of the load in the proposed problem

Furthermore, the formulation of the proposed scheme is presented in Section 2. Its solution process is described in Section 3. In Section 4, the numerical results obtained from different study cases are reported, and finally, the conclusions are discussed in Section 5.

2. Mathematical Model of the Proposed Problem

The proposed problem includes the following objectives:

(i) Improving the voltage profile of the distribution network in the presence of DGs
(ii) Improving the unbalance of the three-phase four-wire system in the distribution network in the presence of DGs
(iii) Reducing distribution network losses
(iv) Reducing network voltage drop
(v) Considering different load models

To achieve the abovementioned goals in the distribution network, this paper presents the optimal operation of DGs in unbalanced four-wire distribution networks by considering load models. Therefore, this scheme includes an optimization formulation. The optimization work contains objective functions [19–27] and constraints [28–36]. Also, to apply optimization to the distribution network, smart technologies [37–41] and telecommunications equipment [42–45] should be used in the network. In the objective function of the proposed problem, the minimization of the voltage deviation from the desired value and the minimization of the distribution network losses are expressed, respectively, to achieve the goals of improving the network voltage profile and reducing losses. In addition to the voltage deviation function, it has two parts, one of which is related to the minimization of the bus voltage deviation from the reference bus voltage, and the other part is related to the minimization of the voltage unbalance indices. Also, this problem is subject to the equations of optimal AC power flow, the limitation of unbalanced indices, and the operation model of power sources and loads. Therefore, the formulation of the proposed scheme is as follows:

$$\min \overbrace{\sum_{p\in\varphi_p}\sum_{i\in\varphi_i}\frac{\left|V_{i,p}-V_{ref}\right|}{V_{ref}}+\sum_{i\in\varphi_i}\left(VUF_i^{-}+VUF_i^{0}\right)}^{\text{Voltage deviation}}+\overbrace{\frac{1}{P_{\text{base}}}\sum_{i\in\varphi_i}\sum_{p\in\varphi_p}\left(PG_{i,p}+P\ DG_{i,p}-PD_{i,p}\right)}^{\text{Active power loss}}+\overbrace{\frac{1}{P_{\text{base}}}\left(R_{ref}^{N}\left(I_{ref}^{N}\right)^2+\sum_{l\in\varphi_l}R_l^{N}\left(I_l^{N}\right)^2\right)}^{\text{Nule power loss}}, \tag{1}$$

subject to

$$PG_{i,p}+P\ DG_{i,p}-PD_{i,p}=V_{i,p}^{r}I_{i,p}^{r}+V_{i,p}^{\text{im}}I_{i,p}^{\text{im}}=\sum_{j\in\varphi_i}A_{i,j}PL_{i,j,p}\quad\forall i,p, \tag{2}$$

$$QG_{i,p}+Q\ DG_{i,p}-QD_{i,p}=V_{i,p}^{\text{im}}I_{i,p}^{r}-V_{i,p}^{r}I_{i,p}^{\text{im}}=\sum_{j\in\varphi_i}A_{i,j}QL_{i,j,p}\quad\forall i,p, \tag{3}$$

$$I_{i,p}^{r}=\sum_{j\in\varphi_i}\left\{G_{i,j}V_{j,p}^{r}-B_{i,j}V_{j,p}^{\text{im}}\right\}\quad\forall i,p, \tag{4}$$

$$I_{i,p}^{im}=\sum_{j\in\varphi_i}\left\{G_{i,j}V_{j,p}^{\text{im}}+B_{i,j}V_{j,p}^{r}\right\}\quad\forall i,p, \tag{5}$$

$$\theta_{i,p}=0\quad\forall i=\text{ref},p, \tag{6}$$

$$I_l^{N}=\sum_{j\in\varphi_i}C_{l,j}\sqrt{\left(\sum_{p\,\in\,\varphi_p}I_{j,p}^{r}\right)^2+\left(\sum_{p\,\in\,\varphi_p}I_{j,p}^{\text{im}}\right)^2}, \tag{7}$$

$$V_{\mathrm{ref}}^{N}=\left|Z_{\mathrm{ref}}^{N}\right|.I_{\mathrm{ref}}^{N}\quad \forall I_{\mathrm{ref}}^{N}=I_{l|l\in(\mathrm{ref},\mathrm{ref}+1)}^{N}, \tag{8}$$

$$V^{\min}\leq V_{i,p}\leq V^{\max}\quad \forall i,p, \tag{9}$$

$$\sqrt{\left(PL_{i,j,p}\right)^{2}+\left(QL_{i,j,p}\right)^{2}}\leq SL_{i,j,p}^{\max}\quad \forall i,j,p, \tag{10}$$

$$\sqrt{\left(PG_{i,p}\right)^{2}+\left(QG_{i,p}\right)^{2}}\leq SG_{i,p}^{\max}\quad \forall i,p, \tag{11}$$

$$\sqrt{\left(PDG_{i,p}\right)^{2}+\left(Q\ DG_{i,p}\right)^{2}}\leq SDG_{i,p}^{\max}\quad \forall i,p, \tag{12}$$

$$PDG_{i,p}\leq PDG_{i,p}^{\max}\quad \forall i,p, \tag{13}$$

$$PDG_{i,p}^{\max}=f\left(r_{i},v_{i}\ \text{and others parameters}\right)\quad \forall i,p, \tag{14}$$

$$\mathrm{VUF}_{i}^{-}=\frac{V_{i}^{-}}{V_{i}^{+}}\quad \forall i, \tag{15}$$

$$\mathrm{VUF}_{i}^{0}=\frac{V_{i}^{0}}{V_{i}^{+}}\quad \forall i, \tag{16}$$

$$\mathrm{VUF}_{i}^{-}\leq 0.02\quad \forall i, \tag{17}$$

$$\mathrm{VUF}_{i}^{0}\leq 0.02\quad \forall i, \tag{18}$$

$$\begin{gathered}\begin{bmatrix}V_{i}^{+}\\ V_{i}^{-}\\ V_{i}^{0}\end{bmatrix}=\frac{1}{3}\begin{bmatrix}1&\alpha&\alpha^{2}\\ 1&\alpha^{2}&\alpha\\ 1&1&1\end{bmatrix}\begin{bmatrix}V_{i,p=1}\\ V_{i,p=2}\\ V_{i,p=3}\end{bmatrix}\quad \forall i,\alpha=e^{j(2\pi/3)},\\ V_{i,p}=\sqrt{\left(V_{i,p}^{r}\right)^{2}+\left(V_{i,p}^{\mathrm{im}}\right)^{2}},\end{gathered} \tag{19}$$

$$PD_{i,p}=P_{i,p}^{0}\left(Z^{P}.\left(\frac{V_{i,p}}{V_{i,p}^{0}}\right)^{2}+I^{P}.\left(\frac{V_{i,p}}{V_{i,p}^{0}}\right)+P^{P}\right)\quad \forall i,p,Z^{P}+I^{P}+P^{P}=1, \tag{20}$$

$$QD_{i,p}=Q_{i,p}^{0}\left(Z^{Q}.\left(\frac{V_{i,p}}{V_{i,p}^{0}}\right)^{2}+I^{Q}.\left(\frac{V_{i,p}}{V_{i,p}^{0}}\right)+P^{Q}\right)\quad \forall i,p,Z^{Q}+I^{Q}+P^{Q}=1. \tag{21}$$

2.1. Objective Function. The objective function of the proposed problem is stated in (1), which has three parts. The first part is related to the minimization of voltage deviation. It should also be noted that the voltage deviation function includes two terms, which are given as follows [46]:

(i) Voltage deviation from the desired value: This function is mentioned in the first term of the voltage deviation function, where V_{ref} expresses the desired value of the voltage amplitude. Also, based on this function, the objective is to minimize the network voltage drop in all phases and buses.

(ii) Unbalanced voltage: This function is mentioned in the second term of the voltage deviation function, which expresses the minimization of zero and negative sequence voltages in all buses.

The second part of the objective function is related to the minimization of the total active losses of the network, which is equal to the difference between power generation and power consumption. The advantage of this formula is that it can be used for three-wire four-wire systems. We should note that in both systems, the index p is equal to 1 to 3. That is, in this model, there is no need for an index related to the null (neutral) wire [15]. It is worth mentioning that in the mentioned objective function, the loss of the neutral wire is also calculated in the third term. It is worth noting that all parts of the objective function are percentage or relative; therefore, each function is dimensionless. So, there is no need to model the objective function in the form of multiple objectives, and the objective function is expressed as a single objective.

2.2. Power Flow Equations in an Unbalanced System. AC power flow constraints are also mentioned in (2)–(6) [47–50], which include active and reactive power balance in each bus and each phase, (2) and (3), real and imaginary current balance, (4) and (5), and the voltage angle in the reference bus (6) [46]. It is worth mentioning that the terms *PG* and *QG* are related to the power transferred by the distribution substation to the consumers, which is assumed to exist only in the reference bus (ref). Hence, the values of *PG* and *QG* in other buses are equal to zero [46]. Additionally, in (2) and (3), the active and reactive power of the lines are calculated. In (4) and (5), the real and imaginary current of the phases is calculated. The neutral wire current of the lines is also calculated in (7). Finally, the zero-point voltage of the distribution substation is expressed in (8).

2.3. Limitation of Network Technical Indices. The limitation of distribution network indices is provided in (9) to (11) [51–53], which, respectively, express the limitation of the voltage amplitude of buses in each phase, the limitation of the transmission power of the lines, and the limitation of transmission power of the distribution network substation [46]. We should note that the left side of (10) and (11) represents the apparent power of the distribution line and substation, respectively.

2.4. Constraints Governing DGs. The constraints of DGs are stated in (12)–(14). It should be noted that (12) refers to the limitation of DG capacity. This limit is equal to a circle with the radius of DG capacity ($SDG^{\max}$) and the origin in (0, 0) in coordinates of the active-reactive power of the DG (*PDG*, *QDG*). The left side of (12) is equal to the apparent power of the DG. Also, constraint (13) is the limitation of active power generation by renewable DGs such as wind and solar systems. The active power generation by renewable DGs depends on weather conditions. Constraint (14) provides the method of calculating the maximum active power generation of these systems. Finally, constraint (14) for wind and solar systems is expressed as (22) and (23), respectively [54].

$$PDG^{\max}\big|_{\text{Windsystem}} = \begin{cases} 0, & v \le V_{ci}, \\ P_r\left(\dfrac{v - V_{ci}}{V_r - V_{ci}}\right), & V_{ci} \le v \le V_r, \\ P_r, & V_r \le v \le V_{co}, \\ 0, & v \ge V_{co}, \end{cases} \tag{22}$$

$$PDG^{\max}\big|_{Solarsytem} = \eta.S.r. \tag{23}$$

In these equations, v, V_{ci}, V_r, and V_{co} are, respectively, the wind speed, the threshold wind speed of the wind turbine, the nominal wind speed of the wind turbine, and the cut-off wind speed of the wind turbine. Moreover, η, S, and r also represent the efficiency of the solar system, the solar radiation area on the solar system, and the solar irradiation, respectively.

2.5. System Unbalance Constraints. Equations (15)–(19) are the constraints related to the unbalance of the three-phase four-wire system, in which in (15) and (16), the voltage unbalance factor (VUF) is calculated in negative and zero sequences, respectively, and then their limits are presented based on IEC [55] and IEEE [55] standards in (17) and (18). Finally, the positive, negative, and zero sequence voltages are calculated based on (19) from the voltage of phases 1 to 3 [46]. This paper considers the unbalanced four-wire low-voltage distribution network. In the low-voltage distribution network, the network has generally four wires, one of which is neutral. In unbalanced conditions of the network, the current passes through the neutral wire and leads to losses in the neutral wire. Therefore, it is important to consider the losses of the neutral wire in such a network.

2.6. Load Model Constraint. There are different models for the consumption loads of the distribution network, including the following:

(i) *Constant Impedance Load Model.* This type of model is for loads whose impedance is always constant and the power consumption is proportional to the squared power of the voltage
(ii) *Constant Current Load Model.* This type of model is for loads whose current is always constant and the power consumption is proportional to the voltage
(iii) *Constant Power Load Model.* This type of model is for loads whose power is always constant and the power consumption is independent of voltage

Generally, the loads include the three abovementioned items. This type of load model is known as constant impedance, constant current, and constant power, which is displayed as ZIP. It should also be noted that the constraints associated with this load model for active and reactive loads are (20) and (21), respectively. Parameters Z, I, and P are the fraction of constant impedance to constant power, the fraction of constant current to constant power, and the fraction of power to constant power, respectively, which are repeated for active and reactive loads [56].

3. Problem Solution

The model of the proposed problem is a constrained nonlinear problem, which in this paper, a mathematical method is used to solve. In this study, the SQP method is adopted. This method is an iteration-based method whichis applied to CNLP problems. This method exists in GAMS optimization software as a ready-made toolbox, which can be obtained under the title of SNOPT solver [57]. It is worth mentioning that the use of this toolbox in the mentioned software will eliminate the coding error of the solution method in the MATLAB software by the problem user. In addition, the problem model is an integrated problem and there is no need to solve the power flow problem separately by the Newton–Raphson algorithm, backward-forward, and other approaches. In other words, in this paper, all the proposed equations (1)–(23) will be solved integrally by the SQP algorithm in the GAMS software. Finally, it should be noted that there is no restriction for using other solvers in solving the proposed problem.

4. Numerical Results

4.1. Problem Data. In the present study, the problem is implemented on a three-phase four-wire standard IEEE 13-bus radial distribution network, whose single-line diagram is shown in Figure 1 [58]. Also, this network has a base voltage and power of 4.16 kV and 5 MW, the minimum and maximum voltage amplitudes of 0.9 to 1.05 per unit (p.u.) [59–65]. In addition, the network has 12 lines, the various specifications of which are presented in [58]. This network has 8 load points, the active and reactive load values of each point in different phases are specified in [58]. According to [58], the source of unbalance in this 13-bus distribution network is the existence of single-phase loads, the unequal loads in each phase, and the different characteristics of each phase line (there are also single-phase lines). In the proposed problem, the load model including the ZIP load model was used, the parameters of which are reported in Table 1 [56]. The impedance of the wire connecting the zero point of the distribution substation to the ground is considered 0.2 ohms. In this paper, two types of RESs are used, i.e., wind and solar systems. The wind system is located on Bus 11 and the solar system is located on Bus 9 of the proposed network [66]. According to [66], the capacity of wind and solar systems is considered 1500 kVA and 1250 kVA, respectively. It is assumed that the weather conditions are such that the average active power corresponding to the weather conditions (PDG^{max}) of both sources is 80% of their nominal capacity. In other words, this value is equal to 1200 and 1000 kV for wind and solar systems, respectively.

4.2. Case Studies. In this section, to check the capabilities of the proposed scheme in the four-wire distribution network, six different studies are carried out, which are described as follows:

(i) *Case I.* Analysis of the power flow results of an unbalanced four-wire 13-bus distribution network without DGs
(ii) *Case II.* Analysis of the results of the proposed scheme considering the minimization of only network losses as the objective function of the problem
(iii) *Case III.* Analysis of the results of the proposed scheme considering the minimization of only the losses of the neutral wire as the objective function of the problem

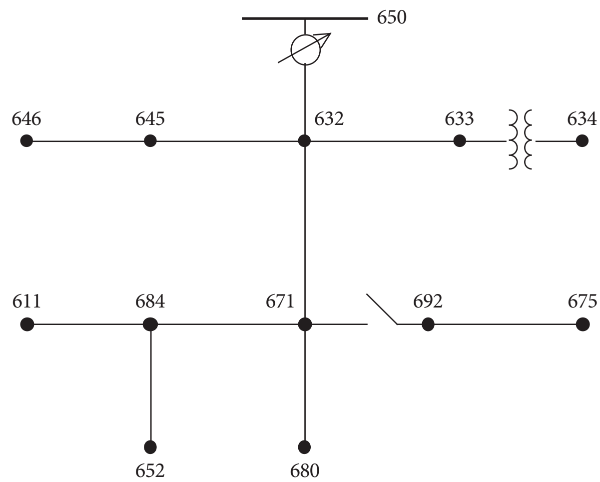

Figure 1: Single-line diagram of standard IEEE 13-bus radial distribution network [58].

Table 1: Data of the ZIP load model [56].

Parameter	Value (%)
Z^P	20
Z^Q	20
I^P	30
I^Q	30
P^P	50
P^Q	50

(iv) *Case IV.* Analysis of the results of the proposed scheme considering the minimization of only the voltage deviation from the desired value as the objective function of the problem
(v) *Case V.* Analysis of the results of the proposed scheme considering the minimization of only the unbalanced voltage of the network as the objective function of the problem
(vi) *Case VI.* Analysis of the results of the proposed scheme by considering the minimization of total network losses, neutral wire losses, voltage deviation from the desired value, and unbalanced voltage of the network as the objective function of the problem

4.3. Results and Discussion. The proposed problem is coded in the GAMS optimizer software environment and is solved by the SNOPT solver [57].

4.3.1. Investigating the Value of the Objective Function. The values of different parts of the objective function are presented in Table 2. Based on this table, in cases II, IV, and IV, network loss has decreased significantly compared to Case I, but in cases III and IV, network loss is not decreased. This is because in cases III and IV, the minimization of the unbalanced effect was considered, but in cases II and IV, the minimization of network losses and voltage deviation was addressed. Also, due to the high changes in network losses

Table 2: The values of different parts of the objective function.

Case	I	II	III	IV	V	VI
Network losses (kW)	68.359	9.441	88	25.329	67.242	26.249
Neutral wire losses (kW)	4.832	5.104	4.693	5.149	5.036	5.086
Average voltage (kV)	4.021	4.135	4.106	4.155	4.195	4.164
Zero-point voltage (V)	2.482	3.239	0.194	3.353	2.325	3.188
$\sum_{i\in\varphi_i}(\mathrm{VUF}_i^- + \mathrm{VUF}_i^0)$	0.113	0.098	0.383	0.102	0.014	0.07

and voltage deviation compared to the network unbalance indices, these parameters in Case VI have become less than the unbalance parameters. The neutral wire loss has the lowest value in Case III, but generally, its changes are small in different study cases. The voltage in all cases II–VI has been able to be closer to the desired value of 4.16 kV (distribution substation voltage) compared to Case I. Additionally, the lowest zero-point voltage has been obtained in Case III (minimization of neutral wire losses). Finally, the lowest value of the network unbalance index has been evaluated in Case V (minimization of unbalanced voltage only). Comparing cases V and VI, it can be seen that in Case V, the neutral wire losses and the zero-point voltage have lower values compared to those in Case VI, because in this study case, the unbalanced effects are minimized. Nonetheless, the voltage deviations compared to the reference voltage (4.16 kV) and the overall losses of the network in Case VI are lower than those in Case V. The reason is that the minimization of these cases has not been investigated in Case V. It is clearly observed that the minimization of unbalanced effects and the minimization of network losses or voltage deviations do not move in the same direction so that if there is a minimum value for one case, the other case does not have the minimum value. Finally, Case VI concerns the unbalanced effects, network losses, and voltage deviations together, which has obtained an interaction point between different objective functions.

4.3.2. Investigating Network Indices. The results of this section are listed in Tables 3 and 4 and Figure 2. Table 3 shows the amount of active power sent by the distribution substation to the consumers. Based on this table, it can be seen that this amount in cases II, IV, and VI has been greatly reduced compared to that in Case I, which means that in these study cases, consumers are fed by local power sources (solar system in Bus 9 and wind system in Bus 11). This is because cases II, IV, and VI consider the minimization of network losses and voltage deviation. Therefore, to minimize these cases, it is better to shorten the distance between consumers and producers. However, it should be noted that in cases III and V, the minimization of the unbalance indices such as neutral wire loss and unbalanced voltage is considered; therefore, the power distribution will be such that the unbalance is reduced. Consequently, in cases III and V, the values of the active power of the distribution substation are close to that of Case I. These results also hold for the reactive power transferred by the distribution substation to the consumers based on Table 4. In other words, based on Table 4, it can be seen that in cases II, IV, and VI, the consumers are fed by local producers, and in cases III and V, the local producers are used to resolve the unbalanced situation.

Table 3: The active power generation of the distribution substation (p.u.).

Case	Phase 1	Phase 2	Phase 3
I	0.230	0.193	0.225
II	0.061	0.086	0.065
III	0.230	0.206	0.204
IV	0.132	0.048	0.161
V	0.119	0.125	0.237
VI	0.057	0.090	0.067

Table 4: Reactive power generation of the distribution substation (p.u.).

Case	Phase 1	Phase 2	Phase 3
I	0.134	0.131	0.162
II	0.019	0.036	0.024
III	0.134	−0.222	0.160
IV	−0.033	0.023	−0.041
V	0.097	0.134	−0.124
VI	−0.016	0.021	0.004

Figure 2 illustrates the voltage profile of different phases in different case studies. Based on this, in cases II–VI, the voltage profile is close to 1 p.u. (voltage of the distribution substation which is equal to 4.16 kV or 1 p.u.), and also, the voltage in all the studied cases is within the permissible range of 0.9–1.05 p.u. This shows the ability of DGs in voltage regulation. Regarding the voltage values in different phases, the difference between phase voltages based on Figures 2(a)–2(c) is low for different case studies, which is due to the minimization of unbalanced effects in the proposed problem. If the unbalance effect is low, the current of all three phases is close to each other, and therefore, the difference between the voltages of the phases should be small. Based on Figure 2, the phase voltage distance is low, so it can be said that the proposed scheme has been able to reduce the negative effects of unbalance, which will be an advantage.

4.3.3. Investigating the Neutral Wire Current and the Zero-Point Voltage of the Distribution Substation. Figure 3 shows the neutral wire current for the distribution lines in different case studies. Based on this figure, Line 12 has zero neutral wire current, because according to [58], the neutral wire current of this line depends on the loading of Bus 12, and the amount of loading in Bus 12 is zero. Moreover, the neutral wire current of all lines in Case III is lower than in other case studies. This is because that in this case, the minimization

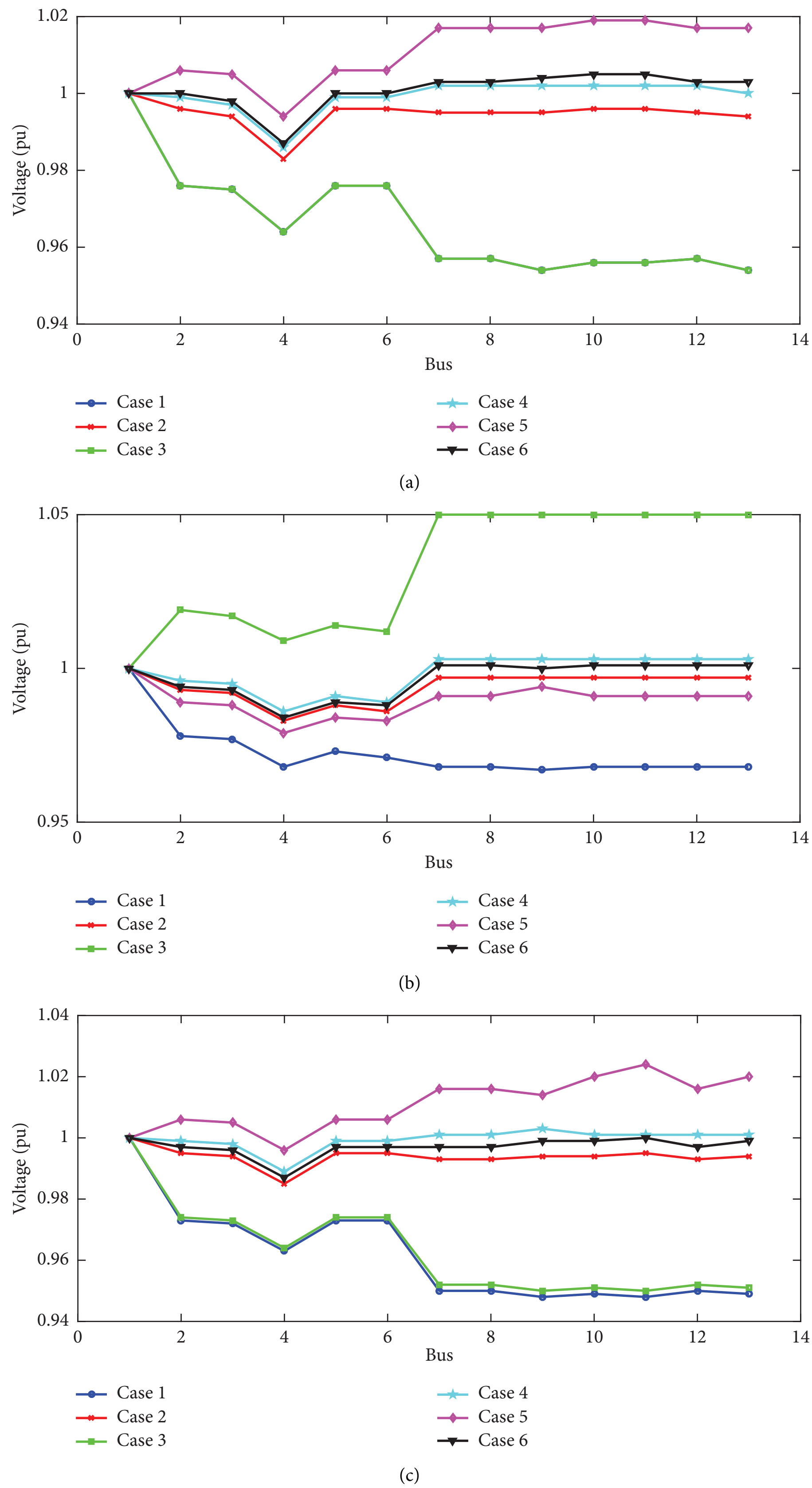

Figure 2: Voltage profile in different case studies: (a) the first phase, (b) the second phase, and (c) the third phase.

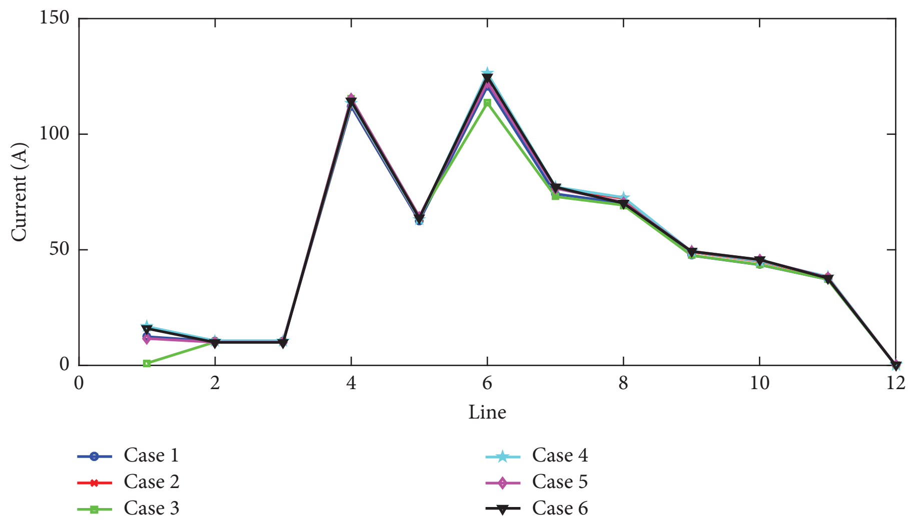

Figure 3: Neutral wire current of the lines in different case studies.

studies consider only the loss of the neutral wire, which depends on the amount of current passing through that line; therefore, to achieve the minimum value for the neutral wire losses, the power distribution of the substation and local producers should be in such a way that the current of the neutral wire of each line is low. Also, the minimum value is observed in Line 1, which is equal to 0.97 A.

Table 5 shows the zero-point voltage of the distribution substation and the current of the wire that connects the zero-point of the distribution substation to the ground. Based on this table, the lowest value of the zero-point voltage and the current of the zero-point connecting wire has been obtained in Case III which considers the minimization of neutral wire losses. This goal will be achieved when the current passing through the neutral wire is minimum. Also, these losses include the zero-point connection of the distribution substation. Therefore, by minimizing the losses of the neutral system, the power distribution of DGs and distribution substations in the distribution network will be such that the current passing through the zero-point connecting wire of the distribution transformer is minimum. Therefore, the zero-point voltage will also have the lowest value. In Table 6, the effects of the zero-point impedance of the distribution substation transformer on the current of the zero-point connecting wire and the zero-point voltage have been investigated in cases III and VI. The reason for selecting Case III is that it has more favorable results for the zero-point voltage based on Table 5. Also, Case VI is chosen because it fits the proposed problem model (1)–(23). Based on Table 6, the increase of the zero-point impedance only increases the zero-point voltage, but the current passing through the zero-point connecting wire is unchanged. So, the lower the impedance of the zero point, the better results will be obtained.

4.3.4. Investigating Power Generation of DGs. Figures 4–7 show the active and reactive power generation of solar and wind systems for different phases in cases II to VI. Figure 4 plots the active power of solar systems, and the reactive power of this system shows in Figure 5. Figure 6 shows the active power of the wind system, and Figure 7 plots the reactive power of this system. Based on these figures, it is observed that in cases II, IV, and VI, compared to cases III and V, the mentioned DGs produce significant power in different phases. This is to further reduce network losses and improve the voltage profile. It should be noted that the power changes of DGs in each case study are proportional to the objective function of the problem. That is, if the objective function is equal to the minimization of unbalanced negative effects, then the power distribution of DGs is such that the power balance between the phases is established. These results can also be extracted from the previous section.

4.3.5. Examining the Load Model. In this section, the effects of the ZIP load model on various parameters of the objective function are examined in Case VI. Table 7 reports the results of this section. Two studies are conducted; in one case, the ZIP model is not considered, so the parameters Z^P, Z^Q, I^P, and I^Q are zero, and P^P and P^Q are 100%. Based on the results of Table 7, the ZIP load model has been able to obtain better values for different parts of the objective function, because it can control the voltage by controlling the load level. As observed results in Table 7, the first and second terms of (20) and (21) are removed in the ZIP load model. Thus, the capability of voltage control by the load is removed. In this situation, loads consume only active and reactive power, thus for increasing the voltage drop on buses compared to a case, the ZIP load model is considered. This can be seen in the fourth row of Table 7. To elaborate more, in the ZIP load model, the average voltage is about 3.8% ((4.164 – 4.148)/4.164) higher than that in the case where the ZIP is not included. This results in increased network losses in the case where the ZIP is not available compared to its opposite case; this can be seen in the second and third rows of Table 7. Concerning the unbalance, since there is no control voltage by the load in the case of the ZIP load model, the zero-point voltage and $\sum_{i\in\varphi_i}(\mathrm{VUF}_i^- + \mathrm{VUF}_i^0)$ were increased more than the case with the ZIP model.

Table 5: Zero-point voltage and current of the wire connecting the zero-point of the distribution substation to the ground.

Case	Current of wire connecting the zero-point of distribution substation to the ground (A)	Zero-point voltage (V)
I	12.41	2.482
II	16.195	3.239
III	0.97	0.194
IV	16.765	3.353
V	11.175	2.325
VI	15.94	3.188

Table 6: Investigating the effects of zero-point impedance on characteristics of zero-point of the distribution substation.

Case	Impedance (ohm)	Current of wire connecting the zero-point of distribution substation to the ground (A)	Zero-point voltage (V)
III	0.1	0.97	0.097
III	0.2	0.97	0.194
III	0.3	0.97	0.291
VI	0.1	15.94	1.594
VI	0.2	15.94	3.188
VI	0.3	15.94	2.782

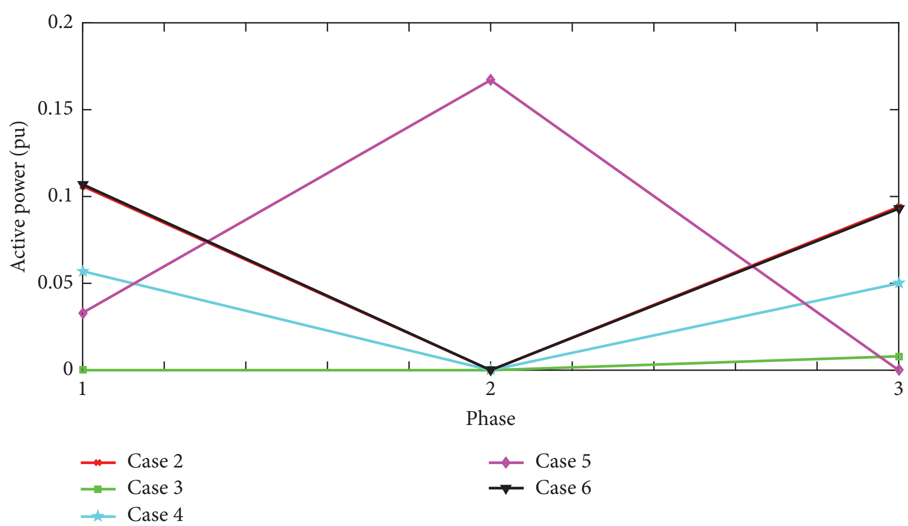

Figure 4: The active power produced by each phase of the solar system in different case studies.

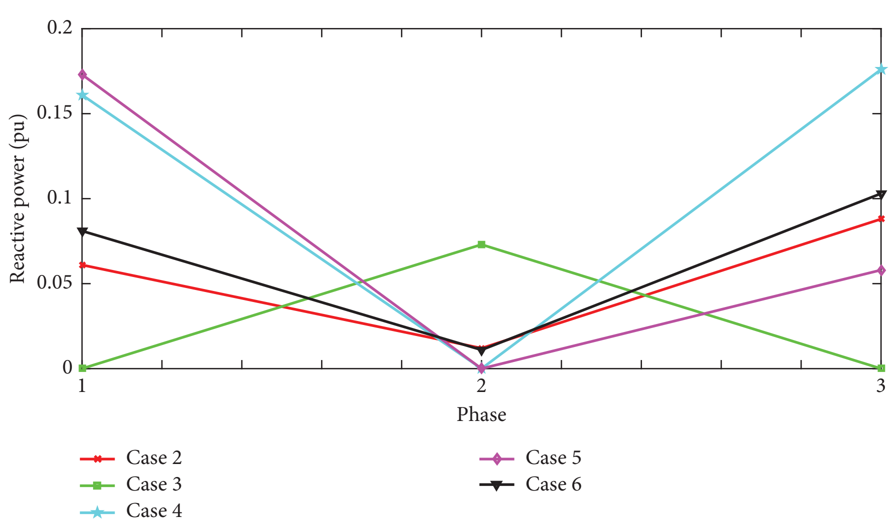

Figure 5: Reactive power generation of each phase of the solar system in different case studies.

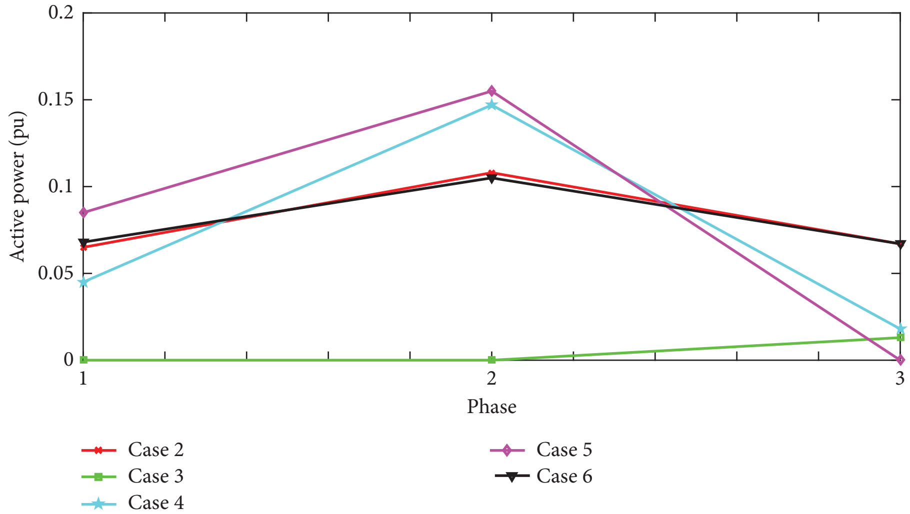

Figure 6: Active power generation of each phase of the wind system in different case studies.

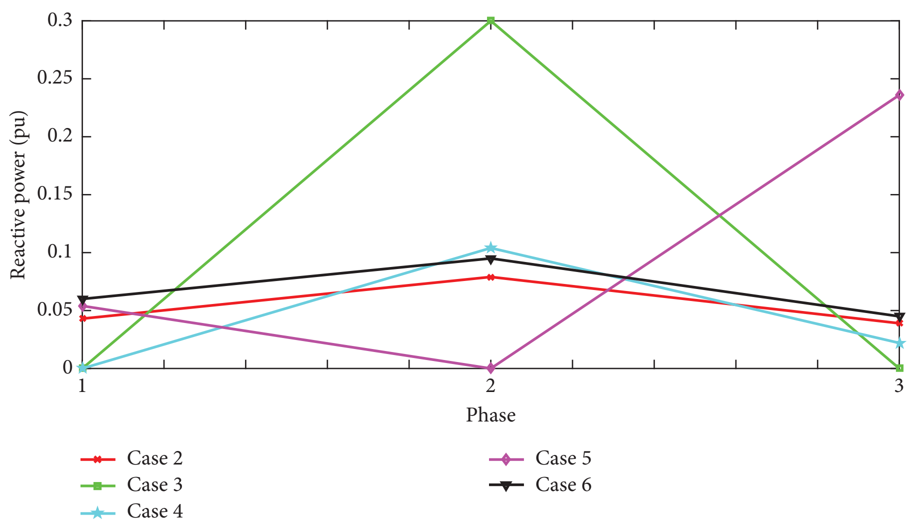

Figure 7: Reactive power generation of each phase of the wind system in different case studies.

Table 7: Evaluation of the ZIP load model on the results of the proposed optimization problem in case VI.

Parameter	Considering the ZIP model	Neglecting the ZIP model
Network losses (kW)	26.249	27.531
Neutral wire losses (kW)	5.086	5.153
Average voltage (kV)	4.164	4.148
Zero-point voltage (V)	3.188	3.564
$\sum_{i\epsilon\varphi_i}(\mathrm{VUF}_i^- + \mathrm{VUF}_i^0)$	0.07	0.08

4.3.6. Convergence State of Scheme. In Table 8, the state of convergence of the proposed scheme in Case VI is reported for SQP, CONOPT, IPOPT, and BARON solvers [57]. Based on this table, it can be seen that the SQP algorithm provides more optimal values for the components of the objective function than the other stated algorithms. However, based on this table, the SQP algorithm needs a higher computation time than CONOPT and IPOPT. In terms of reaching the optimal point, the SQP algorithm is the most suitable solver, and this is important in solving nonlinear problems. In other words, in solving nonlinear problems, an algorithm with a more optimal point is desirable because it is expected that

Table 8: Convergence state of proposed scheme in case VI for different solvers.

Solver	SQP	CONOPT	IPOPT	BARON
Calculation time (sec)	791	698	524	809
Network losses (kW)	26.249	27.342	26.891	27.472
Neutral wire losses (kW)	5.086	5.567	5.211	5.611
Average voltage (kV)	4.164	4.151	4.158	4.149
Zero-point voltage (V)	3.188	3.467	3.312	3.502
$\sum_{i\in\varphi_i}(\mathrm{VUF}_i^- + \mathrm{VUF}_i^0)$	0.07	0.079	0.073	0.081

the point is closer to the global optimal point. In terms of convergence speed, the IPOPT algorithm is preferred because it needs a low computation time.

5. Conclusion

This paper presented the operation of an unbalanced distribution network with a ZIP load model in the presence of DGs. The suggested minimization scheme considered the normalized objective function, which is equal to the sum of network power losses, neutral wire losses, and voltage deviations. It was subject to the optimal AC power flow equations, network unbalance constraints, and operation models of the load and DGs. Then, the SQP mathematical method was used to solve the problem. Eventually, based on the numerical results, it was observed that consumers tend to be supplied by local producers such as solar and wind systems to minimize network losses and improve the voltage profile. In this situation, the power distribution of local producers in the network can be effective in reducing the unbalanced situation of loads to have the lowest neutral wire losses, unbalanced voltage, and zero-point voltage of the distribution substation. Improvement of network and unbalance indices is obtained in the case of optimal operation of DGs in unbalanced four-wire distribution networks.

As it is seen that based on the numerical results, the SQP algorithm obtained a more optimal point than other mathematical solvers suitable for solving the nonlinear problem. Yet its computation time was high compared to other algorithms. According to this issue, it is possible that solving the proposed problem in large-scale networks by SQP does not have an optimal solution. To address this issue, decomposition algorithms (such as Benders decomposition or master-slave decomposition) and evolutionary solvers can be suitable. Therefore, the proposed scheme, according to the stated solvers, is considered as future work.

Nomenclature

i: Bus counter
j: Bus counter
p: Phase counter for the four-wire system
l: Line counter
Ref: Reference bus
φ_i: Set of buses
φ_p: Set of phases (1 to 3)
φ_l: Set of lines
PD: Consumption active power
PG: Active power transfer from the distribution substation (on the reference bus) toward the consumption loads
PDG: Active power generation by DG
$PDG^{\max}$: Maximum active power generation by DGs
PL: Active power flow through the lines
QD: Reactive power consumption
QG: Reactive power transfer from the distribution substation (on the reference bus) toward the consumption loads
QDG: Reactive power generation by DGs
QL: Reactive power flow through the line
V^r: Real voltage
V^{im}: Imaginary voltage
V^+: Positive sequence voltage
V^-: Negative sequence voltage
V^0: Zero sequence voltage
VUF^-: Voltage unbalance factor in the negative sequence
VUF^0: Voltage unbalance factor in the zero sequence
I^r: Pure real current injection to the bus
I^{im}: Pure imaginary current injection to the bus
I^N: Neutral wire current
V^N: Zero-point voltage of the distribution substation
V_{ref}: Voltage amplitude of the reference bus (which is assumed to be the desired value)
P_{base}: Base power
A: A matrix that specifies which buses the lines are between
G: Network conductance
B: Network susceptance
C: A matrix that specifies which buses the lines are connected to when calculating the neutral wire current
$V^{\max}$: Maximum voltage amplitude
$V^{\min}$: Minimum voltage amplitude
$SL^{\max}$: Maximum power flow through the line
$SG^{\max}$: Maximum power transfer from the distribution substation
$SDG^{\max}$: Maximum power generation by DGs
Z^P: The fraction of impedance to constant power in active load
Z^Q: The fraction of impedance to constant power in reactive load
I^P: The fraction of current to constant power in active load
I^Q: The fraction of current to constant power in reactive load
P^P: The fraction of power to constant power in active load
P^Q: The fraction of power to constant power in reactive load
P^0: Active power of the consumption load
Q^0: Reactive power of the consumption load
V^0: Initial voltage in the load model.

Data Availability

The data used to support the finding of this study are included within the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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