Power Quality and Reliability Considerations of Photovoltaic Distributed Generation

Ali M. Eltamaly^{1,2,3} · Yehia Sayed Mohamed⁴ · Abou-Hashema M. El-Sayed⁴ · Mohamed A. Mohamed⁴ · Amer Nasr A. Elghaffar^{4,5,6}

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Abstract

Worldwide energy consumption is increasing at a faster pace than energy generation because of enhanced industrialization, growing population and, improved living standards. Using the Distributed Generation (DG) near the end consumers can support the electrical grid stability and enhance the power system quality. The DG is consisting of a small-scale technology to generate electrical power near the end consumers, which can be renewable energy or generators. Solar Photovoltaic (PV) system is considered as one of the best renewable energy sources, due to its low running cost and low environmental affection comparing with traditional power plants. The proposed PVDG units are employing maximum power point tracking (MPPT) system to track the maximum power available in PV arrays. The proposed DG system used Particle Swarm Optimization (PSO) technique to optimally allocate the PVDG units for minimum cost, transmission line losses, and improved voltage profile of busbars under different operating conditions. This paper proposes a smart optimization technique employing PSO in the design, operation, and control of the proposed system. Also, the paper discusses the PSO algorithm for optimal DGs sizing and allocations. The simulation in this paper uses the IEEE-7 busbars system with an extension of IEEE-3 busbars as a new remote load. The simulation has been carried out by the power world simulator software to compare the voltage and the power losses with and without PVDGs connected to the system. The simulation results showed an acceptable reduction in generating cost, transmission line losses, and improvement of the busbars voltage profile which proves the success of the proposed system.

Keywords Distributed generator · Voltage control · Photovoltaic · Particle swarm optimization · Power quality

✉ Amer Nasr A. Elghaffar
amernasr70@yahoo.com

Ali M. Eltamaly
eltamaly@ksu.edu.sa

Mohamed A. Mohamed
dr.mohamed.abdelaziz@mu.edu.eg

- ¹ Electrical Engineering Department, Mansoura University, Mansoura, Egypt
- ² Sustainable Energy Technologies Center, King Saud University, Riyadh 11421, Saudi Arabia
- ³ K.A. CARE Energy Research and Innovation Center, Riyadh 11451, Saudi Arabia
- ⁴ Electrical Engineering Department, Minia University, Minia 61517, Egypt
- ⁵ Alfannar Engineering Service, Alfannar Company, Riyadh, Saudi Arabia
- ⁶ SRGE Ambassador, Scientific Research Group in Egypt, Cairo, Egypt

Abbreviations

<i>DG</i>	Distributed Generation
<i>PV</i>	Photo Voltic
<i>PSO</i>	Particle Swarm Optimization
<i>FACTS</i>	Flexible AC Transmission System
<i>VD</i>	Voltage Deviation
<i>MPPT</i>	Maximum Power Point Tracking
<i>VSI</i>	Voltage Stability Indicator
<i>IMPP</i>	Current Maximum Power Point
<i>VMPP</i>	The Voltage of Maximum Power Point
<i>CS</i>	Current Sweeping
<i>MT</i>	Micro-Turbine

Nomenclature

R_K	Line resistor
X_K	Line reactance
U_1	Voltage values at sending end
U_2	Voltage values at receiving end
P	Active power
Q	Reactive power

$\bar{Z}$	Transmission line Impedance
Δu	Voltage drop Longitudinal component
δu	Voltage drop transversal component
N_D	Number of possible DGs combination
$f_3(x)$	Voltage deviation function
V_i^k	Voltage magnitude at i-th busbar of k-th time period
$V_i^{k\text{ spec}}$	Specified voltage magnitude
$V_i^{k\text{ max}}$	Upper limit at i-th bus
$V_i^{k\text{ min}}$	Lower limit at i-th bus
V_0	Voltage in grid system bus
V_1	Voltage in the load bus
P_{DG}	Active power generated by the DG
Q_{DG}	reactive power generated by the DG
N	Number of busbar system
δ	Voltage angle
k	Proportional real constant
$p(t)$	output power
C	maximum PV array current
I_{max}	maximum current
S	Solar panels area
Φ	Irradiation of sun
T_e	Temperature in Celsius
P_{PV}	The output power of solar systems
K_{PV}	Solar systems gain
T_{PV}	Solar systems time constant
K_{IN}	The gain of the inverter
T_{IN}	Inverter time constant
$f(S)$	Probability density function of S
S_{K-min}	Lower bound state K (KW/m^2)
S_{K-max}	Upper bound state K (KW/m^2)
μ_g	Historical solar irradiance data for time segment g
σ_g	Standard deviation of the historical solar irradiance data for time segment g
S_{rated}	PV's rated solar irradiance (KW/m^2)
$P_{S-rated}$	PV's rated active power output (KW)
S_{rated}	Rated capacity of the installed PV inverter (kVA)
S_i^k	Velocity of individual constant
p_{best}	Best value attained by individual i
g_{best}	Global best value i at iteration k
C_1, C_2	Acceleration of the group
W	Inertia weight factor
$r a n d$	Uniform random number between 0 and 1
$*$	()
S_{id}^k	Current position of individual i at iteration k
Δt	The time step
C_1	The constants of the acceleration terms of p_{best}
C_2	and g_{best}
w_{max}	Maximum value of inertia weight
w_{min}	Minimum value of inertia weight
$iter_{max}$	Maximum iteration number (generations)
$iter$	Current iteration number

Z	Value of the inequality constraint
z_{min}	Lower limits inequality constraints
z_{max}	Upper limits inequality constraints

Introduction

The power quality is an important characteristic of today's distribution power systems as loads become more sensitive on the other hand nonlinear loads are increasing in the electrical distribution system [1]. Considering the distributed nature of harmonic loads, the need for distributed power quality improvement (PQI) is inevitable. However, with the increasing power demand, population growth, and the increase in the life stander requirements, the electrical system must be supported by transmission line extension with the new power plants [2]. Comprehensive improvement of power system quality levels in specific areas of the electrical distribution network can have a wider application scope and provide higher overall benefits when network compensate activity is implemented at the optimum point in the distribution network level [3]. The Distributed Generator (DG) is considered as more economic and environmental aspects as compared with adding the power plants with the new remote load. The photovoltaic (PV) and wind generation are the famous and economical sources of electric power generation. The DG can support the power system for improving the voltage profile, reducing the power losses, system efficiency, and eliminating the system upgrades [4]. The DGs sources can be PV systems, wind turbines, biomass, or small hydropower plants. On another hand, the high DG penetration level may impact the power system operation strategies and control. Hence, it's important to analyze the DGs system with the loads to prevent the instability voltage and frequency problems [5]. Therefore, it is important to plan for the power system operation by considering voltage stability. The reactive power reduction can be compensated by adding multi-units of the DGs with the distribution power network to improve the voltage stability [6]. Moreover, it is necessary to study the impact of the different reactive power compensation techniques by the DGs on voltage stability [7]. The capacitor bank is one of the famous methods capable to improve reactive power and reduces power losses. The installation of many capacitor banks at different busbars can't save the voltage stability with the increasing loads. Due to inaccurate adding capacitance values, the power losses can be increased. Moreover, it is more cost at comparing with the installation of the DGs units. However, the significant impact of the DG can be obtained by the determination of the optimum capacitor placement with saving the accurate stable system [7]. Also, the power system quality can improve the voltage and compensate for the reactive power by utilizing the Flexible AC Transmission System (FACTS) devices, which can be shunt or series connected with the system [8, 9]. On

another hand, the FACTS devices are considered not an economic way of comparing with the DGs. Smart grid technology has been grown for allowing bi-directional communication between the consumers and the power generation. The management of the power demand side is the main challenge to reach the optimum balancing and the reliability system also can be managed by the DGs. Renewable energy technologies are considered one of the hottest topics in the electric power system, which is clean and more economical compared with conventional power plants. The basic principle of a solar PV cell is the conversion of sunlight into electricity, which can be either used directly or stored in the batteries. The PV can operate as combined with one or more other electricity generators or more renewable energy sources. But, the insertion of DG units can also vary the voltage profile due to the intermittency of the power generated by the PV system, especially on cloudy days with a voltage collapse possibly leading to a complete interruption of power [10]. PV system is demonstrated in the form of a schematic diagram as shown in Fig. 1. The operating and control for the PVDG to save the power system stability can use Automatic Generation Control (AGC) which is a very impressive problem in restructured power system operation for providing electric power with high quality and reliability, the three-area multi-units system has chosen for the AGC in the restructured power system [11].

Using the efficiently transform DC output of PV source to a high voltage AC source, by DC to AC inverters to connect with the power grid [12]. The PV characteristic contains a unique Maximum Power Point (MPP) for each weather condition, a unique MPP will be generated to be tracked efficiently which is discussed in this paper.

Particle Swarm Optimization (PSO) algorithm begins with a population (called a swarm) of candidate solutions (called particles) [13]. These particles are assigned with random velocities and it keeps the track of their positions in hyperspace with the obtained their best solution (fitness) to be called 'pbest'. Moreover, the particle swarm optimizer holds the overall best value of its particles and the corresponding position to the global best value called 'gbest'. The PSO changes the velocity and hence the position of each particle with every iteration [14].

In this paper, a comprehensive analytical methodology for enhancing the power system quality by compensating the drop voltage using the PVDGs near the remote loads. Additionally, the methodology for assessing technical DG to operate stand-alone or in connection with the power system is introduced. The PVDG units can be installed at or near the load-related using PSO algorithm for optimum PV allocation, unlike large central power plants. The main objectives of this article are introducing prospective analysis of the voltage drops in the distribution network due to the known value of the voltage deviation can help to ensure an optimum voltage level in the distribution system. Then, an objective function that incorporates technical and economic perspectives into the optimization of using PV renewable energy with the discussion of MPPT is presented. Also, in this paper, a complete discussion for compensating the voltage drop by using the PVDGs planning approach is introduced. Moreover, the optimum allocation to select the optimum busbar in the distribution system to add the PVDG for the optimum compensation is presented by the PSO algorithm. Finally, the losses reduction and the benefits of applying the proposed techniques to compensate for

Fig. 1 PV system integration with a distribution network

the voltage system by the PVDGs with the power system is presented. The remaining parts of the paper have been organized as follows: “**Problem Formulation**” section presents A prospective analysis of the voltage drops in the distribution network. A proposed strategy using DGs technology for voltage control is introduced in “**DG Units Benefits**” section. “**PV System Operation Logic for DGs**” section shows the importance and influence of using PV renewable energy with the discussion of MPPT for enhancing the power system quality. “**PSO for Optimal PVDGs Allocation**” section presents the optimum placement of the DGs by the PSO algorithm. “**Simulation and Analysis**” section uses the software to illustrate the impact of using the PVDGs with the power system. Finally, “**Conclusion**” section is the conclusions of the work.

Problem Formulation

Due to using conventional power sources like fossil fuels, hydropower, nuclear energy, etc. there are many bad effects occurs such as environmental problems and economic issues, and security issues due to the exhaust of conventional sources in the future [15]. Based on the DGs, the PV system can be used for enhancing the power quality with satisfying different constraints is counted as one of the best options to improve distribution systems [16]. The DGs technologies can be classified into three modules depending on the output characteristics as state variable active power, state variable reactive power, and state variable active and reactive power.

Drop Voltage and Power Losses through the Transmission Line

The long-distance remote loads are facing a critical impact due to voltage drop. Also, with the increasing power demand in remote locations, it's required to increase the transmission power or construct the new power plants in the remote sites to feed the new loads, which all translated to high cost. In the long transmission lines, when the resistance (R) and inductance (L) are too high, the voltage drop across the line increases [17, 18]. To calculate the transmission line drop voltage, by assuming the line resistor is (R_K) and the line reactance is (X_K), the voltage drop can be calculated as shown in Eq.(1). With considering the voltage values at sending end and receiving end are (U_1, U_2) respectively, ($\bar{I}_1, \bar{I}_2$) are the currents at the line extremities and P, Q are the transmission active and reactive power respectively.

$$\Delta U = U_1 - U_2 \quad (1)$$

The power losses can be computed from eq. (2):

$$P = I^2 R = \frac{U_1^2 - U_2^2}{R} \quad (2)$$

The supposed absence of the shunt admittance leads to $\bar{I}_1 = \bar{I}_2 = \bar{I}$ in the long line. By taken the angle between the current and the voltage, so the current components $\bar{I}$ is $I_i = I \cos \varnothing$, $I_r = I \sin \varnothing$. Also, by assuming the voltage of U_1 is constant, so the voltage drops, ($\Delta U = \bar{Z} * \bar{I}$) which is two components:

$$\Delta u = R I_i + X I_r, \delta u = X I_i - R I_r \quad (3)$$

Where, $\bar{I} = I_i - j I_r$ for inductive loads, and $\Delta u, \delta u$ are the longitudinal and transversal components of the voltage drop. And by indicating the three-phase complex power [19].

$$\bar{S}_2 = U_2(I_i + j I_r) = P_2 + j Q_2 \quad (4)$$

$$\Delta u = \frac{R P_2 + X Q_2}{U_2}, \delta u = \frac{X P_2 - R Q_2}{U_2} \quad (5)$$

Due to $R \ll X$ for transmission lines, it turns out that,

$$\Delta u = \frac{X Q_2}{U_2}, \delta u = \frac{X P_2}{U_2}, \quad (6)$$

Selecting DG Allocation

The DGs allocation is the main challenge to reach the optimum system operation which considers the environmental weather for the PV design. Hence, the complex optimization problem for the DGs design is the selection of the optimal allocation [20]. When the allocation (N_{DGs}) with using the same DGs technology module and the number of possible allocations is (N_B). So, the number of DGs possible combination is (N_C) can be computed using eq. (7).

$$N_C = \frac{N_B!}{N_{DG}! * (N_B - N_{DG})!} \quad (7)$$

As using different DGs technology, the number of possible DGs combination (N_D) can be computed from the following equation:

$$N_D = \frac{N_B!}{(N_B - N_{DG})!} \quad (8)$$

From eq. (3) and eq. (4), its multi busbars possible combinations to uses the DG, which is higher at using DGs different types at comparing with the combination by one DG type? So, it's important to select and determine the optimum DGs allocation and the required value to save the system stability at a low cost.

The Voltage Deviation (VD) is considered the main object for the optimization model to minimize the deviation between nodal voltage and the specified voltage magnitude. The nodal voltage magnitude is the indicator to evaluate the power quality and system security [21]. The decreasing voltage deviation can help to ensure an optimum voltage level in the distribution system. The voltage deviation function can be formulated in eq. (9).

$$\text{Min } f_3(x) = \min_{\sum_{k=1}^{N_h}} \left\{ \sum_{k=0}^N \left(\frac{V_i^k - V_i^{k \text{ spec}}}{V_i^{k \text{ max}} - V_i^{k \text{ min}}} \right) \right\} \quad (9)$$

Where, V_i^k is the voltage magnitude at i -th busbar of k -th time period, $V_i^{k \text{ spec}}$ is the specified voltage magnitude and $V_i^{k \text{ max}}$ is the upper limit at i -th busbar and $V_i^{k \text{ min}}$ is the lower limit at i -th busbar.

DG Units Benefits

Maintaining the consumers' terminal voltage within its allowable limits at all operating conditions is considered one of the most significant challenges of the distribution network operation. For a long radial distribution feeder, the voltage profile decreases as it moves from the feeding source to the end of the feeder. The DGs in distribution networks set significant challenges to voltage regulation networks. The DGs can cause power loss and voltage magnitude to increase or decrease [22]. DG can operate stand-alone or in connection with the power system and can be installed at or near the load, unlike large central power plants. The DG - PV rating power range from 5.0 kW up to 100 MW and for all DG sources as mentioned in Appendix Table 10. With the DGs, the embedded power between DG and the conventional generators is impacted by the power system quality to improve the voltage profile and their stable angle, reactive power, and system reliability. The famous DGs sources are wind energy and solar power which can operate by coupling with the grid system or independent isolation, this operation depending upon the requirements [16] [19–23]. Some of DG benefits are summarized as shown in the following subsections:

Reliable Electricity Supply

The DG is a small-scale system that can cover by a diesel generator at the distribution busbars, but the conventional power plant can reach 500 MW which difficult to cover at failure or disturbance [10].

Reducing Transmission Power Losses

Due to the transmitting power to the end consumers from the conventional power plant, the power losses will be greater than the use of DG near the load due to the power losses depending on the transmission line resistance RI^2 , which directly decreases the feeder capacity.

Integration of Renewable Energy Sources

Renewable energy sources can be photovoltaic (PV) or wind generation, etc. These sources do not emit CO_2 i.e., so the renewable DGs are environmentally friendly [10].

DG Operation for Voltage Stability

The power quality will be affected by the reliability of the system which can be supported by the superpower capacitors, batteries, etc. To analyze the DG with the existing system. Figure 2 shows the DGs connected to the grid that supplies the system by reactive power for voltage control. V_0 and V_1 are the voltage in the grid system busbar and load busbar which are tied by transmission line by Z impedance. P_{DG} and Q_{DG} are the active and reactive power generated by the DG in the load bus, the load value is $P_1 + jQ_1$. The drop voltage between the grid busbar and the load busbar is depended on the value of transmission line impedance, which is directly related to the distance value between the loads and the generation [24]. So, the DG in the system uses to compensate for the drop voltage on the load bus. The voltage V_1 in the load busbar will affect by the DG system which can calculate by eq. (10).

$$V_1 = \left\{ -\frac{2a1 - V_0^2}{2} + \left[\left[\frac{2a1 - V_0^2}{3} \right]^2 - [a1^2 + a2^2] \right]^{0.5} \right\}^{0.5} \quad (10)$$

Where,

$$\begin{aligned} a1 &= -R(P_{DG} - P_1) - X(Q_{DG} - Q_1) \\ a2 &= -X(P_{DG} - P_1) + R(Q_{DG} - Q_1) \end{aligned}$$

At applying the actual simulation for the DG with the power system, it requires to use of the calculation with (N) number of buses. The branch lines are known as b_{ij} , the respectively two nodes in the branch are i , ($i + 1$) which considers i is the sending end node and ($i + 1$) is the receiving end. The voltage value at the sending end node is $V(i) \angle \delta(i)$ and the voltage value at the receiving end node is $V(i + 1) \angle \delta(i + 1)$. Also, the load flow in the node ($i + 1$) is $\{P(i + 1) + jQ(i + 1)\}$. The impedance of the branch b_{ij} is $\{R(i) + jX(i)\}$ [24]. By neglecting the shunt admittances for the line, the current can

Fig. 2 DG connection with the existing power system

be calculated from the eq. (11).

$$I(i) = \frac{|V(i)|\angle\delta(i) - |V(i+1)|\angle\delta(i+1)}{R(i) + jX(i)} \quad (11)$$

The current calculation by the complex power:

$$I(i) = \frac{P(i+1) - jQ(i+1)}{V^*(i+1)} = \frac{P(i+1) - jQ(i+1)}{|V(i+1)|\angle-\delta(i+1)} \quad (12)$$

By analyzing Eqs. (11) and (12)

$$\frac{P(i+1) - jQ(i+1)}{|V(i+1)|\angle-\delta(i+1)} = \frac{|V(i)|\angle\delta(i) - |V(i+1)|\angle\delta(i+1)}{R(i) + jX(i)} \quad (13)$$

$$[R(i)P(i+1) + X(i)Q(i+1)] + j[X(i)P(i+1) - R(i)Q(i+1)] = |V(i)||V(i+1)|[\cos(\delta(i) - \delta(i+1)) + j\sin(\delta(i) - \delta(i+1))] - |V(i+1)|^2 \quad (14)$$

The difference in two voltage angles is very small in the radial distribution system near to zero. So,

$$V(i)V(i+1) - V^2(i+1) = [R(i)P(i+1) + X(i)Q(i+1)] + j[X(i)P(i+1) - R(i)Q(i+1)] \quad (15)$$

Equation (15) can analyze as:

$$\frac{R(i)}{X(i)} V^2(i+1) - \frac{R(i)}{X(i)} V(i)V(i+1) + P(i+1) \left[\frac{R^2(i)}{X(i)} - X(i) \right] + 2R(i)Q(i+1) = 0 \quad (16)$$

In eq. (16), the discriminate must be greater than or equal to zero, which quadratic in nature and to have real roots, it simulates in eq. (17) as:

$$\frac{R^2(i)}{X^2(i)} V^2(i) - 4 \frac{R(i)}{X(i)} \left\{ P(i+1) \left[\frac{R^2(i) - X^2(i)}{X(i)} \right] \right\} + 2R(i)Q(i+1) \geq 0$$

$$\text{Or } \frac{4Q(i+1)[R(i) + X(i)]^2}{X^2(i)} \leq 1 \quad (17)$$

So, the Voltage Stability Indicator (VSI) in eq. (17) must be less than (1), which indicates the instability system at VSI greater than unity [25, 26].

Hence;

$$VSI = \frac{4Q(i+1)[R(i) + X(i)]^2}{X^2(i)} \leq 1 \quad (18)$$

PV System Operation Logic for DGs

The PV system design is depending on the semiconductor materials, the solar radiation will affect the generated power from the PV system. The PV development historical timeline for the electrical generation is illustrated in Appendix Table 11. The tracking systems help in change the position of the modules with respect to the sun, which allows for a 20–50% improvement in efficiency [27]. In order to maximize the solar radiation falling on the PV module surface.

Solar System Structure

The PV solar system output power can be calculated by the below eq. (19).

$$P_{PV} = \eta S \phi (1 - 0.005(T_e + 25)) \quad (19)$$

Where, the electrical generation by the sun through the panel is shown with ϕ , which is around 12%. Also, S , ϕ , and T_e represent panels area, irradiation of sun, and temperature in Celsius, respectively. Considering the area and efficiency of panels are constant. Moreover, the output power of the panels is proportional to the temperature and sun radiation. The value of ϕ is proportional to the angle of panels, and the output power is also proportional to ϕ and the air temperature in this paper is assumed 25 °C. To analyze the frequency response of solar cells and converters, it's formulated using the first-order transmission function according to eq. (20).

$$\frac{P_{PVT}}{\phi} = \frac{K_{PV}}{1 + sT_{PV}} \frac{K_{IN}}{1 + sT_{IN}} \quad (20)$$

The output power of solar systems, gain, and time constant are defined with u , K_{PV} , and T_{PV} , respectively. Also, the gain and time constant of the inverter is defined with K_{IN} and T_{IN} , respectively [28].

The PV output voltage is DC and to synchronize the PVDG with the AC utility grid by using the DC/AC power inverter, which is considered a fundamental part of the PV power generation, that can be used both in off-grid or on-grid modes [29]. Where, the Pulse Width Modulated Inverter (PWMI) Model can using for converting the PV output DC to a 3-phase AC. There are many circuits that can be utilized, the 12 pulses inverter and 6 pulses inverter have more applications between multi-level inverter. The advantage of 12-pulse inverter toward the other types of inverters (such as 6 pulse inverter) is lower THD, as shown in Fig. 3. This advantage is derivatives of the number of waveform level. The waveform level in 12 pulses inverter is more than 6 pulses inverter and this causes the output waveform to be close to sinusoidal. The amplitude of the inverter output voltages is controlled by tuning the amplitude of the DC control voltages and the output of the photovoltaic system [30].

Maximum Power Point Tracking (MPPT)

Tracking the maximum power point for PV can enhance the output power of the PV array. The famous MPPT methods are the hill-climbing, perturbation, the conductance increment, and observation. Which are independent of the external environment as well as the load [31]. The hill-climbing method includes the perturbation of the power converter duty cycle and observes its affection on the array output power and it regenerate a new duty cycle output maximum power value. Figure 4 illustrates the I-V curve related to a PV array presented under uniform solar irradiance.

Figure 5 shows the I-V curve of the first PV silicon solar generation under varying levels of solar irradiation. The P-V curve for the PV array is illustrated in Fig. 6, which simulates the solid line for the partial shading PV array condition and the dashed line for no partial shading PV array condition [32]. There are some algorithm methods used with the conventional MPPT to describe the current IMPP and the voltage VMPP to increase the PV output power. On another hand, the actual practice found multipoint indicated to MPP, as illustrated in Fig. 5. However, the multi MPPs occur due to the shading conditions as birds, trees, buildings, passing clouds, and so on. The short-circuit current of a PV cell depends on the irradiance value, which will be affected by the partial shading on the PV modules [33, 34].

Analysis of MPPT by the Current Sweeping Method

The current sweeping method is considered one of the optimal MPPT algorithms which depend on the sweeping PV array current conditions to obtain the current-voltage (I-V)

characteristic curve. The captured I-V characteristic is the first step to calculate the voltage at MPP, where, the calculation obtains with the same sweep interval [33]. The calculation steps are considered the PV waveform direct variate related to its derivative, which illustrates in eq. (21), with present the proportional real constant by k .

$$f(t) = k \frac{df(t)}{dt} \quad (21)$$

By using eq. (15) with the basic equation to evaluate the output power in the eq. (22) as:

$$p(t) = v(t)i(t) = v(t)f(t) \quad (22)$$

At using MPP with the derivative of eq. (21) to illustrate eq. (22).

$$p(t) = v(t)ik \frac{df(t)}{dt} + f(t) \frac{dv(t)}{dt} = 0 \quad (23)$$

From the combination of eq. (21) and eq. (23), it can obtain eq. (24) as:

$$\frac{dp(t)}{dt} = \left[v(t) + k \frac{df(t)}{dt} \right] \frac{df(t)}{dt} \quad (24)$$

From analyzing the eq. (21) with present the maximum PV array current by a symbol C , and the constant k is negative as:

$$f(t) = C e^{\frac{t}{\tau}} \quad (25)$$

The negative k in eq. (25) can be derived with a time constant $k = -\tau$ so,

$$f(t) = I_{max} e^{\frac{-t}{\tau}} \quad (26)$$

Fig. 3 DC/AC 12 pulses converter by 2 systems 6-Pulses inverter

Fig. 4 I-V PV array curve related to uniform solar irradiance

The capacitor discharged current can be observed to calculate the maximum current I_{max} . And by simplifying eq. (24) to obtain eq. (27).

$$\frac{dp(t)}{di(t)} = v(t) + k \frac{dv(t)}{dt} = 0 \quad (27)$$

From eq. (27), MPPT can reach the MPP as long as VMPP is computed. With considers, this method was performed by an analog process with approximately 50 ms sweeping time, which leads to some losses of power. So, the MPPT is practical at the increase of power to the entire PV system is more than the power consumption of the tracking unit.

Probability of PVDGs

The VSI-based PV solar farm and the natural gas-based Micro-Turbine (MT) are considered as candidate DGs that can be integrated into the distribution system. There are a lot

Fig. 5 I-V characteristic curve under varying solar irradiance

Fig. 6 MPPT P-V curves with and without partial shading

of studies proved the uncertainties of PV radiations that can be represented through stochastic theory with a Beta distribution [35, 36].

$$f(S) = \frac{\Gamma(\alpha + \beta)}{\Gamma\alpha\Gamma\beta} \cdot \left(\frac{s}{s_{max}}\right)^{\alpha-1} \cdot \left(\frac{1-s}{s_{max}}\right)^{\beta-1} \quad (28)$$

Where, $f(S)$ is the probability density function of S . For each time segment, the shape parameters of Beta, distribution can be determined through statistical analysis of the historical data [33–37].

α and β of segment g can be calculated as:

$$\alpha = \mu_g \left(\frac{\mu_g (1 - \mu_g)}{\sigma_g^2} - 1 \right) \quad (29)$$

$$\beta = (1 - \mu_g) \left(\frac{\mu_g (1 - \mu_g)}{\sigma_g^2} - 1 \right) \quad (30)$$

The particle Beta distribution in the eqs. (23) and (24), matches with each time segment. Also, the multi-state theory is important to discretize the continuous of $f(S)$. The continuous probability density function has been clearly discusses in Fig. 7, which divided each time segment into N states and each state has the same span of S . Where, N is the trade-off between accuracy and complexity of the planning problem. So, the probability solar irradiance falls in state k can be illustrated by representing the lower bound state k by S_{K-min} and S_{K-max} is the upper bound state k , as shown in eq. (31).

$$prob(S_K) = \int_{S_{K-min}}^{S_{K-max}} f(S) ds \quad (31)$$

Fig. 7 Discretization of the continuous $f(S)$

Analysis of PVDGs Output

The PV active power output is depending on the solar irradiance, the design of the PV panel, and the ambient temperature [37]. However, to analyze and simulate the output power it is needed to perform several complex iterations, which can be simplified by the piecewise function to analyze the relationship between the solar irradiant and the PV output active power as shown in Fig. 8, which formulated by eq. (32).

$$P_s = \begin{cases} P_{S-rated} \cdot \frac{S}{S_{rated}} & 0 \leq S \leq S_{rated} \\ P_{S-rated} & S < S_{rated} \end{cases} \quad (32)$$

The PV reactive power output is depending on the un-used PV capacity, which can be utilized as the reactive power output to be operated at a specific time [37, 38]. The adjustable output reactive power range is determined by the corresponding components formulated in eq. (33).

$$|Q_s| \leq \sqrt{S_{rated}^2 - P_s^2} \quad (33)$$

PSO for Optimal PVDGs Allocation

PSO algorithm is an optimization approach developed in 1995 by Kennedy and Eberhart, imitating by the social behavior of birds flocking and fish schooling [39]. PSO is the evolutionary technique, which can contribute to reaching an effective solution for the optimum DGs allocation and the ability to handle

Fig. 8 Operation characteristics of solar radiation with PV output active power

continuous state variables. PSO can be extended to absorb the continuous variables in the system. Also, the PSO application can act with the system by considering the evaluation part as a volume less particle in the d-dimension search space [40]. PSO consists of the velocity change of each particle at every time step; to reach the better individual and global best busbar voltage location to install the DGs with the distribution network. At every step, the PSO accelerate at random the separate term, toward the best global and individual location. Using the PSO with the population to select the best global, the best particle of all the particles is represented by $gbest$ and $pbest$ respectively [41].

Minimize $f(x)$, where, i_{th} particle in d-dimensional space represented as:

$$x_{i_i} = \{x_{i1}, x_{i2}, x_{i3}, \dots, x_{id}\}$$

The best previous position of i_{th} particle is represented as:

$$pbest_{ii} = \{p_{best_{i1}}, p_{best_{i2}}, \dots, p_{best_{id}}\}$$

Where, the change of the position of the particle 'i' is represented as:

$$S_i = \{Si1, Si2, Si3, \dots, Sid\}$$

The modified velocity and position of each particle can be calculated using the current velocity and the distance from particle best ($pbest$) to global best ($gbest$) as:

$$S_i^{k+1} = w * S_i^k + C_1 * rand() * (pbest_i^k - x_i^k) + C_2 * rand() * (gbest_i^k - x_i^k) \quad (34)$$

$$S^{min} \leq S_i \leq S^{max} \quad (35)$$

$$x_i^{k+1} = x_i^k + S_i^{k+1} \quad (36)$$

Where, S_i^k is the velocity of individual constant, $pbest$ is the best value attained by individual i, $gbest$ is the global best value i at iteration k. C_1 , C_2 acceleration of the group, w inertia weight factor, $rand() * ()$ a uniform random number between 0 and 1, and S_{id}^k is the current position of individual i at iteration k.

In the above procedures, the S^{max} parameters can be used to determine the specified resolution and fitness, that's searched for areas between the current location and the target location. For too the high value of S^{max} , the particles will fly past the good solutions. At the S^{max} is too low value, it may not explore sufficiently beyond local solutions. The S^{max} set from 10% to 20% range of the dynamic variable.

C_1 and C_2 are the constants of the acceleration terms that pull each particle toward $pbest$ and $gbest$. Before the particles being tugged back, the results of the low value allow them to search out far from the target zone. And the higher results in the movement toward the target regions. So, the setting of the

Table 1 IEEE-7 busbar system at normal operation

Busbar No.	Nom Kv PU	Load MW	Load Mvar	Gen MW	Gen Mvar
1	0.98472	23.00	13.00	—	—
2	0.98877	60.00	52.00	—	—
3	0.98701	50.00	31.00	—	—
4	1.00000	100.00	30.00	184.34	43.79
5	1.00698	50.00	40.00	—	—
6	1.00000	57.00	18.00	100.00	11.62
7	1.04001	47.00	24.00	105.14	117.33

Table 2 The main system branches data between the busbars

OHTL No.	Branch from bus	Branch to bus	Branch R (Ω)	Branch X (Ω)
1	One	Two	0.02000	0.12000
2	One	Six	0.08000	0.24000
3	One	Three	0.02000	0.20000
4	Two	Six	0.06000	0.18000
5	Two	Four	0.06000	0.18000
6	Two	Seven	0.02000	0.06000
7	Two	Three	0.04000	0.12000
8	Three	Four	0.01000	0.03000
9	Four	Five	0.08000	0.24000
10	Six	Seven	0.02000	0.06000
11	Sven	Five	0.08000	0.24000

Fig. 9 The operation of area-A IEEE-7 busbar system without extension system

Table 3 New Remote IEEE-3 Load busbars System data

Busbar No.	Busbar Name	Area Name	Nom. Voltage	Load MW	Load MVAR
8	Eight	B	138.00	12.30	7.07
9	Nine	B	138.00	21.00	13.00
10	Ten	B	138.00	12.17	50.72

Table 4 The new required system branches data

Branch No.	Branch from name	Branch to name	Branch R (Ω)	Branch X (Ω)
1	Eight	Six	0.03000	0.25000
2	Ten	Seven	0.08000	0.24000
3	Eight	Nine	0.03000	0.15000
4	Eight	Ten	0.00000	0.20000
5	Nine	Ten	0.05000	0.35000

Table 5 System operation after adding the extension load to the main system

Busbar No.	Nom KV PU	Load MW	Load Mvar	Gen MW	Gen Mvar
1	0.98446	23.00	13.00	—	—
2	0.9866	60.00	52.00	—	—
3	0.98695	50.00	31.00	—	—
4	1.00000	100.00	30.00	184.41	43.97
5	1.00700	50.00	40.00	—	—
6	1.00000	57.00	18.00	100.00	48.07
7	1.04000	47.00	24.00	153.59	158.53
8	0.91868	12.30	7.07	—	—
9	0.89385	21.00	13.00	—	—
10	0.90237	12.17	50.72	—	—

Table 6 The branches losses after adding the extension load to the main system

Branch No.	Branch From Bus	Branch To Bus	Branch MW Losses	Branch MVAR Losses
1	One	Two	0.01	5.78
2	One	Six	0.03	0.29
3	One	Three	0.04	4.75
4	Two	Six	0.12	4.58
5	Two	Four	0.13	3.56
6	Two	Seven	0.74	0.88
7	Two	Three	0.02	3.86
8	Three	Four	0.43	0.68
9	Four	Five	0.08	4.79
10	Six	Seven	0.21	4.59
11	Sven	Five	0.68	2.15
12	Eight	Six	0.12	0.59
13	Ten	Seven	0.39	3.24
14	Eight	Nine	0.00	0.24
15	Eight	Ten	0.04	0.3
16	Nine	Ten	2.49	2.74

C1 and C2 are often 2.0 according to past experiences [42, 43].

In eq. (34), the inertia weight w is the balance between global, local exploration and the exploitation on average results. Where, w often decreases from 0.9 to 0.4 linearly varying. So, w can be set according to the next eq. (37):

$$w = w_{max} - \left(\frac{w_{max} - w_{min}}{iter_{max}} \right) * iter \quad (37)$$

Where, w_{max} is the maximum value of inertia weight (0.9 in this study), w_{min} is the minimum value of inertia weight (0.4 in this study), $iter_{max}$ maximum iteration number (generations) and $iter$ is the current iteration number [44, 45].

PSO Limitation Treatment

The best particle is found regarding the fitness and converts the inequality constraints to penalty function that's added to the best particle. But, in this method, the excellent particle can be rejected regarding the penalty factors. Also, the empirical

Fig. 10 The operation of area-A and area-B IEEE-10 busbar system

Table 7 Voltage PU value at PVDG with the new remote busbars

Busbar No.	Adding the DG with Busbar-8 - PU	Adding the DG with Busbar-9 - PU	Adding the DG with Busbar-10 - PU
1	0.98481	0.98477	0.98467
2	0.98880	0.98878	0.98875
3	0.98703	0.98702	0.98700
4	1.00000	1.00000	1.00000
5	1.00697	1.00697	1.00699
6	1.00000	1.00000	1.00000
7	1.04001	1.04000	1.04000
8	1.00001	0.98120	0.98324
9	0.97048	1.00000	0.97013
10	0.96421	0.96281	1.00000

Fig. 11 The voltage comparison between extension busbar bars after uses the PVDG

Table 8 Total IEEE-10 busbars system operation after adding the PVDGs with busbar-10

Busbar No.	Busbar Name	Nom KV PU	Load MW	Load Mvar	Gen MW	Gen Mvar
1	One	0.98467	23.00	13.00	—	—
2	Two	0.98875	60.00	52.00	—	—
3	Three	0.98700	50.00	31.00	—	—
4	Four	1.00000	100.00	30.00	184.35	43.82
5	Five	1.00699	50.00	40.00	—	—
6	Six	1.00000	57.00	18.00	100.00	19.03
7	Seven	1.04000	47.00	24.00	101.10	133.57
8	Eight	0.98324	12.30	7.07	—	—
9	Nine	0.97013	21.00	13.00	—	—
10	Ten	1.00000	12.17	50.72	50.00	44.66

approach is directly affecting the penalty parameters for solving the problem model. This affection can be avoided by using binary fitness [43].

One binary fitness for optimal particle and other for the binding constraints. Optimal particle fitness is the equalized value of the eq. (34) that indicates the cost of energy losses and the DGs installed [40–44]. By binding the fitness, it directly extends the violation level, that's can be calculated by eq. (38).

$$\text{Binding fitness } (z) = \begin{cases} z_{\min} - z & , \quad z < z_{\min} \\ z - z_{\max} & , \quad z > z_{\max} \\ 0 & \text{else} \end{cases} \quad (38)$$

Where; Z is the value of the inequality constraint, $z_{\min}$ is the lower limits inequality constraints and $z_{\max}$ represents the upper limits of inequality constraints. The fitness for binding constraints considered as the first for the best particle, but if it doesn't satisfy, so, it's regenerated. By this method, the particles can be generated, that guarantees to complete the infeasible particles that violate the binding constraints.

Simulation and Analysis

Aging electric power grid infrastructures, continuous increase in the load demand, integration of renewable energy resources and electric vehicles, transmission power losses, and improving the efficiency of the power system, are

Fig. 12 The operation of Area-A and Area-B IEEE-10 busbar system with adding PVDG source with busbar-10

Fig. 13 Busbar voltage without and with adding extension IEEE-3 load busbars with the system

several challenges in modern power systems [46]. The load flow analysis is important for voltage control when adding new loads to the system. A continuation load flow solution to calculate the voltage profile of the system up to a critical point [47]. Many methods can be used for the load flow

analysis as the Gauss-Siedel method [48], or Newton-Raphson method [49, 50] which discusses in Appendix part A.1 for an example to find the voltage stability margin depending on the Jacobian matrix for the load flow analysis [51]. The IEEE-7 Busbar system is the example to be

Table 9 System losses after adding the PVDG with the extension busbar-10 system

OHTL No.	Branch from name	Branch to name	Losses MW	Losses Mvar
1	One	Two	0.01	5.79
2	One	Six	0.04	0.36
3	One	Three	0.03	4.78
4	Two	Six	0.19	4.37
5	Two	Four	0.12	3.61
6	Two	Seven	0.67	1.07
7	Two	Three	0.01	3.87
8	Three	Four	0.41	0.73
9	Four	Five	0.12	4.67
10	Six	Seven	0.21	4.58
11	Seven	Five	0.66	2.22
12	Eight	Six	0.04	0.18
13	Ten	Seven	0.02	0.13
14	Eight	Nine	0.00	0.69
15	Eight	Ten	0.11	0.77
16	Nine	Ten	0.35	4.16

Fig. 14 Active power losses without adding the PVDG with busbar-10

Fig. 15 Reactive power losses without adding the PVDG with busbar-10

used in this paper for the power system design to describe the operating system with a new extension system and with adding the PVDGs to enhance the system quality. Table 1 shows the IEEE-7 busbars system data which describes the nominal voltage, the load values, and the generators. Also, Table 2 shows the links branches data between the busbars which consider the overhead transmission line. The system is feeding by three generators linked with busbar-4, busbar-6 and busbar-7. This example is illustrated by the power world simulation software with Laptop computer (intel(R) core(TM)-i5-3230M-CPU @ 2.60 GHZ 32-bit operating system), where Fig. 9 shows the nominal system attached by the simulation software.

Simulation Adding the Remote Loads with the Main System

The system is required to feed the extension (Area-B), which is the remote IEEE-3 load buses, Table 3 shows the data for the new load buses, Table 4 shows the branches' data. Table 5 shows the operation IEEE-10 busbars system after connecting the new IEEE-3 busbars system with the main system by closing the two circuits (busbar-8 to busbar-6) and (busbar-

10 to busbar-7). The system losses after adding the remote loads to the main system are shown in Table 6. Figure 9 shows the operation IEEE-10 busbars system after adding the new remote loads which shows the voltage drop value at the new busbars is a high gap which has bad affection on the system quality Fig. 10.

Simulation and Selecting the Optimum PVDG with the Remote Load Busbars

By adding the new PVDG with the remote load which is PV solar 65 MW generation capacity. First, it's important to check the optimum busbar to add the DG for the optimum operating system. The simulation system in this paper contains three new remote busbars, so this paper simplified the selecting busbar by added the PV system with the three busbars separately, which will be easy to use the PSO during the multi-busbar system. Table 7 shows the per-unit voltage value at the IEEE-10 busbars at adding the PVDGs with busbar-8, busbar-9, and with busbar-10, which is illustrated the voltage data in Fig. 11, which shows the optimum selection is busbar-10 to improve the voltage value.

Analysis of the PVDG with the Remote Load Busbars

By using the PVDGs with busbar-10 as discussed in the last item by 65 MW generation capacity. Table 8 shows the system operation after adding the PVDGs with an extension load to Busbar-10. Its note, the voltage value at the new remote load busbars has been improved and the generation value for the area-A is deceased. Figure 12 shows the attached operation by the software simulation after adding the PVDG with the busbar-10. Figure 13 illustrates the difference in the voltage value for the IEEE-10 busbars system with and without PVDG.

Table 10 DG technology range power

Item	DG Technology	Module Size
1	Small Hydro	1 MW to 100 MW
2	Micro-hydro	25KW to 1 MW
3	Wind turbine	200 W to 3 MW
4	Photo Voltage Cell	5 M W to 100 MW
5	Biomass gasification	100 kW to 20 MW
6	Geothermal	5 MW to 100 MW
7	Ocean Energy	100 kW to 5 MW

Table 11 PV technology historical time

Year	Event
1839	Discovery of photovoltaic effect by Alexandre-Edmund Becquerel
1876	Demonstration of photovoltaic effect on selenium bar by William Grylls Adams and Richard Evans Day
1883	Construction of the first solar cell by using the semiconductor selenium with gold by Charles Fritts
1941	Patent for p-n junction solar cell using semiconductor silicon was applied by Russel Shoemaker Ohl for Bell Telephone Laboratories
1954	First practical silicon solar cell with an efficiency of 6% was constructed by Daryl M. Chapin, Calvin S. Fuller and Gerald L. Pearson for Bell Laboratories

Analysis of the PVDG with the Remote Load Busbars

Table 9 shows the losses values at all branches after adding the PVDG with busbar-10. By comparing the active power losses without and with PVDG its notes the losses value has been decreased as shown in Fig. 14. And by comparison between the reactive power losses at the branches without and with adding the PVDG is illustrated in Fig. 15.

Conclusion

The integration of embedded power generation systems to existing power systems influences the power quality and causes voltage quality, over-voltage, reactive power, and safety issues. The widely popular generation resources are the wind and photovoltaic systems. Due to the penetration of renewable energy, poor power quality arises which creates problems for electric systems. DGs are considered as a small generator that can operate stand-alone or in connection with the distribution networks and can be installed at or near the loads, unlike large central power plants. This paper discussed the contribution of the DG focused on the PVDGs. The MPPT of the PV has been described in this paper to increase the PVDG electrical generation from 20 to 50%. The DG operation with the system is illustrated in this paper by using the power world simulation software to describe the operation and the influence of the PVDG to improve the power system quality. Particle Swarm Optimization (PSO) algorithm is discussed in this paper to be used for selecting the optimum busbar to add the DG with the distribution network. The simulation in this paper is done for IEEE-7 busbar system with extension by IEEE-3 busbar as a new remote load, which showed the voltage was improved in busbar-8 from 0.918 to 1.0 PU, the voltage busbar-9 has been improved from 0.893 to 0.970 PU and the busbar-10 has been improved from 0.902 to 0.964 PU. Also, the total power losses have been decreased after adding the PVDG with the distribution system, where the total active power has been decreased from 5.53 MW to 2.99 MW and the reactive power losses have

been decreased from 43.02 MVAR to 41.98 MVAR. Finally, the results obtained from this paper showed the superiority of using DG for improving the generated cost, transmission line losses, and the power system quality.

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Appendix

Part A.1 Load Flow Analysis by Newton-Raphson Method

This part discusses the solution of a set of nonlinear equations through Newton-Raphson method. by the consideration that the setting of n nonlinear equations of a total number of n variables $x_1, x_2, \dots, x_n$. Let these equations be given by

$$\begin{aligned} f_1(x_1, \dots, x_n) &= \eta_1 \\ f_2(x_1, \dots, x_n) &= \eta_2 \\ &\vdots \\ f_n(x_1, \dots, x_n) &= \eta_n \end{aligned} \quad (\text{A.1})$$

where $f_1, \dots, f_n$ are functions of the variables $x_1, x_2, \dots, x_n$. By defining another set of functions $g_1, \dots, g_n$, as given below

$$\begin{aligned} g_1(x_1, \dots, x_n) &= f_1(x_1, \dots, x_n) - \eta_1 = 0 \\ g_2(x_1, \dots, x_n) &= f_2(x_1, \dots, x_n) - \eta_2 = 0 \\ &\vdots \\ g_n(x_1, \dots, x_n) &= f_n(x_1, \dots, x_n) - \eta_n = 0 \end{aligned} \quad (\text{A.2})$$

And by assuming that the initial estimates of the n variables are $x_1(0), x_2(0), \dots, x_n(0)$. By adding corrections $\Delta x_1(0), \Delta x_2(0), \dots, \Delta x_n(0)$ to these variables such that result is the correct solution of these variables defined by

$$\begin{aligned} x_1^* &= x_1^{(0)} + \Delta x_1^{(0)} \\ x_2^* &= x_2^{(0)} + \Delta x_2^{(0)} \\ &\vdots \\ x_n^* &= x_n^{(0)} + \Delta x_n^{(0)} \end{aligned} \quad (\text{A.3})$$

The functions in (A.2) then can be written in terms of the variables given in (A.3) as

$$g_k(x_1^*, \dots, x_n^*) = g_k(x_1^{(0)} + \Delta x_1^{(0)}, \dots, x_n^{(0)} + \Delta x_n^{(0)}), \quad k = 1, \dots, n \quad (\text{A.4})$$

We can then expand the above equation in Taylor's series around the nominal values of $x_1(0)$, $x_2(0)$, ..., $x_n(0)$. Neglecting the second and higher-order terms of the series, the expansion of g_k , $k = 1, \dots, n$ is given as:

$$g_k(x_1^*, \dots, x_n^*) = g_k(x_1^{(0)}, \dots, x_n^{(0)}) + \Delta x_1^{(0)} \left. \frac{\partial g_k}{\partial x_1} \right|^{(0)} + \Delta x_2^{(0)} \left. \frac{\partial g_k}{\partial x_2} \right|^{(0)} + \dots + \Delta x_n^{(0)} \left. \frac{\partial g_k}{\partial x_n} \right|^{(0)} \quad (\text{A.5})$$

where $\partial g_k / \partial x_i^{(0)}$ is the partial derivative of g_k evaluated at $x_1(0)$, ..., $x_n(0)$

Equation (A.5) can be written in vector-matrix form as:

$$\begin{aligned} &\begin{bmatrix} \partial g_1 / \partial x_1 & \partial g_1 / \partial x_2 & \dots & \partial g_1 / \partial x_n \\ \partial g_2 / \partial x_1 & \partial g_2 / \partial x_2 & \dots & \partial g_2 / \partial x_n \\ \vdots & \vdots & \ddots & \vdots \\ \partial g_n / \partial x_1 & \partial g_n / \partial x_2 & \dots & \partial g_n / \partial x_n \end{bmatrix}^{(0)} \begin{bmatrix} \Delta x_1^{(0)} \\ \Delta x_2^{(0)} \\ \vdots \\ \Delta x_n^{(0)} \end{bmatrix} \\ &= \begin{bmatrix} 0 - g_1(x_1^{(0)}, \dots, x_n^{(0)}) \\ 0 - g_2(x_1^{(0)}, \dots, x_n^{(0)}) \\ \vdots \\ 0 - g_n(x_1^{(0)}, \dots, x_n^{(0)}) \end{bmatrix} \end{aligned} \quad (\text{A.6})$$

The square matrix of partial derivatives is called the Jacobian matrix J with $J(0)$ indicating that the matrix is evaluated for the initial values of $x_2(0)$, ..., $x_n(0)$. the solution of (A.6) can be write as

$$\begin{bmatrix} \Delta x_1^{(0)} \\ \Delta x_2^{(0)} \\ \vdots \\ \Delta x_n^{(0)} \end{bmatrix} = [J^{(0)}]^{-1} \begin{bmatrix} \Delta g_1^{(0)} \\ \Delta g_2^{(0)} \\ \vdots \\ \Delta g_n^{(0)} \end{bmatrix} \quad (\text{A.7})$$

Since the Taylor's series is truncated by neglecting the 2nd and higher order terms, we cannot expect to find the correct solution at the end of the first iteration. We shall then have

$$\begin{aligned} x_1^{(1)} &= x_1^{(0)} + \Delta x_1^{(0)} \\ x_2^{(1)} &= x_2^{(0)} + \Delta x_2^{(0)} \\ &\vdots \\ x_n^{(1)} &= x_n^{(0)} + \Delta x_n^{(0)} \end{aligned} \quad (\text{A.8})$$

These are then used to find $J(1)$ and $\Delta g_k(1)$, $k = 1, \dots, n$. We can then find $\Delta x_2(1)$, ..., $\Delta x_n(1)$ from an equation like (A.7) and subsequently calculate $x_2(1)$, ..., $x_n(1)$. The process continues till Δg_k , $k = 1, \dots, n$ becomes less than a small quantity

By analysis the Jacobina formulation;

$$P_i = |V_i|^2 G_{ii} + \sum_{\substack{k=1 \\ k \neq i}}^n |Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \quad (\text{A.9})$$

$$Q_i = -|V_i|^2 B_{ii} - \sum_{\substack{k=1 \\ k \neq i}}^n |Y_{ik} V_i V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \quad (\text{A.10})$$

Formation of J_{11}

By define J_{11} as

$$J_{11} = \begin{bmatrix} L_{22} & \dots & L_{2n} \\ \vdots & \ddots & \vdots \\ L_{n2} & \dots & L_{nn} \end{bmatrix} \quad (\text{A.11})$$

It can be seen that M_{ik} 's are the partial derivatives of P_i with respect to δ_k . The derivative P_i (A.9) with respect to k for $i \neq k$ is given by

$$L_{ik} = \frac{\partial P_i}{\partial \delta_k} = -|Y_{ik} V_i V_k| \sin(\theta_{ik} + \delta_k - \delta_i), \quad i \neq k \quad (\text{A.12})$$

Similarly, the derivative P_i with respect to k for $i = k$ is given by

$$L_{ii} = \frac{\partial P_i}{\partial \delta_i} = \sum_{\substack{k=1 \\ k \neq i}}^n |Y_{ik} V_i V_k| \sin(\theta_{ik} + \delta_k - \delta_i)$$

Comparing the above equation with (A.12) we can write

$$L_{ii} = \frac{\partial P_i}{\partial \delta_i} = -Q_i - |V_i|^2 B_{ii} \quad (\text{A.13})$$

Formation of J_{21}

By define J_{21} as

$$J_{21} = \begin{bmatrix} M_{22} & \cdots & M_{2n} \\ \vdots & \ddots & \vdots \\ M_{n_p2} & \cdots & M_{n_p n} \end{bmatrix} \quad (\text{A.14})$$

The elements of J_{21} are the partial derivative of Q with respect to δ . From (A.10) we can write

$$M_{ik} = \frac{\partial Q_i}{\partial \delta_k} = -|Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i), \quad i \neq k \quad (\text{A.15})$$

Similarly, for $i = k$ we have

$$M_{ii} = \frac{\partial Q_i}{\partial \delta_i} = \sum_{k=1, k \neq i}^n |Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) =$$

$$P_i - |V_i|^2 G_{ii}$$

The last equality of (A.16) is evident from (A.14).

Formation of J_{12}

By define J_{12} as

$$J_{12} = \begin{bmatrix} N_{22} & \cdots & N_{2n_p} \\ \vdots & \ddots & \vdots \\ N_{n2} & \cdots & N_{n_p n} \end{bmatrix} \quad (\text{A.17})$$

The elements of J_{21} involve the derivatives of real power P with respect to the magnitude of busbar voltage $|V|$. For $i \neq k$,

$$N_{ik} = |V_k| \frac{\partial P_i}{\partial |V_k|} =$$

$$|Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) = -M_{ik} \quad i \neq k$$

For $i = k$ we have

$$\begin{aligned} N_{ii} &= |V_i| \frac{\partial P_i}{\partial |V_i|} = \\ &= |V_i| \left[2|V_i| G_{ii} + \sum_{k=1, k \neq i}^n |Y_{ik} V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \right] \\ &= 2|V_i|^2 G_{ii} + \sum_{k=1, k \neq i}^n |Y_{ik} V_i V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \\ &= 2|V_i|^2 G_{ii} + M_{ii} \end{aligned} \quad (\text{A.19})$$

Formation of J_{22}

For the formation of J_{22} , by define

$$J_{22} = \begin{bmatrix} O_{22} & \cdots & O_{2n_p} \\ \vdots & \ddots & \vdots \\ O_{n_p2} & \cdots & O_{n_p n} \end{bmatrix} \quad (\text{A.20})$$

For $i \neq k$

$$\begin{aligned} O_{ik} &= |V_i| \frac{\partial Q_i}{\partial |V_k|} = \\ &= -|V_i| |Y_{ik} V_i V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \\ &= L_{ik}, \quad i \neq k \end{aligned} \quad (\text{A.21})$$

Finally, for $i = k$

$$\begin{aligned} O_{ii} &= |V_i| \frac{\partial Q_i}{\partial |V_k|} \\ &= |V_i| \left[-2|V_i| B_{ii} - \sum_{k=1, k \neq i}^n |Y_{ik} V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \right] \\ &= -2|V_i|^2 B_{ii} - \sum_{k=1, k \neq i}^n |Y_{ik} V_i V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \\ &= -2|V_i|^2 B_{ii} - L_{ii} \end{aligned} \quad (\text{A.22})$$

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Ali M. Eltamaly (Ph.D.-2000) is a full professor at Mansoura University, Egypt, and King Saud University, Saudi Arabia. He received the B.Sc. and M.Sc. degrees in electrical engineering from Al-Minia University, Egypt in 1992 and 1996, respectively. He received his Ph.D. Degree in Electrical Engineering from Texas A&M University in 2000. His current research interests include renewable energy, smart grid, power electronics, motor drives, power quality, artificial intelligence,

evolutionary and heuristic optimization techniques, and distributed generation. He published 20 book and book chapters and he has authored or coauthored more than 200 refereed journal and conference papers. He published several patents in the USA patent office. He has supervised several M.S. and Ph.D. theses worked on several National/International technical projects. He got distinguish professor award for scientific excellence, Egyptian supreme council of Universities, Egypt, June 2017, and he has awarded many prizes in different universities in Egypt and Saudi Arabia. He is participating as an editor and associate editors in many international journals and chaired many international conferences'

sessions. He is chair professor of Saudi Electricity Company Chair in power system reliability and security, King Saud University, Riyadh, Saudi Arabia.

Prof. Dr. Yehia Syed Mohamed was born in Egypt. He received the B.Sc., and M.Sc. degrees in electrical engineering from Asuit University, Egypt and Ph.D degree from Minia University, Egypt. Currently, he is a professor and chairman of electrical engineering department, faculty of engineering, Minia University, Egypt. He has been with the Department of Electrical Engineering, Faculty of Engineering, Minia University, as a Teaching Assistant, a

Lecturer Assistant, Assistant Professor, Associate Professor, and Professor. He is a Distinguished Professor from the Egyptian Supreme Council of Universities; Minia University; Egypt. His current research interests include electrical machines, power electronics, energy management system, distribution automation system, power system quality and renewable energy. He has supervised a number of M.Sc. and Ph.D theses, supervised and published Multi-books, many book chapters and a lot of technical papers.

Prof. Dr. Abou-Hashema M. El-Sayed received his B.Sc., and M.Sc. in Electrical Engineering from Minia University, Minia, Egypt, in 1994 and 1998, respectively. He was a Ph.D. student in the Institute of Electrical Power Systems and Protection, Faculty of Electrical Engineering, Dresden University of Technology, Dresden, Germany from 2000 to 2002. He received his Ph.D. in Electrical Power from the Faculty of Engineering, Minia University, Egypt in 2002, according to a channel system program, which means a Scientific Co-operation between the Dresden University of Technology, Germany and Minia University, Egypt. Since 1994, he has been with the Department of Electrical Engineering, Faculty of Engineering, Minia University, as a Teaching Assistant, a Lecturer Assistant, Assistant Professor, Associate Professor, and Professor. He is a Distinguished Professor from the Egyptian Supreme Council of Universities; Minia University; Egypt. He was a Visiting Researcher at Kyushu University, Japan, from 2008 to 2009. He is the head of Mechatronics and Industrial Robotics Program, Faculty of Engineering, Minia University from 2011 till now. His research interests include Protection systems, renewable energy, and power systems.

cording to a channel system program, which means a Scientific Co-operation between the Dresden University of Technology, Germany and Minia University, Egypt. Since 1994, he has been with the Department of Electrical Engineering, Faculty of Engineering, Minia University, as a Teaching Assistant, a Lecturer Assistant, Assistant Professor, Associate Professor, and Professor. He is a Distinguished Professor from the Egyptian Supreme Council of Universities; Minia University; Egypt. He was a Visiting Researcher at Kyushu University, Japan, from 2008 to 2009. He is the head of Mechatronics and Industrial Robotics Program, Faculty of Engineering, Minia University from 2011 till now. His research interests include Protection systems, renewable energy, and power systems.

Mohamed A. Mohamed (M'16) received B.Sc. and M.Sc. degrees in electrical engineering from Minia University, Minia, Egypt in 2006 and 2010, respectively. He received the Ph.D. degree in electrical engineering from King Saud University, Riyadh, Saudi Arabia in 2016. He joined the College of Electrical Engineering & Automation, Fuzhou University, China as a Postdoctoral Research Fellow in 2018. He has been a faculty member in the Department of

Electrical Engineering, College of Engineering, Minia University, Minia, Egypt, since 2008. His research interests include power system analysis, renewable energy integration, energy management, electrical vehicles, power quality, optimization, smart islands, smart cities and smart grids. He has supervised multiple M.Sc. and Ph.D. theses, worked on a number of technical projects, and published various papers and books. He has also joined the editorial board of some scientific journals and the steering committees of many international conferences.

Amer Nasr A. Elghaffar received B.Sc., M.Sc. degree in electrical engineering from Minia University, Egypt followed with Power and Machine in 2009; and 2016 respectively. Currently, he is a Ph.D. researcher in Electrical Engineering Department, Minia University, Minia, Egypt. His current research interests include renewable energy, power system protection and control, Microgrid, power quality and high voltage. In 2013, he joined Alfajar company, Saudi Arabia, as a testing and commissioning engineer. He has the enough experience about the

electrical high voltage substations testing and commissioning field. He was published a lot of technical papers, and attended a lot of conferences in the electrical power system field. He has the licenses and certifications on Agile in The Program Management Office (PMI), Exam Tips: Project Management Professional (PMP), Project Management Foundations: Risk, Managing Project Stakeholders, Leading Productive Meetings (PMI and CPE), and Goal Setting