Original Research Article

Phase Domain Modelling for Optimal Distributed Generator Placement and Clean Power Production Using Particle Swarm Optimization Assisted Target Seeking Algorithm

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ABSTRACT

The impact of power injection at various positions in the grid is not consistent due to the uneven electrical sensitivity caused by varying power characteristics. This issue requires a comprehensive search method to analyze all the buses in recursive sequence manner to maximize the output of the fitness function. In response to this problem, the present research work addresses an objective based particle swarm optimization algorithm method to determine the optimum location for installing a single photovoltaic generator. The aim of this study is to optimize the voltage and power factor profiles of all the buses by controlling the power flow using distributed generation at a specific bus. A photovoltaic module equipped with a pulse width modulation inverter and LCL filter is integrated into the grid with its bus location and capacity decided by the designed particle swarm optimization algorithm to provide either active or reactive power. The validation of the proposed method is shown through the results obtained by implementing the proposed technique at IEEE-3 bus system.

KEYWORDS

INTRODUCTION

The electrical power system has undergone significant changes in recent decades, leading to the development of industries in distribution, transmission, and generation to create a competitive environment. Power utilities are facing challenges due to increasing power demand that exceeds the capacity of current transmission line infrastructure. The purpose of the power system operation is to make sure that electricity supplied across the entire network is

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dependable and economical for the end user. To meet the demand, there should be the proper coordination of several components of the power system while maintaining stability and efficiency. For electricity generation, energy sources like hydro power, fossil fuels and nuclear plants are used mostly but they are centrally controlled by utility generators.

However, the use of large central power station plants is becoming progressively less standardized because the cost is increasing, resources are declining and the process is being deregulated, with growing environmental concerns and advancements in the technology. When the power system networks grow to incorporate the enhanced demands, factors like power loss, unbalanced load, voltage drop, and stability issue may arise. Distributed generation (DG) thus provides a solution to new challenges arising in the power system through integration of small power producers such as fuel cell, storage device and the renewable sources like wind for a wind turbine or photovoltaic system for a solar power plant [1].

If compared with centralized generation, DG offers a range of advantages consisting in the decrease of power losses and emissions, the enhancement of the stability of net-works, and the absence of network congestion. But again, the location of DG units is critical, since inappropriate sizing, location of DG units may lead to higher costs and eradicating benefits. Therefore, this research recommends the use of particle swarm optimization (PSO) algorithms for identifying the optimized location of DG units in power systems because it has been observed to be effective in finding global solutions and the literature shows that PSO is a reliable means of escaping from the usual limitations associated with traditional algorithms. This strategy seeks to improve the voltages by de-creasing the power losses in an electrical system and this will be done through the PSO technique in the placement of DG units. PSO emulates the food searching process of animals with a view of minimizing energy loss and maximizing the power factor as well as voltages of electrical systems. The adoption and applications of DG unit integration and its use in already existing conventional distribution networks are becoming accept-able due to the technical and financial benefits. From **Figure 1**, one can see how the DG unit is connected into the current traditional radial distribution feeder.
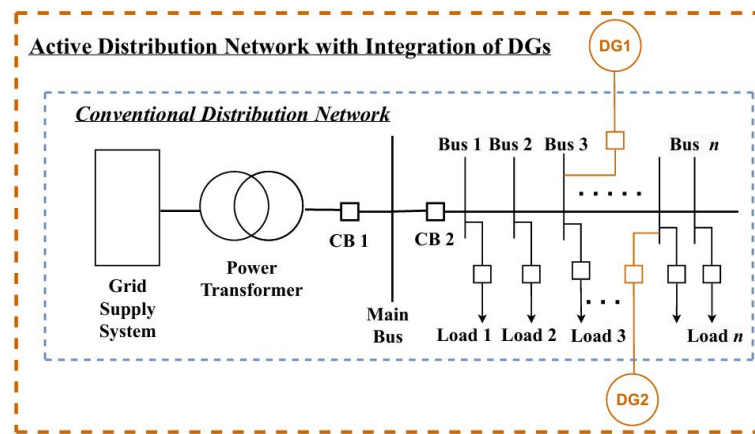

Figure 1. Demonstration of DG units' integration in an electrical system

The installation of small-sized renewable energy sources near the load centers for localized power production is referred to as DG [2]. This technique is therefore regarded as a dependable alternative source of power to conventional sources especially for the heavy loaded distribution feeders. They are commonly installed at or near the point of application making it easier to minimize distribution and transmission losses and improve the reliability of electricity supply. Renewable energy is also referred to as non-depletable sources and it comprises ocean energy, wind, solar heat, biomass, falling water and geothermal energy as defined by the International Energy Agency (IEA). Some of the advantages of DG are increased feeder hosting, reduced power losses, improved system performance, low-cost standby generation and high-power system stability. The environmental issues and increased demand of electrical power has seen

most DG units incorporated with green energy sources, which if deployed can increase voltage magnitude maintain transient stability and minimize power losses.

When the percentage of DG in power networks is increased, it leads to enhancement in voltage stability. It is important to identify the right place of the bus for DG installation since it could affect the stability of the system. The DG units positioning can significantly affect either the system voltage stability or the global efficiency. The studies concerning the specific location of DGs are useful for minimizing system losses and postponing the necessity to invest in the extension of the transmission and distribution network [3], [4]. DG placement in power systems has been identified as placing DG at the most appropriate bus; this is an optimization problem that can be solved by using evolutionary algorithms [5].

DG is an advantageous option in power systems for four main reasons: it can reduce line loading and provide voltage reserve [6]; it can reduce the occurrence of an outage level of voltage for an extended period [7]; improve voltage quality [8]; it can help out in network corporations such as in the boosting of the feeder voltage, reducing the amount of loss [9]. Different techniques have been put forward in the literature to determine an optimal placement of DGs in power systems. To identify the most suitable combination of DG units for a specific power network, an optimization technique consisting of a mixed integer linear programming has been utilized [10].

In the recent past, numerous approaches and techniques have been introduced to trace the optimal position of the PV-DG systems, based on load modeling. Such methods are analytic method (AM), probabilistic methods, Monte Carlo approach, PSO approach, genetic algorithm (GA), imperialistic competitive algorithm (ICA), firefly algorithm (FA), crow search algorithm (CSA), strength pareto evolutionary algorithm (SPEA), teaching learning-based optimization (TLBO) as well as hybrid techniques [11]. The approaches that use these methodologies are multi-objective index based on AM, load injection to bus voltage matrix based on AM, butterfly-PSO algorithm and other optimization for finding the location for PV based DG systems. This evolution of these techniques is perhaps testimony to the realization that the incorporation of PV systems into existing electricity networks is not straightforward. Conventional and innovative models are employed by researchers and practitioners in efforts to improve the effectiveness and credibility of DG systems [12].

A Tabu search (TS) approach was presented by [13], to solve the problem of optimal DG placement. But TS was criticized due to its tendency to get stuck in local minima and time-taking nature. Another research by [14], introduced a multi-objective optimization technique using an enhanced version of honey-bee mating optimization (HBMO) method to improve voltage profile, decrease emissions and losses, and lower expenses in the distribution system. To decrease the costs associated with active and reactive power production, the best location for DG units was identified by using combination of GA and optimal power flow (OPF) techniques. Despite the computational intensity of GA, it can find the best solutions. Innovative optimization techniques like simulated annealing (SA) have been used by [15], to address the DG allocation problem to reduce emissions, power losses, and contingency. Methods to minimize system losses and the amount of DG to reduce overall costs were suggested by [16]. A machine learning (ML) technique by [9] and enhanced analytical (EA) technique in [17] have been demonstrated to address the issue of power loss, along with the cuckoo search (CS) approach. Only a limited number of approaches are currently utilized with renewable (DGs).

Several research works have concentrated on determining the most suitable location for DG within power networks through the application of PSO techniques. PSO algorithms have been extensively utilized in these studies for allocation of DG units in power systems. In [18], a numerical method was proposed to identify target voltage support zones by reducing the search space and improving solution accuracy. A method was introduced in [19] that considered power losses and voltage profile as variables in the objective function for optimal DG placement. A linear fragmented PSO algorithm was developed by [20], for optimal switch

allocation in distribution systems. For radial distribution systems, a PSO algorithm was designed by [21] to reduce power losses through optimal DG placement. The study by [22] introduced a methodology that utilizes the ICA and GA to optimize the allocation of DG sources and capacitor banks simultaneously. In [23], the investigation for optimal DG allocation using PSO to reduce losses and improve voltage was carried out. An effort by [24], to reduce power loss, enhance voltage profile and load balancing of system using simultaneous reconfiguration and optimal placement of distribution static synchronous compensator (DSTATCOM) and PV array. A study to reduce power losses and enhance voltage profile through multiple DG placements using PSO was examined by [25]. A techno-economic and environmental approach for optimal placement of renewable DGs in distribution systems, considering dispatchable and non-dispatchable renewable energy sources was presented by [26]. To find the optimal placement for DG and controlled flow of active reactive power, an approach using dq0 mode was presented by [27]. In the above study, model domain approach was used for control designing.

Significant research effort is required to further investigate the topics, but existing literature reviews have already presented survey papers with practical applications. The field is currently at the initial phase of research and more work is needed to advance the understanding of the topics. Unlike numerous other optimization issues, the DG placement optimization problem has not been adequately assessed. Figure 2 displays the re-search published on location and sizing using the IEEE Explore Digital Library database, indicating a noticeable increase in published works.
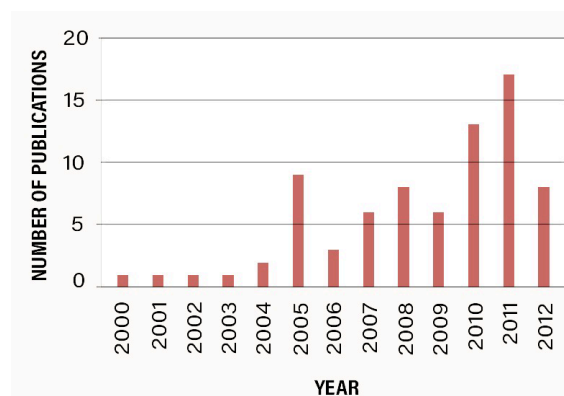

Figure 2. Distribution of papers published on DG placement

The importance of the topic has been highlighted by the abundance of publications; the present study examines the installation of a single DG unit at a PQ bus through PSO algorithm. The selection of power factor (*PF*) as an objective function is motivated by its role in determining reactive power and transmission capacity which is a previously un-explored area [28]. The voltage profile of designated buses is incorporated into the fitness function to enhance it by adjusting and situating the DG at the optimal bus. The key innovation of this research lies in the thorough assessment of global maxima by treating each bus as potential DG unit to establish a standard for comparison. Furthermore, enhancing the power quality has a beneficial impact on the system, leading to improved performance and reduced stress on the grid by integrating DGs into the network. In this work, the phase domain control approach is used because it gives accurate results at the cost of higher complexity as compared to DQ Mode. The proposed system has been successfully implemented, resulting in improved power factor and voltage profile for all buses. The outcomes closely align with the results obtained through PSO Algorithm.

This paper is divided into four main sections. The first section consists of introduction and literature review including the overview, problem formulation and objectives of this research work. Further, readers are provided with an in-depth overview and current advancements in the

topic under discussion. This encompasses definitions and impacts of DG placements. Additionally, various techniques for DG placement are also discussed. The second section is about the methodology of proposed work. It describes the selection of an IEEE bus system and its implementation in MATLAB with designing of PSO algorithm, controller, pulse width modulation (PWM) inverter and LCL filter. The results of the proposed method are shown with confirmation in subsequent section. The last section includes the conclusion, prospects, and potential research directions.

METHODS

Initially, an IEEE-3 bus system is implemented in MATLAB/SIMULINK for the evaluation of buses, followed by the designing of a PSO algorithm to optimize the placement of DG, with the allocated bus evaluated for required power injection to lower grid stress and enhance system stability. Next, a PV module is selected for the proposed PV-based DG system, along with the design of a phase domain controller and PWM inverter with an LCL filter. The proposed technique is then executed in MATLAB and results are obtained. **Figure 3** depicts a modified IEEE-3 bus system model implemented in MATLAB/SIMULINK for analysis purposes. The model comprises a generator at Bus-1 and distributed generations (DG-2 and DG-3) at Bus-2 and Bus-3 interconnected through breakers and buses for monitoring. The three buses are interconnected via transmission lines represented by equivalent π models with loads being connected at Bus-2 and Bus-3 and represented by parallel RL branch. Transmission line parameters like positive sequence resistances, zero sequence resistances, inductances, and capacitances are evaluated for analysis purposes. Both breakers are utilized for integrating DGs, with a switch controlled by a binary switch sequence to ensure only one DG is connected at a time for analysis while the others remain disconnected during the tuning phase.
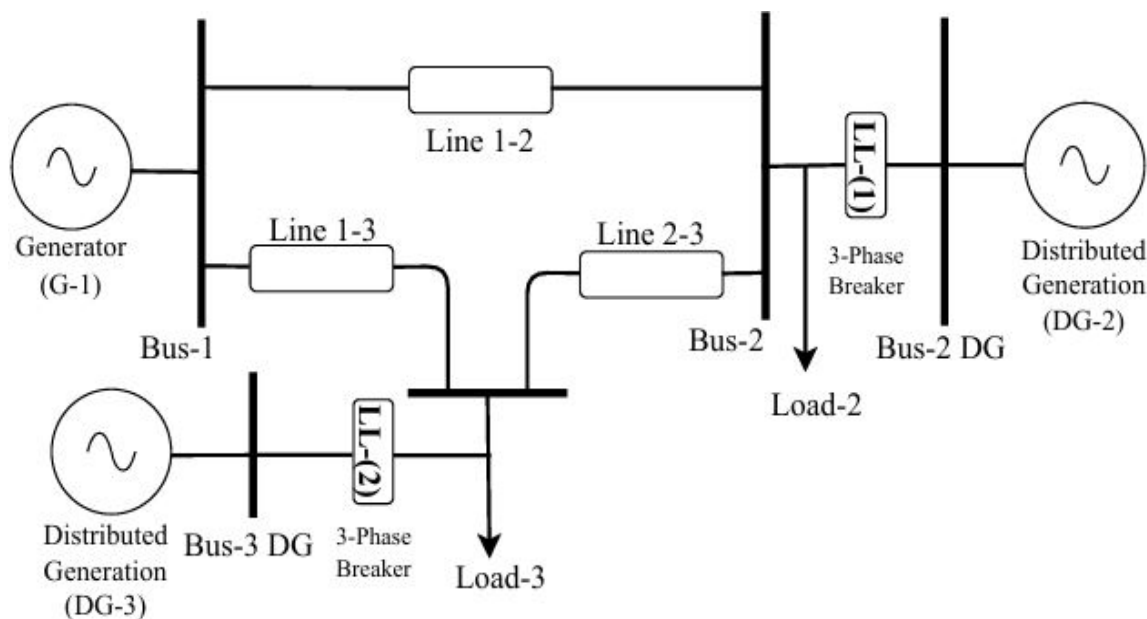

Figure 3. Schematic diagram of IEEE-3 bus system with interconnected DGs at buses

The designed model includes a generator (G-1) and two DGs with a base voltage of 25 kV and assuming the system frequency of 60 Hz. The resistances and inductances of the above shown transmission lines are provided in **Table 1**. Two loads are connected at Bus-2 and Bus-3 respectively with different active and reactive power values, as detailed in **Table 2**.

Table 1. Inductances and resistances of the transmission lines

Sr.	Bus Code (From-To)	Transmission Line	Resistance (Ω)	Inductance (H)
1	B1 to B2	Line 1-2	0.02	$106.1e^{-6}$
2	B1 to B3	Line 1-3	0.01	$79.58e^{-6}$
3	B2 to B3	Line 2-3	0.0125	$66.31e^{-6}$

Table 2. Parameters of connected loads

Sr.	Description	Load 2	Load 3
1	Voltages V_{rms} (V)	1000	1000
2	Active Power P (VA)	$256.6e^{6}$	$138.6e^{6}$
3	Reactive Power Q (VAR)	$110.2e^{6}$	$45.2e^{6}$

Designing and Implementation of Particle Swarm Optimization Algorithm

Particle Swarm Optimization (PSO) is a method utilized to optimize the location of DG units in a power system. PSO involves particles moving through a search space and adjusting their positions based on their own (p_{best}) and nearby (g_{best}) particles' experiences to improve their movements continuously. A two-stage PSO methodology is utilized for optimizing the location of distributed generation units and determining the active and reactive power values (P_{DG} and Q_{DG}) at the DG bus. The improved power factor, reduced power losses and enhanced voltage stability of the system are the main objectives of this optimization process. The algorithm indirectly adjusts PDG and Q_{DG} values by stochastically modifying the voltage magnitude ($|V_{DG}|$) and phase (δ_{DG}) values in the DG block, which are considered as state variables. The objective is to optimize voltage and power factor across all buses in response to the deployment of a single DG unit.

Both PQ buses, i.e. Bus-2 and Bus-3, are equipped with 3-φ switches that connect the DGs as shown in **Figure 3**. For complete bus screening, only one switch needs to be turned ON to integrate a single DG at once. The network model in the loop undergoes a specified number of iterations (i) and swarms (N) to update the location (x) and velocity (v) of every swarm, and to calculate the fitness function (FF) outlined in eqs. (1) and (2). W represents the inertia coefficient, c_1 and c_2 represents the acceleration coefficients, random numbers are represented by r_1 and r_2, p_{best} (g_{best}), represents individuals' (global) optimum location with j showing the bus number. A restriction is imposed on the problem to ensure that $|V_{DG}|$ remains below 25 kV while tuning, which aligns with the maximum voltages of the system as specified in eqs. (3), (4), and (5):

$$x = [|V_{DG}| \qquad \delta_{DG}]_{N \times 2} \tag{1}$$

$$FF = \max\left\{\frac{\Sigma_{j=1}^{3} PF_j}{3} + \frac{\Sigma_{j=1}^{3} V_j}{\Sigma_{j=1}^{3} V_{base,j}}\right\} \tag{2}$$

$$V_{i+1} = wv_i + c_1 r_1 (p_{best} - x_i) + c_2 r_2 (g_{best} - x_i) \tag{3}$$

$$x_{i+1} = x_i + v_{i+1} \tag{4}$$

$$v_j \leq 25 \text{ kV}$$

(5)

The proposed PSO algorithm is evaluated by conducting a thorough scan of each bus and workflow of the PSO algorithm for DG placement is shown in **Figure 4**. This involves storing position and *FF* values, including switch sequences for the final evaluation of DG configurations. Following the completion of simulations, the switch sequence is applied to connect DG at different buses with *FF* values and positions saved after each iteration. The switch sequence for connecting DGs at Bus-2 and Bus-3 are [1 0] and [0 1] respectively. After screening all buses, the final solution is determined based on the maximum *FF* value, associated bus, and particle positions ($|V_{DG}| \angle \delta_{DG}$). By continuously connecting DG to buses and scanning them separately, particles under PSO training gradually converge towards their target.
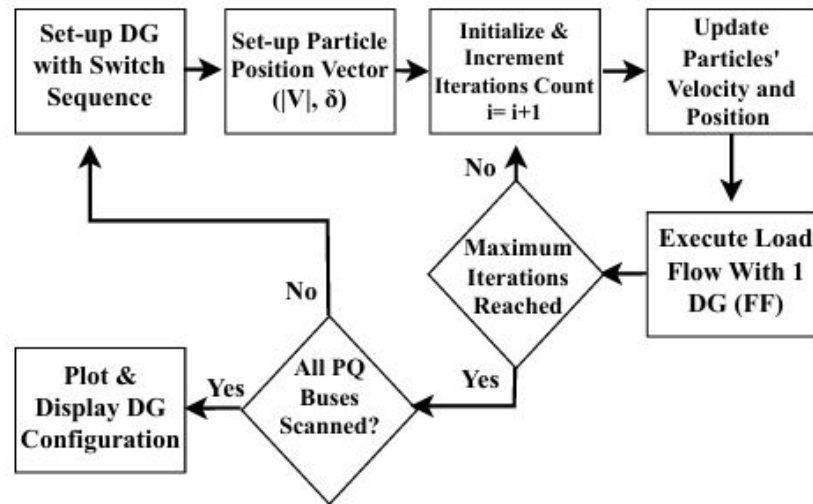

Figure 4. Workflow of PSO algorithm for DG placement

Through an iterative switch sequence, each PQ bus is selected as the DG bus in a standard PSO implementation, allowing for the exploration of all potential combinations of particle positions. This method ensures eventual convergence towards the focal point upon completion of the entire process, although it demands substantial memory, computational resources, and time. This outcome serves as a benchmark for validating convergence precision and evaluating the effectiveness of the process. The parameters utilized in the simulation setup for optimization are detailed and quantified in **Table 3**, where the optimization procedures are executed.

Table 3 Parameters for PSO algorithm

Constant	Description	Value
N	Number of swarms	11
c_1, c_2	Acceleration coefficient	1.5
w	Inertia coefficient	0.9
LB_1, UB_1	Lower & upper bound for $|V_{DG}|$	20 kV, 25 kV
LB_2, UB_2	Lower & upper bound for δ_{DG}	–20°, 20°

The designed PSO algorithm successfully determined the optimal placement of a DG unit in an IEEE-3 bus system at Bus-2 with a binary sequence [1 0] for maximum output. An IEEE-3 bus system with a DG allocated at Bus-2 was utilized to obtain both powers (P_{DG} and

Q_{DG}) necessary for the system. The DG bus is evaluated during optimization along with the active and reactive powers to maximize power factor and bus voltages by connecting generators at each PQ bus through switches. The identification of the most suitable bus, such as Bus-2, led to the determination of the exact values of required powers. Following the PSO implementation for optimal DG location, the active and reactive power values (P_{DG} and Q_{DG}) were obtained (see **Figure 5**), revealing that connecting DG at Bus-2 with $|V_{DG}|$ of 25 kV and δ_{DG} of -31° resulted in active (P_{DG}) and reactive (Q_{DG}) power values of 3.284×10^{10} VA and 1.513×10^{10} VAR, respectively.
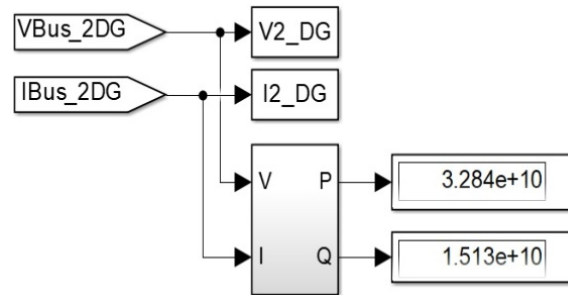
Figure 5. Results for required power values for DG-bus

Configuration of Photovoltaic-Distributed Generator System

The next stage is to design the PV based DG system that will be installed at the DG bus after the DG position (DG bus) has been evaluated and its parameters must be adjusted for maximum throughput. The PV module is integrated with a control stage and PWM inverter subsystem to produce the three-phase reference signal for the necessary active and reactive power values. The main concept behind creating the active and reactive power pair integrating from the PV system is to create a reference signal with specific phase and amplitude, and then operate the PWM switches accordingly. The active and reactive power values required (P_{DG} and Q_{DG}) are considered as reference values (P_{ref} and Q_{ref}) for the control stage. Optimization of the grid is achieved through fine-tuning of the parameters in the DG system to regulate the flow of active and reactive powers. This includes adjusting voltage magnitude and phase, while ensuring that constraints are met during the optimization process. Next, the Photovoltaic module, Pulse Width Modulation inverter, and LCL filter are placed at the designated bus and synchronized with an advanced control system to inject the targeted active and reactive powers calculated via the PSO algorithm. Main goal of the control system is to ensure effective operation and stability by implementing phase domain control, which is facilitated by a dedicated controller shown in **Figure 6**.
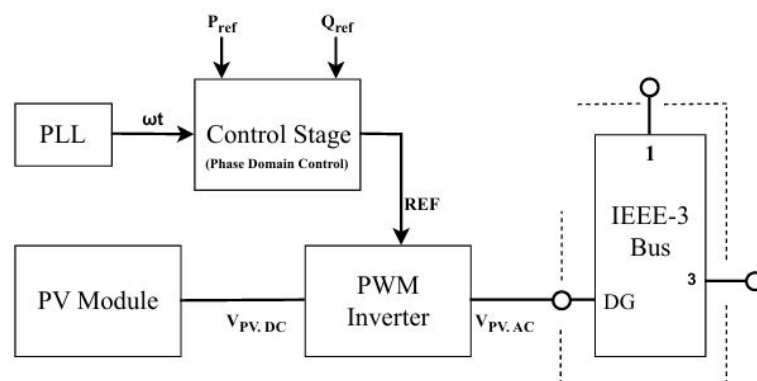
Figure 6. Block diagram of PV integration in IEEE-3 bus system.

The connection of PV system to a grid network is more challenging since the photovoltaic modules produce the DC output which needs to be converted into 3-φ AC. A control interface block that incorporates a control section along with the LCL filter, and PWM inverter is positioned in between IEEE-3 bus specific DG bus (Bus-2) and PV module. The presence of this interface block is important for PV systems integration into grid network and addition of the control section, LCL filter and the PWM inverter into the interface block assists in the control of flow of power and stabilizing the grid. $V_{PV,DC}$ is the desired DC output of the PV module (1SOLTECH-STH-215P) used in this project with 120 parallel (N_P) and 900 series (N_S) strings [29].

Controller Stage

P_{ref} and Q_{ref} mean the optimal active and reactive power output that is expected from the DG unit (P_{DG} and Q_{DG}) and has been calculated using PSO algorithm. These values are important for the PV system located at the DG bus regarding regulating flow of active and reactive powers in the PV module, which is both DG and grid based on the values of P_{ref} and Q_{ref}. The control of the active power (P_{PV}) and reactive power (Q_{PV}) in the PV module is done by comparing these with the reference signals (P_{ref} and Q_{ref}). This comparison is done by using two proportional-integral (PI) controllers for which the output is used as the input to the proportional-resonant (PR) controller as depicted in **Figure 7**. To its further power management, the PR controller then generates a voltage reference (V_{ref}) for the inverter input.
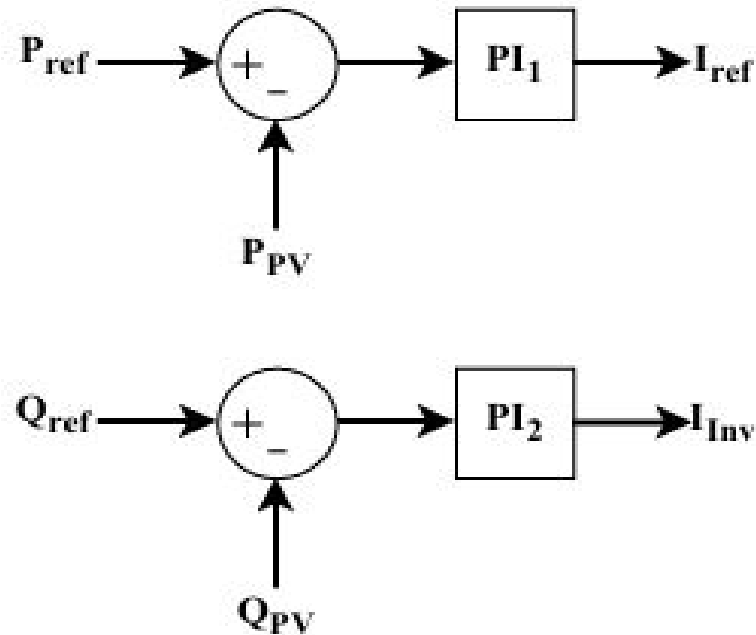

Figure 7. Controller stage for tuning PPV and QPV

A 3-φ phase domain controller is designed to generate three-phase reference voltages $V_{ref\,(a,\,b,\,c)}$ for a three-phase PWM inverter. The phase domain approach is used for controlling the flow of powers being injected, providing more accurate results than the DQ Mode approach but with higher complexity. **Figure 8** shows a phase locked loop (PLL) block, used to determine system phase (ωt) using DG bus voltage V_{DG}, which is then used to calculate active and reactive currents (I_A and I_R). These current values are input to the phase domain controller, which consists of a pair of PI controllers and a single PR controller for each phase, resulting in higher design and computational costs but improved performance compared to the DQ Mode approach.
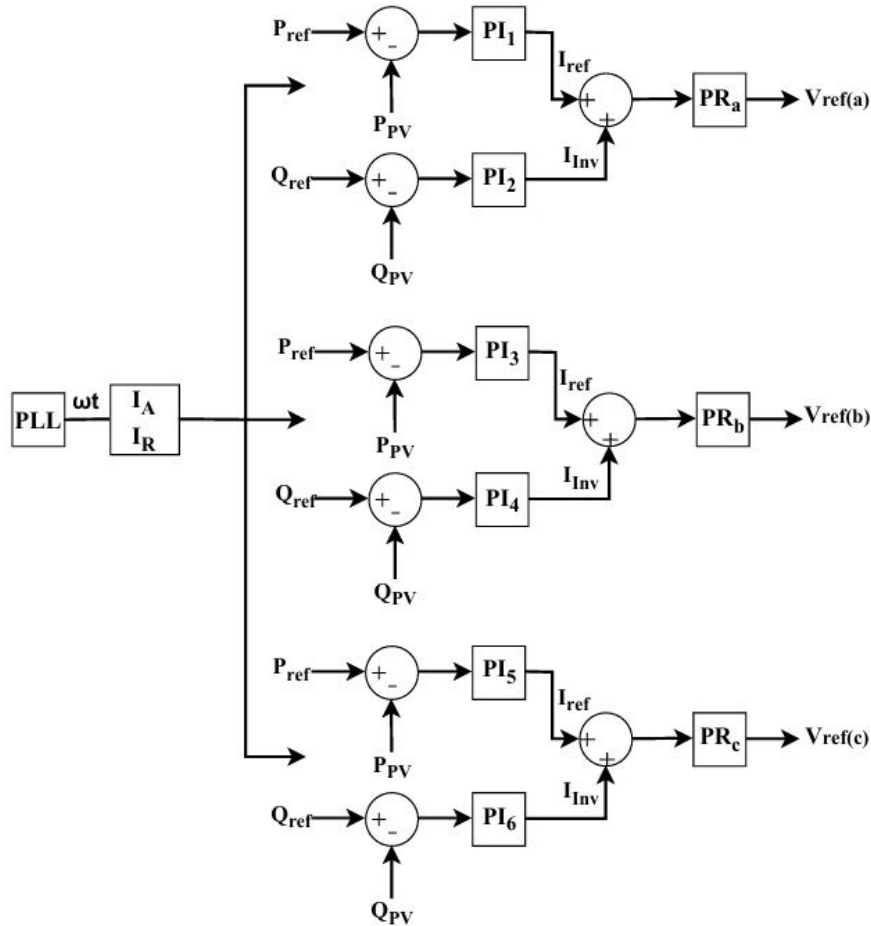
Figure 8. Design of phase domain controller for generation of 3-φ Vref

As discussed above the controller consists of a pair of PI controllers and a PR controller for each phase. The phase domain controller has two control loops, first the active power control loop and secondly the reactive power control loop. In the active power control loop, a simple computing block is fed by the reference active power (P_{ref}) required to be injected in system and photovoltaic generated active power (P_{PV}). In the process, PV produced active power (P_{PV}) is compared to the reference active power (P_{ref}) values to obtain a controlled required value of reference current (I_{ref}). In reactive power control loop, a computing block is fed by the reference reactive power (Q_{ref}) and PV generated reactive power (Q_{PV}). The same process is repeated for this loop but obtained output is inverter current (I_{Inv}). Lastly, the I_{ref} and I_{Inv} are added by using a computing block and fed to the PR controller whose output is V_{ref}. The explained process is just for a single phase, and it must be done for all three phases to obtain a three phase reference voltages $V_{\text{ref}(a, b, c)}$ as shown in **Figure 8**. It can be seen that overall six PI controllers; PI_1, PI_2, PI_3, PI_4, PI_5, PI_6 to regulate $P_{\text{ref,a}}$, $Q_{\text{ref,a}}$, $P_{\text{ref,b}}$, $Q_{\text{ref,b}}$, $P_{\text{ref,c}}$, and $Q_{\text{ref,c}}$, three PR controllers; PR_a, PR_b, PR_c, are used for this phase domain approach as compared to the DQ Mode approach which uses only four PI controllers and two PR controllers due to which the computational cost and time for used approach is increased but obtained results are accurate in compete with DQ Mode. Here, the control system for the present work is completed and in the next section the output of phase domain controller is fed to the 3-φ PWM inverter and designing of PWM inverter is made accordingly.

Pulse Width Modulation Inverter Design

The 3-φ PV inverter is commonly structured as a closed-loop feedback control system to fulfil the static and dynamic demands of the load in the DG system. Precision in capturing the essential connection between input and output serves as the basis for examining and managing

the closed-loop control system [30]. Here, the design of the three-phase PWM inverter is carried out to obtain a three-phase fundamental sinusoidal waveform output. The input to this PWM inverter is the controlled DC power generated by solar, which is the output of the phase domain controller, designed in the previous section. As shown in **Figure 9**, a single-phase PWM Inverter consist of four insulated gate bipolar transistor (IGBT) connected in specific pattern for switching purpose to get a sinusoidal output waveform, when dc input is provided. The four PWM signals are used here for triggering at the gate of every IGBT in an inverter design. The four switches (IGBT) are arranged in such a way that the collectors of IGBT$_{1,3}$ are connected via $V_{dc}+$ input and emitters of IGBT$_{2,4}$ are connected via $V_{dc}-$ input. Next, emitters of IGBT$_{1,3}$ are connected to the collectors of IGBT$_{2,4}$ respectively. The output of single-phase inverter is taken from common point of IGBT$_{3,4}$ and IGBT$_{1,2}$ (V_a, V_{aN}). The same pattern is designed for all three phases of a 3-φ PWM inverter. The output of a designed 3-φ inverter is fed to a filter to get a smooth sinusoidal waveform. The filter designing is carried out in the next section.
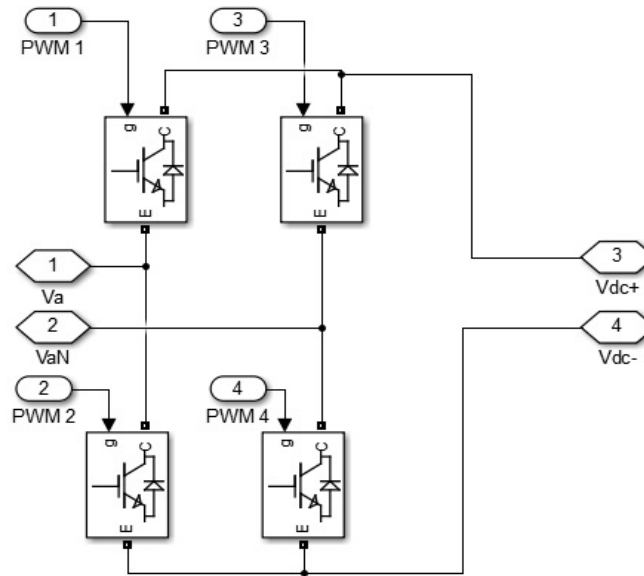

Figure 9. Arrangement of switches for one phase of three phase PWM inverter

LCL Filter Designing

The initial step in the design process of the LCL filter involves establishing simulation parameters for an IEEE 3 bus system, such as $f_{sw} = 10$ kHz, $f = 60$ Hz and $V_{base} = 25$ kV ($\forall$ PQ buses). DG is required to inject the specific values of P_{ref} and Q_{ref}, these values are determined by the PSO algorithm, which represents the inverter's equivalent load, and subsequently derive the base values of resistance, inductance, and capacitance through eqs (6), (7), (8) and (9):

$$R_{base} = \frac{V^2}{|P_{ref}|} \tag{6}$$

$$L_{base} = \frac{V^2}{2\pi f |Q_{ref}|} \tag{7}$$

$$Z_{base} = \frac{1}{\sqrt{\left(\frac{1}{R_{base}}\right)^2 + \left(\frac{1}{2\pi f L_{base}}\right)^2}} \tag{8}$$

$$C_{base} = \frac{1}{2\pi f Z_{base}} \tag{9}$$

The determination of DC input voltage ($V_{\text{PV,DC}}$), maximum inverter current (I_{max}) and voltage drop across the filter (V_{f}) is conducted using mathematical eqs. (10), (11) and (12). The modulation index is denoted by $M = V_{\text{ref}}/V_{\text{c}}$. The values of P_{ref} and Q_{ref} obtained from the PSO algorithm may be positive or negative, reflecting on power injection or withdrawal from the system. Regardless of the direction of power flow, only the positive values are used to calculate filter parameters for logical outcomes:

$$V_{\text{PV,DC}} = \frac{2\sqrt{2}V_{\text{base}}}{M\sqrt{3}} \tag{10}$$

$$V_{\text{f}} = 10\% \ of \ V_{\text{PV,DC}} \tag{11}$$

$$I_{\text{max}} = \frac{S\sqrt{2}}{3V_{\text{f}}} \tag{12}$$

The ultimate calculated values of capacitance (C_{f}) and inductance (L_f) of filter are determined using eqs. (13) and (14):

$$C_{\text{f}} = 5\% \ of \ C_{\text{base}} \tag{13}$$

$$L_{\text{f}} = \frac{V_{\text{PV,DC}}}{6 \ \times 0.1 \ \times f_{\text{sw}}I_{\text{max}}} \tag{14}$$

RESULTS AND DISCUSSION

During the optimization phase, DGs are connected at each PQ bus using switches to evaluate DG bus and determine appropriate active and reactive power values. This evaluation aims to maximize *PF* and bus voltage, which is the primary objective of this research. Once the most suitable bus for connection is identified, all power DG units and related switches are removed. Instead, a PV module with controlled three-phase sinusoidal output is connected to the target bus.

Results for IEEE-3 Bus System without Distributed Generator

The initial step in the methodology involved choosing a case for the study of the proposed method. After selecting the IEEE-3 bus system as the model for implementing the proposed technique, the results were obtained after implementing the IEEE-3 bus system in MATLAB/SIMULINK without any DG placement.
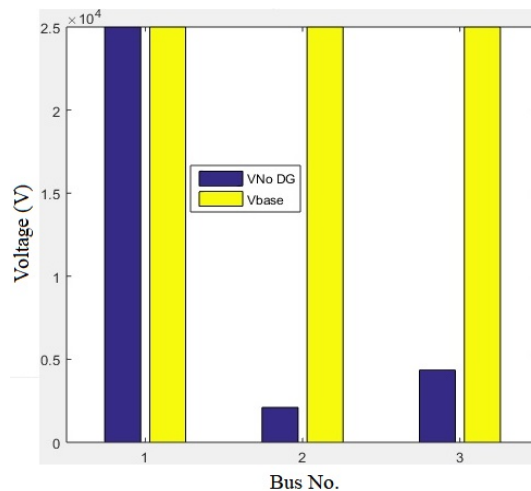

Figure 10. Plots of voltage profile at all three buses without DG

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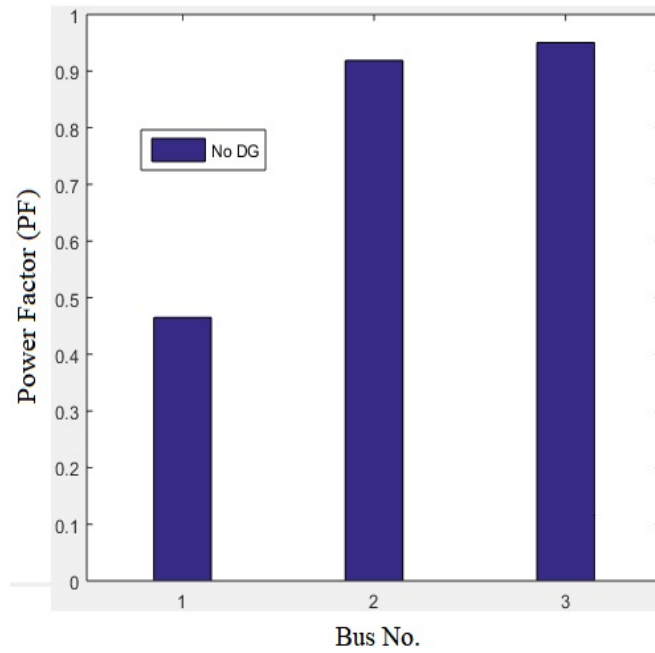
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Figure 11. Plots of power factor (PF) at all three buses without DG

In **Figure 10**, the voltage profile of a network is depicted using bar graphs for V_{base}(yellow) and $V_{\text{No DG}}$ (blue). $V_{\text{No DG}}$ represents the bus voltage without any distributed generation (DG) placement, while V_{base} is the voltage of buses directly connected to a generator with the same voltage level across all buses. In a standard IEEE-3 bus system without DG allocation, the resultant voltage for PQ buses is lower than the respective base voltages due to power losses. **Figure 11** illustrates the power factor profile of all three buses, showing $PF_{\text{No DG}}$ (blue). Here, $PF_{\text{No DG}}$ represents the power factor of each bus without any DG placement in the network. The value of PF at each bus in the IEEE-3 bus system is calculated by first evaluating the phase difference between the voltage and current waveform at that bus and then taking the cosine of the phase. The resultant values of voltage and power factor without any DG placement can be found in **Table 4** with fitness function (FF) value of 0.7781.

Table 4. Resultant values of V and PF without DG placement

Sr.	V_{base} (V)	V_{NoDG} (V)	PF_{NoDG}
1	25×10^3	25×10^3	0.4649
2	25×10^3	2.098×10^3	0.9188
3	25×10^3	4.346×10^3	0.9507

When a bus (Bus-2) is selected, the parameters P_{ref} and Q_{ref} for the DG are adjusted using PSO by randomly adjusting $|V_{\text{DG}}|$ and δ_{DG} to find the optimal values for the fitness function. The process is iterated for every bus connected to the DG, with DG location, position vectors of particle and values of fitness function saved for comparison at the end. **Figure 12** displays the convergence plot of the fitness function, with the DG sequentially connected at PQ buses over 20 iterations until convergence is achieved. The fitness function incorporates normalized bus voltage and power factor values, each ranging from 0 to 1, enabling a maximum sum of 1 to be attained. The optimal fitness function value of 0.8393 is attained by connecting the DG to Bus-2 with a voltage magnitude $|V_{\text{DG}}|$ of 25 kV and a phase angle (δ_{DG}) of -31°. This configuration results in P_{ref} and Q_{ref} values of 3.284×10^{10} VA and 1.513×10^{10} VAR,

respectively. It is important to highlight that P_{ref} and Q_{ref} values indicate the total powers that need to be transferred across the DG interface placed between the Bus-2 (DG bus) and the PV module for optimal *PF* and bus voltage.
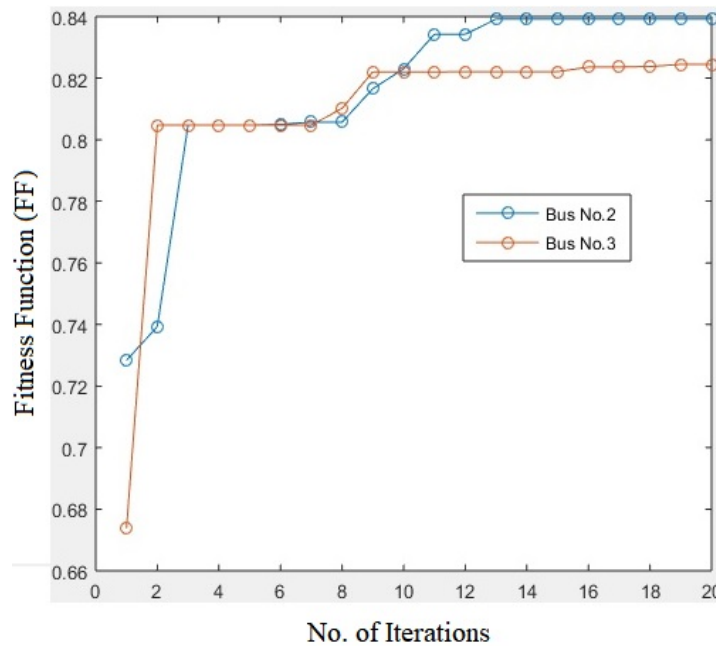

Figure 12. Convergence plot of fitness function

The designing of interface of PV based system with grid network was carried in methodology including PWM inverter and LCL filter designing with their implementation in MATLAB/SIMULINK. The model specifies the calculated values of P_{ref} and Q_{ref}, as well as other parameters listed in **Table 5**, to maintain the flow of power from the photovoltaic bus through the network by tuning the reference signal for the pulse width modulation inverter.

Table 5. Values of parameters used in PV integration module

Sr.	Parameters	Description	Values
1	P_{ref}	Active power reference	3.284×10^{10} W
2	Q_{ref}	reactive power reference	1.513×10^{10} VAR
3	L_f	Filter inductance	0.00162 mH
4	C_f	Filter capacitance	0.0077 F
5	$V_{PV,DC}$	DC output of PV	40.83 kV
6	PI_1	Controller for $P_{ref,a}$ (K_p, K_I)	1×10^{-10}, 1×10^{-8}
7	PI_2	Controller for $Q_{ref,a}$ (K_p, K_I)	1×10^{-10}, 1×10^{-8}
8	PI_3	Controller for $P_{ref,b}$ (K_p, K_I)	1×10^{-10}, 1×10^{-8}
9	PI_4	Controller for $Q_{ref,b}$ (K_p, K_I)	1×10^{-10}, 1×10^{-8}
10	PI_5	Controller for $P_{ref,c}$ (K_p, K_I)	1×10^{-10}, 1×10^{-8}
11	PI_6	Controller for $Q_{ref,c}$ (K_p, K_I)	1×10^{-10}, 1×10^{-8}
12	N_P	Parallel strings of PV	120
13	N_S	Series strings of PV	900

Figure 13 and **Figure 14** display the control response of active reactive powers (P_{PV} and Q_{PV}) regulated by PV at specified P_{ref} and Q_{ref} values. Here, red, yellow, and blue represents

the three phases (a, b, c) of both the power components, which reaches the set reference values as per the control commands over a 2-second simulation period.
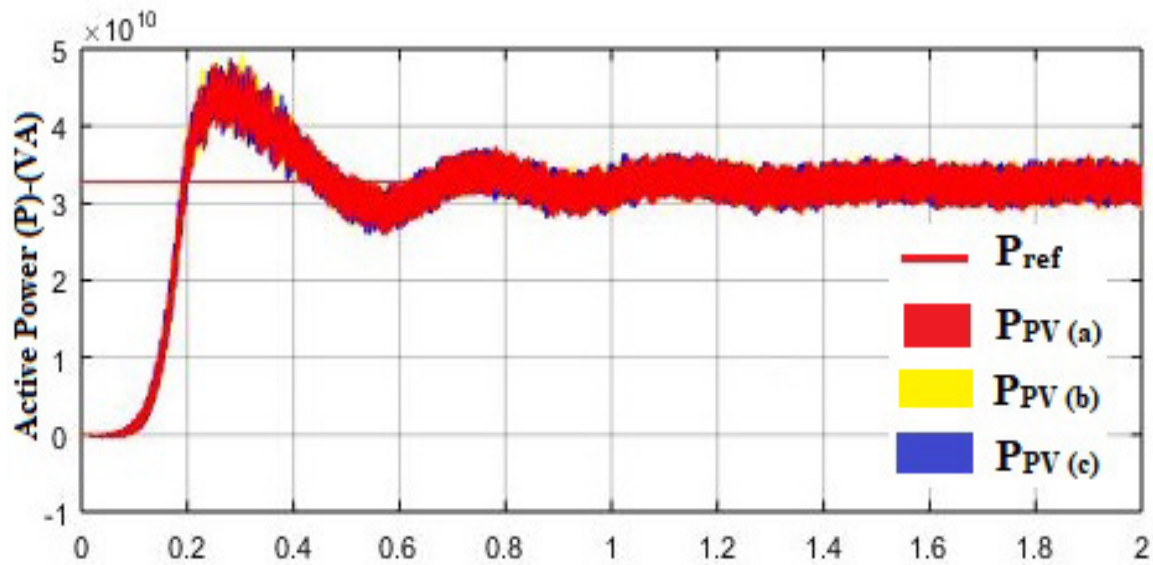

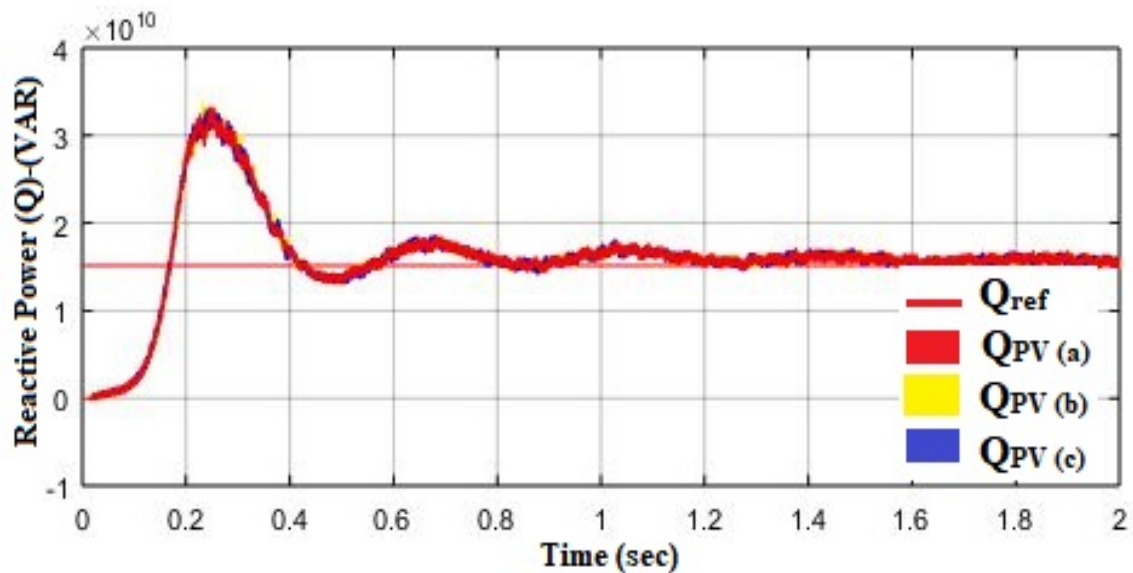Figure 13. Controller response for PPV with Pref = 3.284×1010 VA

Figure 14. Controller response for QPV with Qref = 1.513×1010 VAR

It is evident that Q reaches the reference faster than P because its initial value is closer to the target, resulting in minimal changes during the control task. In contrast, P requires additional adjustments to meet the reference, demonstrating the system's robustness as both P and Q are inter-connected and changes in one quantity impact the other's response. The crucial aspect of the control loop is the optimization of $|V_{\text{PV,AC}}|$ and δ_{PV} at the filter output by adjusting the phase and amplitude of V_{ref} in the inverter. The tuning of V_{ref} by all controllers for PWM inverter operation is illustrated in **Figure 15**, highlighting the adjustments in amplitude and phase.
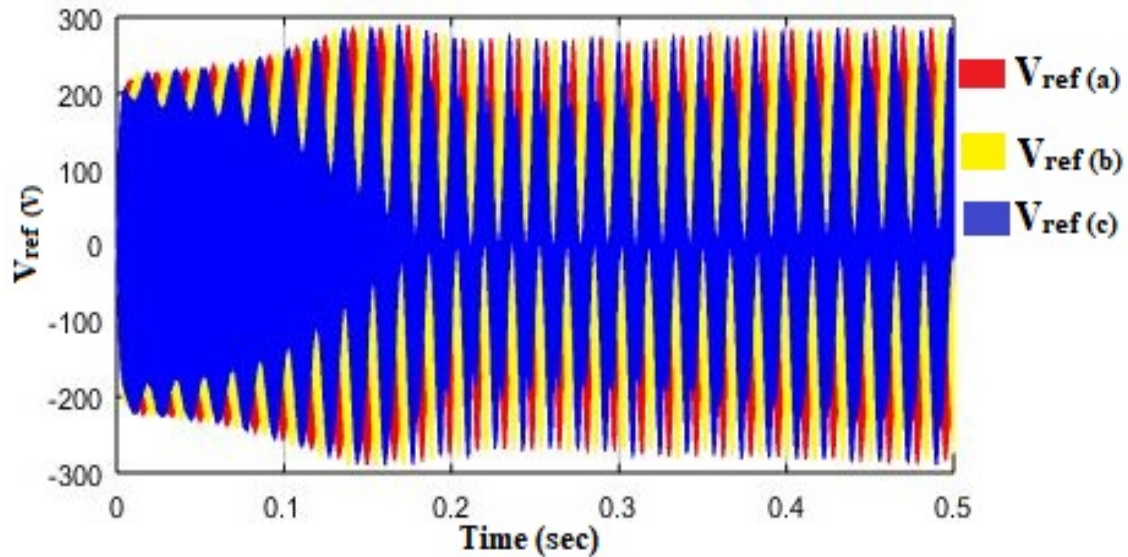
Figure 15. PWM reference tuning as a result of control action

Results for Photovoltaic Placement as Distributed Generator

In this section, the results of voltage and power factor profiles for three buses are analyzed but after placing a PV-based DG system at Bus-2 to inject required power and optimize the voltage and power factors for all three buses in the network.
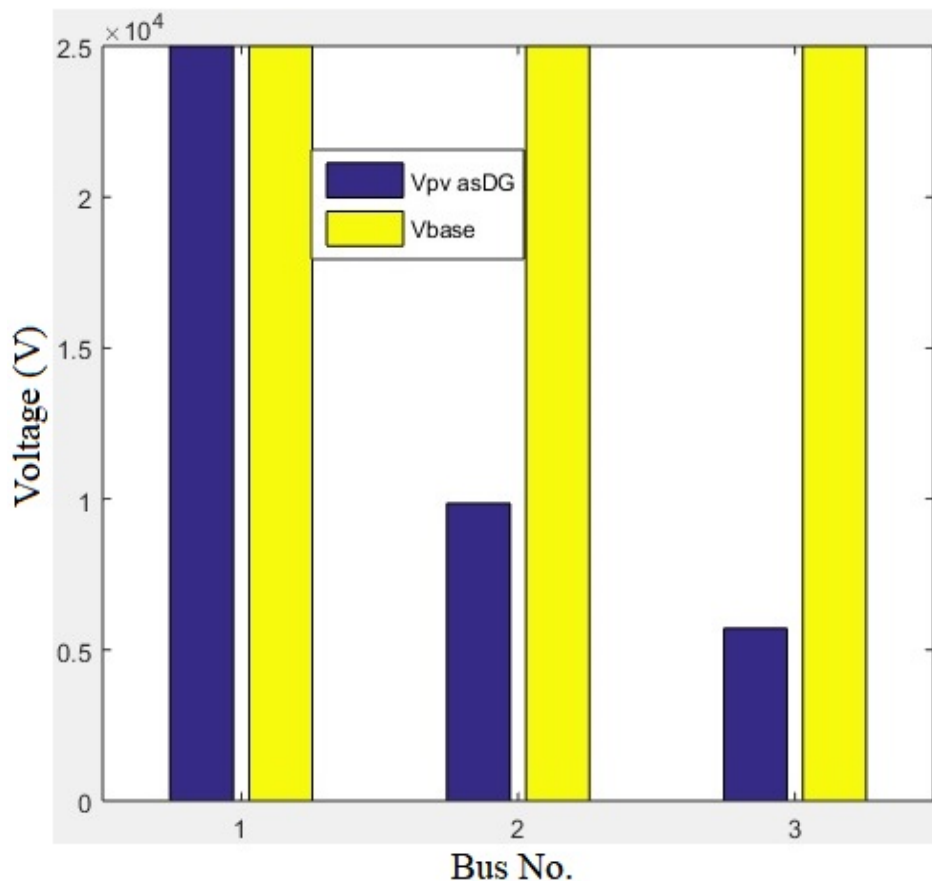

Figure 16. Plots of voltage profile at all three buses with PV placement as DG
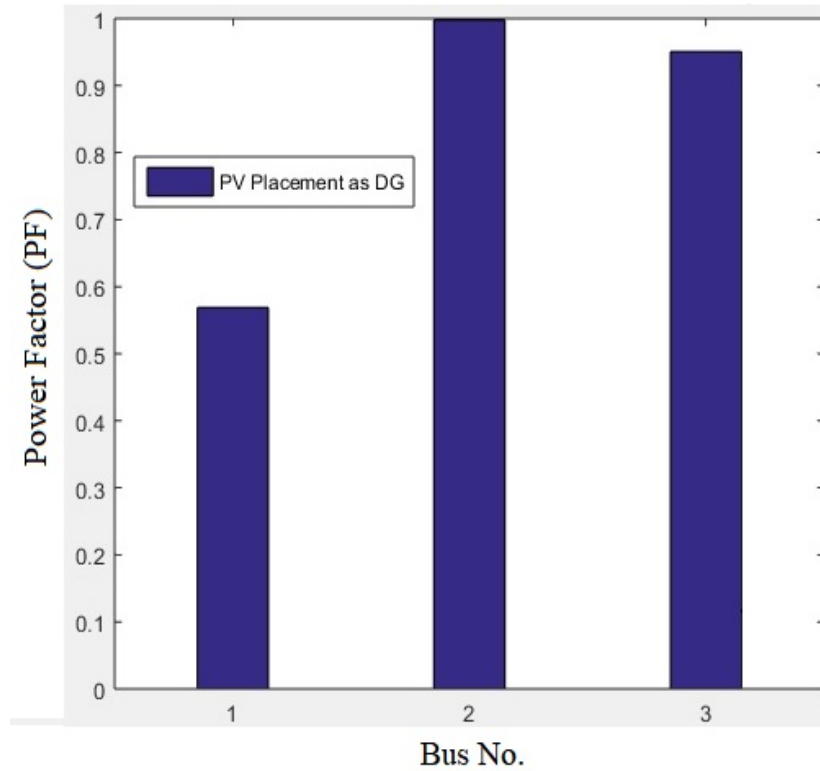
Figure 17. Plots of power factor (PF) at all three buses with PV placement as DG

Figure 16 displays the voltage profile of a network using bar graphs for V_{base} (yellow) and V_{PVasDG} (blue). V_{PVasDG} indicates the bus voltage after PV is placed at Bus-2 as distributed generation, while V_{base} represents the voltage of buses directly connected to a generator with the same voltage level. The voltage level for all PQ buses increases after PV is placed at Bus-2 as a DG, indicating improved system stability and reduced losses. **Figure 17** shows the power factor profile of all three buses, with PF_{PVasDG} representing the power factor of each bus with PV as DG at Bus-2 in the network. The resultant values of voltage and power factor with PV placement as DG can be seen in **Table 6** with fitness function (*FF*) value of 0.8393.

Table 6. Resultant values of V and PF with PV placement as DG

Sr.	V_{base} (V)	V_{PVasDG} (V)	PF_{PVasDG}
1	25×10^3	25×10^3	0.5720
2	25×10^3	9.852×10^3	0.9994
3	25×10^3	5.716×10^3	0.9613

Discussion

After the execution of the control program, the power factors (*PF*) of each of the three buses in the IEEE-3 bus network are displayed as shown in **Figure 18**, without distributed generation (black) and photovoltaic placement as DG (grey). Without DG, *PF* values are lower, particularly at Bus-1. However, on connecting DG at Bus-2 with optimized settings, power factor values increase significantly for all buses. Replacing DG at Bus-2 with PV at specified reference power values results in a simulation completion before plotting *PF* values at all three buses. Due to harmonic losses during the conversion from DC to AC, there are minor discrepancies in *PF* values but overall, the new *PF* values with PV integration closely align with DG placement based on PSO. **Table 4** and **Table 6** provide data for comparative analysis of voltage profiles and power factor at all buses.
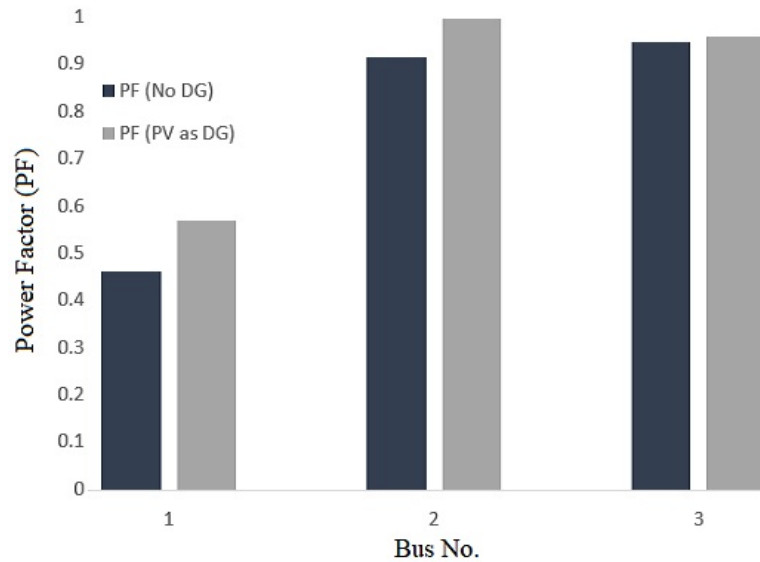
Figure 18. Plot of PF profile of all three buses with no DG and PV placement as DG

Figure 19 consists of bar graphs of V_{base} (blue), $V_{No\ DG}$ (orange), and $V_{PV\ as\ DG}$ (grey) which displays the voltage profiles of IEEE-3 bus network. Here, bus voltages for all the buses after PV placement as DG at Bus-2 are represented by V_{PVasDG} and bus voltage without DG placement is denoted by V_{NoDG}. In an ideal situation, all bus voltages should align with V_{base}, which is observed for the voltage-controlled bus (Bus-1) linked directly to the generator. However, due to the presence of active and reactive power losses in a standard IEEE bus network having no DG, the resultant voltages for PQ buses are below the base voltages of the system.
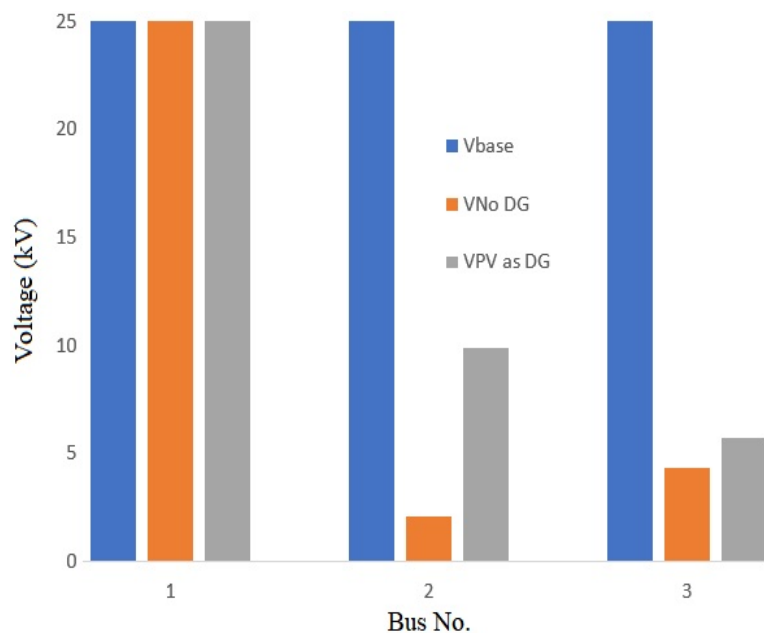

Figure 19. Plot of voltage profile of all three buses with PV placement as DG and without DG

Following the assessment of DG bus and its power values, it was observed that the bus voltages significantly rose and eventually matched V_{base}. This trend continued even after the introduction of PV in place of DG. However, a slight discrepancy in voltage levels was noticed post PV integration, which was linked to harmonic losses presence in the PV output. This highlights the importance of careful consideration in the design of filters to address these issues.

CONCLUSION

This study explores ways to enhance the performance of an IEEE-3 bus system by incorporating renewable energy sources as DG at a specific bus, within the system. The main focus is on improving the power factors and bus voltages of the entire power system, which can be fine-tuned on a chosen bus to achieve performance goals. The proposed method streamlines the process of positioning particles and selecting the DG bus for efficient system operation. Once the appropriate DG bus is defined, the required values of active and reactive powers to be injected in the system are obtained.

Unlike the PSO technique that sets the DG position at one bus and iterates through each bus separately for optimization, our model achieves *FF* values in significantly less time demonstrating its efficiency. The maximum iterations using the proposed method are 20 for 3-Bus network. In the case where the DG is not incorporated, *FF* stands at 0.7781. However, after integrating DG at Bus-2 with power values of 3.284×10^{10} W and 1.513×10^{10} VAR, for P_{ref} and Q_{ref} respectively, *FF* rises to 0.8393 through optimization techniques. The results show that the location of distributed generation is a critical parameter regarding improving the power losses and voltage regulation in an electrical network. With the designed LCL filter, the total harmonic distortion (THD) is found to be 1.14% 1.14% in the voltage and current waveforms which is quite smaller than 1.5 specified in the IEEE standard 519-2022.

The evaluation of the DG bus involves integrating PV with a designed PWM inverter and LCL filter to achieve consistent P_{ref} and Q_{ref} at the DG interface, with the goal of enhancing the performance (power factor and voltage profiles) of the system. To assess the PWM reference signal, a control framework is established using the phase domain approach which provides more accurate and fine results as compared to the dq0 mode, resulting in a 3-phase AC output with specific voltage amplitude and phase. This study demonstrates that PV integration at the DG bus can be effectively optimized, similar to a generator block. This study establishes a foundation for addressing the challenges related to the controlled integration of renewable energy sources into large networks for output optimization. Furthermore, the research paves the way for grid integration of electric vehicles at optimum buses for demand response and peak shaving during the high load durations. This strategy provides cost effective solutions for grid users by utilizing the storage system of electric vehicles which are mostly parked during the peak load timing.

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