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Impact of Photovoltaic Penetration on Distribution System Performance: A Simulink-Based Study Using the IEEE 9-Bus Mode

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Abstract—This study investigates the effects of pho- tovoltaic (PV) system integration at different penetra- tion levels (0%, 10%, 30%, and 50%) on the perfor- mance of a three-phase distribution network modeled in Simulink. Using an adapted IEEE 9-Bus system, the research evaluates key system parameters such as total generation, total PQ load, total shunt impedance, total asynchronous machine count, and total system losses. The simulation model incorporates a detailed PV array design, pulse generation and control, and load flow analysis to capture dynamic behaviors un- der varying renewable energy contributions. Results indicate that while total generation slightly increases and shunt admittance varies with PV penetration, the overall impact on system losses and load remains minimal. The findings provide valuable insights into the feasibility of integrating solar PV systems into traditional power networks while maintaining system stability and efficiency.

Index Terms—Photovoltaic (PV) Integration, Dis-tribution System, PV Penetration Levels, IEEE 9-Bus System, Load Flow Analysis, Simulink Modeling

I. Introduction

The increasing global demand for sustainable and renewable energy sources has led to significant interest in integrating photovoltaic (PV) systems into existing power distribution networks. Solar PV technology offers a clean, reliable, and environmentally friendly alternative to traditional fossil fuel-based generation [1]. However, the integration of PV systems introduces new challenges to the distribution network, such as variations in voltage profiles, power losses, and system stability issues [3].

Studies have shown that the impact of PV penetration levels on system performance param-eters, including total generation, total load, shunt impedance, and network losses, must be carefully analyzed to ensure efficient operation [4]. At low penetration levels, the effect on the distribution system may be minimal, but higher PV penetra- tions can lead to increased voltage fluctuations and reduced system reliability if not properly managed [5].

This study focuses on evaluating the effects of different PV penetration levels (0%, 10%, 30%, and 50%) on a three-phase distribution system modeled in Simulink. By comparing system parameters such as total generation, total PQ load, total Z shunt, total ASM, and total losses across different PV penetration scenarios, the study aims to assess the feasibility and impacts of PV integration on system performance. The findings contribute to a better understanding of how distributed PV generation affects traditional power networks and offer insights into effective integration strategies.

II. Methodology

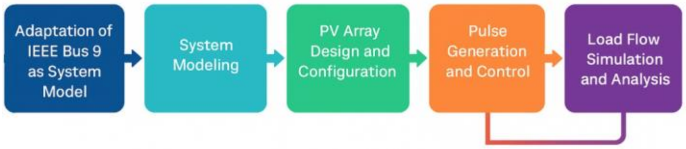


Fig. 1: Workflow Diagram for PV Integration Methodology

The methodology adopted for this study is illus- trated in Figure 1. It begins with the adaptation of the IEEE 9-Bus system model, where a simplified version was configured to serve as the baseline power system. This is followed by the system modeling phase, which involves the development of the distribution system in MATLAB/Simulink, integrating all critical components such as buses, transformers, and measurement blocks. Loads were strategically added at BUS 1, BUS 2, and BUS 3 using Three-Phase Constant Power Loads to rep- resent realistic demand conditions, with parameters adjusted according to desired power levels. Subsequently, the **pulse generation and control** stage is implemented to manage switching signals and simulate converter behavior using a Pulse Generator block. Lastly, **load flow simulation and analysis** is performed using the Simulink powergui tool to assess power flow, voltage stability, and generation metrics. A feedback loop exists between the pulse control and simulation stages to ensure tuning and response accuracy.

This study adopts a structured simulation-based methodology to assess the impact of solar photo- voltaic (PV) penetration on a power distribution network modeled after the IEEE 9-Bus system.

Adaptation of IEEE Bus 9 as System Model

The base model was derived from the IEEE 9- Bus system with small modification made by the researcher, the system was added by three Three- Phase Constant Power Loads tapped to BUS 1, BUS 2 and BUS 3, the modified base model represent three main buses: a slack bus (reference generator), a load bus, and a PV connection point. This config- uration enables efficient analysis while maintaining power system realism.

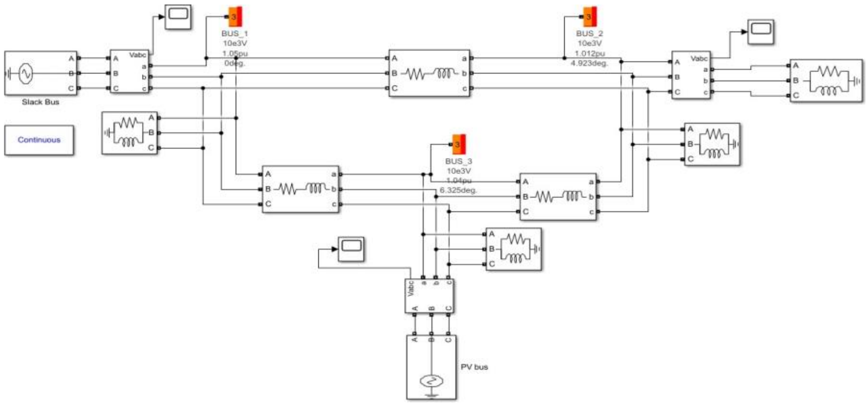


Fig. 2: Modified IEEE Bus 9 as System Model

The system model represents a three-phase dis- tribution system model with a Slack Bus, multiple Load Buses (BUS_1, BUS_2, and BUS_3), and a Photovoltaic (PV) Bus integrated into the network. The Slack Bus serves as the reference point for the system, maintaining a fixed voltage and phase angle during power flow analysis, typically around 10 kV. Transmission lines connect the buses and are represented with series impedance blocks indicating resistance and inductance components. Each load is connected at different buses and modeled as R-L loads, simulating realistic consumer demands.

Voltage magnitudes and angles are indicated at each bus; for instance, BUS_1 operates at 1.05 pu and 0 degrees. The PV Bus introduces renewable energy into the system, connected near BUS_3.

System Modeling

The entire system was implemented in MAT- LAB/Simulink using the Simscape Electrical tool- box. The model includes three-phase lines, trans- formers, measurement blocks, and loads. Each bus was parameterized for voltage levels, power de- mand, and interconnection with renewable sources.

PV Array Design and Configuration

The PV system consists of 213.15 W modules, arranged in 12-module series strings. The number of parallel strings was scaled according to penetration targets:

- 10% Penetration: ∼40 MW
- 30% Penetration: ∼120 MW
- 50% Penetration: ∼200 MW

The PV output was interfaced through a boost con- verter and a three-phase Voltage Source Converter (VSC) using the Universal Bridge block.

The number of parallel strings is calculated based on the desired PV penetration level relative to the system's base load, which is approximately 400 MW.

The total power output per string (P_{string}) is given by:

$P_{string} = 12 \times 213.15\ \text{W} = 2557.8\ \text{W} = 2.5578\ \text{kW}$

The number of parallel strings ($N_{parallel}$) re- quired to meet a specific target PV power (P_{target}) is calculated using:

$$N_{parallel} = \frac{P_{target}}{P_{string}}$$

Where P_{target} is defined based on the desired penetration percentage:

The PV array configuration is systematically scaled by adjusting the number of parallel strings while maintaining 12 modules per string for all penetration levels.

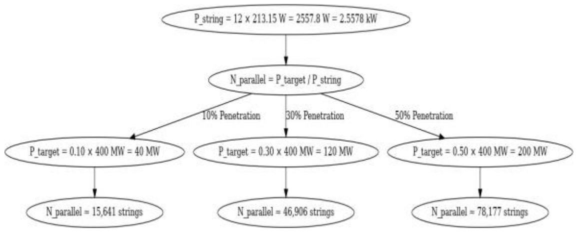


Fig. 3: Calculation Process for PV String Sizing at Different Penetration Levels

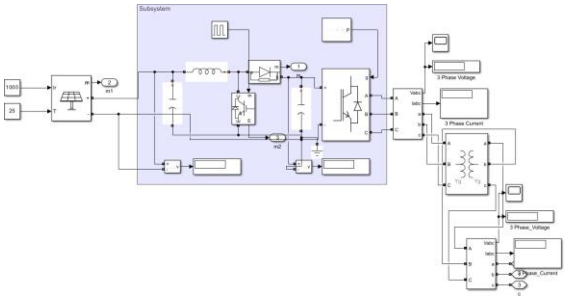


Fig. 4: Workflow Diagram for PV Integration

Figure 3 presents a comprehensive simulation model of a grid-connected photovoltaic (PV) gen- eration system, developed using Simulink and Sim- scape Electrical. This configuration illustrates the complete flow of energy conversion and integration from solar energy capture to grid interface. The primary stages include the PV array, DC-DC boost converter, control logic, inverter, and grid connec- tion.

The PV array block, located on the left side of the model, receives irradiance (1000 W/m²) and temperature (25°C) as inputs to simulate real-world operating conditions. The output of the PV array is a variable DC voltage and current, which is fed into a boost converter to increase the voltage level suitable for grid interfacing. The boost converter, enclosed in a light blue subsystem, consists of an inductor, diode, switching element, and capacitors. It is regulated using a PWM signal generated by a pulse generator, ensuring optimal DC output.

To maintain maximum power extraction from the PV array, a Maximum Power Point Tracking (MPPT) controller is embedded within the same subsystem. This control algorithm dynamically ad- justs the duty cycle of the boost converter to op- erate the PV array at its optimal power point. A Proportional-Integral (PI) controller monitors the output voltage, contributing to stability and dynamic performance.

Following the boost stage, the regulated DC voltage is fed into a three-phase Voltage Source Inverter (VSI), modeled using the Universal Bridge block. This inverter converts the DC power into AC using a six-switch IGBT-based bridge. The inverter control relies on a d-q axis current control strategy synchronized with the grid using a Phase-Locked Loop (PLL). This synchronization ensures accurate injection of active and reactive power into the grid.

The output of the inverter passes through a Yg- Yg transformer, which steps the voltage up or down as required and provides galvanic isolation. Voltage and current measurements are taken at the grid interface using 3-phase measurement blocks. These measurements feed back into the control system and are used for load flow analysis and system mon- itoring. The simulation environment is managed using the powergui block set to continuous mode. This enables time-domain simulations, steady-state analysis, and harmonic assessments.

Pulse Generation and Control

A Pulse Generator block defined the switching pattern for the power electronic interface. The con- verter was controlled via a d-q current control strat- egy with Proportional-Integral (PI) controllers and a Phase-Locked Loop (PLL) for grid synchronization. Reference values for i_d and i_q currents were used to control active and reactive power injection.

Load Flow Simulation and Analysis

The three-phase distribution system model is de- veloped in Simulink, featuring a Slack Bus, multiple Load Buses (BUS_1, BUS_ 2, and BUS_3), and an integrated Photovoltaic (PV) Bus. The Slack Bus, located on the left side of the model, serves as the main voltage and frequency reference source for the network, supplying the necessary active and reactive power to maintain system balance. Each Load Bus is connected to various loads modeled as resistive- inductive (R-L) components, which realistically simulate consumer demands such as household or industrial equipment. The voltage magnitude (in per unit) and phase angles (in degrees) are displayed for each bus, showing, for instance, BUS_1 operating at 1.05 pu and 0 degrees, BUS_2 at 1.012 pu and 4.923 degrees, and BUS_3 at 1.04 pu and 6.325 degrees.

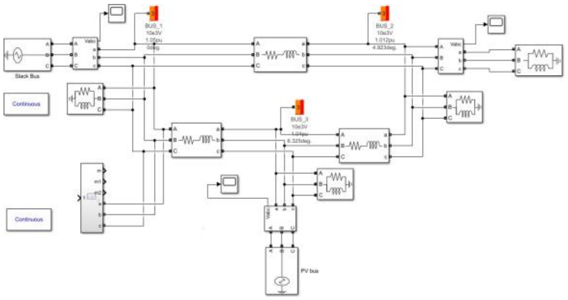


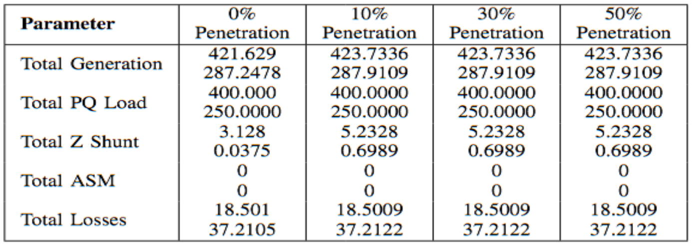
Fig. 5: IEEE Bus 9 Distribution Network with Solar PV Integration

The PV Bus, connected near BUS_3, acts as a renewable energy source injecting solar-generated power into the grid, thereby reducing the load dependency on the Slack Bus and supporting local power demand. The system is modeled under con- tinuous simulation mode, enabling the analysis of real-time dynamic behaviors, voltage profiles, and power flow distribution. Measurement blocks are placed at strategic points to monitor key parameters such as voltage, current, and power. Overall, the model enables the study of power flow analysis, PV integration impact, dynamic system performance under various loading scenarios, and the evaluation of voltage regulation and grid stability when inte- grating renewable energy sources.

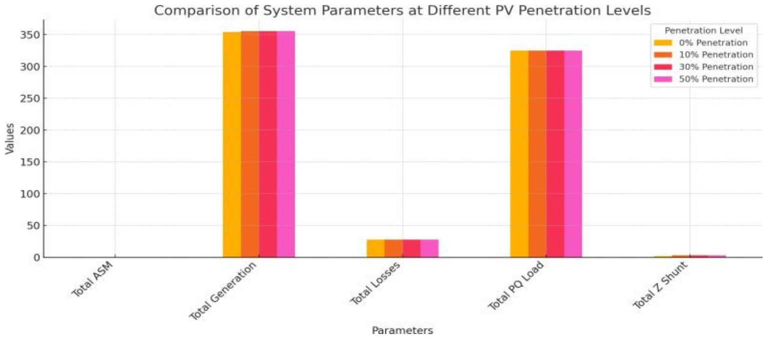
III. Results and Discussion

The comparison of system parameters at different PV penetration levels (0%, 10%, 30%, and 50%) reveals several key observations. Total generation slightly increases from 421.629 units at 0% pene- tration to 423.7336 units as PV penetration is intro- duced and maintained from 10% to 50%, suggesting a minimal adjustment in generation requirements due to PV integration. The total PQ load remains constant across all penetration levels, indicating that the overall system demand does not change with the addition of PV systems. Meanwhile, the total Z shunt increases from 3.128 at 0% to 5.2328 from 10% onward, reflecting a change in the network’s admittance characteristics likely due to PV system integration. The total ASM (Asynchronous Ma- chines) remains at zero across all scenarios, show- ing that no new asynchronous devices are added during the study. Lastly, the total losses show only a negligible increase, from 37.2105 at 0% penetration to 37.2122 at higher penetration levels, implying that PV integration up to 50% has a minimal impact on overall system losses. The integration of PV systems in the network causes only minor variations in system performance parameters.

TABLE I: Comparison of System Parameters at Different PV Penetration Levels



Parameter	0% Penetration	10% Penetration	30% Penetration	50% Penetration
Total Generation	421.629 287.2478	423.7336 287.9109	423.7336 287.9109	423.7336 287.9109
Total PQ Load	400.000 250.0000	400.0000 250.0000	400.0000 250.0000	400.0000 250.0000
Total Z Shunt	3.128 0.0375	5.2328 0.6989	5.2328 0.6989	5.2328 0.6989
Total ASM	0 0	0 0	0 0	0 0
Total Losses	18.501 37.2105	18.5009 37.2122	18.5009 37.2122	18.5009 37.2122



IV. Acknowledgment

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Declaration of generative AI and AI-assisted technologies

During the preparation of this work, the author(s) used *ChatGPT (OpenAI)* in order to assist with technical writing, formatting of LaTeX content, and refining academic language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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