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Performance Analysis of WSCC 9-Bus System Integrated with Photovoltaic under Load Increment Condition

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The integration of renewable energy sources is pivotal for the modernization of power systems. This paper presents a comprehensive performance analysis of the Western Systems Coordinating Council (WSCC) 9-bus system integrated with photovoltaic (PV) under conditions of load increment. The study aims to evaluate the dynamic behavior and stability of the system, highlighting the effects of increased load demand on the integrated system's performance. Using a combination of simulation tools and analytical methods, we model the WSCC 9-bus system with integrated PV to assess various performance metrics. The analysis includes the examination of voltage profiles and active and reactive power flow under normal and increased load scenarios. The authors' results indicate that the integration of PV significantly enhances the system's ability to maintain stable voltage levels, even under substantial load increments. However, the effectiveness of these integrations is highly dependent on the appropriate sizing and placement of the PV within the system. This study provides valuable insights into the operational benefits and challenges of incorporating renewable energy solutions into existing power systems. In the future, it underscores the importance of strategic planning in the deployment of PV to optimize system performance. The findings contribute to the ongoing efforts in achieving a more resilient and sustainable power grid, capable of accommodating higher levels of renewable energy penetration while ensuring reliability. This WSCC-9 bus system is simulated in MATLAB 2021b version.
Keywords: Photovoltaic, Renewable Energy, Multi-Machine System, Voltage Profile Improvement, Load Increment.

1. Introduction

The global energy landscape is undergoing a significant transformation, driven by the imperative to reduce carbon emissions and mitigate climate change. This shift is marked by the increasing integration of renewable energy sources (RES) into power systems worldwide. Among the various RES, photovoltaic (PV) systems have garnered considerable attention due to their abundant availability, declining costs, and potential to contribute significantly to the global energy mix. However, the intermittent nature of PV generation poses substantial challenges to the stability and reliability of power systems. This paper presents an in-depth performance analysis of the Western Systems Coordinating Council (WSCC) 9-bus system integrated with PV under conditions of load increment.

The WSCC 9-bus system, a simplified yet representative model of a power grid, is widely used in research to study power system dynamics, reactive power flow as well as voltage profile. By integrating PV into this system, the author aims to evaluate the impact of these technologies on system performance, especially under scenarios of increasing load demand. This study is particularly relevant as power systems globally are experiencing growing electricity demand, necessitating robust strategies to maintain grid reliability.

2. Background and Motivation

The transition towards renewable energy sources is driven by environmental concerns, energy security, and economic factors. Governments and regulatory bodies worldwide are implementing policies and incentives to promote the adoption of RES. PV systems have seen exponential growth due to advancements in technology and significant cost reductions. However, the variability and intermittency associated with solar energy present unique challenges. PV output is highly dependent on weather conditions, leading to fluctuations that can affect the balance between supply and demand in power systems.

This capability not only enhances the stability of the power grid but also improves the utilization of PV systems. The integration of PV into power systems can provide multiple benefits, including peak shaving, frequency regulation, voltage support, and improved reliability.

Despite the potential benefits, the integration of PV into existing power systems presents several technical challenges. These include issues related to sizing and placement, the development of efficient control strategies, and the need for advanced monitoring and management systems. Moreover, the impact of increasing load demand on the performance of integrated systems needs to be thoroughly understood to ensure reliable operation under varying conditions.

3. Literature Review

The author introduces a new reactive power control method for single-phase photovoltaic (PV) inverters. This method focuses on ease of application and autonomous operation, aiming to improve network operation and optimize reactive power management. The paper presents a novel control algorithm designed for single-phase PV inverters that ensures efficient network operation by managing reactive power and controlling voltage at the point of common coupling. The new control method resulted in a 64% reduction in reactive energy supply from the upstream system, contributing to the LV network's self-sufficiency in reactive power. It also reduced active power losses by up to 1.5% and improved the voltage profile at network nodes. The paper demonstrates that the new control algorithm for single-phase PV inverters is beneficial for reactive power management and voltage control in LV networks [1].

Parallel to the fast uptake of renewable energy sources (RESs) connected to the grid, the electric power industry has experienced several issues related to system strength and inertia. Battery energy storage systems (BESSs) have been proved effective in mitigating numerous stability problems related to the high penetration of renewable energy sources.

This paper investigates the role of BESSs in mitigating the voltage and frequency stability issues in weak grids. The author has utilized a binary grey wolf optimization approach to define the locations and sizes of BESSs to improve voltage and frequency stability in a weak grid. Simulation results show that compared to existing solutions, significant improvements in terms of voltage and frequency stability can be achieved by implementing the author's proposed solution[2].

This paper presents a method for the optimal allocation and sizing of distributed generation (DG) units and capacitor banks (CBs) in medium voltage (MV) and low voltage (LV) networks. The main points are: Simultaneous Allocation and Sizing, Detailed Network Modeling. Simulations on an IEEE 33 bus radial distribution system showed that coordinated allocation using a detailed model achieves better results in terms of loss reduction and voltage profile improvement compared to simpler models. The method ensures improvements in the network without significantly increasing investment costs, demonstrating practical applicability for real-world network enhancements. These papers focus on enhancing power distribution networks' efficiency and stability by optimizing the control and allocation of resources like PV inverters, DG units, and CBs[3].

As the penetration of roof-top solar photovoltaics (PV) becomes very large, voltage regulation to the power grid via transactive energy has emerged to achieve system security and flexibility. Several recent studies have extensively studied transactive mechanisms that directly control either real or reactive power of the prosumers. This paper addresses this gap by exploiting the capacities of prosumers' distributed assets through simultaneous control of both real and reactive powers. In particular, a transactive mechanism is proposed for PV prosumers connected to a remote-area distribution feeder to manage their PV inverters for voltage regulation. In this mechanism, customers are given economic benefits for providing voltage regulation services, which are integrated into their operational objectives. This research provides a substantial benefit to both the system operators like utility companies and the grid-connected renewable asset owners.

Case1: No Power Control, SVR Unavailable

Case2: Distributed Optimization, SVR Unavailable

Case3: Load Real Power Control & PV Inverter Reactive Power Control for Voltage Regulation, SVR Unavailable

Case4: PV Inverters' Real and Reactive Power Control Employing Rule-Based Volt-Watt & Volt-Var Control Strategy Along With Flexible Loads' Real Power Control, SVR Unavailable[4].

When greatly increasing renewable energy in the power system, the renewable energy connected to the power grid must be coupled with corresponding energy-storage technologies. This mechanism not only effectively improves the power floating problem but also more efficiently re-dispatches the power output. The purpose of this paper is to deal with the optimal sizing and location issue of the photovoltaic generation system and the battery energy storage system, which are proposed in order to improve the power loss, bus voltage profile, and voltage unbalance for the actual unbalanced loading distribution system of a large-scale chemical factory.

The power loss, construction cost of the solar power and the energy storage systems, voltage variation ratio and voltage unbalance ratio will be treated as part of the objective function of the optimal problem. A refined GA algorithm, named RGAASCM, was proposed to deal with the optimal locating problem and the integer programming problem of device capacity sizing optimization[5].

The study proposes the use of a capacitor-less Distribution Static Synchronous Compensator (D-STATCOM) based on a matrix converter (MC) for reactive power compensation and voltage profile improvement. The matrix converter uses inductors for energy storage, which potentially extends the service life of the equipment. The proposed D-STATCOM provides ancillary services including reactive power support, enhancing the reliability and operational efficiency of the power distribution network. The authors introduces a capacitor-less D-STATCOM based on a matrix converter, using inductors for energy storage to enhance equipment lifespan and provide real-time reactive power support[6].

IEEE 33 bus RDS is considered in this study, with solar PV sources incorporated for power loss reduction, voltage fluctuation, and improving the system efficiency. For the purpose of charging and discharging, some electric vehicles (EV) are incorporated into the test system. The objective of the study is to analyze how EVs and Renewable energy sources (RES) affect the voltage profile in the RDS. As RES is introduced in the test system, the voltage profile is improved. To decrease voltage fluctuations, the usage of the Hull Moving Average (HMA) is recommended, which avoids the lag problem associated with the commonly used moving average approaches. The genetic algorithm (GA) is used to solve the optimization problem accurately. The proposed method has the advantage of taking into account EV power fluctuation in order to extend the battery life. The usage of HMA is recommended to decrease voltage fluctuations to prevent them[7].

Paper presents a method to manage voltage control in power distribution systems with significant photovoltaic (PV) generation. The proposed method combines coordinated control of voltage regulators (VRs) and cooperative distributed control of PV inverters to maintain voltages within a specified range. Tested on a modified IEEE 123-node test feeder with real measurement data, the method shows improved voltage stability and reduced excessive tap changes compared to existing methods. The approach offers significant improvements in voltage deviation reduction and operational efficiency in systems with high PV penetration[8].

The paper proposes a coordinated control strategy for OLTC and Battery Energy Storage Systems (BESS) to improve voltage regulation. The strategy aims to mitigate voltage deviations and optimize the utilization of both OLTC and BESS. The proposed coordinated control strategy ensures effective utilization of resources, reduces the burden on BESS, minimizes voltage deviations, and keeps the number of OLTC tap changes low. The effectiveness of the proposed method is demonstrated through simulations on the IEEE 13 bus and 33 bus distribution systems. The results show that the coordinated control strategy significantly improves voltage regulation compared to traditional uncoordinated methods.

In summary, the paper presents a novel coordinated control approach to manage voltage regulation in distribution networks with high PV penetration by optimally utilizing OLTC and BESS[9].

The paper addresses the challenges of voltage control and power quality in grid-integrated solar PV systems during abnormal grid conditions. These challenges include voltage fluctuations, power quality degradation, and the need for low voltage ride through (LVRT) capabilities. The authors propose a unique control strategy utilizing an interweaved generalized integrator (IGI) for voltage source converters (VSC). The strategy ensures the delivery of PV power to the grid, maintains the point of common coupling (PCC) voltage within prescribed limits, and provides reactive power support during voltage sags. this paper introduces a robust control strategy for grid-integrated solar PV systems that enhances voltage support and maintains power quality during abnormal grid conditions, ensuring stable and efficient operation of the PV system and the grid[10].

Power loss and voltage instability are major problems in distribution systems. However, these problems are typically mitigated by efficient network reconfiguration, including the integration of distributed generation (DG) units in the distribution network. In this regard, the optimal placement and sizing of DGs are crucial. Otherwise, the network performance will be degraded. This study is conducted to optimally locate and sizing of DGs into a radial distribution network before and after reconfiguration. A multi-objective particle swarm optimization algorithm is utilized to determine the optimal placement and sizing of the DGs before and after reconfiguration of the radial network. An optimal network configuration with DG coordination in an active distribution network overcomes power losses, uplifts voltage profiles, and improves the system's stability, reliability, and efficiency. For considering the actual power system scenarios, a penalty factor is also considered, this penalty factor plays a crucial role in the minimization of total power loss and voltage profile enhancement. The simulation results showed a significant improvement in the percentage power loss reduction (32% and 68.05% before and after reconfiguration, respectively) with the inclusion of DG units in the test system. Similarly, the minimum bus voltage of the system is improved by 4.9% and 6.53% before and after reconfiguration, respectively[11].

4. Result and Discussion

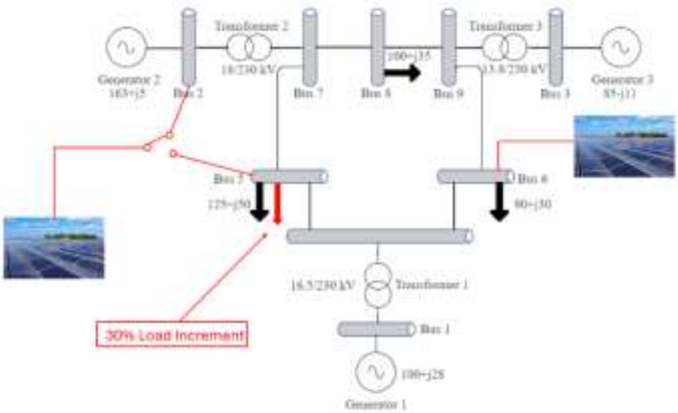

Fig. 1 Modified WSCC 9 Bus system

As per the current scenario of the grid, the integration of renewable energy sources and load demand is increasing day by day. The authors considered 3 cases which are mentioned below.

Case-1: 30% Load increment without PV

India's power grid, one of the largest in the world, is experiencing a significant load increment due to rapid industrialization, urbanization, and electrification of rural areas. The grid must accommodate the rising electricity demand, driven by economic growth and increasing usage of electric appliances. For the analysis of power flow and voltage profile, this case is considered.

Case-2: 30% Load increment with PV at generator bus-2

Integrating a 30% load increment with photovoltaic (PV) systems at Generator Bus-2 presents both opportunities and challenges. The PV systems help meet the increased demand sustainably, reducing reliance on fossil fuels and lowering emissions. However, the variability of solar power can cause fluctuations in power supply, requiring advanced grid management. Effective load balancing, smart grid technologies, and real-time monitoring become essential to accommodate the higher load and maintain grid reliability. Investments in infrastructure and technology are crucial to harness the benefits of PV integration while addressing the challenges of a significant load increase.

Case-3: 30% Load increment with PV at load bus-5

A 30% load increment at Load Bus-5, supported by photovoltaic (PV) systems, offers a sustainable solution to increased energy demands. PV integration at this bus helps to offset the additional load, reducing strain on traditional power sources and lowering emissions. However, solar power's intermittent necessitates advanced grid management and energy storage solutions to maintain reliability. Smart grid technologies, real-time monitoring, and efficient load balancing are crucial to managing the variability of solar power. Investments in grid infrastructure and innovative technologies are essential to effectively handle the increased load while ensuring a consistent and reliable power supply.

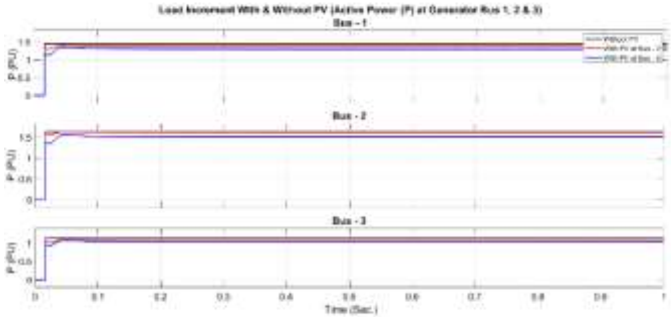

Fig. 2 Active Power at Generator Bus 1, 2 & 3

With the addition of PV at bus 2 it is noticed that active power generation is reduced as compared to without PV. When PV is connected to bus 5 the active power generation is reduced even furthermore. These same results are seen in active power generation on bus 2 and 3. This emphasizes on reduction of carbon footprint with the help of PV integration.

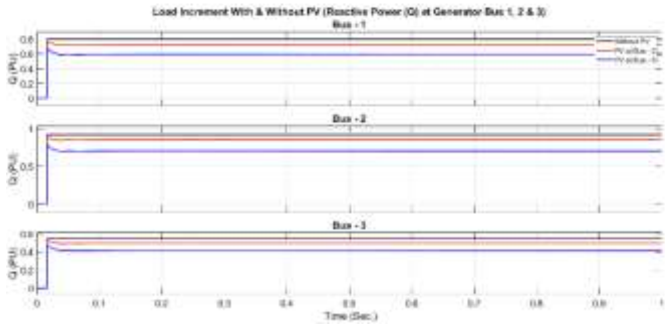

Fig. 3 Reactive Power at Generator Bus 1, 2 & 3

The amount of reactive power generated when PV is connected to bus 2 is less as compared to without PV. When PV is connected to bus 5 the reactive power generation is further reduced. It is clear that by connecting PV at bus 5 there is the least amount of reactive power feeding in the system.

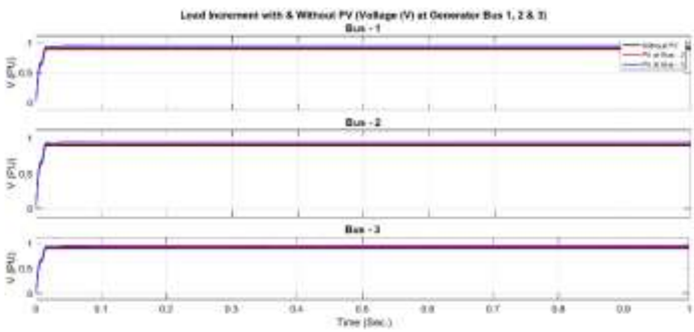

Fig. 4 Voltage Profile at Generator Bus 1, 2 & 3

With the integration of PV on bus 2 and 5 it is noticed that the voltage profile of the system improves substantially. This in turn increases the overall reliability of the system

Table – 1: Active, Reactive and Voltage Profile Analysis at Generator Bus 1, 2 & 3 With and Without Integration of PV at Generator Bus No.2 and Load Bus No. 5

Type of Buses	Measurement Quantity	Bus No.	Load Increment with and without PV		
			Without PV	PV Connected at Generator Bus (Bus 2)	PV Connected at Load Bus (Bus 5)
Generator Bus	P	Bus 1	1.45	1.38	1.34
	Q		0.79	0.72	0.59
	V		0.89	0.91	0.94
	P	Bus 2	1.63	1.62	1.53
	Q		0.92	0.85	0.7
	V		0.89	0.91	0.94
	P	Bus 3	1.12	1.06	1.04
	Q		0.54	0.49	0.41
	V		0.89	0.91	0.94

As seen in the above table the active power at bus 1, 2 and 3 get reduced from 1.45 to 1.38 & 1.34, 1.63 to 1.62 & 1.53 and 1.12 to 1.06 & 1.04 PU respectively. The reactive power on bus 1, 2 and 3 was reduced from 0.79 to 0.72 & 0.59, 0.92 to 0.85 & 0.70 and 0.54 to 0.49 & 0.41 PU respectively. The voltage profile on bus 1, 2 and 3 gets increased from 0.89 to 0.91 & 0.94, 0.89 to 0.91 & 0.94 and 0.89 to 0.91 & 0.94 PU respectively.

From the above results, the authors examine that by connecting PV on bus 5 better results are obtain as compared to PV connecting on bus 2 or without PV system.

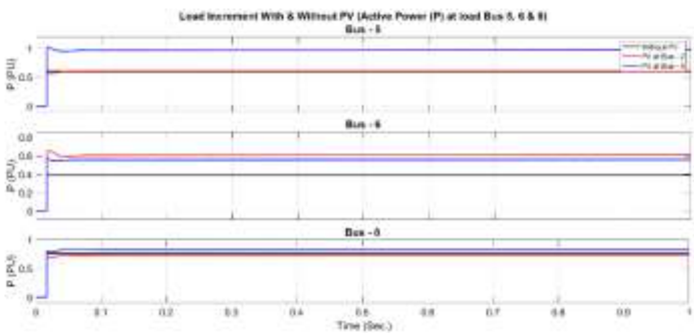

Fig. 5 Active Power at Load Bus 5, 6 & 8

By connecting PV at bus 2 the active power demand increases on bus 5 and 6. But due to far distance the active power demand reduces on bus 8. When PV is connected to bus 5 there is a substantial increase in active power generation on all the three buses because of PV connected on bus 5.

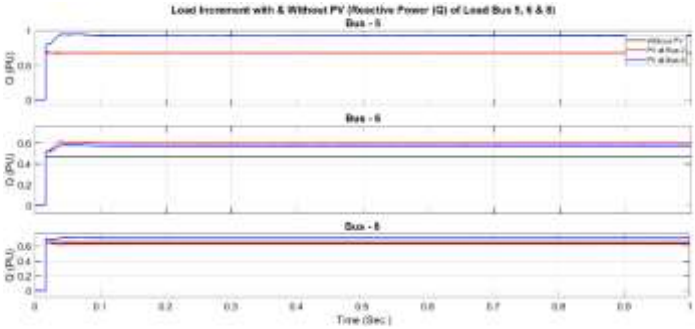

Fig. 6 Reactive Power at Load Bus 5, 6 & 8

When PV is connected to bus 2 the reactive power demand

Increases on bus 5, 6 and 8. But grater increase is seen on bus 5 due to presence of PV on the same bus.

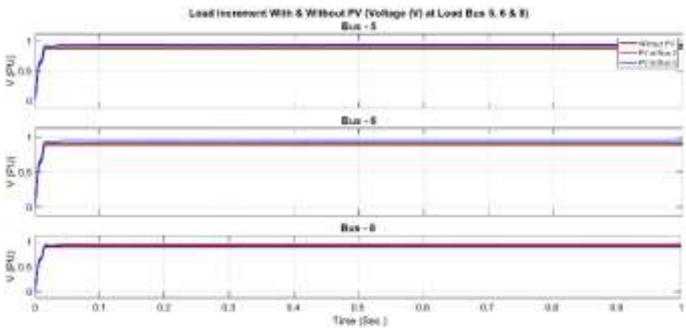

Fig. 7 Voltage Profile at Load Bus 5, 6 & 8

By connection of PV on bus 5 the highest voltage profile improvement is seen on bus 5. There is also voltage profile improvement seen on bus 6 and 8 by connecting PV on bus 5.

Table – 2: Active, Reactive and Voltage Profile Analysis at Load Bus 5, 6 & 8 With and Without Integration of PV at Generator Bus No.2 and Load Bus No. 5

Type of Buses	Measurement Quantity	Bus No.	Load Increment with and without PV		
			Without PV	PV Connected at Generator Bus (Bus 2)	PV Connected at Load Bus (Bus 5)
Load Bus	P	Bus 5	0.6	0.59	0.97
	Q		0.67	0.68	0.93
	V		0.87	0.89	0.93
	P	Bus 6	0.38	0.89	0.55
	Q		0.46	0.6	0.57
	V		0.88	0.91	0.94
	P	Bus 8	0.76	0.73	0.76
	Q		0.64	0.63	0.64
	V		0.89	0.91	0.89

As seen in the above table the active power at bus 5, 6 and 8 get an increase from 0.60 to 0.59 & 0.97, 0.38 to 0.89 , but reduces to 0.55 and 0.76 to 0.73 & 0.76 PU respectively. There is almost no difference seen on bus 8 due to far distance . The reactive power on bus 5, 6 and 8 get increase from 0.67 to 0.68 & 0.93, 0.46 to 0.60 & 0.57 and 0.64 to 0.63 & 0.64 PU respectively. The reactive power on bus 8 almost remains constant because PV connected on far of bus 5. The voltage profile on bus 5, 6 and 8 gets increased from 0.87 to 0.89 & 0.93, 0.88 to 0.91 & 0.94 and 0.89 to 0.91 & 0.89 PU respectively.

From the above results, the authors examine that by connecting PV on bus 5 better results are obtain as compared to PV connecting on bus 2 or without PV system.

5. CONCLUSIONS

From the above result analysis and discussion, the authors can strongly conclude that by connecting PV at load bus 5 there is improvement in the active power generation, reactive power generation and voltage profile on bus generator buses (1, 2 and 3). Also, by PV connecting at load bus 5 the active power demand, reactive power demand and the voltage profile improve on the load buses. (5, 6 and 8).

It can also be concluded that load bus 5 is an ideal bus for integrating PV in the simulated test system. This conclusion is made on the basis of results compared with and without PV connected on generator bus 2 and load bus 5.

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