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Alleviating Power Line Congestion Through the Use of a Renewable Generation

Adeiah James

ALLEVIATING POWER LINE CONGESTION THROUGH THE USE OF A RENEWABLE GENERATION

A Thesis

By

ADEIAH M. JAMES

Submitted to the Office of Graduate Studies of
Prairie View A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2023

Major Subject: Electrical Engineering

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ABSTRACT

Alleviating Power Line Congestion Through the Use of a Renewable Generation

(May 2023)

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As the United States' energy demand has grown substantially within the past few decades, the reliability of its electric grids has become even more pertinent. With millions of customers relying on having consistent electric power to fulfill their daily routines and necessary operations, electric power transmission congestion or the overloading of the electric power transmission network, can be very costly and detrimental to reliability of the network and the environment. Therefore, it is imperative to identify and implement methods of optimally controlling the power flows to limit transmission line congestion.

Throughout recent decades, there has been an ever-increasing penetration of Renewable Energy Generation in the power grid. However, unlike in the past, where fossil fuel generating plants were mostly located in remote areas, and in the proximity of the source of energy, the most common of the renewable generations, such as solar power systems, are haphazardly sited close to the loads. This is due to the fact that energy from the sun can be harnessed almost everywhere. This unplanned siting of renewable generating systems aggravates the power distribution lines congestion that already exists due to the power distribution deregulation. This thesis presents a procedure that takes advantage of utilization and proper placement of Photovoltaic (PV) power systems to alleviate power line congestion. In this procedure, the base case load flow, without the solar generating system, is performed on the distribution network. And the bus with the lowest voltage is identified; this low voltage bus is indicative of congestion in the lines connecting the identified bus. A PV power system is then tied to that bus; the capacity of the PV generation is varied heuristically to determine the optimality that mitigates the congestion on the lines. The procedure is followed to test a 9-bus IEEE power system, and the results are presented.

Keywords: Congestion management; Power line congestion; Renewable energy generation; Transmission lines

DEDICATION

To

My Family & Friends

And

Prairie View A&M University

ACKNOWLEDGMENTS

I would like to acknowledge my Lord and Savior Jesus Christ for life, health, strength, wisdom, knowledge and understanding allowing me to complete this thesis.

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1. INTRODUCTION

1.1 Background

Electric power is an essential part of daily lives; it is used to light up homes, workplaces, and businesses, as well as power up the basic appliances and electronic devices used every day. Currently, electric power demands are at an all-time high with very little addition to utilities infrastructure. This creates congestion on the existing distribution lines, limiting the amount of power that can be transmitted across the system to the areas where it is needed. Therefore, it is essential to improve methods that will assist in minimizing congestion to maintain the existing network reliability and resilience. Congestion in the electric grid occurs when the transmission lines are not able to meet power demands. Hence, managing congestion is very critical to the healthy operation of the power transmission lines, reducing the duration of service disruptions, minimizing the frequency of power outages, and decreasing the strain on the utility's infrastructure.

There are two approaches to congestion mitigation, cost-free methods, and non-cost-free methods. The cost-free strategies are more attractive overall as they improve grid stability without incurring significant additional costs, although they require a considerable amount of coordination between grid operators, utilities, and sometimes consumers, to implement. Common cost-free strategies involve the connection of Flexible AC Transmission (FACT) systems and other compensation devices to appropriate buses on the power network.

This thesis follows the style of the *IEEE Journal of Photovoltaics.*

The non-cost-free approaches involve generation rescheduling and proper management of load transactions by the Transmission System Operator (TSO) [1]. With aging infrastructure resulting in stress to part or the entire electric power network and improving innovations with renewable energy sources, many countries are turning to renewable energy sources to replace the non-renewable generations. These fossil fuel generating plants were built in remote locations in proximity of energy sources such as coal, natural gas, and oil, which are typically away from residential and commercial areas.

Lately, with the penetration of photovoltaic (PV) and other renewable power generating systems on the grid and their locations right where the power demand is, the congestion problem is aggravated. This is a previously unforeseen side effect of the deregulation of the energy market. Prior to deregulation, the energy market was heavily regulated and controlled by government agencies, which meant that the energy companies were limited in the extent to which they set their own prices. On the other hand, this meant that consumers had few energy provider options to choose from. This caused a shift towards deregulation with the main goals to lower prices and improve efficiency.

In the United States, the passing of the Public Utility Regulatory Policies Act (PURPA) and the Energy Policy Act (EPA) paved the way for deregulation and encouraged competition in the energy sector. Deregulation allowed energy companies to compete, and consumers were able to choose from a range of providers offering different prices and services. Now, consumers are incentivized by government agencies, solar industry organizations, and utility companies to implement the use of solar panels on residential and commercial buildings. The application of the photovoltaic systems onto or near the buildings may save the consumer financially but this could amplify existing grid congestion. Renewable generation implementation or placement needs to be assessed from the perspective of grid stability, not just consumer savings.

This thesis addresses the congestion issue by proposing a procedure that strategically connects the PV system to the right bus on the electric grid to efficiently manage the congestion. Most of the research work on existing power system congestion alleviation has focused on the incorporation of FACTS devices [2-5]. The concept of using a PV system for reactive power compensation is discussed in [6]. In [7], a method is proposed to solve the congestion problem where PV power is utilized through the determination of the bus sensitivity factor and generator sensitivity factor to select the optimal bus to which the PV system can be connected. Some techniques to determine how renewable power-generating systems can enhance the operation of the grid are presented in [8]. This article presents a technique to deploy a PV power system at a strategic bus location in the transmission network to alleviate congestion by injecting appropriate real and reactive power into the grid and absorbing the necessary reactive power from the grid.

1.1.1 Power Line Congestion

Power line congestion refers to the inability of transmission lines to meet electric power requirements on the transmission/distribution lines due to excessive demands or transmission, resulting in power loss to consumers. The risk of power loss is among the top stressors for hospitals, data centers, universities, and other such industries [9]. Line congestion can also negatively affect the power network, especially in the form of damaged equipment, resulting in safety hazards. Whenever the transmission lines are congested or heavily loaded, there is a high risk of some lines exceeding their voltage, thermal and stability limits, leading to, damaged wires and equipment and infrastructural integrity. Understandably, power generation and distribution companies have the challenge of generation and delivering consistent and reliable power to its consumers. The typical electric grid is made up of a large system of high-voltage transmission lines which supply electricity to customers through a system of smaller local interconnections. The local grids are typically interconnected for reliability and commercial purposes, forming larger and more reliable networks which make it less complex to coordinate and plan electricity supply [10].

To maintain and organize operation of this bulk electric system, electric reliability organizations such as the North American Electric Reliability Corporation (NERC) in North America, are put in place to develop and enforce necessary grid reliability standards which are approved by an energy regulatory commission such as the Federal Energy Regulatory Commission (FERC) in North America. In this case, grid reliability refers to the ability of the power system network to keep up with dynamic load demands by supplying consistent power with few or short disruptions. To improve grid reliability, the system's physical integrity and power flows through the transmission lines and network must be taken into account. This research focuses on controlling the power flows through transmission lines via the tactical insertion of renewable generation to reduce congestion. Consequently, this improves grid reliability.

1.2 Problem Statement and Motivation

Power line congestion is a common problem in many areas, especially during peak demand periods. The overloading of transmission lines can lead to power outages, equipment failure and damage, as well as safety hazards. This issue is further compounded by the growing demand for electricity, as well as the closure of traditional power plants. It is imperative to limit power line congestion to meet the needs of consumers, reduce unnecessary damage to already aging grid infrastructure and provide cost-efficient options to consumers. To address this issue, new solutions are needed to relieve power congestion. Initially, power generation plants only served local areas, but with the increasing population and load demands, the electric grid expanded to supply power to remote locations. Past research in developing PV technology has encouraged the use of renewable generation as a means of supplying additional power to meet energy demands; however, they have not been placed optimally. With fossil fuel generating plants, there is a need to place the plants near their energy sources, but this limitation does not exist with renewable generation since the ability to harvest the sunlight is possible in an abundance of locations. Despite this advantage, the renewable generation has not been optimally deployed. This problem motivated this research investigation into the effective utilization and proper placement of PV power systems to alleviate power line congestion.

1.3 Objectives

The objectives of this thesis are to investigate power line congestion, review past methods of minimizing power line congestion, explore the use of renewable generation, and propose a new method to mitigate line congestion through the use of PV power systems.

1.4 Thesis Outline

The preceding sections of this thesis such as the “Abstract” and “List of Figures”, along with Chapter 1’s introductions on power line congestion give an overview of what to expect in this thesis. Chapter 2 delves into the causes of power line congestion, previous methods of mitigation and a review on solar power generation from the perspective of existing literature. Next comes the methodology used to investigate and analyze the proposed method focused on in this research. This entails details on the application of PowerWorld Simulator, the Newton-Raphson Method, a simplified look at a small scale 3-bus system then the IEEE 9-Bus System. The results and analysis of the simulation is discussed next in the “Results” section. Lastly, the conclusion and future work are considered, followed by the list of references to literature accredited in this body of work.

2. LITERATURE REVIEW

2.1 Solar Potential as a Renewable Compared to Non-Renewables

From the beginning, non-renewable energy sources such as coal, natural gas, oil and nuclear energy have been the staple in supplying energy to power plants. These fossil fuels or non-renewable energy sources take several lifetimes to create or replenish but are finite with a countdown to depletion with increased usage of these limited resources providing different energy forms. This introduced the investigation into renewable energy sources to overcome this shortcoming.

Overall, renewable energy sources also reduce the impact of the following challenges faced with fossil fuels and their generation plants: high greenhouse gas emissions resulting in negative climate change, deforestation, water pollution, and lack of energy security. The increased use of renewable energy sources will provide security of supply, which means the uninterrupted availability of cheaply priced energy [11]. The cost of solar energy has decreased significantly in recent years due to technological advancements, making it increasingly cost-effective compared to non-renewable energy sources. Non-renewable energy sources, in contrast, are becoming increasingly expensive to extract, transport, and process, and are subject to price fluctuations. Photovoltaic, (PV), energy is currently the most prolific source of renewable energy. It is estimated that one hour of the sun radiation to earth is enough to sustain energy needs worldwide for an entire year. The most consequential challenge with PV technology is solar cell efficiency, and this has been improving continuously with more research, especially in recent years.

The first generation of photovoltaics was predominantly single-junction crystal solar cells which were made of silicon wafers including single and multi-crystalline silicon [12]. The second generation focused on minimizing the amount of material previously needed by creating single and multi-junction devices with thinner films [12]. Third generation PV technologies have progressed towards double and triple junction crystalline III-V compounds and nanotechnology which increases efficiency while becoming more economical [12]. As of 2020, mono-Si, CIGS, multi-Si, CdS based photovoltaic gained record cell efficiencies of 26.7%, 23,4%, 23.2%, and 21%, respectively [13] while multijunction cells (still being researched and not yet commercialized) have reached efficiencies over 45%. With the realization of increased potential, PV systems have been utilized more across the globe, gradually encroaching on the satisfactory performance of the power grid because it is randomly deployed on the grid.

2.2 Power Line Congestion and Its Causes

The increasing challenge to maintain network reliability and resilience requires innovative solutions to achieve optimal levels. The main factor affecting system reliability is power line congestion, therefore, this section of research work investigates some of its causes first, with the purpose of understanding and developing the proposed new method to relieve line congestion.

Power line congestion occurs when there is high demand for electricity in a particular area and the current infrastructure is unable to meet this demand, resulting in power outages, service disruptions, potentially damaged or failed equipment, and voltage drops in the transmission line. Typically, electricity is generated at the power plants and transmitted over high-voltage transmission lines to distribution substations which funnel power to different areas via lower voltage distribution lines. When the demand surpasses the capacity of the transmission lines, there is an increase or spike in electrical energy along the lines that leads to overloading.

Contingencies or failure of equipment such as transmission line, transformer, generator, or circuit breakers, can either cause stress to part of the system or the entire system. The presence of weak elements and aging infrastructure can also burden the system with contingencies which in turn causes or exacerbates congestion. According to [14], congestion refers to situations where transmission constraints reduce transmission throughput to undesired levels. The study also points out that congestion can only occur when there is a desire to increase throughput across transmission lines but is not possible due to one or more constraints. These constraints may be attributed to transformers, a group of closely related pieces such as linked conductors limiting power flows, operational limits on an element or group of elements, or the lack of transmission system capacity to deliver electricity from potential sources of generation without violating reliability rules [14]. These constraints leading to power line congestion can be seen in a typical conventional grid as most of it was built in the early 20th century. As mentioned earlier, these constraints mean that some lines will exceed their voltage, thermal and stability limits, incurring power line congestion or higher levels of energy lost in the transport process of the power from the generating plant along the transmission lines, to the consumer. These factors pose great opportunities to integrate renewable energies to relieve contingencies causing congestion as most of the network is old and components need to be replaced.

2.3 Past Methods Used to Alleviate Congestion

Congestion management refers to methods or tools used for efficiently making use of the power available without violating the system constraints [1]. Congestion management typically falls under two categories, cost-free methods, and non-cost-free methods. The cost-free strategies involve the connection of Flexible AC Transmission (FACT) systems and other compensation devices to appropriate buses on the power network. The non-cost-free approaches involve generation rescheduling and proper management of load transactions by the Transmission System Operator (TSO) [1]. Generation rescheduling is a popular technique of congestion management involving the postponement of the power output by the generator which incurs costs to consumers. Developments and optimizations of this technique can be found in [15] and [16].

FACTS controllers are advantageous in alleviating congestion, improving power system reliability and stability, routing power flows through desired routes and improving the power transfer capability (or the ability of the line to carry electricity) while minimizing operation and transmission investment costs. Srivastava et al. details a review in [17] on the control features of FACTS devices allowing the transmission system to be an active element in improving transient stability, dampening power oscillation and balancing power flows in parallel lines. The three classes of FACTS controllers are the series controller, shunt controller and combined series-shunt controller. The series controllers such as the thyristor-controlled series compensator (TCSC), static synchronous series compensator (SSSC) and thyristor controlled phase-angle regulator (TCPAR) are used in alleviating line overloads and increasing transfer capability [1]. The series controller injects a voltage in series with the line and if the voltage is in phase quadrature with the line, the controller only supplies or consumes variable reactive power. Any other phase means control of both reactive and active power. The shunt controllers such as static var compensators (SVC) and Static synchronous compensator (STATCOM) are used to compensate voltages by directly or indirectly injecting reactive power at low voltage buses [1]. Reference articles [1] and [18] point out that combined series-shunt controllers such as unified power flow controllers (UPFC) can be used to release power flow congestion as well as support voltages.

2.4 Proposed New Method to Alleviate Congestion

This proposed new technique emphasizes the use of a PV power system to diminish power line congestion by strategically placing the PV system at the critical bus and intentionally injecting real power quantities to achieve optimal reactive power consumption. The first step is to determine the ideal location to insert the renewable generation. During congestion, the transmission line becomes choked with reactive power demand, causing a significant undesirable drop in the bus voltages. Therefore, the critical bus or the bus with the highest reactive power will need the assistance of the PV system to absorb some of the reactive power. After determining the critical bus in the power network, it is necessary to determine how much real and reactive power need to be supplied by the renewable generation to reduce the line congestion of the critical bus and overall system to optimal levels.

2.5 Solar Power Generation

According to [19] the U.S Energy Information Administration’s *Monthly Energy Review* (Table 1.3 and 10.1, April 2022, preliminary data), 12% of U.S energy consumption for 2021 was attributed to renewable energy, 36% to petroleum, 32% to natural gas, 11% to coal, and 8% to nuclear electric power. Although fossil fuel is the most prevalent group of energy sources utilized in the U.S, the propulsion for the use of clean or environmentally friendly energy sources has resulted in the greatest increase in renewables, specifically solar and wind electricity over the past decade [20]. These renewable energy sources have a wide range of potential but solar is among water, wind, geothermal, and bioenergy sources as the most abundant and substantially untapped resource. Within the past decade, solar and wind energies have experienced significant growth, most notably in the technologies associated with harnessing those energies; however, both still account for a very small portion of the world's energy. There is great potential for solar technology, especially as there have been so many innovations within the past decade in attempts to create more efficient solar or photovoltaic cells, panels, and systems. Coal and petroleum are on the decline and as the demand for solar energy has increased so rapidly in the past few years, there has been a surge of new technologies and developments making solar viable and more affordable for consumers and homeowners.

Among the top challenges encountered when inserting renewable generation to the grid are voltage stability and power control [7]. The placement of the renewable generation must be strategic since the haphazard placement of these renewable sources introduces new power flows and transmission feeds to the network; the renewable energy source with the most uncertainties is wind energy [1]. In addition, the advances in utilizing PV power to reduce congestion make it more beneficial compared to other renewable sources. [7] proposed and investigated the use of lion optimization algorithm (LOA) as a novel way to select the optimal bus to connect the PV system to through the determination of bus sensitivity factor and generator sensitivity. Some techniques to determine how renewable power-generating systems can enhance the operation of the grid are presented in [8].

Most grid-connected PV solar generating systems usually employ current source inverters (CSI) that are controlled to operate at unity or near unity power factor at the point of interconnection. Lately, VSIs are finding applications in PVs and other renewable energy systems in both the current-controlled and voltage-controlled CCVSI and VCVSI, respectively, because of their efficiency and ease of control. VSIs permit the independent control of both active and reactive power outputs [21].

Fig. 1 illustrates a PV system that incorporates a VSI tied to the grid to effect relief of congestion on the transmission/distribution lines [22]. Referring to Fig. 1, active and reactive power transfer between the generator and load [23] can be expressed as in (1) and (2).

$$P = \left(\frac{EV}{X_s}\right) sin\delta \tag{1}$$

And $$Q = \left(\frac{EV}{X_s}\right) cos\delta - \frac{V^2}{X_s} \tag{2}$$

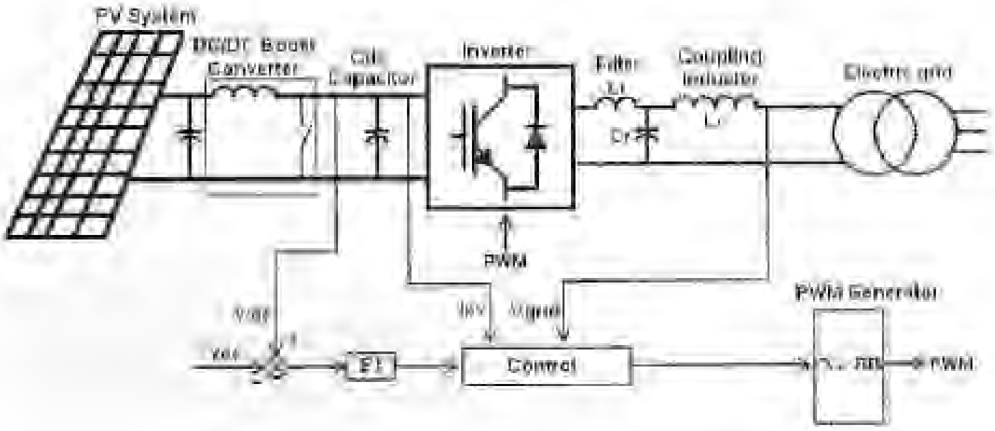


Fig. 1 Power system and control of PV for electric grid [22]

3. METHODOLOGY

3.1 PowerWorld Simulator and Newton-Raphson Method

Originally introduced in 1994 for non-technical people involved in the electricity industry, PowerWorld Simulator has become an excellent software package for analyzing any size power system. According to the Simulator section of the PowerWorld Corporation site, PowerWorld Simulator is designed to simulate high voltage power systems with the ability to efficiently perform power flow analyses on systems with a maximum of 250,000 buses. It features drag and drop interactive and animated components that allow the user to better understand the effects and various load flows resulting from changes in parameters of the power system. It is especially useful for analyzing realistic large-scale power systems to take appropriate precautions for anticipated faults and contingencies and resulting congestion. The simulator allows the user to build original models or edit pre-existing ones with capabilities ranging from adding generation and transmission, switching transmission lines in or out of service, performing short-circuit analysis, contingency analysis, and several economic analyses while also computing power transfer distribution factors among many other possibilities [24].

Transmission line congestion can be determined through load flow calculations. With any power system, a load-flow analysis must be performed to determine the preferred amount of electrical energy to be distributed in the lines and to optimize the power system configuration. The load-flow study is a numerical analysis of the electric power flowing through the power system under steady-state conditions. It takes into consideration the voltages, real and reactive power, and the voltage phase angle to obtain the resultant real and reactive power outputs. The three most common methods for calculating the system's power flow are Gauss-Seidel, Newton-Raphson, and Fast-Decoupled. PowerWorld Simulator can solve the load flows with the Newton-

Raphson, Fast Decoupled and Gauss Seidel methods as well as less popular methods, but it defaults to using the built-in Newton-Raphson algorithm since it is the most used method for solving power flow equations. Compared to the other methods, the Newton-Raphson method is more efficient, taking up to 20 iterations to converge to a solution. Utilizing software is advantageous in calculating these load flow solutions as it can be tedious otherwise for large networks. Thus, PowerWorld Simulator software was chosen to simulate the load flow on the IEEE 9-bus system presented in the methodology section of this thesis, using the Newton-Raphson Method.

3.1.1 Illustrative Example of 3-Bus System

Before testing and analyzing the simulations with the 9-bus, the 3-bus system was used to exemplify analyzing the load flows on a simpler system. Fig. 2 displays the Western System Council (WSCC) 3-bus test case system of an approximation of the WSCC with three buses and three generators.

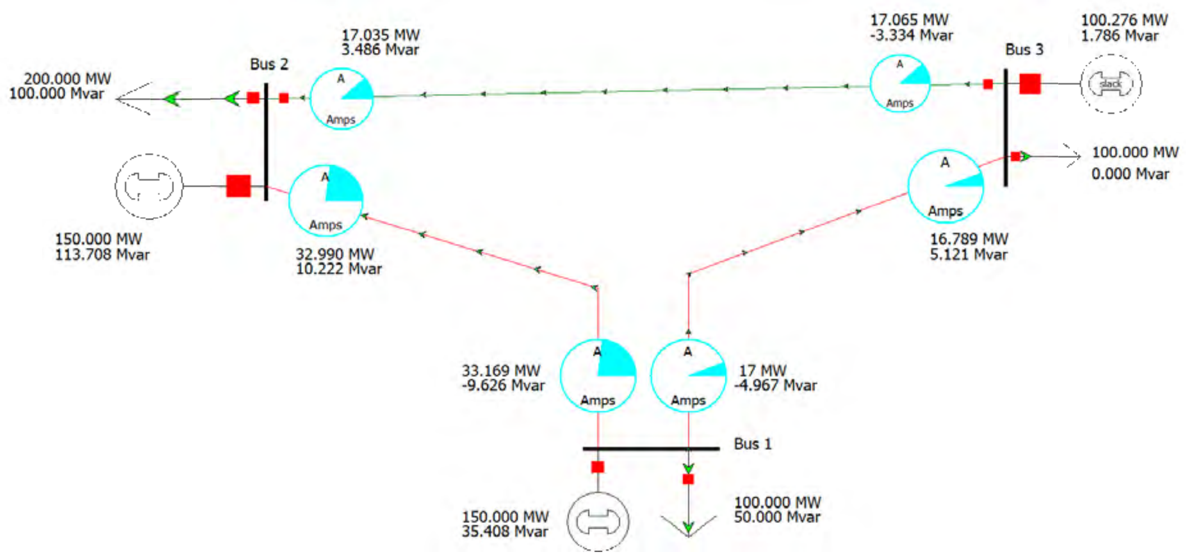


Fig. 2 One-Line Representation of the WSCC 3-bus Test Case

Whatever power is injected into the bus must equal the power leaving the bus. The Fig. above shows that 33.169MW and 17MW 100MW (a total of 150.169 MW) leave bus one. This energy is supplied by the 150MW generator tied to bus one. At bus one, the total reactive power leaving the bus is 35.407MVar (50MVar -9.626MVar - 4.967MVar) which is also supplied by the generator at bus one. These same calculations are made on the large 9-bus system to determine line losses.

3.1.2 IEEE 9-Bus System

The simulation software, PowerWorld, is used to do the congestion study in this thesis. First, the base case load flow analysis of the 9-bus IEEE power system is performed to identify the load bus with the smallest voltage and high reactive power demand. The PV system of Fig. 1 is then grid-connected at this bus. This base case load flow is indicated in Fig. 3, with P, the real power, and Q, the reactive power, injected at bus 6 equal to zero. Following the base case load flow and the placement of the PV system, a few subsequent cases are run. Case 1 has the injection of P = 25 MW and Q = 0 MVar at bus 6 by the PV system; equivalently, the load at bus 6 is reduced by 25 MW, resulting in P = 75 MW from the 100 MW base case. Similarly, case 2 has P = 50 MW injected. Case 3 has P = 0 MW and Q = 10 MVar power injections at bus 6. Case 4's power injections are P = 0 and Q = 30 MVar; case 5 has P = 0 MW and Q = 50 MVar and finally, for case 6, P = 0 MW and Q = 70 MVar. The figures and corresponding Tables on the following pages indicate the real and reactive powers for these cases. It is worth noting here that since the emphasis in this thesis is not on the control aspect of the PV system, very little attention has been given to the PV system control. The detailed control strategy of the PV system is presented in [21]. Besides, the harmonic filtering required in a VSI is simple, as Pulse Width Modulation (PWM) can be used to control the amplitude and the frequency of its output voltage.

4. RESULTS

The load flow results obtained in this work are shown in the Figs. and Tables in the following pages starting with the base case in Fig. 3, to identify congested lines, bus voltages, and line losses. The numerical data are also displayed on the Figs., but for ease of analysis, the relevant quantities are clearly indicated in the corresponding Tables. Aside from the generator buses, bus 6 in the transmission network has the lowest voltage of 222.38 kV. This is the result of large reactive power flows in the adjoining lines (6-4, 6-5, and 6-9) and the large reactive power demand at the bus.

Fig. 10 displays the percent increase in voltage of bus 6 as congestion mitigation is accomplished through the use of the PV system to inject power into the bus. It is observed from Fig. 10 that the injection of reactive power corrects the voltage drop at the affected bus by over 40% more compared to the real power injection. However, a combination of real and reactive power will surely be advantageous depending on the local bus load demand. Nevertheless, to demonstrate the dependency of the reactive power, Q, on the magnitude of the bus voltages, it suffices to treat the real power, P, and the reactive power, Q, as separate entities as done in this thesis.

4.1 Base Case Simulation for the Injection at Bus 6 of P=0.000 MW, Q=0.000 MVar

Fig. 3, the Base Case, displays the 9-bus model where the Newton-Raphson load flow method was carried out via PowerWorld Simulator, without any distributed generation added to the system. Each iteration or case line flow is determined by utilizing the Newton-Raphson method, which is the default load flow analysis method for PowerWorld Simulator.

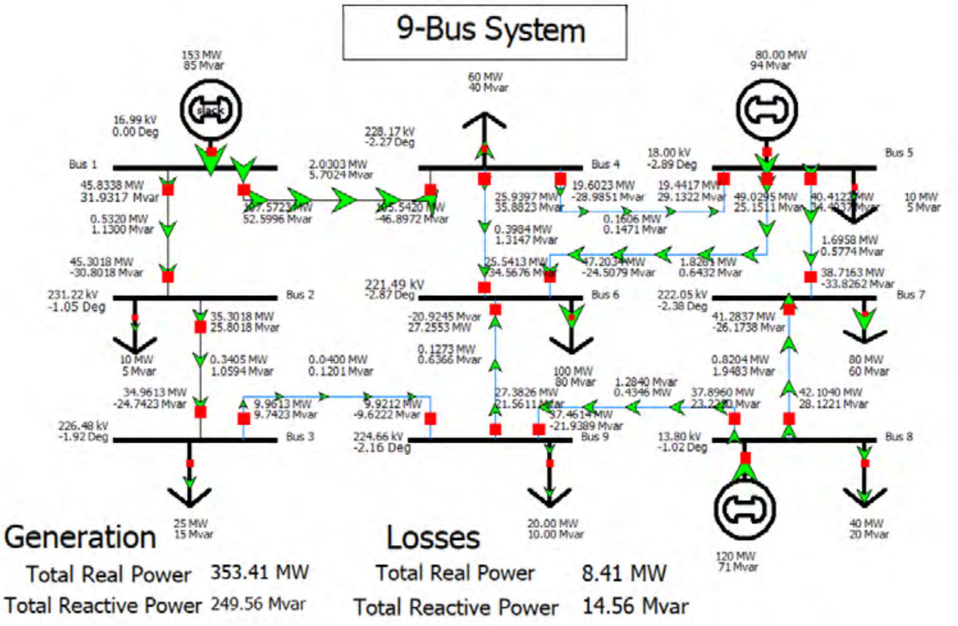


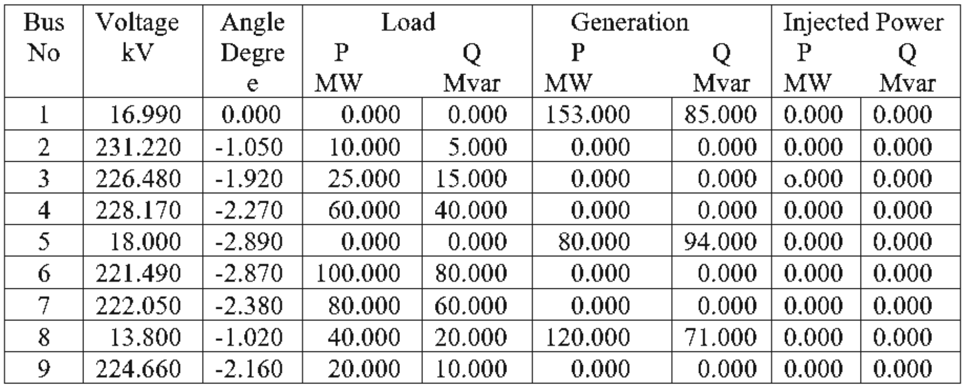
Fig. 3 Base case simulation for the injection at bus 6 of P = 0.000 MW, Q = 0.000 MVar

The total real power generation, 353.41MW, takes into account the real power supplied by each generator at buses one, five and eight, while the total reactive power, 249.56MVar, accounts for the sum of reactive power supplied by these same generators. The total real power loss of 8.41MW accounts for the difference in the total real power (353.41MW) supplied by each of the three generators and sum of real power values taken away by the load at buses two through nine. Similarly, the total reactive power loss of 14.56 MVar is the difference between the total reactive power (249.56MVar) supplied by the three generators and sum of reactive power values supplied by the load at buses two through nine.

Table 1 shows the bus voltages, angles, and power measurements for the base case system model. These are the baseline values that cases one through six will be compared to determine the effect of injecting varying increments of real power at bus 6 via the addition of a renewable distributed generation. Of the non-generator buses, bus six having the lowest voltage and highest reactive power makes it critical; this is where the real and reactive power from the renewable generation will be inserted to analyze the impact of real versus reactive power injection.

TABLE I

SIMULATION RESULT FOR THE BASE CASE



Bus No	Voltage kV	Angle Degree	Load		Generation		Injected Power	
			P MW	Q Mvar	P MW	Q Mvar	P MW	Q Mvar
1	16.990	0.000	0.000	0.000	153.000	85.000	0.000	0.000
2	231.220	-1.050	10.000	5.000	0.000	0.000	0.000	0.000
3	226.480	-1.920	25.000	15.000	0.000	0.000	o.000	0.000
4	228.170	-2.270	60.000	40.000	0.000	0.000	0.000	0.000
5	18.000	-2.890	0.000	0.000	80.000	94.000	0.000	0.000
6	221.490	-2.870	100.000	80.000	0.000	0.000	0.000	0.000
7	222.050	-2.380	80.000	60.000	0.000	0.000	0.000	0.000
8	13.800	-1.020	40.000	20.000	120.000	71.000	0.000	0.000
9	224.660	-2.160	20.000	10.000	0.000	0.000	0.000	0.000

Table 2 lists the real and reactive power flowing through the transmission lines, along with the line losses derived from the difference between the respective sending versus receiving real power and reactive power on each line.

TABLE II

RESULT OF LINE FLOW AND LOSSES FOR THE BASE CASE

From Bus	To Bus	Sending End		Receiving End		Line Losses	
		P MW	Q Mvar	P MW	Q Mvar	P MW	Q Mvar
1	2	45.8338	31.9317	45.3018	-30.8018	0.5320	1.1300
1	4	107.5723	52.5996	105.5420	-46.8972	2.0303	5.7024
2	3	35.3018	25.8018	34.9613	-24.7423	0.3405	1.0594
3	9	9.9613	9.7423	9.9212	-9.6222	0.0400	0.1201
4	5	19.6023	-28.9851	19.4417	29.1322	0.1606	0.1471
4	6	25.9397	35.8823	25.5413	-34.5676	0.3984	1.3147
5	6	49.0295	25.1511	47.2034	-24.5079	1.8261	0.6432
5	7	40.2122	34.4037	38.7163	-33.8262	1.6958	0.5774
8	7	42.1040	28.1221	41.2837	-26.1738	0.8204	1.9483
8	9	37.8960	23.2230	37.4614	-21.9389	1.2840	0.4346
9	6	27.3826	21.5611	27.2553	-20.9245	0.1273	0.6366

4.2 Simulation of Case 1 for Injection at Bus 6 of P = 25 MW, Q = 0 MVar

Fig. 4 represents case one, where 25MW was injected into bus 6, resulting in a lesser value of 75MW being taken from the bus by the load.

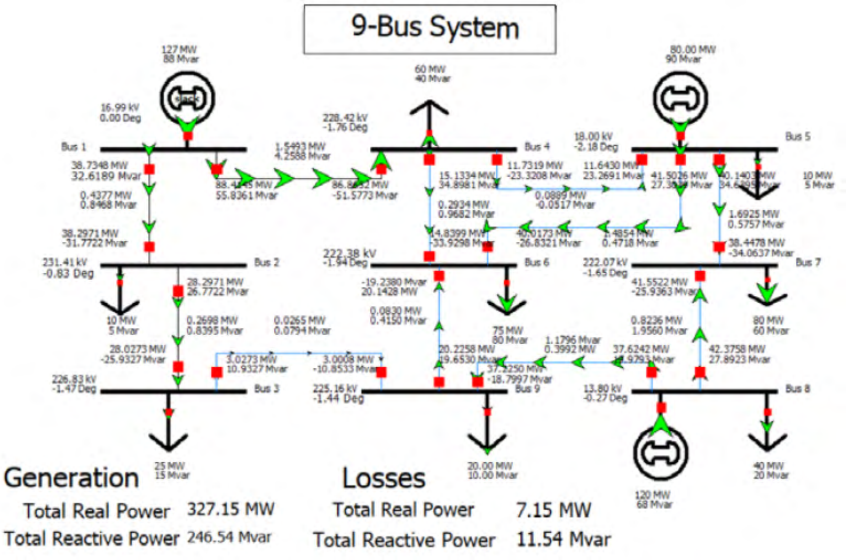
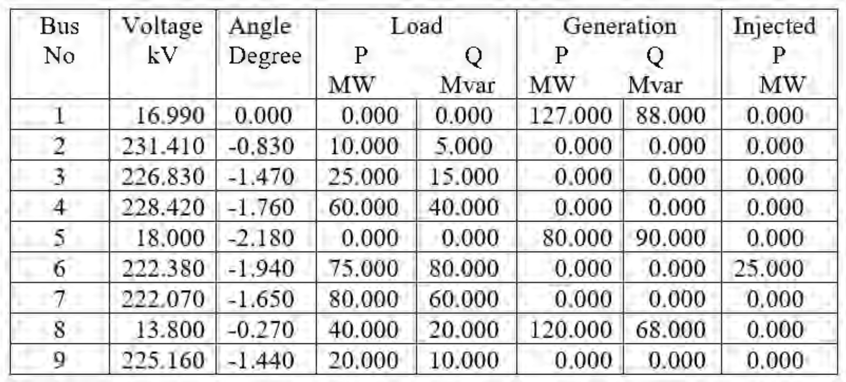


Fig. 4 Simulation of case 1 for injection at bus 6 of P = 25 MW, Q = 0 MVar

TABLE III

SIMULATION RESULT FOR CASE 1

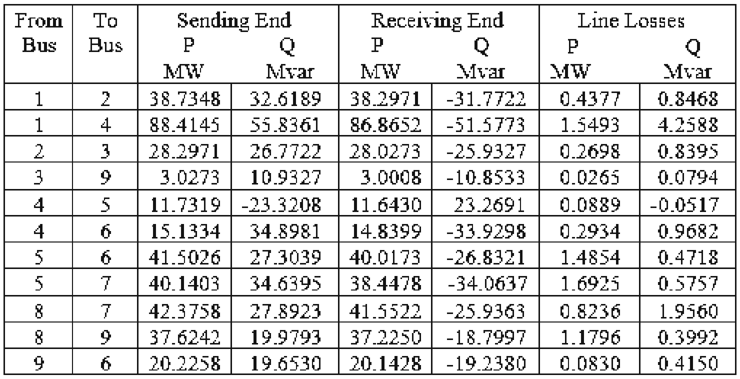


Bus No	Voltage kV	Angle Degree	Load P MW	Load Q Mvar	Generation P MW	Generation Q Mvar	Injected P MW
1	16.990	0.000	0.000	0.000	127.000	88.000	0.000
2	231.410	-0.830	10.000	5.000	0.000	0.000	0.000
3	226.830	-1.470	25.000	15.000	0.000	0.000	0.000
4	228.420	-1.760	60.000	40.000	0.000	0.000	0.000
5	18.000	-2.180	0.000	0.000	80.000	90.000	0.000
6	222.380	-1.940	75.000	80.000	0.000	0.000	25.000
7	222.070	-1.650	80.000	60.000	0.000	0.000	0.000
8	13.800	-0.270	40.000	20.000	120.000	68.000	0.000
9	225.160	-1.440	20.000	10.000	0.000	0.000	0.000

Table 4 shows the line losses for each transmission line. Comparing the baseline line values from table 2 to table 4, it is evident that there was a reduction in the line losses per transmission line. There was less than half a percent increase in the reactive power loss on the transmission line from bus eight to bus seven; however, the total overall real and reactive power losses were improved by 14.98% and 20.74%, respectively, from 8.41MW and 14.56MVAR to 7.15MW and 11.54MVAR. The total line losses at bus 6 decreased by about 0.490 MW and about 0.740 MVAR compared to the base case resulting in a 0.40% kV increase in at bus 6.

TABLE IV

SIMULATION RESULT OF LINE FLOW AND LOSSES FOR CASE 1



From Bus	To Bus	Sending End P MW	Sending End Q Mvar	Receiving End P MW	Receiving End Q Mvar	Line Losses P MW	Line Losses Q Mvar
1	2	38.7348	32.6189	38.2971	-31.7722	0.4377	0.8468
1	4	88.4145	55.8361	86.8652	-51.5773	1.5493	4.2588
2	3	28.2971	26.7722	28.0273	-25.9327	0.2698	0.8395
3	9	3.0273	10.9327	3.0008	-10.8533	0.0265	0.0794
4	5	11.7319	-23.3208	11.6430	23.2691	0.0889	-0.0517
4	6	15.1334	34.8981	14.8399	-33.9298	0.2934	0.9682
5	6	41.5026	27.3039	40.0173	-26.8321	1.4854	0.4718
5	7	40.1403	34.6395	38.4478	-34.0637	1.6925	0.5757
8	7	42.3758	27.8923	41.5522	-25.9363	0.8236	1.9560
8	9	37.6242	19.9793	37.2250	-18.7997	1.1796	0.3992
9	6	20.2258	19.6530	20.1428	-19.2380	0.0830	0.4150

4.3 Simulation of Case 2 for Injection at Bus 6 of P = 50 MW, Q = 0 MVar

Fig. 5 represents case two, where 50MW was injected into bus 6, resulting in a lesser value of 50MW being taken from the bus by the load. In other words, the renewable distributed generation was able to supply an additional 50MW to the bus and load lines tied to that bus.

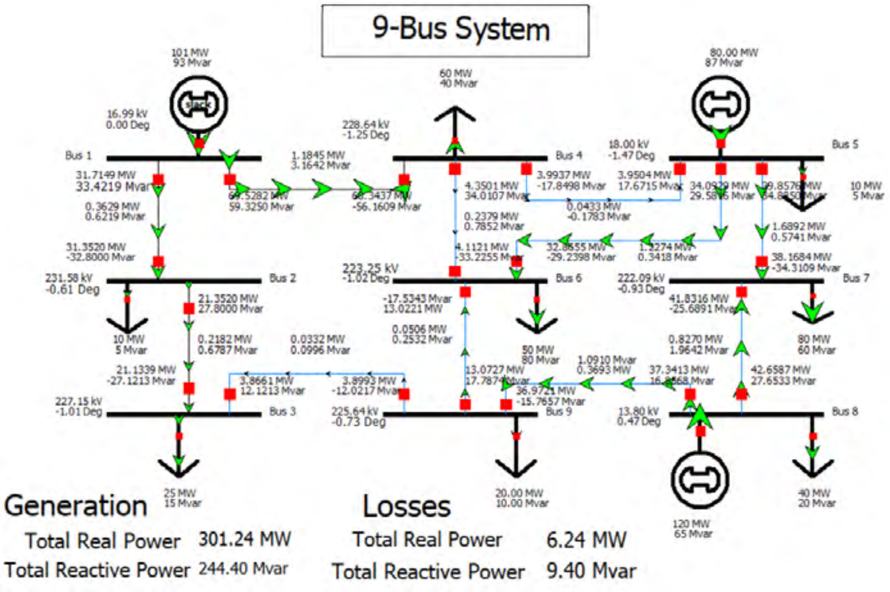


Fig. 5 Simulation of case 2 for injection at bus 6 of P = 50 MW, Q = 0 MVar

TABLE V

SIMULATION RESULT FOR CASE 2

Bus No	Voltage kV	Angle Degree	Load P MW	Load Q Mvar	Generation P MW	Generation Q Mvar	Injected P MW
1	16.990	0.000	0.000	0.000	101.000	93.000	0.000
2	231.580	-0.610	10.000	5.000	0.000	0.000	0.000
3	227.150	-1.010	25.000	15.000	0.000	0.000	0.000
4	228.640	-1.250	60.000	40.000	0.000	0.000	0.000
5	18.000	-1.470	0.000	0.000	80.000	87.000	0.000
6	223.250	-1.020	50.000	80.000	0.000	0.000	50.000
7	222.090	-0.930	80.000	60.000	0.000	0.000	0.000
8	13.800	0.470	40.000	20.000	120.000	65.000	0.000
9	225.640	-0.730	20.000	10.000	0.000	0.000	0.000

Table 6 shows the line losses for each transmission line after the injection of 50MW into bus 6. Comparing the baseline line values from Table 2 to Table 6, there are increases in the real power losses from lines three to nine, four to five and eight to seven, and reactive power losses from lines three to nine, four to five, eight to seven and eight to nine. Overall, the total real and reactive power losses were improved by 25.80% and 35.44%, respectively, from 8.41MW and 14.56MVAR to 6.24MW and 9.4MVAR. With this iteration, the total line losses at bus 6 decreased by approximately 0.836 MW and approximately 1.214 MVAR, leading to a 0.79% kV increase at bus 6.

TABLE VI

SIMULATION RESULT OF LINE FLOW AND LOSSES FOR CASE 2

From Bus	To Bus	Sending End P MW	Sending End Q Mvar	Receiving End P MW	Receiving End Q Mvar	Line Losses P MW	Line Losses Q Mvar
1	2	31.7149	33.4219	31.3520	-32.8000	0.3629	0.6219
1	4	69.5282	59.3250	68.3437	-56.1609	1.1845	3.1642
2	3	21.3520	27.8000	21.1339	-27.1213	0.2182	0.6787
3	9	3.8993	-12.0217	3.8661	12.1213	0.0332	0.0996
4	5	3.9937	-17.8498	3.9504	17.6715	0.0433	-0.1783
4	6	4.3501	34.0107	4.1121	33.2255	0.2379	0.7852
5	6	34.0929	29.5816	32.8655	-29.2398	1.2274	0.3418
5	7	39.8576	34.8850	38.1684	-34.3109	1.6892	0.5741
8	7	42.6587	27.6533	41.8316	-25.6891	0.8270	1.9642
8	9	37.3413	16.8568	36.9721	-15.7657	0.3693	1.0910
9	6	13.0727	17.7874	13.0221	-17.5343	0.0506	0.2532

4.4 Simulation of Case 3 for Injection at Bus 6 of P = 0.0 MW, Q = 10.0 MVar

Fig. 6 represents case three, where 10MVar was injected into bus 6, reducing the reactive power supplied by the load attached to bus 6.

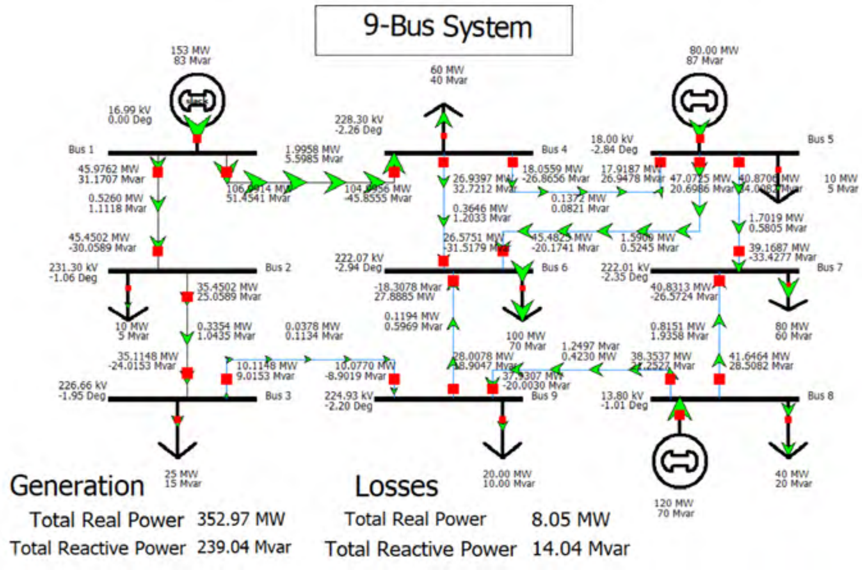
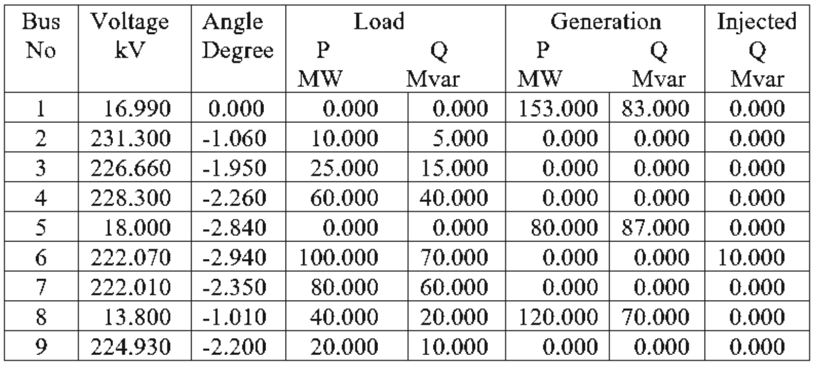


Fig. 6 Simulation of case 3 for injection at bus 6 of P = 0.0 MW, Q = 10.0 MVar

TABLE VII

SIMULATION RESULT FOR CASE 3

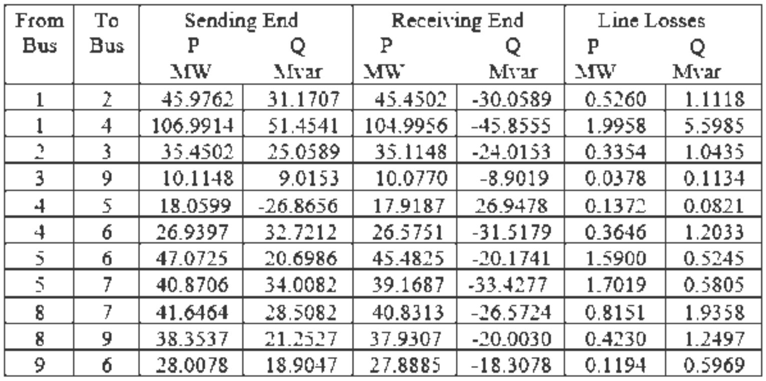


Bus No	Voltage kV	Angle Degree	Load P MW	Load Q Mvar	Generation P MW	Generation Q Mvar	Injected Q Mvar
1	16.990	0.000	0.000	0.000	153.000	83.000	0.000
2	231.300	-1.060	10.000	5.000	0.000	0.000	0.000
3	226.660	-1.950	25.000	15.000	0.000	0.000	0.000
4	228.300	-2.260	60.000	40.000	0.000	0.000	0.000
5	18.000	-2.840	0.000	0.000	80.000	87.000	0.000
6	222.070	-2.940	100.000	70.000	0.000	0.000	10.000
7	222.010	-2.350	80.000	60.000	0.000	0.000	0.000
8	13.800	-1.010	40.000	20.000	120.000	70.000	0.000
9	224.930	-2.200	20.000	10.000	0.000	0.000	0.000

Table 8 shows the line losses for each transmission line after the injection of 10MVar into bus 6. There was an increase in the reactive line losses from lines five to seven and lines eight to nine, only. Overall, the total real and reactive power losses were improved by 4.28% and 3.57%, respectively, from 8.41MW and 14.56MVAR to 8.05MW and 14.04MVAR. For case 3, the total line losses at bus 6 decreased by approximately 0.278 MW and approximately 0.270 MVAR, resulting in a 0.26% kV increase in the bus voltage.

TABLE VIII

SIMULATION RESULT OF LINE FLOWS AND LOSSES FOR CASE 3



From Bus	To Bus	Sending End P MW	Sending End Q Mvar	Receiving End P MW	Receiving End Q Mvar	Line Losses P MW	Line Losses Q Mvar
1	2	45.9762	31.1707	45.4502	-30.0589	0.5260	1.1118
1	4	106.9914	51.4541	104.9956	-45.8555	1.9958	5.5985
2	3	35.4502	25.0589	35.1148	-24.0153	0.3354	1.0435
3	9	10.1148	9.0153	10.0770	-8.9019	0.0378	0.1134
4	5	18.0599	-26.8656	17.9187	26.9478	0.1372	0.0821
4	6	26.9397	32.7212	26.5751	-31.5179	0.3646	1.2033
5	6	47.0725	20.6986	45.4825	-20.1741	1.5900	0.5245
5	7	40.8706	34.0082	39.1687	-33.4277	1.7019	0.5805
8	7	41.6464	28.5082	40.8313	-26.5724	0.8151	1.9358
8	9	38.3537	21.2527	37.9307	-20.0030	0.4230	1.2497
9	6	28.0078	18.9047	27.8885	-18.3078	0.1194	0.5969

4.5 Simulation of Case 4 for Injection at Bus 6 of P = 0.0 MW, Q =30.0 MVar

Fig. 7 represents case four, where 30MVar was injected into bus 6, reducing the reactive power supplied by the load attached to bus 6.

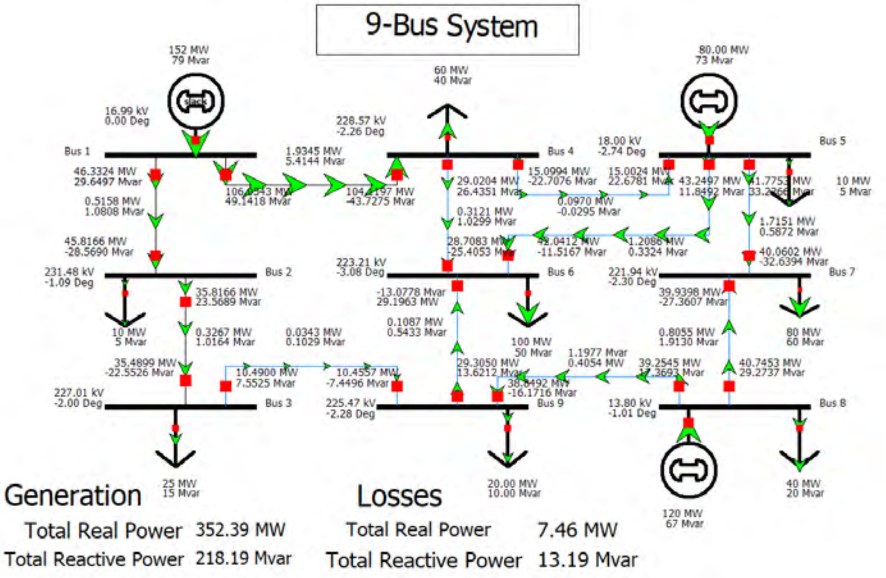
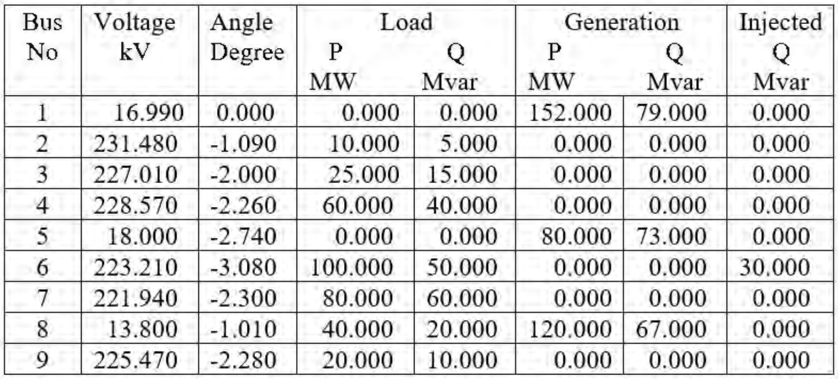


Fig. 7 Simulation of case 4 for injection at bus 6 of P = 0.0 MW, Q =30.0 MVar

TABLE IX

SIMULATION RESULT FOR CASE 4

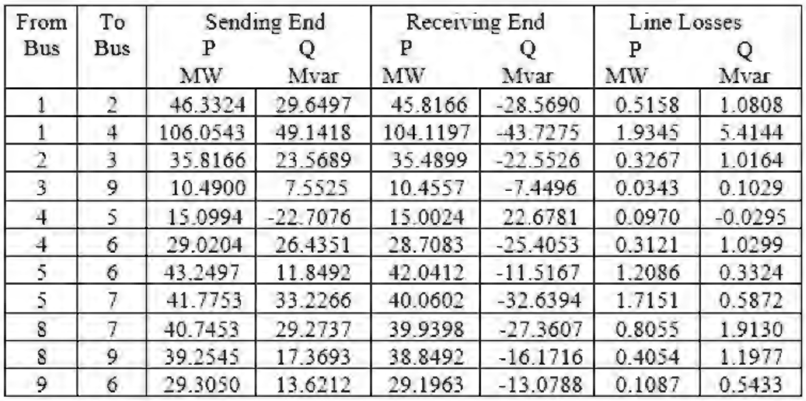


Bus No	Voltage kV	Angle Degree	Load		Generation		Injected
			P MW	Q Mvar	P MW	Q Mvar	Q Mvar
1	16.990	0.000	0.000	0.000	152.000	79.000	0.000
2	231.480	-1.090	10.000	5.000	0.000	0.000	0.000
3	227.010	-2.000	25.000	15.000	0.000	0.000	0.000
4	228.570	-2.260	60.000	40.000	0.000	0.000	0.000
5	18.000	-2.740	0.000	0.000	80.000	73.000	0.000
6	223.210	-3.080	100.000	50.000	0.000	0.000	30.000
7	221.940	-2.300	80.000	60.000	0.000	0.000	0.000
8	13.800	-1.010	40.000	20.000	120.000	67.000	0.000
9	225.470	-2.280	20.000	10.000	0.000	0.000	0.000

Table 10 shows the line losses for each transmission line after the injection of 30MVar into bus 6. There was an increase in the real and reactive line losses from lines five to seven, only. Overall, the total real and reactive power losses were improved by 11.30% and 9.41%, respectively, from 8.41MW and 14.56MVAR to 7.46MW and 13.19MVAR. In this iteration, the accumulated line losses at bus 6 were reduced by about 0.772 MW and approximately 0.689 MVAR, resulting in a 0.78% KV increase in the bus voltage.

TABLE X

SIMULATION RESULT OF LINE FLOWS AND LOSSES FOR CASE 4



From Bus	To Bus	Sending End		Receiving End		Line Losses	
		P MW	Q Mvar	P MW	Q Mvar	P MW	Q Mvar
1	2	46.3324	29.6497	45.8166	-28.5690	0.5158	1.0808
1	4	106.0543	49.1418	104.1197	-43.7275	1.9345	5.4144
2	3	35.8166	23.5689	35.4899	-22.5526	0.3267	1.0164
3	9	10.4900	7.5525	10.4557	-7.4496	0.0343	0.1029
4	5	15.0994	-22.7076	15.0024	22.6781	0.0970	-0.0295
4	6	29.0204	26.4351	28.7083	-25.4053	0.3121	1.0299
5	6	43.2497	11.8492	42.0412	-11.5167	1.2086	0.3324
5	7	41.7753	33.2266	40.0602	-32.6394	1.7151	0.5872
8	7	40.7453	29.2737	39.9398	-27.3607	0.8055	1.9130
8	9	39.2545	17.3693	38.8492	-16.1716	0.4054	1.1977
9	6	29.3050	13.6212	29.1963	-13.0788	0.1087	0.5433

4.6 Simulation of Case 5 for Injection at Bus 6 of P = 0.0 MW, Q = 50.0 MVar

Fig. 8 represents case five, where 50MVar was injected into bus 6, reducing the reactive power supplied by the load attached to bus 6.

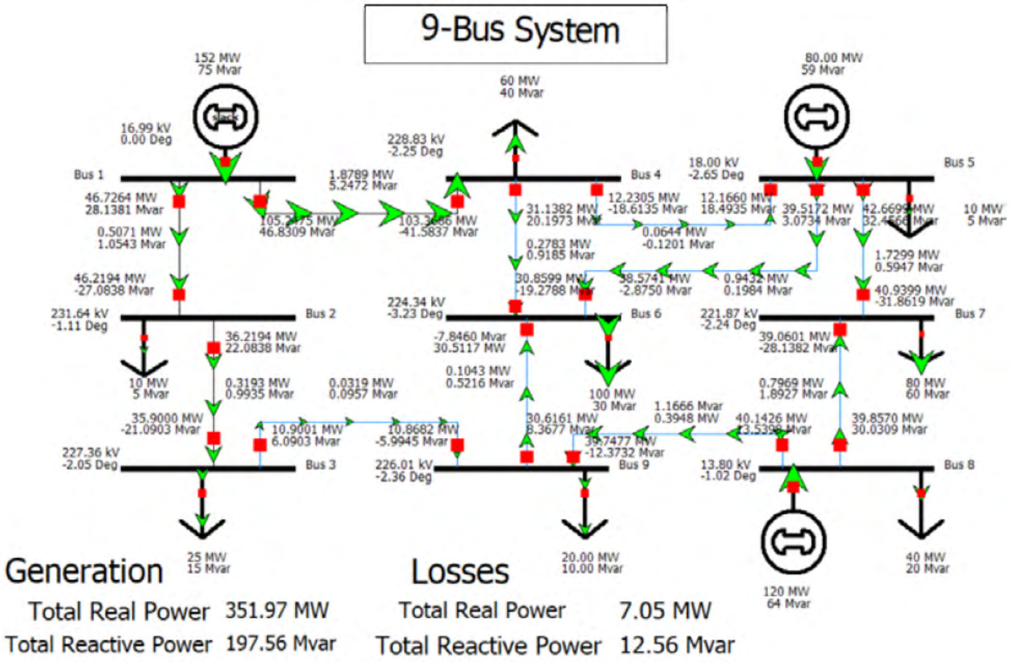


Fig. 8 Simulation of case 5 for injection at bus 6 of P = 0.0 MW, Q = 50.0 MVar

TABLE XI

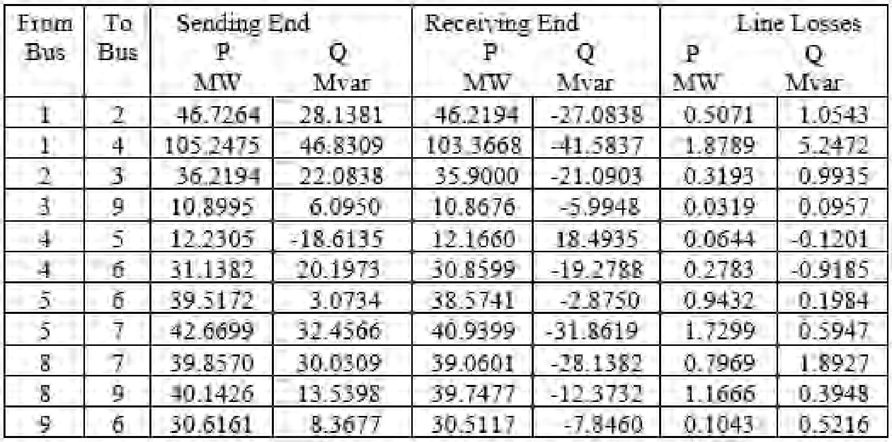
SIMULATION RESULT FOR CASE 5

Bus No	Voltage kV	Angle Degree	Load P MW	Load Q Mvar	Generation P MW	Generation Q Mvar	Injected Q Mvar
1	16.990	0.000	0.000	0.000	152.000	75.000	0.000
2	231.640	-1.110	10.000	5.000	0.000	0.000	0.000
3	227.360	-2.050	25.000	15.000	0.000	0.000	0.000
4	228.830	-2.250	60.000	40.000	0.000	0.000	0.000
5	18.000	-2.650	0.000	0.000	80.000	59.000	0.000
6	224.340	-3.230	100.000	30.000	0.000	0.000	50.000
7	221.870	-2.240	80.000	60.000	0.000	0.000	0.000
8	13.800	-1.020	40.000	20.000	120.000	64.000	0.000
9	226.010	-2.360	20.000	10.000	0.000	0.000	0.000

Table 12 enumerates the line losses for each transmission line after the injection of 50MVar into bus 6. There was an increase in the real and reactive line losses from lines five to seven, only. Overall, the total real and reactive power losses were improved by 16.17% and 13.74%, respectively, from 8.41MW and 14.56MVAR to 7.05MW and 12.56MVAR. With case 5, there is a reduction in the total line losses by 1.026MW and 2.793MVAR, resulting in a 1.29% kV increase in bus voltage.

TABLE XII

SIMULATION RESULT OF LINE FLOWS AND LOSSES FOR CASE 5



From Bus	To Bus	Sending End P MW	Sending End Q Mvar	Receiving End P MW	Receiving End Q Mvar	Line Losses P MW	Line Losses Q Mvar
1	2	46.7264	28.1381	46.2194	-27.0838	0.5071	1.0543
1	4	105.2475	46.8309	103.3668	-41.5837	1.8789	5.2472
2	3	36.2194	22.0838	35.9000	-21.0903	0.3193	0.9935
3	9	10.8995	6.0950	10.8676	-5.9948	0.0319	0.0957
4	5	12.2305	-18.6135	12.1660	18.4935	0.0644	-0.1201
4	6	31.1382	20.1973	30.8599	-19.2788	0.2783	-0.9185
5	6	39.5172	3.0734	38.5741	-2.8750	0.9432	0.1984
5	7	42.6699	32.4566	40.9399	-31.8619	1.7299	0.5947
8	7	39.8570	30.0309	39.0601	-28.1382	0.7969	1.8927
8	9	40.1426	13.5398	39.7477	-12.3732	1.1666	0.3948
9	6	30.6161	8.3677	30.5117	-7.8460	0.1043	0.5216

4.7 Simulation of Case 6 for Injection at Bus 6 Of P = 0.0 MW, Q =70. 0 MVar

Fig. 9 exemplifies case five, where 70MVar was injected into bus 6, reducing the reactive power supplied by the load attached to bus 6.

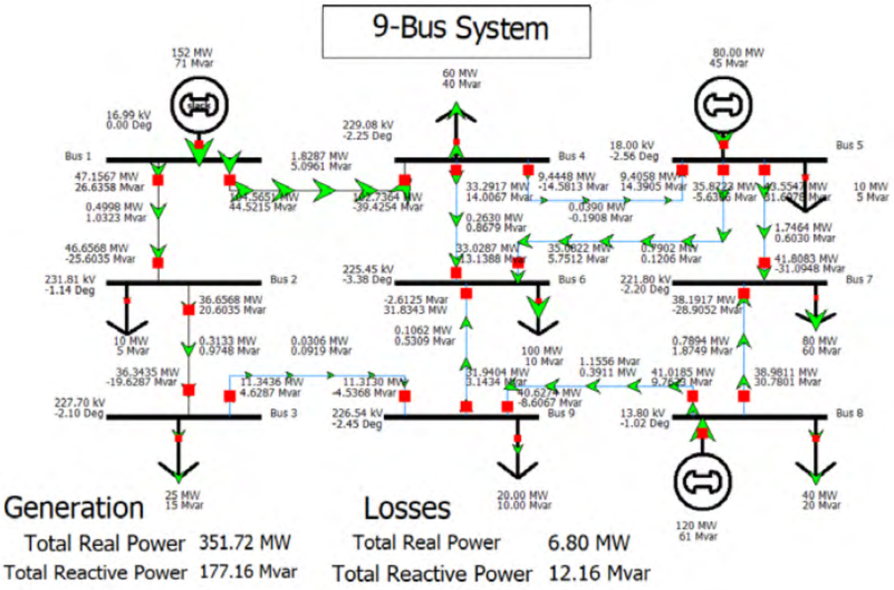


Fig. 9 Simulation of case 6 for injection at bus 6 of P = 0.0 MW, Q =70. 0 MVar

TABLE XIII

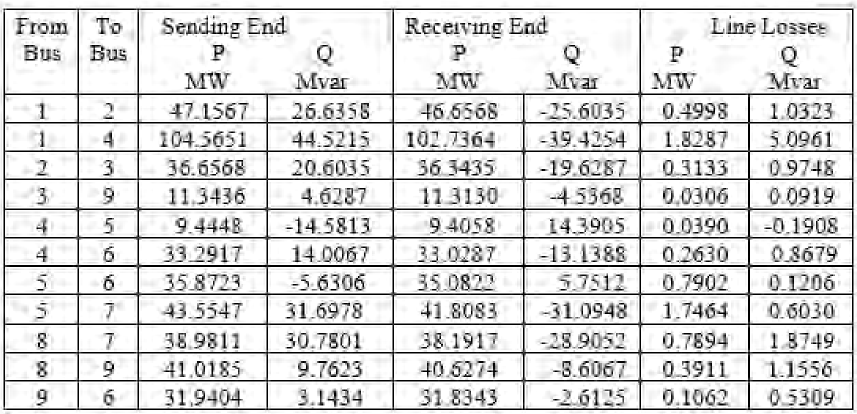
SIMULATION RESULT FOR CASE 6

Bus No	Voltage kV	Angle Degree	Load P MW	Load Q Mvar	Generation P MW	Generation Q Mvar	Injected Q Mvar
1	16.990	0.000	0.000	0.000	152.000	71.000	0.000
2	231.810	-1.140	10.000	5.000	0.000	0.000	0.000
3	227.700	-2.100	25.000	15.000	0.000	0.000	0.000
4	229.080	-2.250	60.000	40.000	0.000	0.000	0.000
5	18.000	-2.560	0.000	0.000	80.000	45.000	0.000
6	225.450	-3.380	100.000	10.000	0.000	0.000	70.000
7	221.800	-2.200	80.000	60.000	0.000	0.000	0.000
8	13.800	-1.020	40.000	20.000	120.000	61.000	0.000
9	226.540	-2.450	20.000	10.000	0.000	0.000	0.000

Table 14 lists the line losses for each transmission line after the injection of 70MVar into bus 6. Again, there was an increase in the real and reactive line losses from lines five to seven. The load flow from line eight to nine underwent an increase in reactive power losses. Overall, the total real and reactive power losses were improved by 19.14% and 16.48%, respectively, from 8.41MW and 14.56MVAR to 6.8MW and 12.16MVAR. Case 6 showed about 1.192 MW and approximately 1.075 MVAR decrease in the line losses at bus 6, with a 1.79% kV bus voltage increase.

TABLE XIV

SIMULATION RESULT OF LINE FLOWS AND LOSSES FOR CASE 6



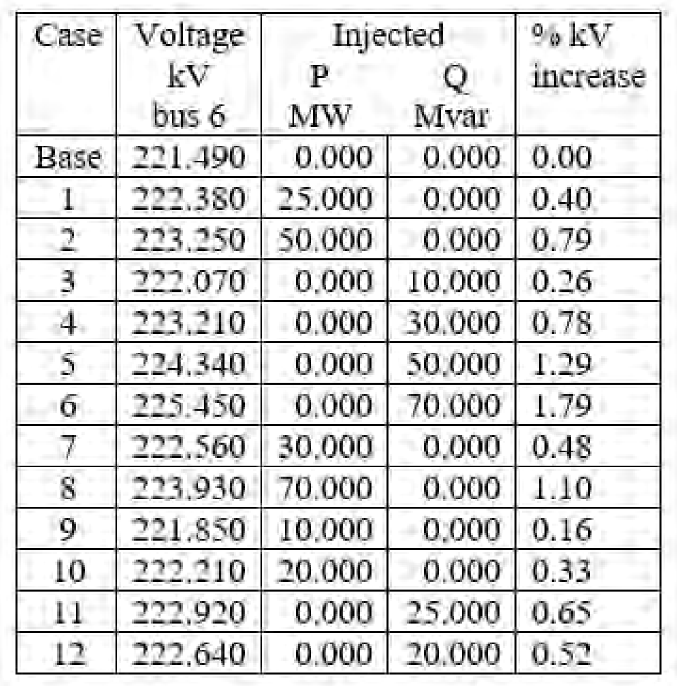
From Bus	To Bus	Sending End		Receiving End		Line Losses	
		P MW	Q Mvar	P MW	Q Mvar	P MW	Q Mvar
1	2	47.1567	26.6358	46.6568	-25.6035	0.4998	1.0323
1	4	104.5651	44.5215	102.7364	-39.4254	1.8287	5.0961
2	3	36.6568	20.6035	36.3435	-19.6287	0.3133	0.9748
3	9	11.3436	4.6287	11.3130	-4.5368	0.0306	0.0919
4	5	9.4448	-14.5813	9.4058	14.3905	0.0390	-0.1908
4	6	33.2917	14.0067	33.0287	-13.1388	0.2630	0.8679
5	6	35.8723	-5.6306	35.0822	5.7512	0.7902	0.1206
5	7	43.5547	31.6978	41.8083	-31.0948	1.7464	0.6030
8	7	38.9811	30.7801	38.1917	-28.9052	0.7894	1.8749
8	9	41.0185	9.7623	40.6274	-8.6067	0.3911	1.1556
9	6	31.9404	3.1434	31.8343	-2.6125	0.1062	0.5309

4.8 Percentage Increase in Bus 6 Voltage Relative to the Base Case Voltage

Table 15 presents the mitigation of congestion from the perspective of the voltage profile at each bus. This is evidence of the relationship between the voltage and reactive power; whenever the voltage increases, reactive power is reduced. The bus voltages were calculated for cases 7 through 12 by switching the P and Q injected values from cases 1-6 for the purpose of comparison between the impact of injecting a full range of real vs reactive powers at the critical bus.

TABLE XV

RESULT FOR PERCENTAGE INCREASE IN VOLTAGE AT BUS 6 RELATIVE TO THE BASE CASE RUN



Case	Voltage kV bus 6	Injected P MW	Injected Q Mvar	% kV increase
Base	221.490	0.000	0.000	0.00
1	222.380	25.000	0.000	0.40
2	223.250	50.000	0.000	0.79
3	222.070	0.000	10.000	0.26
4	223.210	0.000	30.000	0.78
5	224.340	0.000	50.000	1.29
6	225.450	0.000	70.000	1.79
7	222.560	30.000	0.000	0.48
8	223.930	70.000	0.000	1.10
9	221.850	10.000	0.000	0.16
10	222.210	20.000	0.000	0.33
11	222.920	0.000	25.000	0.65
12	222.640	0.000	20.000	0.52

Fig. 10 depicts the rate at which increments of injected real and reactive powers produce a voltage increase at the buses in the network.

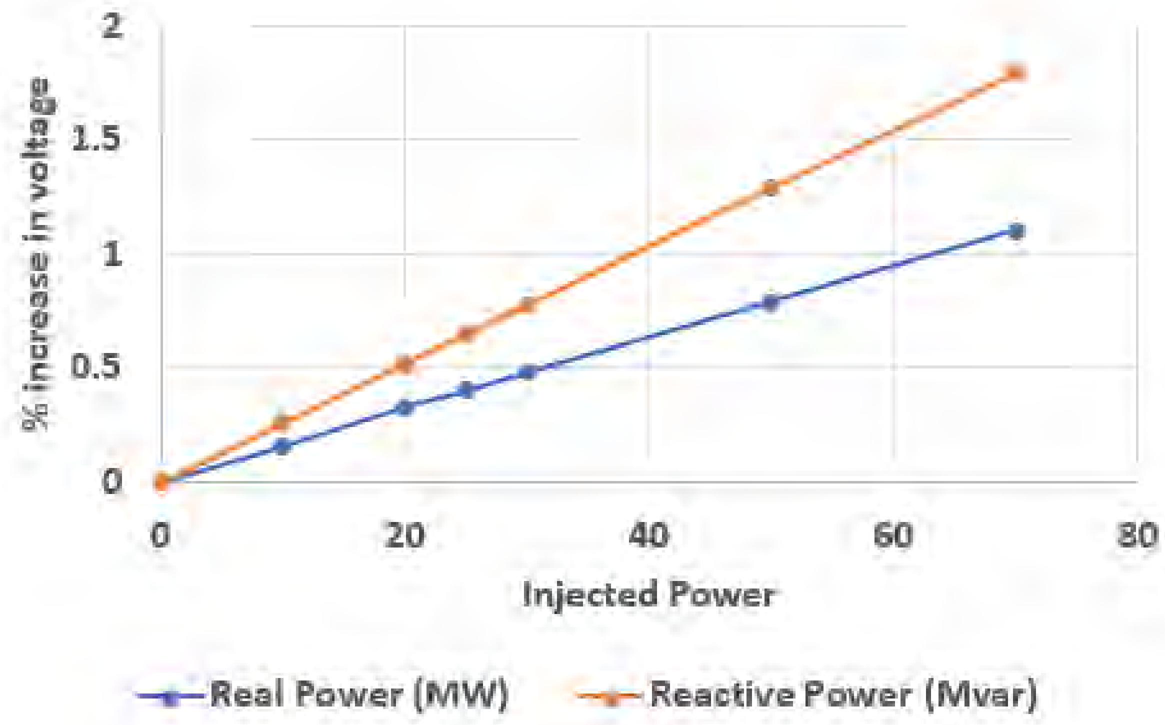


Fig. 10 Percentage increase in bus 6 voltage relative to the base case voltage as injected real and reactive powers increase.

5. CONCLUSION AND FUTURE WORK

A technique to identify a location to implement the mitigation of congested power distribution lines using load flow analysis and a PV system is presented. This procedure employs PowerWorld software simulations applied to a 9-bus IEEE power system, and the results show the impact of strategically placing renewable generation into a power system. Past works on decreasing transmission line congestion focused on the use of FACTS devices to improve voltage profiles and minimize power losses [2-5], PV systems for reactive power compensation [6], PV power by establishing bus and generator sensitivity factors to determine where to connect the PV system [7], and techniques on how renewable power generating systems can improve power grid operations [23]. This research simulated the load flows and line losses for each transmission line when real and reactive power was injected by the renewable generation. Most notably, the renewable generation should be placed at the critical bus which is where congestion is highest. This is demonstrated by the non-generator bus having the highest reactive power and lowest voltage in the network. The injection of different real and reactive power values into bus 6 resulted in lower real and reactive line losses for the entire system; however, the focus will remain on reducing line losses at critical bus 6 since this is the bus with the highest congestion or lowest bus voltage. Bus 6 having the highest congestion levels compared to the other buses means that it (i.e equipment/components, lines tied to bus 6) is at risk of being overloaded which could lead to potentially permanent damage to the lines, its components, and the equipment.

The results obtained in this work show that it is most impactful to inject higher amounts of reactive power at the critical bus to satisfy load demands. The injection of 70MVAR at bus 6 resulted in the most effective approach in reducing real and reactive power losses in the most balanced manner through the absorption of reactive power from the power network. This work exemplifies the impact of strategically placing renewable generation with different real and reactive power outputs in the power system network. The incremental injection of real and reactive power by the renewable generation supplemented real power while absorbing reactive power to effectively relieve power line congestion. Fig. 10 can be used to properly plan the amount of real and reactive power to be injected to achieve desired power flow levels.

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