World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(Review Article)

Alleviating power line congestion through the use of a renewable generation

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World Journal of Advanced Engineering Technology and Sciences, 2022, 07(02), 013–028

Publication history: Received on 26 September 2022; revised on 28 October 2022; accepted on 31 October 2022

Article DOI: https://doi.org/10.30574/wjaets.2022.7.2.0117

Abstract

Over the past few 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 are 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 because the source of energy, the sun, exists 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 paper 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: Power line congestion; Congestion management; Renewable energy generation; Transmission lines

1. Introduction

Electric power is an essential part of our lives; we use it to light up our homes, workplaces, and businesses, as well as power up the basic appliances and electronic devices we use every day. Currently, electric power demands are at an all-time high with very little additions to utilities infrastructure; this creates congestion on the existing distribution lines. Therefore, it is essential to improve on 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. Managing congestion is very critical to the healthy operation of the power transmission lines. There are two approaches to congestion mitigation, 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]. 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 the 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 being aggravated. This paper 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.

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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. The rest of the paper is organized as follows: Section 2 outlines the methodology employed in the technique; this is followed by the results and discussion, and finally, the conclusion is presented.

2. Methodology

2.1. Excessive Reactive Power Flow and Effect on Lines

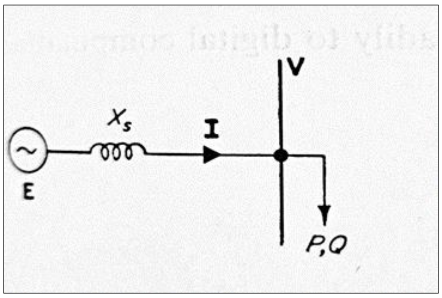

Figure 1 A line diagram of a power system

To determine the effect of excessive reactive power flow in the power grid, Figure 1 is considered; this figure is representative of a one-line diagram of a utility supplying a load through a short transmission line. The utility generates at a sending end-rated voltage of **E** volts. The transmission line has a reactance of **X**$_s$ Ohms and a negligible resistance, as is characteristic of most transmission lines. The P**, Q,** load at the end of the line is fed at **V** volts resulting in a current of **I** Amps flowing through the lines. Let us take the load voltage, **V,** as the reference voltage; so, **V**=V<0 and **E**=E<δ. Then,

$$E - V = jX_s\mathbf{I} \tag{1}$$

But $$V\mathbf{I}^* = P + JQ \tag{2}$$

And $$\mathbf{I} = (\mathrm{P} - \mathrm{jQ})/\mathrm{V} \tag{3}$$

Substituting (3) into (1) gives

$$E - V = (X_sQ + j(X_sP))/V \tag{4}$$

To examine the role Q plays in the system of Figure 1, let the load be purely reactive; P set equal to zero, implying $\delta^{\circ} = 0$ since P is EV sin δ [9] and E and V are non-zero. Also, let the sending end generator voltage, E, and X$_s$, the parameter of the line, be constant. Then rearranging (4),

$$V^2 - EV + X_sQ = 0 \tag{5}$$

Solving $$V = (E + (E^2 - 4X_sQ)^{1/2})/2 \tag{6}$$

Or $$V = (E - (E^2 - 4X_sQ)^{1/2})/2 \tag{7}$$

From (6) and (7), clearly, V drops in value as Q increases and line voltage drop (E-V) increases. During congestion, the transmission line becomes choked with reactive power demand. This causes a significant undesirable drop in the bus voltages. It, therefore, becomes crucial to mitigate the congestion to avoid system collapse. A possible method to mitigate the congestion is through the placement of voltage source inverters (VSI) incorporated PV system at the affected buses.

2.2. PV Power Systems with VSI in Congestion Mitigation Scheme

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 [10]. 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.

Figure 2 illustrates a PV system that incorporates a VSI tied to the grid to effect relief of congestion on the transmission lines [11]. Referring to Figure 1, active and reactive power transfer between the generator and load [9] can be expressed as in (8) and (9).

$$P = \left(\frac{EV}{X_s}\right) sin\delta \text{.................................} (8)$$

And

$$Q = \left(\frac{EV}{X_s}\right) cos\delta - \frac{V^2}{X_s} \text{..} (9)$$

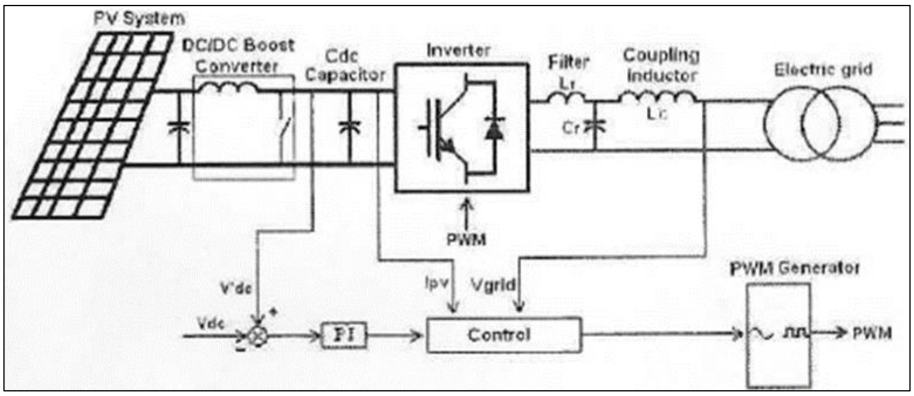

Figure 2 Power system and control of PV for electric grid [11]

2.3. Load Flow Calculations

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. The Newton-Raphson iterative method is mostly used since this method reaches a convergence with less iterations than the other methods. Thus, PowerWorld Simulator software was chosen to simulate the load flow on the IEEE 9-bus system presented in the methodology section of this paper, using the Newton-Raphson Method. Reference [12] gives a detailed presentation of the load flow problem.

Transmission line congestion takes into account the amount of real and reactive power flowing in and out of each bus. The goal is to have the generators be able to supply enough real and reactive power into the bus to compensate for the real and reactive power leaving the bus. In other words, when the line is overloaded or congested, reactive power increases, and the bus voltages drop, and there needs to be real power injected to mitigate the congestion. Unlike past models where the non-renewable energy plants were fixed, located at a great distance from the consumer of the electricity, the renewable energy generation can be positioned nearer to the consumer and bus. With this freedom to place the renewable energy source at more locations in the electric grid, all higher system efficiencies are achieved depending on where the renewable energy generation is placed. This paper presents a method of alleviating power line congestion by controlling power flows in the network, which in turn reduces the flows in heavily loaded lines [13].

2.4. Application of the Load Flow to Congestion: 9-Bus System Case Study

The simulation software, PowerWorld, is used to do the congestion study in this paper. 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 Figure 2 is then grid-connected at this bus. This base case load flow is indicated in Figure 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 paper 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 [10].

3. Results and discussion

The load flow results obtained in this work are shown in the figures and tables in the following pages starting with the base case in Figure 3, to identify congested lines, bus voltages, and line losses. The numerical data are also displayed on the figures, 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.

Figure 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 Figure 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 paper.

BASE CASE

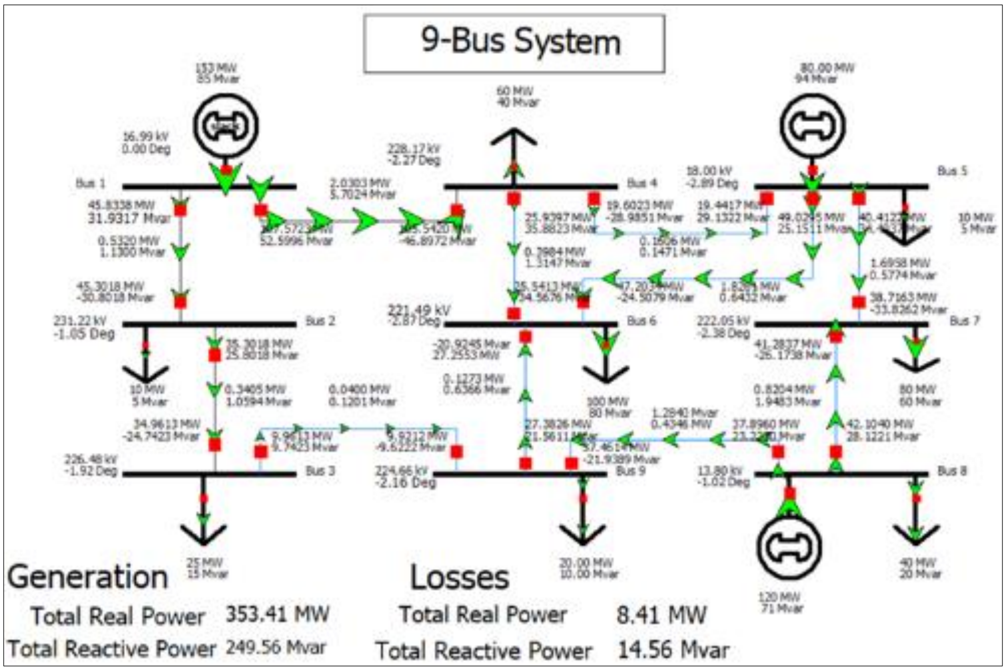

Figure 3 Base case simulation for the injection at bus 6 of P = 0.000 MW, Q = 0.000 MVAr

Table 1 Simulation result for the base case

Bus No	Voltage kV	Angle Degree	Load		Generation		Injected Power	
			P	Q	P	Q	P	Q
			MW	Mvar	MW	Mvar	MW	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	0.000	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 Result of line flow and losses for the base case

From Bus	To Bus	Sending End		Receiving End		Line Losses	
		P	Q	P	Q	P	Q
		MW	Mvar	MW	Mvar	MW	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

CASE 1

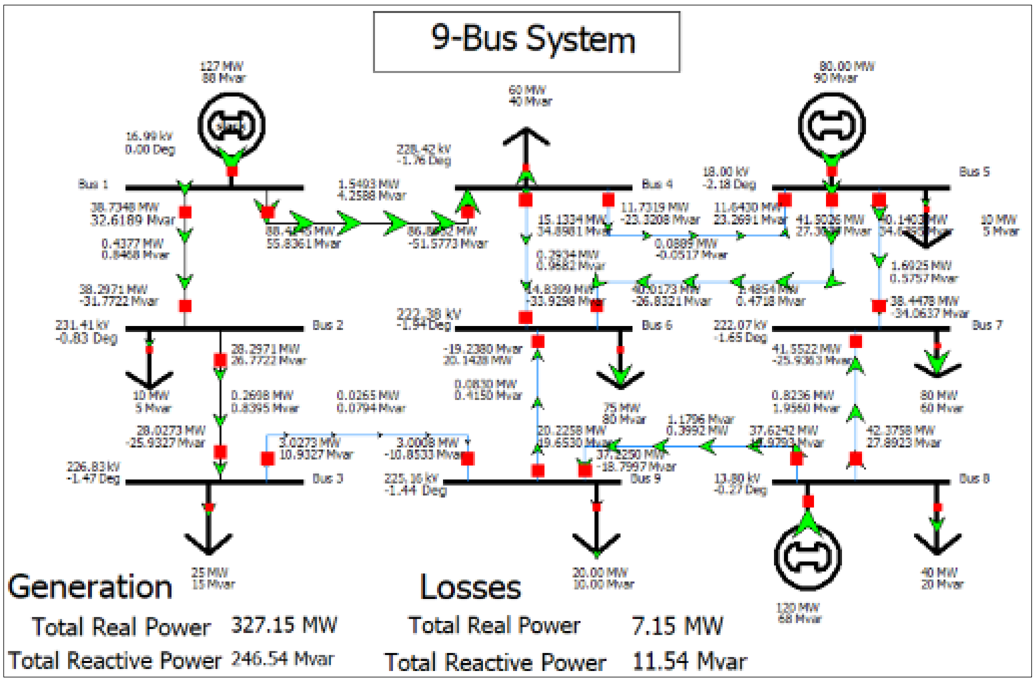

Figure 4 Simulation of case 1for injection at bus 6 of P = 25 MW, Q = 0 MVAr

Table 3 Simulation result for case 1

Bus No	**Voltage kV**	**Angle Degree**	**Load**		**Generation**		**Injected**
			P	**Q**	**P**	**Q**	**P**
			MW	**Mvar**	**MW**	**Mvar**	**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 Simulation result of line flow and losses for case 1

From Bus	To Bus	Sending End		Receiving End		Line Losses	
		P	Q	P	Q	P	Q
		MW	Mvar	MW	Mvar	MW	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

CASE 2

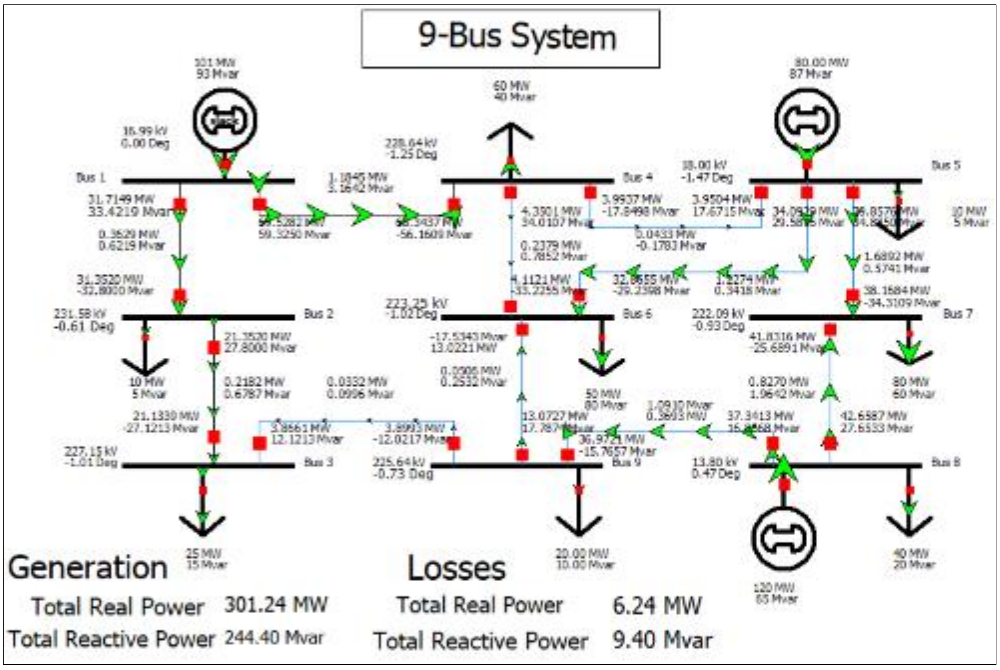

Figure 5 Simulation of case 2 for injection at bus 6 of P = 50 MW, Q = 0 MVAr

Table 5 Simulation result for case 2

Bus No	Voltage kV	Angle Degree	Load		Generation		Injected
			P	Q	P	Q	P
			MW	Mvar	MW	Mvar	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 Simulation result of line flow and losses for case 2

From Bus	To Bus	Sending End		Receiving End		Line Losses	
		P	Q	P	Q	P	Q
		MW	Mvar	MW	Mvar	MW	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

CASE 3

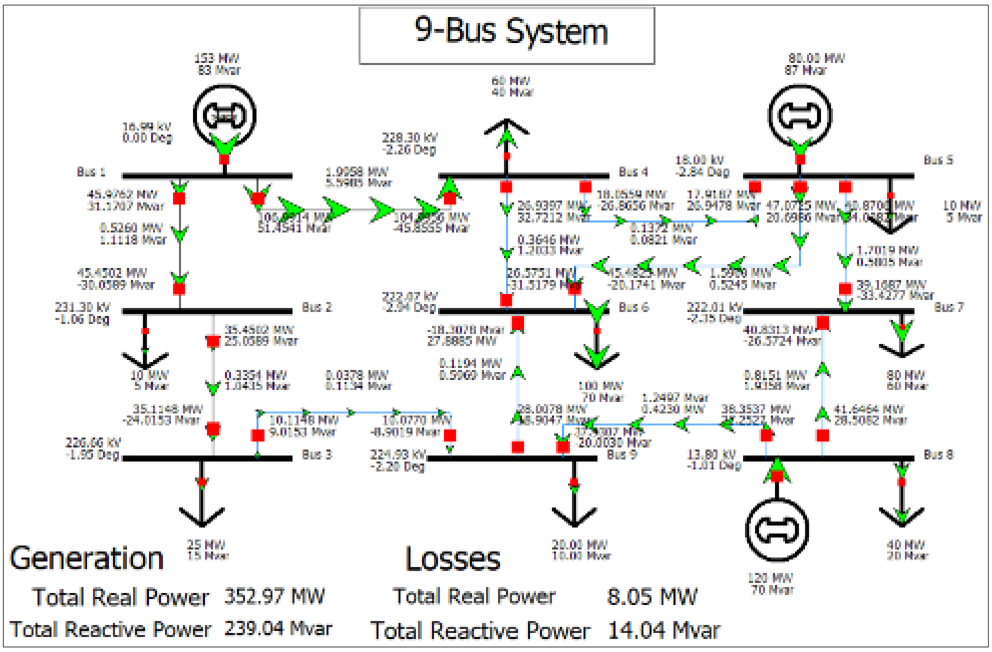

Figure 6 Simulation of case 3 for injection at bus 6 of P = 0.0 MW, Q = 10.0 MVAr

Table 7 Simulation result for case 3

Bus No	Voltage kV	Angle Degree	Load		Generation		Injected
			P	Q	P	Q	Q
			MW	Mvar	MW	Mvar	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 Simulation result of line flows and losses for case 3

From Bus	To Bus	Sending End		Receiving End		Line Losses	
		P	Q	P	Q	P	Q
		MW	Mvar	MW	Mvar	MW	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

CASE 4

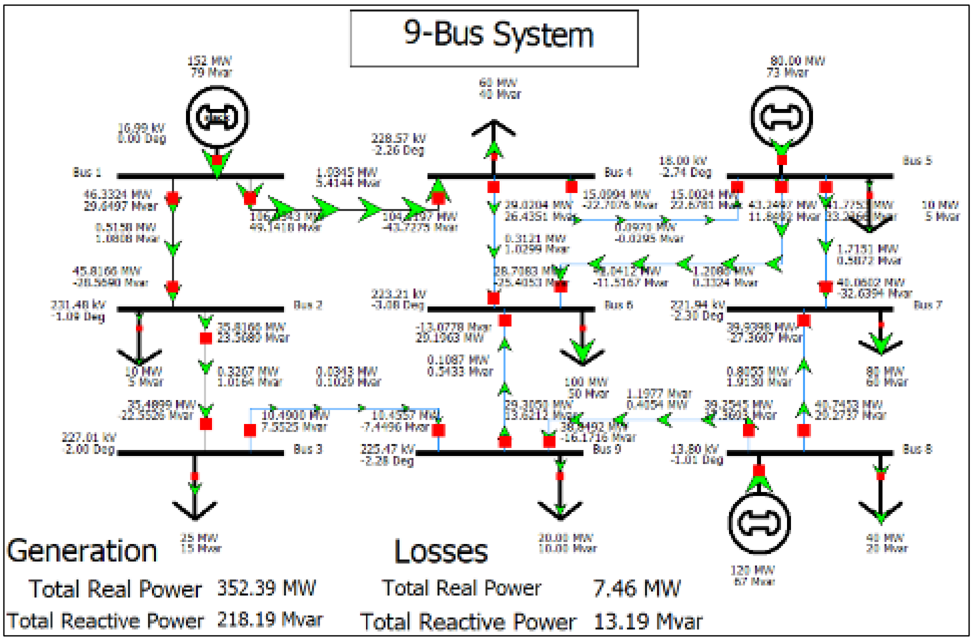

Figure 7 Simulation of case 4 for injection at bus 6 of P = 0.0 MW, Q =30.0 MVAr

Table 9 Simulation result for case 4

Bus No	Voltage kV	Angle Degree	Load		Generation		Injected
			P	Q	P	Q	Q
			MW	Mvar	MW	Mvar	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 Simulation result of line flows and losses for case 4

From Bus	To Bus	Sending End		Receiving End		Line Losses	
		P	Q	P	Q	P	Q
		MW	Mvar	MW	Mvar	Mvar	MW
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

CASE 5

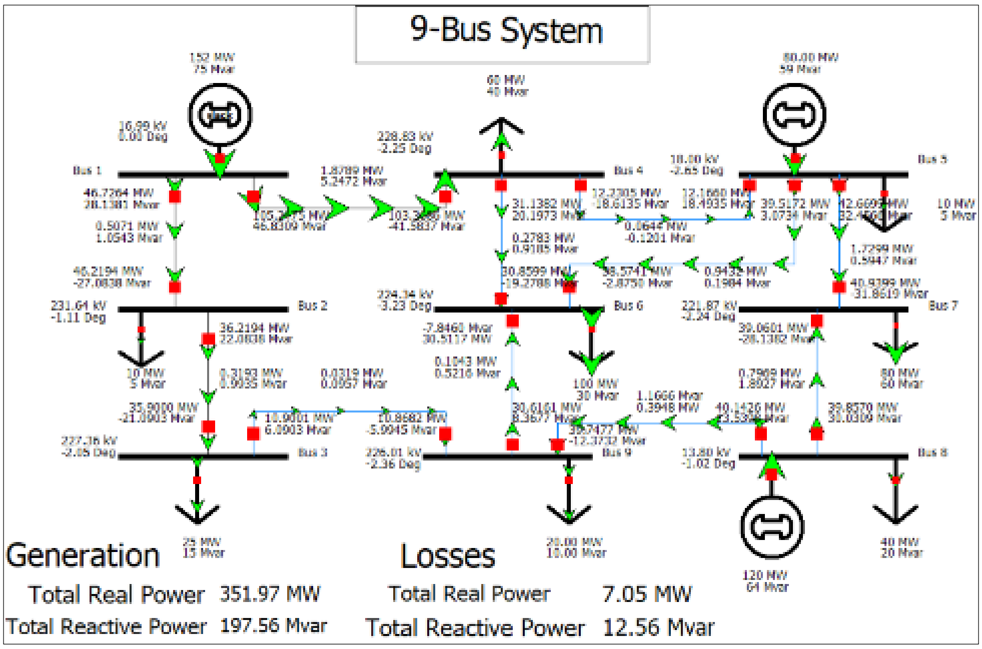

Figure 8 Simulation of case 5 for injection at bus 6 of P = 0.0 MW, Q = 50.0 MVAr

Table 11 Simulation result for case 5

Bus No	Voltage kV	Angle Degree	Load		Generation		Injected
			P	Q	P	Q	Q
			MW	Mvar	MW	Mvar	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 Simulation result of line flows and losses for case 5

From Bus	To Bus	Sending End		Receiving End		Line Losses	
		P	Q	P	Q	P	Q
		MW	Mvar	MW	Mvar	MW	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

CASE 6

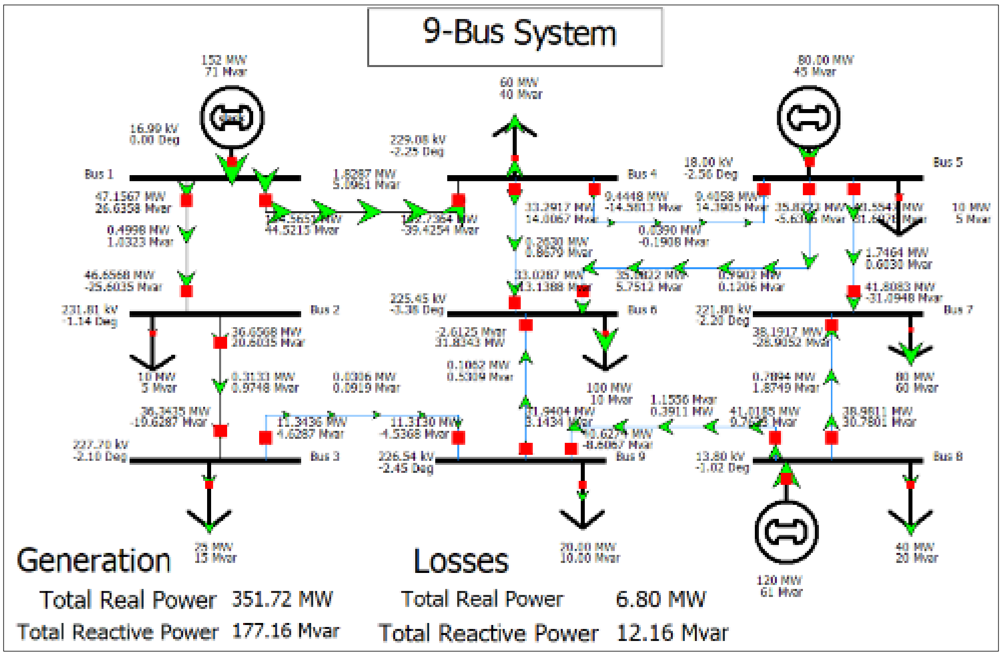

Figure 9 Simulation of case 6 for injection at bus 6 of P = 0.0 MW, Q =70. 0 MVAr

Table 13 Simulation result for case 6

Bus No	Voltage kV	Angle Degree	Load		Generation		Injected
			P	Q	P	Q	Q
			MW	Mvar	MW	Mvar	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 Simulation result of line flows and losses for case 6

From Bus	To Bus	Sending End		Receiving End		Line Losses	
		P	Q	P	Q	P	Q
		MW	Mvar	MW	Mvar	MW	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

Table 15 Result for percentage increase in voltage at bus 6 relative to the base case run

Case	Voltage kV bus 6	Injected		% kV increase
		P	Q	
		MW	Mvar	
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

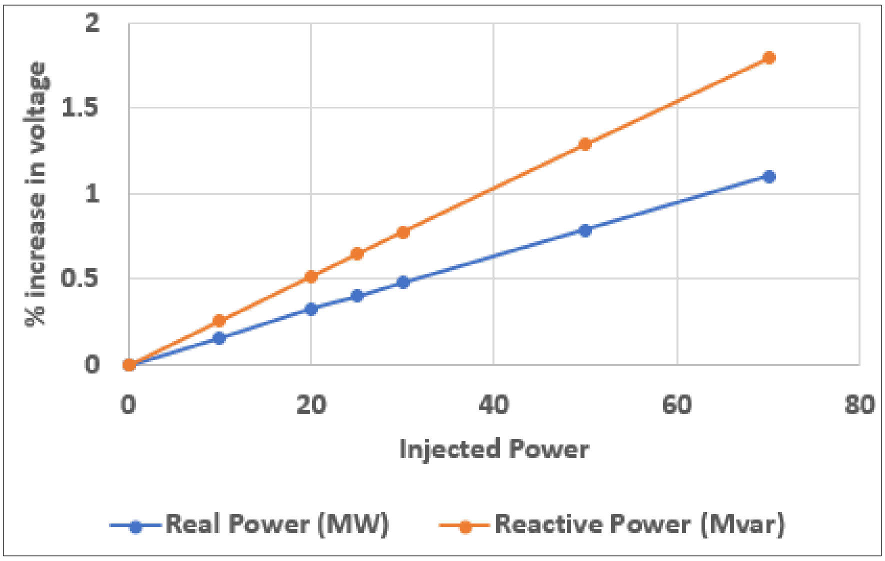

Figure 10 Percentage increase in bus 6 voltage relative to the base case voltage as injected real and reactive powers increase

4. Conclusion

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 are presented.

Compliance with ethical standards

Acknowledgments

I acknowledge the contributions made by my co-authors and those who supported us during our research.

Disclosure of conflict of interest

The authors declare that no conflict of interest exists between them.

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