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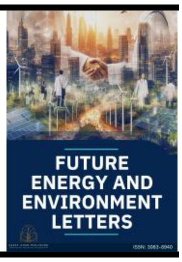

Voltage Stability Analysis on Transmission Grid Interconnected to Solar Photovoltaic

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ABSTRACT

Humans depend on electricity, which is also a major contributor to a nation's economic development and to fulfill the needs, a reliable power system is very important. In achieving carbon free electricity, many countries started to implement utility scale solar photovoltaic (PV) into the transmission level. However, due to the 'must take' characteristics of solar PV output, it brings technical challenges and have a significant impact on system stability. Voltage stability is the ability of a power system network to maintain its reliable operation based on the safety operation across all network buses both during normal operation and during contingencies. The impact of solar PV energy as a source of network disturbance is the main issue of this study. Voltage Stability Indices (VSI) is used to identify the system's weakest point and the voltage stability for each line is measured using Line Stability Factor (LQP). All the simulation works is done using Power System Simulator for Engineering (PSS/E) and the IEEE 30-bus is used as the test system. The results present the impact of each solar PV penetration to the voltage stability and show the impact of solar PV penetration to the thermal loading percentage.

1. Introduction

In recent years, solar energy has been one of the most dependable and rapidly expanding energy sources in the world. Many countries throughout the world have considering to the installation of utility scale solar PV systems to the appropriate network in order to address the political, economic, and environmental difficulties associated with producing electricity. The primary goal of this project is due to each nation's growing need for power and energy [1]. China had installed about 30.1 GWh of PV system power, followed by European nations with 16.0 GWh and the United States of America with 13.3 GWh, updated 2020 [2-7]. Aside from all these international nations, Malaysia is also currently using solar-grid integration technologies. This nation has already taken the effort to switch to alternative energy sources, notably solar PV, in order to become less dependent on hydropower plants and thermal power plants. In addition, Malaysia has already set a new objective to reach 20 percent clean energy by 2030 in order to build the grid of the future [8-10].

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Although solar-grid technology had numerous advantages, there were still some problems that needed to be considered in the power grid system. The input power from the sun cannot be controlled, making solar energy a non-dispatchable energy source theoretically. The sun does not shine continuously throughout the day, and occasionally cloud cover has an impact. Since solar PV output is in the mode of 'must take', there may be periods when the entire amount of power generated will exceed the total amount of load demand, which leads to voltage instability [11-14]. In order to lessen its reliance on coal and other fossil fuels, Malaysia must prioritise the development of renewable energy sources. Malaysia is located on the equator, therefore at some point during the day, the sun always shines at an exact 90-degree angle. The capacity of this country to produce solar energy ranges from 1400 to 1900 kWh/m2, with an average of about 1643 kWh/year [10]. A solar PV project makes sense considering Malaysia's geographical location. Voltage stability is the ability and capacity of the grid operation to maintain the steady-state voltage on all buses [15]. The 132 kV network system's stable voltage shall, under normal circumstances, fall within the range of -5 and +10 percent, according to Malaysia TNB Grid Code [16]. Otherwise, problems with voltage stability might occur.

The strongest area should theoretically become less sensitive as the system's load increases while the weakest area of in a power system network is prone to be exposed to serious compromising parameters, which may result in unforeseen system disasters. In this study, locating the weakest area is done to observe the worst vulnerable bus in the system to face the challenges of voltage instability causes by solar PV integration [17]. The voltage stability of the electricity grid will be monitored and analysed after solar PV has been introduced into the system.

Voltage stability indices (VSI) have been used by many researchers to observe the stability of the network. There were number of indices under VSI, but only the FVSI and LQP indices will be employed in this study. Fast Voltage Stability Index, or FVSI, is a concept put forth by Musirin *et al.,* based on the idea that the voltage quadratic equation discriminant. The indicator is used to forecast voltage breakdown in the system and analyse the contingency brought on by a line loss [18]. In addition, this index serves as the best tool for locating the system's weakest link. The power grid is getting near to the instability point of the system if line branches have FVSI values close to 1.0. The area with the lowest sustainable load on the electricity grid is represented by the area with the greatest rank in the system. Formula for VVSI as follows:

$$FVSI = \frac{4Z^2 Q_j}{{V_i}^2 X} \tag{1}$$

Furthermore, using the single line idea of the power grid, Mohamed *et al.,* [19] developed the line stability factor, or LQP. This method's primary goal is to calculate the line's critical state. Additionally, this index's safety limit must not exceed 1.0. The system won't be able to keep itself secure otherwise [10]. The following formula is used:

$$LQP = 4\left(\frac{X}{{V_i}^2}\right)\left(\frac{X}{{V_i}^2}{P_S}^2 + Q_R\right) \tag{2}$$

Both indices, which determine the voltage stability of the system, operate under the same principles. Additionally, the critical value of the limit, which must be smaller than 1.0, remains the same in order to guarantee that the system is in a stable system condition. In terms of the formula and component of the indices that are linked to either the bus or the line, there are still some discrepancies that may be noted on different sides of the indices. This study is restricted to line indices that share a crucial value of unity as a common characteristic. In this study, the weakest area will be identified using FVSI, and the voltage stability of the system will be assessed using LQP. FVSI index is used as the index is among the preferred index used by the researchers to study the weakest and strongest bus in a system while LQP is used in this research work as the index can be used to observe the voltage stability of the network as the impact of increasing real power flow in the system. Unit 2 will discuss the methodology of the voltage stability analysis. In Unit 3, the analysis of the simulation results is presented where the analysis focuses on the stability of the test system before and after the system is connected to the solar PV plant and the impact of high penetration solar PV on the thermal loading of the systems and the voltage stability index. Finally, Unit 4 presents the conclusion of the research work.

2. Methodology

The simulation work in this study started with the development of the test system in PSS/E software which is a standard IEEE 30-bus system. The base case study is conducted to study the behavior of the system without solar PV integration during steady state conditions in term of bus voltage limits and thermal loading. After that, the installation of solar PV to the weakest bus is done where the weakest bus is determined by the bus with the highest FVSI value [16]. The voltage stability of all the lines connected to the solar PV point of coupling (POC) is then assessed using LQP. The thermal loading and LQP index are monitored for every 20MW solar PV penetration to the grid. Finally, a discussion, observation, and conclusion are drawn from the simulation results. Figure 1 presents the flowchart of the research methodology.

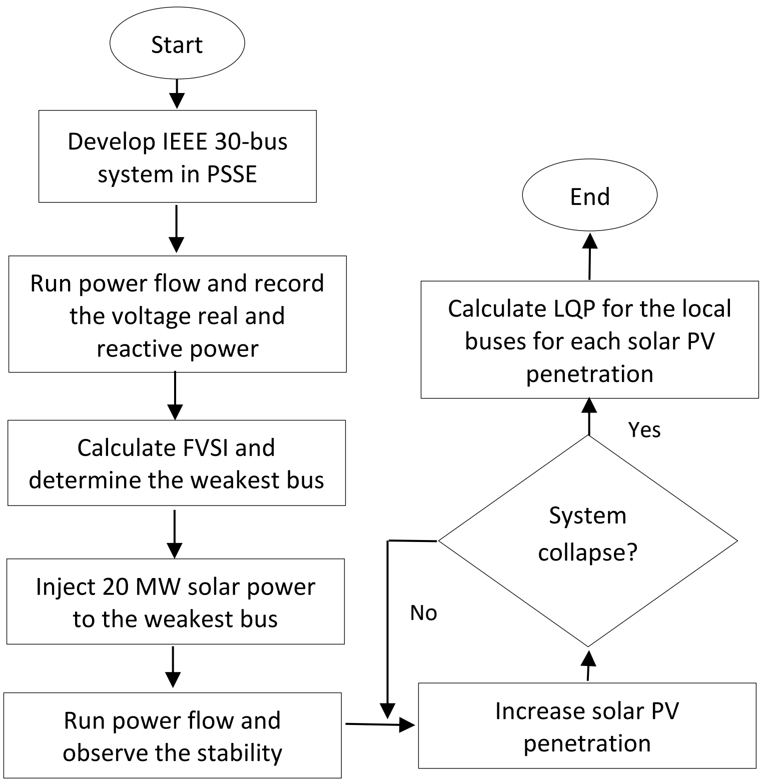

Fig. 1. Flowchart of research methodology

3. Results

3.1 Weakest Area Analysis

The IEEE 30-bus system's weakest point is located using FVSI where the bus is selected to integrate with solar PV. The power grid is getting near to the instability point of the system if line branches have FVSI values close to 1.0. Bus voltages, V line impedance, X and reactive power, Q for the receiving bus of the system were the factors that affected the FVSI index values [16]. From the simulation of the IEEE 30-bus test system, power flow solution which recorded all the parameter required for FVSI calculation is given in the Appendix 1.

Appendix 1
FVSI value for IEEE 30-bus system

Line Branches	Vs (p.u.)	Line R (p.u.)	Line X (p.u.)	Line Z (p.u.)	Reactive Power of Receiving Bus Q (p.u)	FVSI
1 to 2	1	0.02	0.06	0.063	0.021	0.0056
1 to 3	1	0.05	0.19	0.196	-0.057	0.0461
1 to 4	1	0.06	0.17	0.18	-0.068	0.0518
2 to 5	1	0.05	0.2	0.206	-0.064	0.0543
2 to 6	1	0.06	0.18	0.189	-0.091	0.0722
3 to 4	0.9879	0.01	0.04	0.041	-0.044	0.0076
4 to 6	0.9859	0.01	0.04	0.041	-0.132	0.0228
4 to 12	0.9859	0	0.26	0.26	0.039	0.0417
5 to 7	0.9865	0.05	0.12	0.13	-0.071	0.0411
6 to 7	0.9817	0.03	0.08	0.085	-0.038	0.0142
6 to 8	0.9817	0.01	0.04	0.041	-0.239	0.0417
6 to 9	0.9817	0	0.21	0.21	0.014	0.0122
6 to 10	0.9817	0	0.56	0.56	0.008	0.0186
6 to 28	0.9817	0.02	0.53	0.531	0.019	0.0418
8 to 28	0.9757	0.06	0.23	0.237	0.044	0.0451
9 to 10	0.9770	0	0.11	0.11	0.015	0.0069
9 to 11	0.9770	0	0.21	0.21	0	0
10 to 17	0.9746	0.03	0.08	0.085	-0.055	0.0209
10 to 20	0.9746	0.09	0.21	0.228	0.071	0.0740
10 to 21	0.9746	0.03	0.07	0.076	-0.022	0.0076
10 to 22	0.9746	0.07	0.15	0.166	0.003	0.0023
12 to 13	0.9895	0	0.14	0.14	0.153	0.0875
12 to 14	0.9895	0.12	0.26	0.286	-0.007	0.0089
12 to 15	0.9895	0.07	0.13	0.148	0.016	0.0110
12 to 16	0.9895	0.09	0.2	0.219	-0.022	0.0216
14 to 15	0.9794	0.22	0.2	0.297	0.009	0.0166
15 to 18	0.9817	0.11	0.22	0.246	0.023	0.0263
15 to 23	0.9817	0.1	0.2	0.224	0.031	0.0323
16 to 17	0.9755	0.08	0.19	0.206	-0.003	0.0028
18 to 19	0.9659	0.06	0.13	0.143	0.033	0.0223
19 to 20	0.9604	0.03	0.07	0.076	0.068	0.0243
21 to 22	0.9756	0.01	0.02	0.022	0.091	0.0093
22 to 24	0.98	0.12	0.18	0.216	-0.025	0.0269
23 to 24	1	0.13	0.27	0.299	-0.042	0.0557
24 to 25	0.9785	0.19	0.33	0.381	0	0
25 to 26	0.9863	0.25	0.38	0.455	-0.023	0.0515
25 to 27	0.9863	0.11	0.21	0.237	0.025	0.0275
27 to 29	1	0.22	0.42	0.474	-0.015	0.0321
27 to 30	1	0.32	0.6	0.68	-0.014	0.0432
28 to 27	1.0303	0	0.45	0.45	-0.063	0.1068
29 to 30	0.9796	0.24	0.45	0.51	-0.005	0.0121

In Appendix 1, the findings indicate that every value was below the FVSI limit. Thermal loading is therefore not compromised. Results in Appendix 1 demonstrates that line branches connecting bus 28 to bus 27 have been identified as the system's weakest location.

3.2 Analysis of Test System Voltage Stability with and without Solar PV

Investigating the voltage stability of the system in connection to the effects of solar PV integrated into the established system is the main objective of this sub-chapter. An evaluation of the power grid's weakest and most unstable points that could endanger future load increase owing to an unanticipated voltage collapse is known as a voltage stability analysis. As a result, effective voltage stability is crucial for long-term interoperability and planning of power grid systems [5]. Furthermore, there are benefits and drawbacks to installing solar PV through the system.

Installing solar PV into the electricity grid can enhance the voltage profile and lower VSI indices. But occasionally, especially in the immediate region, overloading might happen at specific spots when a greater rating of solar PV is integrated into the system. A new generator of solar farm (SF) marked in the Figure 2 as SF 132KV is connected to the weakest bus, point of connection (POC) bus 28 in the system to observe the impact of different PV penetration to thermal loading and voltage stability.

The local area, defined as the line branches connected to bus 28, is the sole area that is the subject of the voltage stability analysis for this study. If overloading happens, this local area, which is specifically specified as a vulnerable area of the power grid system, will be impacted. The system will also be initially integrated with a PV system. The system's LQP index will be raised by 20MW increments until it reaches a more stable limit. Bus voltages, line impedance, active power at the transmitting bus, and reactive power at the receiving bus of the system were the factors that manipulated index values, according to the LQP formula given in the related works [17]. The power flow solution which recorded all the parameters value for LQP calculation and the calculated LQP is given in Appendix 2.

Appendix 2
LQP value for each 20MW solar PV penetration

Solar PV power (MW)	Line Branches	Voltage (p.u.)	Line Impedance X (p.u.)	Active Power at Sending Bus P (p.u.)	Reactive Power at Receiving Bus Q (p.u.)	LQP
Without Solar PV	6-28	0.9817	0.53	0.002	0.084	0.1823
	8-28	0.9757	0.23	-0.065	0.204	0.2123
	28-27	1.0303	0.45	0.066	0.082	0.0911
20MW	6-28	0.9847	0.53	-0.058	0.09	0.2661
	8-28	0.9795	0.23	-0.178	0.201	0.2337
	28-27	1.0367	0.45	0.04	0.085	0.1143
40MW	6-28	0.9864	0.53	-0.119	0.093	0.3439
	8-28	0.9816	0.23	-0.291	0.19	0.2477
	28-27	1.0417	0.45	0.018	0.097	0.1485
60MW	6-28	0.9875	0.53	-0.179	0.096	0.4202
	8-28	0.9828	0.23	-0.403	0.181	0.2638
	28-27	1.0455	0.45	-0.004	0.106	0.1772
80MW	6-28	0.988	0.53	-0.239	0.099	0.4968
	8-28	0.9831	0.23	-0.513	0.173	0.2809
	28-27	1.0481	0.45	-0.027	0.112	0.2016
100MW	6-28	0.9879	0.53	-0.298	0.104	0.5774
	8-28	0.9827	0.23	-0.622	0.166	0.2993
	28-27	1.0495	0.45	-0.05	0.116	0.2229
120MW	6-28	0.9872	0.53	-0.357	0.109	0.6594
	8-28	0.9813	0.23	-0.729	0.16	0.3192
	28-27	1.0497	0.45	-0.073	0.117	0.2398
140MW	6-28	0.9859	0.53	-0.415	0.114	0.7421
	8-28	0.9792	0.23	-0.834	0.155	0.3407
	28-27	1.0486	0.45	-0.097	0.115	0.2532
160MW	6-28	0.9839	0.53	-0.473	0.121	0.8321
	8-28	0.976	0.23	-0.937	0.152	0.3653
	28-27	1.0462	0.45	-0.121	0.11	0.2627
180MW	6-28	0.9812	0.53	-0.529	0.128	0.9231
	8-28	0.972	0.23	-1.037	0.15	0.3919
	28-27	1.0423	0.45	-0.147	0.103	0.2715
200MW	6-28	0.9778	0.53	-0.585	0.135	1.0184
	8-28	0.9668	0.23	-1.136	0.149	0.4218
	28-27	1.0369	0.45	-0.173	0.092	0.2752

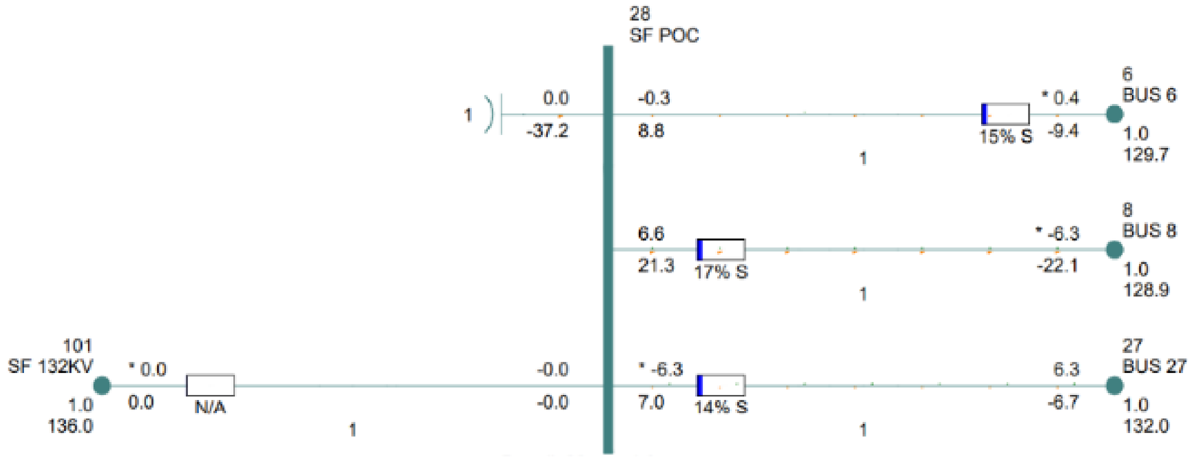

Fig. 2. Solar PV installation on bus 28

3.3 Impact of Solar PV System Integration on Thermal Loading Percentage

This sub-chapter presents the changes in thermal loading percentage for different penetration of solar PV. The point of connection for solar PV in Figure 3 through 12 is connected at bus 28. In order to observe the impact of solar PV integration into the system to the voltage stability, the results of thermal loading, voltage, and power are recorded for each solar PV penetration. Based on the results, the voltage stability index is calculated and listed in Appendix 2. In Figure 3, the output of solar PV injected into the grid is 20 MW and from the LQP values for all the branches calculated in Appendix A, it is shown that all the branches in the local area do not violate the voltage stability in the system.

The solar PV output is then increased every 20 MW until it reaches 200 MW as shown in Figure 12 and it is found that the LQP index for the branch connecting the bus 6 to bus 28 system exceed the safety level for voltage stability where the LQP is 1.0148.

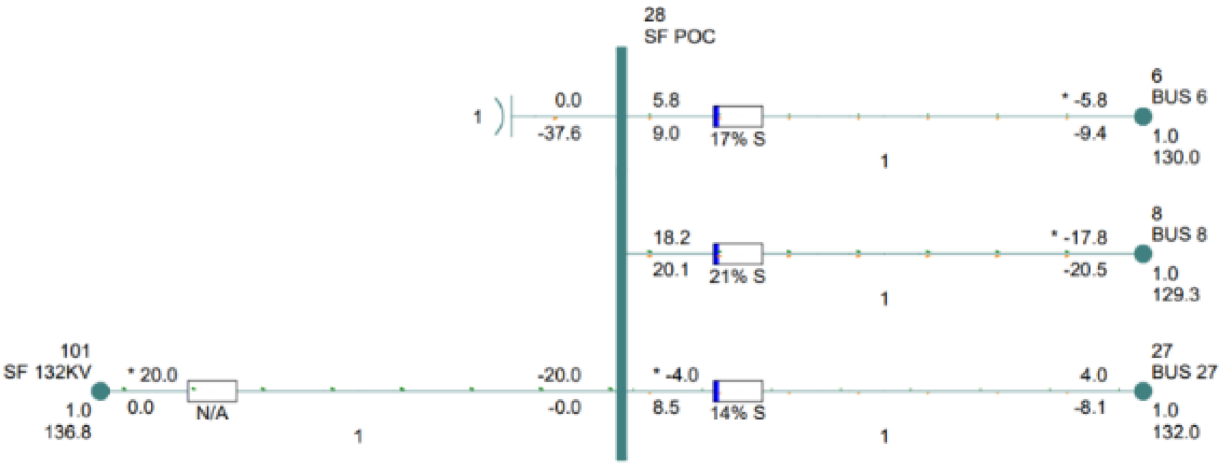

Fig. 3. Thermal loading percentage for local area at 20 MW

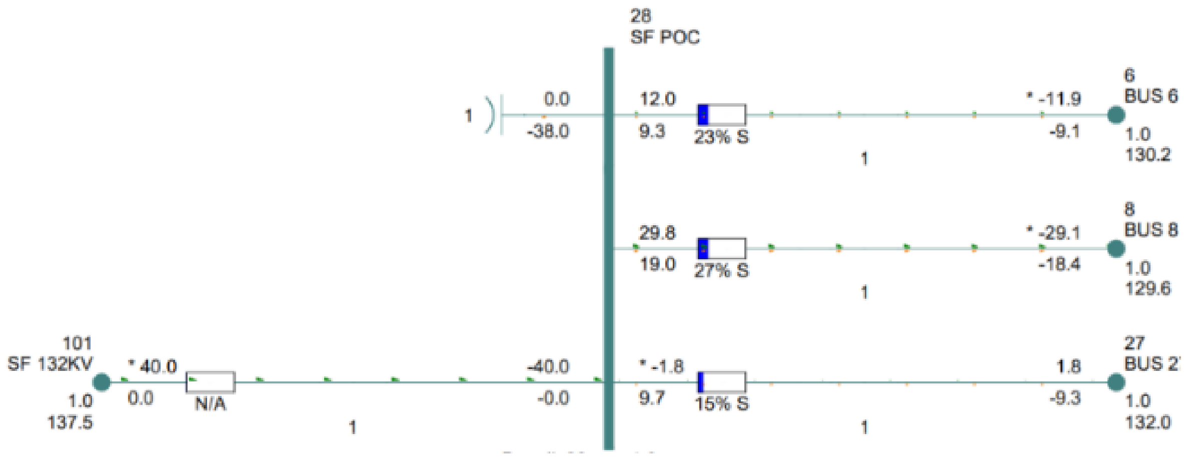

Fig. 4. Thermal loading percentage for local area at 40 MW

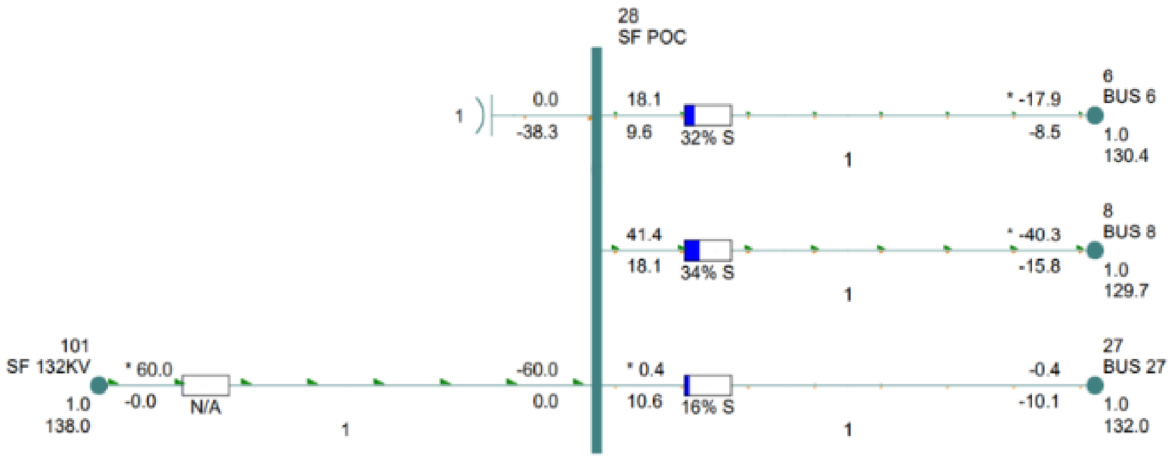

Fig. 5. Thermal loading percentage for local area at 60 MW

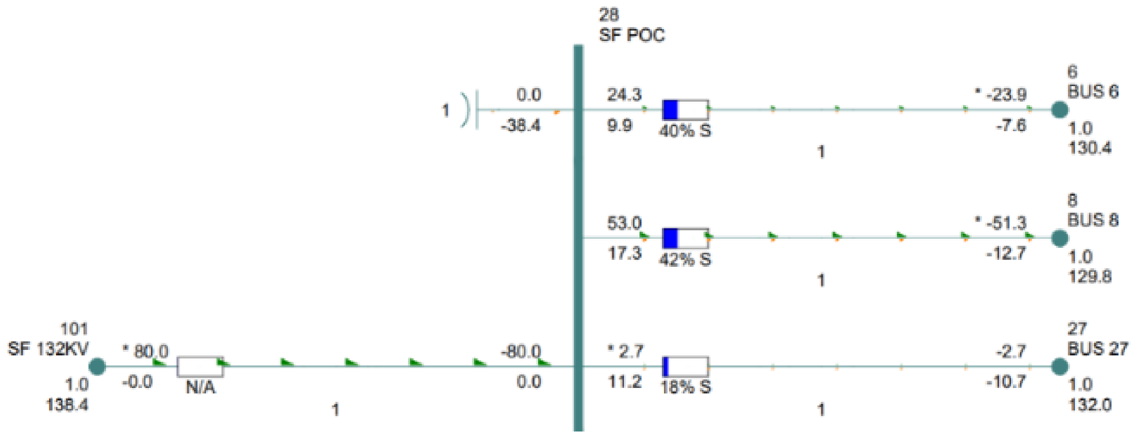

Fig. 6. Thermal loading percentage for local area at 80 MW

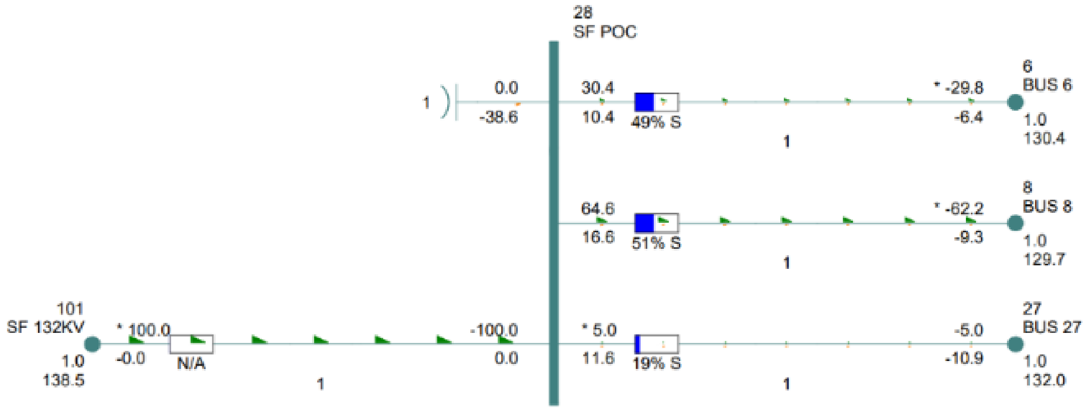

Fig. 7. Thermal loading percentage for local area at 100 MW

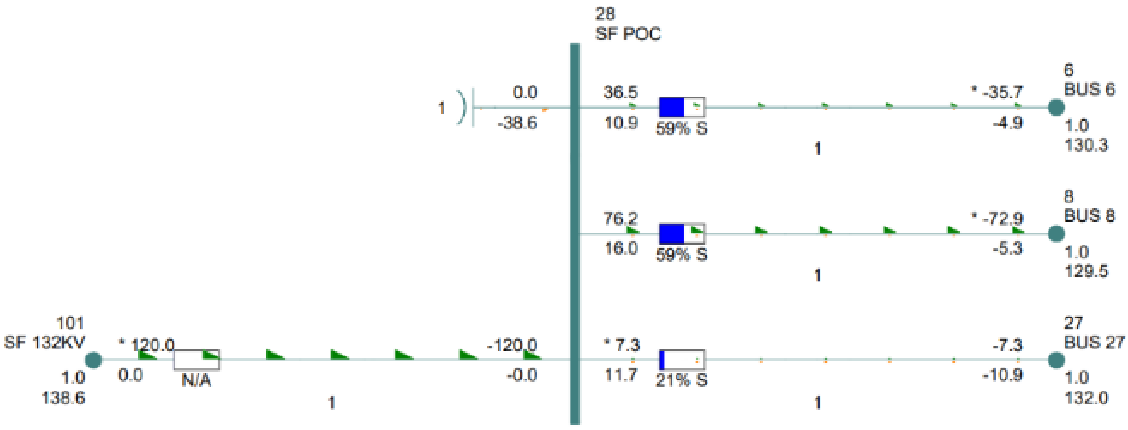

Fig. 8. Thermal loading percentage for local area at 120 MW

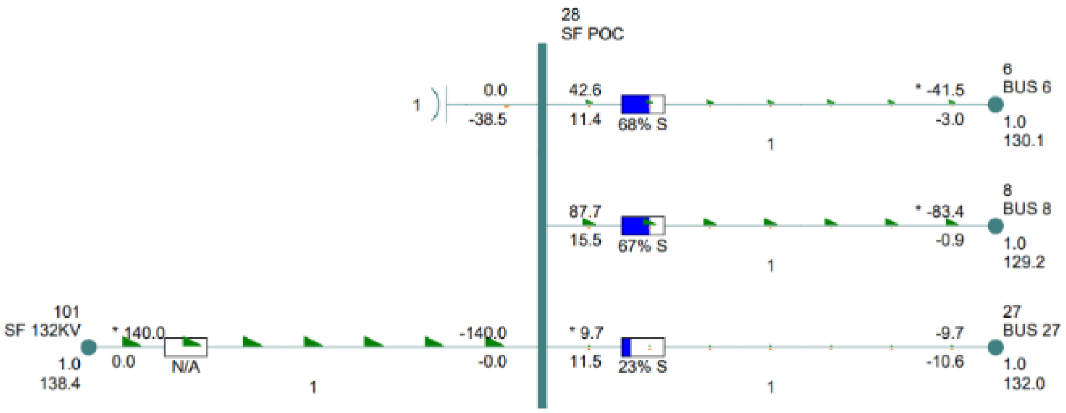

Fig. 9. Thermal loading percentage for local area at 140 MW

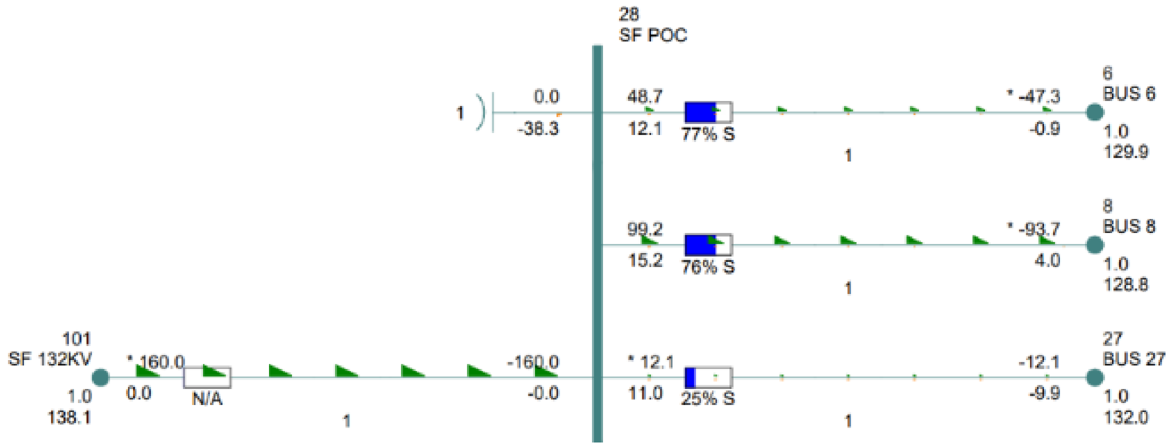

Fig. 10. Thermal loading percentage for local area at 160 MW

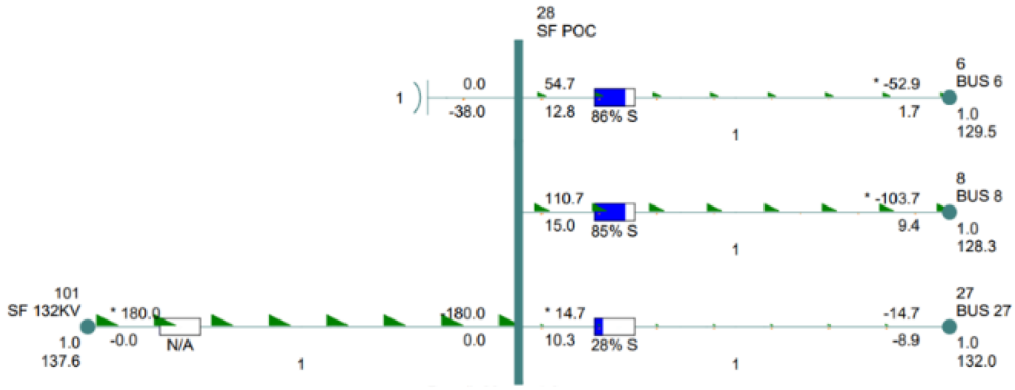

Fig. 11. Thermal loading percentage for local area at 180 MW

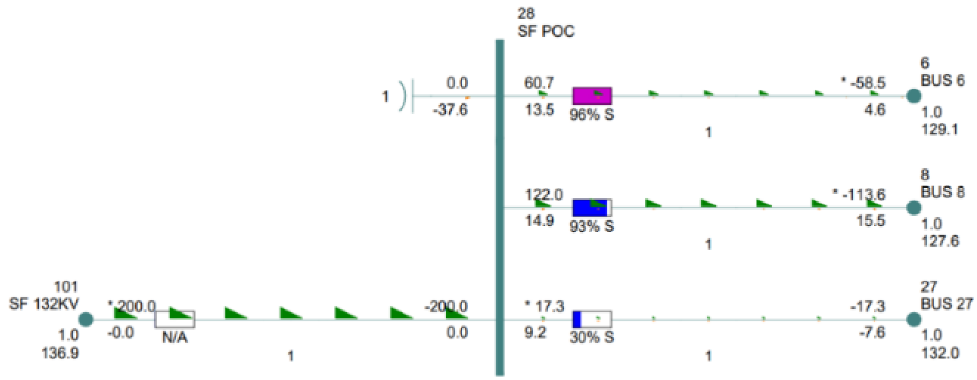

Fig. 12. Thermal loading percentage for local area at 200 MW

According to Figures 3 through Figure 12, the thermal loading percentage for all buses increased every time the solar power increased. According to the observation, lines 8-28 and the connecting bus numbers 6-28 are the most affected in terms of the loading percentage. While lines 28–27 are the least impacted. As seen in Figure 22, when 200 MW of solar PV production is added to the system, thermal loading for lines 6-28 rises until it reaches 96 percent. If solar output continues to rise, this figure should rise much further. As a result, the device requires more power than the permitted maximum power that can be carried. The system may suffer if the condition is repeated frequently since it reduces the lifespan and condition of the cable and other components [20]. Based on the observation, it is evident how much of the thermal loading is impacted by the solar PV system's output. The findings demonstrate that adding solar PV to a system with high output can have an impact on the percentage of line loading that contributes to grid congestion.

4. Conclusions

This research uses PSSE software and the selected test system is IEEE 30-bus test system to analyze the voltage stability on the power grid connected to solar PV. Additionally, this study paper's goals have all been attained. In conclusion, FVSI is an effective mechanism for identifying the system's weakest link. To choose the ideal location for Solar PV installation, the weakest component of the system must be identified. Next, LQP is one of the reliable indicators for determining the line's critical status and the system's voltage stability. This index can also monitor how a power grid is now operating, assess a long-term development trend under specific circumstances, and forecast how the nature of the system will change in the future. Last but not least, as the system's output solar PV integration increases, so does the thermal loading percentage. The functioning of the electrical grid may be impacted indirectly by the increased proportion of thermal loading by shortening the lifespan and degrading the condition of the cable and other equipment.

Additionally, there are some suggestions that can be made to enhance this study. The algorithm for rerouting the flow of power was first introduced. This algorithm's key advantages over VSI are its computing speed and capacity for overcoming numerical challenges close to the voltage collapse point. The algorithm can also control the excess electricity in the electrical grid. Finally, voltage stability can be preserved by using energy storage. Grid voltage stability can be increased while simultaneously increasing the grid's flexibility and dependability by managing the active and reactive power of energy storage.

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