Proceedings of 11th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2022 Month: March Volume: 11

Impacts of Photovoltaic Penetration on Transient stability of Power System

Radhika Kumari Sah [a], Hari Bhusal [b], Nawaraj Kumar Mahato [c], Binod Tamang [d]

[a, b, c, d] *Kathmandu University, School of Engineering, Department of Electrical and Electronics Engineering*

[a] radhikasah67@gmail.com, [b] haribhusal49@gmail.com, [c] nawaraj.mahato@ku.edu.np, [d] btamang2051@gmail.com

Abstract

The increased penetration of solar generation in the traditional power grid may changes the transient characteristics of it as they are connected to the grid through technologies different than traditional power system. In particular, the Critical Clearing Time (CCT) which is very necessary for performance of protective system during transient period are affected due to the increased penetration of non-synchronous generators. This paper studies transient stability analysis of power system and the impacts of photovoltaic (PV) penetration on it in a standard IEEE 9 bus test system. The Simulink model for the transient stability of IEEE 9 bus test system is prepared in MATLAB and Simulink environment. Three-phase fault is considered in the study and rotor angle stability is analyzed through multiple simulation. CCT is used as index to analyze the transient stability analysis of IEEE 9 bus test system for base case and Transient Stability Index (TSI) is used for the comparison of the transient stability in different cases i.e. with and without PV in the system. It is found that transient stability depends on duration of fault, location of fault as well as power in that location. The transient stability of the power system in critical locations been reduced by the integration of PV in the system whereas it has improved in other locations.

Keywords

CCT, PV, rotor swing, Transient Stability Analysis (TSA), TSI

1. Introduction

Transient stability of power system is the ability of power system to remain in synchronism when subjected to large disturbance like a short circuit, transmission line and generator outages etc. [1]. The transient stability is mainly related to rotor angle stability [2]. During severe disturbances, Transient Stability Analysis (TSA) of the power system helps to figure out the behavior of rotor angle deviation [1]. If the large disturbances are not cleared within a certain time interval, it may lead the generators to lose the synchronism and result in the blackout of the entire system. The maximum time within which the fault should be cleared to maintain the stability of the system is known as Critical Clearing Time (CCT) [2], and is one of the key factors of transient stability. The longer the CCT, the more time the power system has to clear the fault, and hence the system is more secured [3]. The power system is considered to be stable when a fault is cleared within an established CCT. The value of the CCT depends on various factors, like size of the generator, generator inertia, generator dispatch, line impedances, network topology, fault location, etc. Along with these factors, weather also has an impact on the transient stability of the multi-machine system [4]. The growing usage of fossil fuels in recent years has pushed the environment to the brink of irreversible climate change [5]. Renewables Portfolio Standards (RPS) has set the requirement of annual electricity sales from a renewable source to 15-30% by 2020- 2025 [6]. This kind of increasing penetration of renewables, especially photovoltaic generations has made the photovoltaic system as an attractive option for generation and a major area of research. Also, the past data reviled that the demand of PV has increased by 20%-25% per annum over the past 20 years, with the growth in grid-connected applications [7]. On the other hand, replacing the conventional synchronous generators with non-synchronous generators may cause various issues like voltage fluctuation, insufficient reactive power, and lack of inertia, which finally threaten the stability, and reliability of the entire network [8]. The short-circuit current characteristics of non-synchronous generators have shown significant differences from those fed by synchronous generator [9].

The impact of photovoltaics on the grid have been studied extensively. [10, 11] studied the impacts of replacing conventional generating units by PV system on voltage stability whereas [12, 13, 14, 15] studied impacts on transient stability. Following a disturbance, transient stability is generally evaluated in a 3 to 5 second of time period [10], with CCT being the most commonly utilized indicator of transient stability as in [7, 13, 14]. Rotor angle differences vs. time variation based on method was also preferred to perform a more efficient analysis in multi-machine systems for transient stability [15]. After integrating PV, disturbances on some buses create large oscillation after the fault is cleared in the system [16]. PV's impact is strongly influenced by the fault's position [10]. Time-domain simulations have traditionally been used to investigate the transient stability of multi-machine systems by solving differential algebraic equations (DAE) based on simple assumptions [4]. Center of inertia (COI) reference plane is also used to perform transient analysis [3]. Transfer conductance has been considered in [14] for the fast approximation of the rotor angle and angular velocities. However, a comparison of the performance of Lyapunov's method and the Equal Area Criterion (EAC) methods suggested that time doamin simulation and matrix reduction technique are most critical operations [17]. Transient rotor angle severity index (TRASI) was used for the transient analysis with high solar-PV generation, by maintaining steady-state system parameters constant using the Prony analysis tool in DIgSILENT Power Factory [10].

In this paper, IEEE 9 bus test system is modeled in MATLAB Simulink environment to study the transient stability of the system. Simulation is done by applying three-phase fault at various location and clearing it after few milliseconds. Rotor angle differences is observed after the application of fault and based on it, CCT is determined. Also, the Transient Stability Index (TSI) has been used as an indicator for the comparison of transient stability of the system with and without PV.

2. Rotor Angle Stability

2.1 Transient Stability Index

Transient Stability Index (TSI) is a tool that shows the risk involved in the power system operation and to take corrective action when it occurs, finally maintaining the system stability and security. There are various ways to identify critical system conditions and find the corrective action required to reduce their criticality. Among them, rotor angle-based stability index [15] is employed in this project and is defined as follows:

$$TSI = \frac{(360 - |\delta_{\max}|)}{(360 + |\delta_{\max}|)} \tag{1}$$

The synchronous generator rotor angles (relative to the reference machine angle) can range from 180° to -180° under major disturbances. Therefore, during a transient fault, the maximum angle difference is theoretically 360°. TSI is index that quantify the rotor angle separation of synchronous generator with respect to grid after fault occur in the system. The index varies from -1 to 1, with value near to 1 is more stable and values less than zero is considered unstable.

2.2 Swing Equation of SMIB

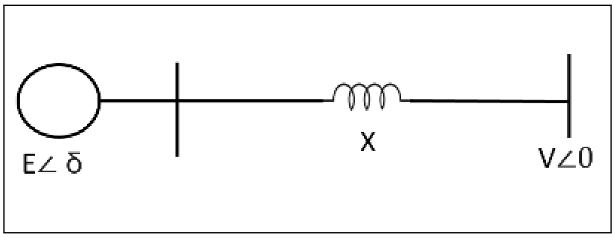


Figure 1: Single machine connected to infinite bus

Rotor angle stability of power system can be evaluated considering a single machine connected to infinite bus system as shown in figure 1 [2]: Power delivered by the synchronous generator can be expressed as:

$$P_e(\delta) = \frac{E_1 E_0}{X} \sin\delta \tag{2}$$

From swing equation

$$\frac{d\delta}{dt} = \omega \tag{3}$$

$$M\frac{d\omega}{dt} = P_m - P_e(\delta) \tag{4}$$

where,

δ - rotor angle of the generator [rad],
ω - angular velocity [rad/s],
M - inertia constant [s],
P_m - mechanical input [p. u.], and
P_e - electrical output [p. u.].

2.3 Equal Area Criteria

For SMIB system, EAC can provide the information regarding the maximum rotor angle and stability [14]. Though it is not applicable for multi machine system directly, it helps to understand the basic factor that affects the transient stability of any system. Rotor angle – time relationship can be used to find out the stability of system in the multi machine system. Figure 2 illustrates the concept of equal area criteria as well as rotor angle behavior in a time axis.

where,

δ_0- initial angle,
δ_c- critical clearing fault angle,
δ_m- maximum rotor swing angle,
t_c- critical clearing time

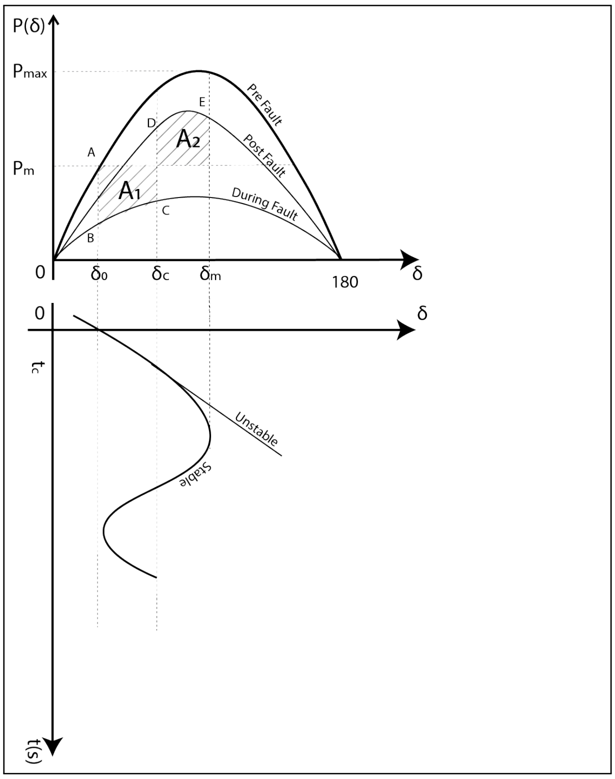


Figure 2: Equal area criteria for SMIB system

3. Methodology

In this study, the standard IEEE 9 bus power system model [15] is used to study the impacts of PV in transient stability of power system. First of all, the test model is prepared in Simulink environment. There are three synchronous generator SG1, SG2 and SG3 interconnected with each other through transformers and transmission lines. Load flow analysis is performed to know the initial condition of power system.

The TSA is performed by applying 3-phase short circuit faults to all the bus bar one by one of the electrical network in order to observe the relative rotor swing (δ_{ij}) of all generators at corresponding fault location. CCT and maximum rotor angle of each generator with respect to swing generator is evaluated. After the TSA of standard bus test system for base case, the synchronous generator is replaced by PV generator and relative rotor angle is observed and compared. TSI for both the cases are calculated and plotted in the graph for the comparison of transient stability of the system with PV and without PV. For this, three phase fault is applied at same location and for the same fault duration in two different cases and the maximum rotor angle of each case is noted.

The study is divided in two cases. In first case TSA of system without PV (base case) is performed where three phase fault block is applied to different location in the interconnected system and the relative rotor swing $\delta 21$ and $\delta 31$ of generator SG2 and SG3 is observed respectively. Based on the relative rotor swing of generators, CCT for different fault location is determined. These fault are applied at only one location at one time and the fault is cleared at different intervals of time to find out the maximum fault clearing time of that location. The maximum fault clearing time in which the system remained stable is critical clearing time of each faults.

In second case, transient stability of system with PV is compared with/without PV scenario (base case). SG3 is replaced by PQ source of same real and reactive power, the relative rotor swing of SG2 with and without PV is observed and compared for same fault, same fault location and same fault duration. For this, three phase fault is applied at 15 second and is removed at 15.2 second for both the above cases. Using equation (1) TSI is calculated and the stability of the system with and without solar is discussed.

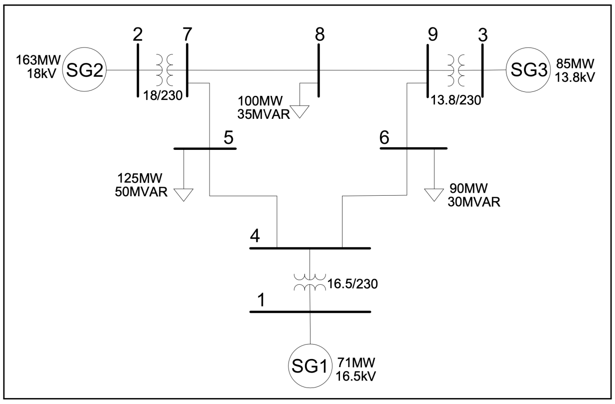


Figure 3: Standard IEEE nine bus test system

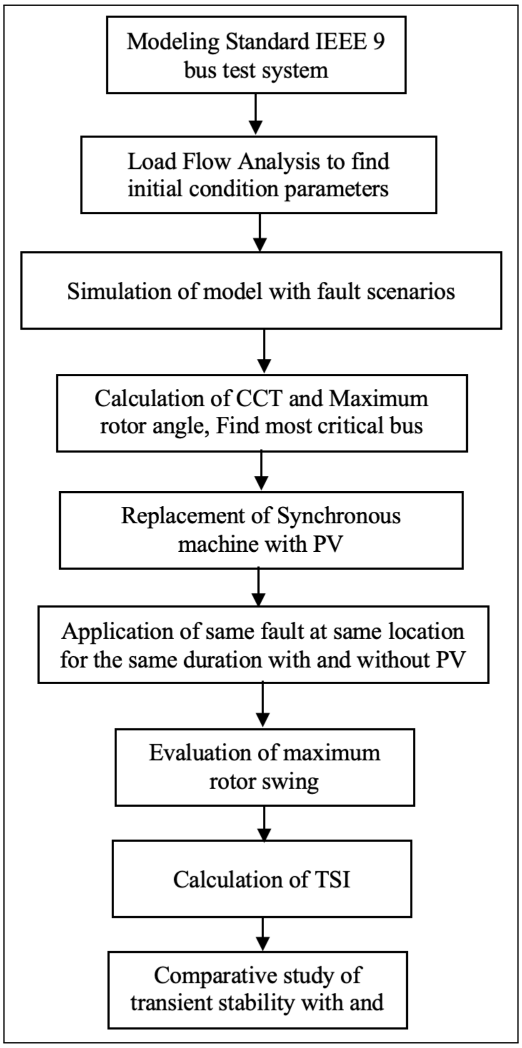


Figure 4: Flow chart of proposed methodology

4. Results and Discussion

Load flow analysis is performed using NR method to know the initial condition of IEEE 9 bus system. Among all the short circuit faults, three phase fault is the most severe having low CCT. Thus it is selected for the study and applied at different buses to analyze the transient stability. Figure 5 give the view of rotor angle curve of SG2 at steady state, transient state and unstable state. In the graphs, curve shown by solid line represents the rotor angle when no fault occurs in the system and is almost straight. When there is no disturbance in the system, the power flow almost remains constant at steady state. But when there occurs any disturbance in the network, the electrical power from the generator is changed and this mismatch of electrical output and mechanical input in very short period of time impacts the rotor angle. If three phase short circuit fault occurs in the system, the power gets reduced and the mechanical power becomes greater than electrical power thus generator rotors starts accelerating and rotor angle goes on increasing. This condition is represented by transient state condition in the graph where three phase fault was applied at bus 4 at 15 second and removed at 15.2 seconds, the relative rotor angle started accelerating after 15 second until the fault was cleared. The relative rotor swing is damped in the graph. This condition is known as transiently stable system. Similarly, if the three phase fault was applied at 15 second and removed at 15.3 second at bus 4, the relative rotor angle went on increasing up to infinite and the generators loose the synchronism as represented by unstable condition. This condition is known as unstable state.

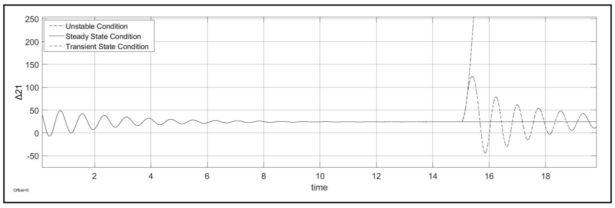


Figure 5: relative rotor angle curve of SG2 (Δ21) in three different conditions

4.1 Case 1

In the model showed in figure 3, three phase fault is applied at the bus 4,5,6,7,8 and 9 for different fault duration and CCT is calculated. CCT is very necessary for performance of protective system when any fault occurs in the system. CCT is the maximum time within which the fault should be cleared to keep the power system stable. CCT is an indicator of transient stability of the power system.

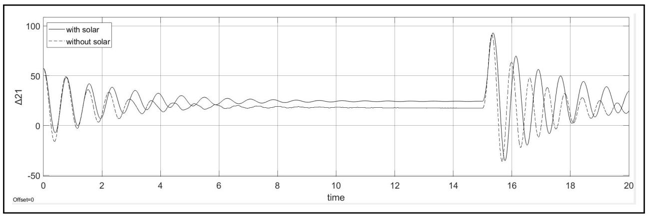
Table 2 contains the value of CCT and maximum rotor swings Δ21 and Δ31 of SG2 and SG3 respectively.

The maximum relative rotor angle is the angle when the fault clearing time is equal to CCT. Large CCT indicates that system has more time to clear disturbance, thus a system is more stable. If a fault is cleared before CCT then the system will be stable. The value of CCT can helps to determine the TSA. The maximum CCT was observed when the three phase fault occurred at bus 6 and minimum CCT was observed when the fault is occurred at bus 7 . The value of CCT of corresponding fault location in table 2 shows that the value of CCT depends on the location of three phase fault. The CCT of the fault near to generators are smaller than the CCT of the fault that is far from that generators. From fig 5, it is clear that bus 5,6 and 8 which are load bus, are farther from generator than bus 4,7 and 9 . Among these load buses, bus 6 has the least load connected to it. It means the power flow at that location is less than other two load buses. Hence, the maximum CCT can be obtained at the location far from the generator with low power flow. Among the buses near to generators, near to SG2 having high power generation and CCT at that location is minimum. Therefore, it again verified the previous statement that amount of power in the fault location also impacts the transient stability of the power system. Higher the power flow, higher will be the risk of transient stability of system. Finally, it is concluded that transient stability of power system depends on location of fault. Along with location, transient stability also depends on the amount of power following in that location.

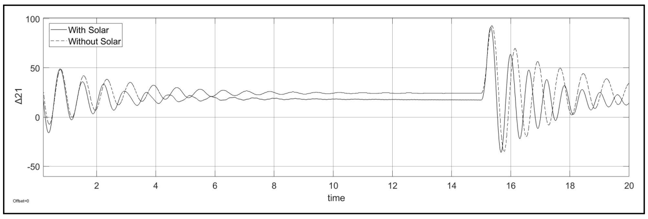
4.2 Case 2

In case 2, SG3 is replaced by PV source injecting same power as that of SG3. The acceptable limit for PV integration in the grid is 20 to 40% [18]. SG1 is swing generator and SG2 is 163 MW generator. Considering the high penetration that can provide acceptable impact on the network, replacement of SG3 is suitable option. The percentage PV penetration can be calculated as follows where P_{PV} is power from PV source and P_{SG} is power from synchronous generators.

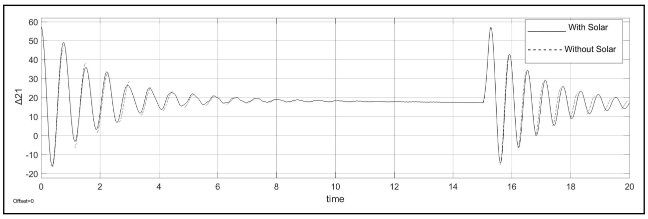
$$\begin{aligned}\%\text{PV penetration level } &= \frac{P_{PV}}{(P_{PV}+P_{SG})} \times 100 \\ &= 26.6\%\end{aligned}$$



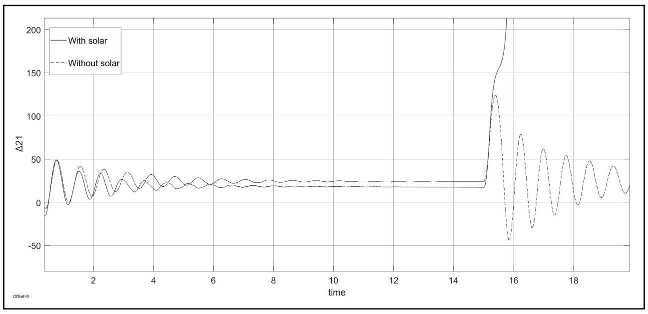
(a) Bus 4



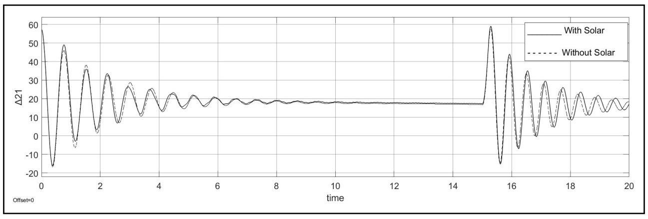
(b) Bus 5



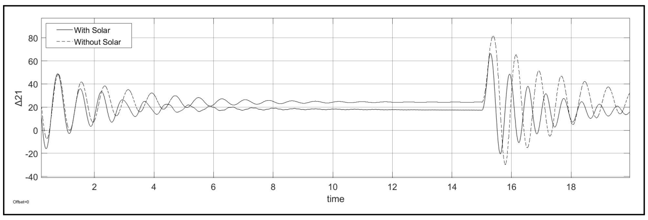
(c) Bus 6



(d) Bus 7



(e) Bus 8



(f) Bus 9

Figure 6: $\delta 21$ when fault applied at different bus at 15sec and removed at 15.2sec

Three phase fault is applied at the bus $4, 5, 6, 7, 8$ and 9

Table 1: Load flow results

	Block Type	Bus Type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (MVar)	Qmin (Pu)	Qmax (pu)	V_LF	Vangle_ LF (deg)	P_ LF (MW)	Q_ LF (Mvar)
1	SM	swing	BUS_1	16.5	1.04	0	150	0	-Inf	Inf	1.04	0	72.24	26.8
2	SM	PV	BUS_2	18	1.025	0	163	0	-Inf	Inf	1.025	9.17	163	6.69
3	SM	PV	BUS_3	13.8	1.025	0	85	0	-Inf	Inf	1.025	4.56	85	-10.78
4	Bus	-	BUS_4	230	1	0	0	0	0	0	1.026	-32.23	0	0
5	RLC load	PQ	BUS_5	230	1	0	125	50	-Inf	Inf	0.9962	-34	125	50
6	RLC load	PQ	BUS_6	230	1	0	90	30	-Inf	Inf	1.0131	-33.7	90	30
7	Bus	-	BUS_7	230	1	0	0	0	0	0	1.0259	-26.38	0	0
8	RLC load	PQ	BUS_8	230	1	0	100	35	-Inf	Inf	1.016	-29.37	100	35
9	Bus	-	BUS_9	230	1	0	0	0	0	0	1.0324	-28.14	0	0

Table 2: CCT and maximum rotor swings Δ21 and Δ31

Fault on Bus	CCT (sec)	Maximum Δ21 (degree)	Maximum Δ31 (degree)
4	0.260	173	129
5	0.338	172	115
6	0.369	176	166
7	0.221	176	143
8	0.271	172	138
9	0.250	166	175

at 15 second for the duration 0.2 second and removed at 15.2 second and results of rotor angle with and without PV of SG2 is plotted in fig 6.

Here, in case 2, δ_{21} with and without PV are compared by applying same fault, at same location and for same fault duration.

In figures 6, there are two curves, the curve represented by solid line is the rotor angle curve of SG2 when SG3 is present and dotted line curve represents the rotor angle curve of SG2 when SG3 is replaced by PV source. As three phase short-circuit fault in this case is applied at 15 second and removed at 15.2 second, the fault period for all the cases are less than CCT without PV in the network. Rotor angle is plotted for the time frame of 20 second. Fig 6 ((a), (b), (c), (d), (e) and (f)) are the curve representing relative rotor swing of SG2 when three phase fault occurs at bus 4, bus 5, bus 6, bus 7, bus 8 and bus 9 respectively. The rotor angle swings less with PV than without PV when fault occurs at bus 9. This shows that at bus 9, the transient stability has been increased with the integration of PV. Rotor swing with PV and without PV are almost similar except the critical location. Fig 6(d) represents curve of relative rotor angle when the fault occurs at bus 7 for 0.2 second. It shows that the rotor swing with PV has increased to infinite and the system has lost synchronism whereas without PV the system is transiently stable. This again verifies that among all buses, Bus 7 is the most critical bus because after integration of 26 % of PV in the system, rotor angle is unstable.

4.3 Transient Stability Index

Figure 7 shows the TSI of faults at different bus. X-axis represent bus number where fault has been occurred and y- axis represents TSI value of corresponding fault. Fault is applied at each bus at a time and is applied at 15 second and removed at 15.2 second. The fault period for each case is 0.2 second.The graph clearly showed that TSI when fault is at bus 7 is least stable without PV in the system, because its value is far from 1 than fault at other buses. With the integration of PV, the TSI of fault at bus 7 has become unstable because the index has moved to negative region. In almost all the cases except bus 7, transient stability of system with PV has been improved. Integration of PV is severe for fault occurring at the most critical locations in the network and makes the system more unstable. However, when a fault occurs at less critical locations, transient stability has improved.

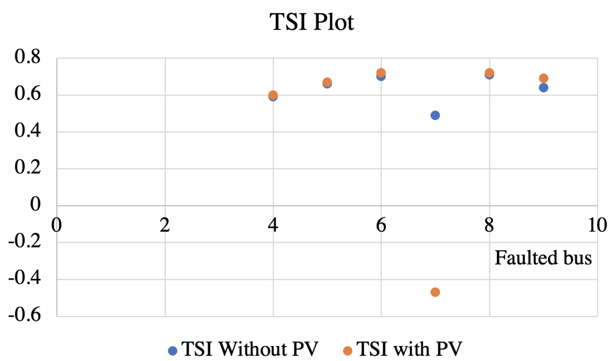


Figure 7: TSI plot of fault at different location with and without Solar

5. Conclusion

In this study, transient stability analysis has been performed taking a standard IEEE 9 bus test system in MATLAB Simulink environment. Transient stability of a power system depends on various factors like location of fault, duration of fault and type of generators. The CCT value depends on the distance of fault from generator and also depends on the amount of power in that location. With the replacement of conventional synchronous generators with 26.6% of PV penetration level, the transient stability of the faults at critical locations has been decreased, whereas at least critical locations, the transient stability has been increased. TSI showed that bus 7 has move to unstable region with 26.6% of PV integration while applying three phase fault for duration 0.2 second.

References

[1] Sharma Kolluri, Mei Li, Adrian Lazo, Peng Yu, Michael Vaiman, and Marianna Vaiman. Automated critical clearing time calculation for analyzing faults at entergy. In *2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, pages 1–5. IEEE, 2016.

[2] Jian Sun. Small-signal methods for ac distributed power systems–a review. *IEEE Transactions on Power Electronics*, 24(11):2545–2554, 2009.

[3] Halimatun Hashim, MR Zulkepali, YR Omar, N Ismail, IZ Abidin, and S Yusof. An analysis of transient stability using center-of-inertia: angle and speed. In *2010 IEEE International Conference on Power and Energy*, pages 402–407. IEEE, 2010.

[4] Arif Ahmed, Fiona Stevens McFadden, Ramesh Rayudu, and Tobias Massier. Investigation of the impact of weather on multi-machine transient stability analysis. In *2020 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, pages 1–5. IEEE, 2020.

[5] Ozge Tuttokmagi and Asim Kaygusuz. Transient stability analysis of a power system with distributed generation penetration. In *2019 7th International Istanbul Smart Grids and Cities Congress and Fair (ICSG)*, pages 154–158. IEEE, 2019.

[6] GE Energy. Western wind and solar integration study. Technical report, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2010.

[7] Ayman Hoballah. Power system dynamic behavior with large scale solar energy integration. In *2015 4th International Conference on Electric Power and Energy Conversion Systems (EPECS)*, pages 1–6. IEEE, 2015.

[8] Dhivya Sampath Kumar, Anurag Sharma, Dipti Srinivasan, and Thomas Reindl. Stability implications of bulk power networks with large scale pvs. *Energy*, 187:115927, 2019.

[9] Rafat Aljarrah, Hesamoddin Marzooghi, James Yu, and Vladimir Terzija. Sensitivity analysis of transient short circuit current response to the penetration level of non-synchronous generation. *International Journal of Electrical Power & Energy Systems*, 125:106556, 2021.

[10] Enkhtsetseg Munkhchuluun, Lasantha Meegahapola, and Arash Vahidnia. Impact on rotor angle stability with high solar-pv generation in power networks. In *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, pages 1–6. IEEE, 2017.

[11] Enkhtsetseg Munkhchuluun and Lasantha Meegahapola. Impact of the solar photovoltaic (pv) generation on long-term voltage stability of a power network. In *2017 IEEE Innovative Smart Grid Technologies-Asia (ISGT-Asia)*, pages 1–6. IEEE, 2017.

[12] Masaki Yagami, Naohito Kimura, Masanori Tsuchimoto, and Junji Tamura. Power system transient stability analysis in the case of high-penetration photovoltaics. In *2013 IEEE Grenoble Conference*, pages 1–6. IEEE, 2013.

[13] Ioanna Xyngi, Anton Ishchenko, Marjan Popov, and Lou van der Sluis. Transient stability analysis of a distribution network with distributed generators. *IEEE Transactions on Power Systems*, 24(2):1102–1104, 2009.

[14] Tomomi Sadakawa, Ako Sato, Ryu Tanabe, and Shinichi Iwamoto. Transient stability evaluation by the time domain equal-area criterion using the taylor series expansion. In *TENCON 2017-2017 IEEE Region 10 Conference*, pages 66–71. IEEE, 2017.

[15] Sebota Mokeke and Leboli Z Thamae. The impact of intermittent renewable energy generators on lesotho national electricity grid. *Electric Power Systems Research*, 196:107196, 2021.

[16] Sara Eftekharnejad, Vijay Vittal, Gerald Thomas Heydt, Brian Keel, and Jeffrey Loehr. Small signal stability assessment of power systems with increased penetration of photovoltaic generation: A case study. *IEEE transactions on sustainable energy*, 4(4):960–967, 2013.

[17] Tilman Weckesser, Hjörtur Jóhannsson, Stefan Sommer, and Jacob Østergaard. Investigation of the adaptability of transient stability assessment methods to real-time operation. In *2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, pages 1–9. IEEE, 2012.

[18] Yeboh Ngalo Lucky de Marco, Tao Zheng, and Srete Nikolovski. Overcurrent protection assessment with high pv penetration in a distribution network. *International Journal of Renewable Energy Research*, 8(1), 2018.