Power System Dynamic Behavior with Large Scale Solar Energy Integration

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Abstract—**The paper presents a study for the impacts of solar energy integration on the power system dynamic stability. A detailed photovoltaic model incorporated active and reactive power controller is used to investigate the effect of replacement of conventional steam power station by solar system considering changing in size and location. The controller depends on decoupled inner d-q current control loops and outer dc voltage regulator. The critical fault clearing time (CCT) is used as indicator for the power system transient stability. CCT is used to identify the interaction between generating units following large disturbances and can be used to initiate preventive or remedial actions against system instability. The critical fault clearing times are determined and compared within different levels of photovoltaic (PV) power integration. The effect of insertion point of PV is considered to specify effect of the location from the viewpoint of power system dynamic. The results have revealed that the transient stability performance of the system deteriorates with increasing the replacement level of conventional power station by PV system and significantly affected by the location on integration. The simulation and analysis are implemented using PowerFactory (DigSILENT) software. The test system used during the analysis is 11-bus system.**

Keywords— transient stability, PV system, distributed generation

I. INTRODUCTION

Renewable energy sources such as photovoltaic (PV) and wind turbine systems become a vital option to meet the rapid increase in power demand. The main advantages of the generated power from renewable sources are the absence of harmful emissions and the infinite availability of the prime mover that is converted to electricity. PV system installation is expected to rapidly increase with the continuous reduction in capital cost and the output power is expected to change when are working under different climate conditions such as working temperature and fluctuations in solar irradiation. The PV power generation performs a nonlinear operating characteristic depends on the array temperature, solar irradiance and load and several methods have been used to draw the maximum power of the solar grid. The location and size of PV system can significantly affect the steady state as well as dynamic performance of the power system. The increase of PV penetration level can lead to alteration of the steady state voltage magnitude and oscillations during disturbances [1][2].

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The reactive power support to grid voltage following grid faults is important aspect to improve system stability and should be considered to provide additional ancillary services during large integration of solar energy [3]. The dynamic response of solar energy based generation systems and conventional generators are different because of the associated control systems and inertia. Dynamic stability had investigated in previous works such as in [4] and [5] from the few point of power quality and small signal stability where few previous works have investigate the transient stability [6].

This paper presents the impacts of replacing conventional generating units by PV system on power system dynamic performance operating conditions. The effect of changing the location of connecting PV system on dynamic stability is investigated. The rest of paper is organized as follows: section II presents the relation between PV system integration and power system stability. Section III presents the basic modeling of PV system. Section IV presents the modeling pf PV system in DigSILENT software.[7] The description of the test system is presented in section V. Finally discussion of obtained results and conclusion are in section VI.

II. PV SYSTEM AND POWER SYSTEM STABILITY

The power system dynamic stability mainly depends on the system ability to respond to the power fluctuation following disturbances. The integration or replacement of traditional generating units by PV generating system results a reduction in system total inertia and may deteriorate system dynamic stability. In addition to the effect of system inertia on system stability, the sudden large change in irradiance may have a great effect on AC grid voltage level and system dynamic behavior. Therefore, the modeling of the PV system should integrated by reactive power control loop to help with the voltage control and active power control. The active power control can be related direct to the frequency fluctuations and DC input voltage to the inverter. The most used voltage control loops are the constant power factor control and automatic voltage control [8]. In the constant power factor control, the difference between the reference and measured reactive power derives PI controller to determine the amount of reactive power supplied or absorbed by the PV inverter. In the automatic voltage control technique, the driving signal is the difference between the reference terminal voltage and the measured terminal voltage.

III. Basic Photovoltaic System Modeling

The main part of the PV system is the PV cell. The PV cell is basically a semiconductor diode which converts sunlight into electricity during exposing whose p-n junction to light. The photovoltaic system is represented by an equivalent circuit for the PV array, inverters and controller. Array is composed of several connected PV modules in series and parallel to increase the output current and voltage. Module refers to a number of cells connected in series. There are various ways of approaching the simulation of the PV cell [9]. The parameters of the PV array are always provided with reference to the standard test conditions (STC) and need to modify where PV power output is proportional to the radiation that hit PV cell and the cell temperature. The power output is then converted from DC to AC before it is transferred to the electrical network. The complete system is called PV system (PVS). The PV system consists of PV array, DC-bus capacitor, inverter and integrated control system. In order to reflect the dynamic characteristics, various components within the PV system need to be modeled and connected through a certain structure. The DC-bus capacitor provides isolation between the grid side and PV modules and controls of power flow through charging and discharging process. The other output that can be controlled is voltage and power factor at the point of interconnection. For grid connection, most of the inverter is operated as voltage source with current control. Power electronic devices IGBTs are normally utilized for switching. The layout of PV interface to the grid through voltage source inverter (VSI) is depicted in Fig. 1.

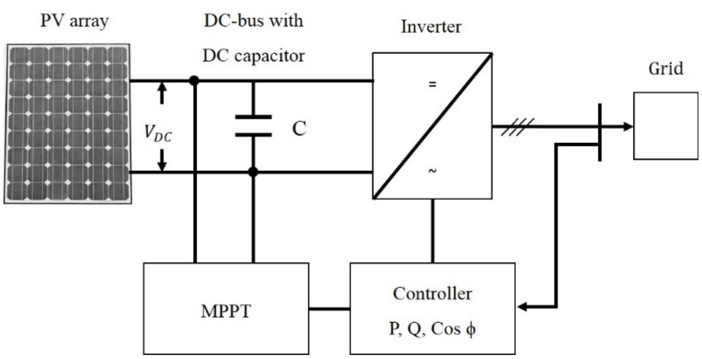

Figure 1: Typical PVS layout

The controller works by determining the magnitude and angle of the voltage at inverter terminal VAC so that the correct amount of electrical power PDC from PV is transferred to the electrical grid. The controller is implemented for enabling active and reactive power be controlled independently. Active power is controlled through regulating the DC voltage across the capacitor terminals compared to the reference PV array output voltage for maximum power point. The capacitance inside DC-bus circuit acts as energy storage which provides isolation between grid and PV modules. The voltage of the DC capacitor can also be kept constant using the PV system controller by balancing the amount of power transfer from PV module to electrical grid. Reactive power can be controlled by reactive component of reference current according to the specified control strategy based on the terminal voltage or remote signals. Sinusoidal voltage from DC voltage can be achieved using a modulating circuit.

IV. Modeling of PV System in PowerFactory

Static generator model introduced in DigSILENT software environment to represent elements such as photovoltaic generators, storage devices and HVDC terminals. Detailed PV template model based current source is modeled in the DigSILENT software environment and is used during the study with modifications. Fig. 2 presents the basic components of the composed model. The model mainly consists of four parts PV array model, DC voltage controller, current controller and static generator in addition to measurement units. The control accomplished by creating a combined composite of the complete PV module.

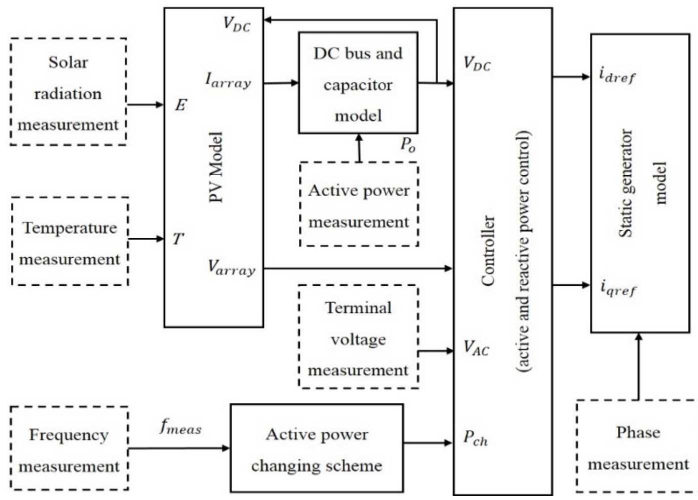

Figure 2: Composed model for PV system in DigSILENT

The PV array model consists of many solar cells which are connected in series and parallel to provide the desired level of voltage and power. The paper uses a single diode equivalent circuit for the PV model as shown in Fig. 3.

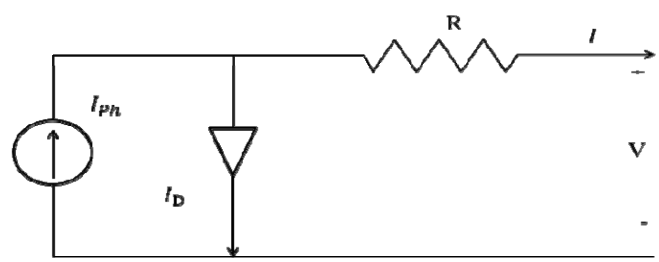

Figure 3: Equivalent circuit of a solar PV cell

The output current from each PV cell is the difference between the photo electric current (I_{Ph}) and the diode effect current (I_D). The photo electric current is equal to the short circuit current of the PV cell.

$$I = I_{Ph} - I_D = I_{Ph} - I_o\left(e^{(V+IR)/v_t} - 1\right) \quad (1)$$

$$I = f(I,V), I_{Ph} = I_{sc}\ , v_t = \frac{kT_c}{q} \quad (2)$$

Where R is the cell resistance, k is the Boltzmann's gas constant, q is the electron charge and is T_c the absolute temperature. The saturation current (I_o) can be calculated from the open circuit condition based on the cell temperature (T_{cell}) by:

$$I_o = \frac{I_{sct}}{e^{\left(V_{oct}/v_t\right)} - 1} \quad (3)$$

The voltage and current output are available at standard rating conditions of solar irradiation (1000 W/m^2) and temperature (25 degree). The short circuit current and open circuit voltage at the operating cell temperature as a function of the temperature change and temperature coefficients that provide the rate of change with respect to temperature of the PV performance parameters, can be express as:

$$I_{sct} = I_{sct}^{SCT}(1 + k_{ti}(T_{cell} - T_{ref})) \quad (4)$$

$$I_{sc} = I_{sct}\left(\frac{E}{E^{SCT}}\right) \quad (5)$$

$$V_{oct} = V_{oc}^{SCT}(1 + k_{tV}(T_{cell} - T_{ref}) \quad (6)$$

$$V_{oc} = V_{oct}\left(\frac{ln(E)}{ln(E^{SCT})}\right) \quad (7)$$

Where I_{sct} and I_{sct}^{SCT} are the short circuit current at cell temperature and SCT. V_{oct} and V_{oc}^{SCT} are the open circuit voltages at cell temperature and SCT. k_{ti} and k_{tV} are the temperature correction factors for current and voltage respectively. E and E^{SCT} are the irradiance at cell temperature and SCT. T_{ref} is the room temperature at SCT. Newton-Raphson is employed to solve for the output current.

The power at each instant is obtained by multiplying the PV current and terminal voltages. The output voltage is controlled for maximum power point tracking (MPPT) using approximating linear prediction and error correction algorithm as given in [10]. The algorithm is implemented using DIgSILENT Programming Language (DPL). The output current feeds into the DC voltage controller to control the DC output voltage across the capacitor terminals to produce the desired operating output power via static generator model. Simplified connection diagram of the internal control loops shown in Fig. 4. The DC voltage specified according to the operating conditions and the rating of the capacitor. The charging and discharging of the capacitor can be used to control the supplied active power and support the frequency control. The active power is controlled using a built in current controller to provide the reference current for the static generator. The active component of the reference current is controlled via PI controller. The inputs of the PI controller are the DC voltage across the capacitor and additional signal from active power control loop. This signal is added to control the frequency deviation during transient operation. The variation of the output active power (P_{ch}) depends on the percentage active power frequency response of the PV system during over-frequency and under-frequency operating regions.

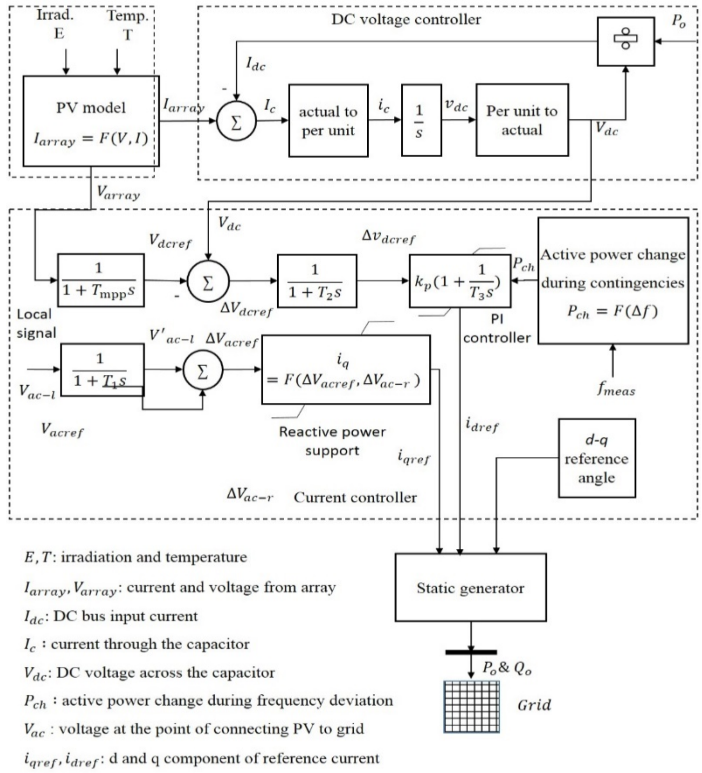

Figure 4: Control loops in PV system composite model

The active power curtailment prevents the PV system to inject all available solar energy during power oscillations to keep the system frequency with specified limits as shown in Fig. 4. The active component of the reference current injected to the static generator is controlled to reduce the active power transfer to the grid during fault ride through or increased to match the active power output to the setpoint value. The fluctuation of voltage increases with large integration of PV system due to the stochastic variation of irradiation. The voltage control can be achieved by reactive power control through local or remote feedback signals. In the used modified model, the reactive power is regulated based on reference value of the voltage at the connection point and remote location to provide the capability to absorb or inject reactive power. The regulation occurred via reactive support function based on the desired grid code in the current controller as shown in Fig. 5. The reactive power support is limited according to the limits voltage and current magnitudes based on the rating of inverter hardware. The utilization of remote signal can be used to improve voltage stability and make it is possible to inject the full available solar energy and avoid overvoltage.

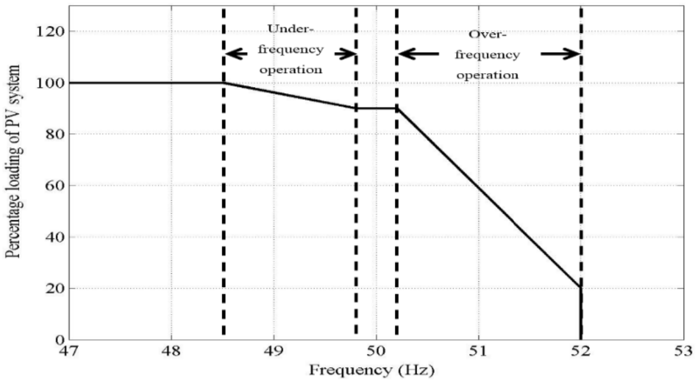

Figure 5: Variation of PV system power with frequency deviation

The active and reactive components of the reference current are fed to static generator to produce the corresponding active and reactive power. The calculated d-q component of the reference current fed to the static generator and synchronized with the grid using d-q reference angle to produce the desired active and reactive power. Static generator is provided in PowerFactory to represent the static source of energy such as photovoltaic and fuel cells. Current source model is used where the output active and reactive power depend on the d-q components of reference input current. The active power of the static generator is defined by the real part of the reference current if we assume constant bus voltage.

V. DESCRIPTION OF TEST POWER SYSTEM

The investigation of the impacts of the PV system integration on power system dynamic behavior is illustrated using the 11-Bus test system [11]. The single line diagram is shown in Fig. 6.

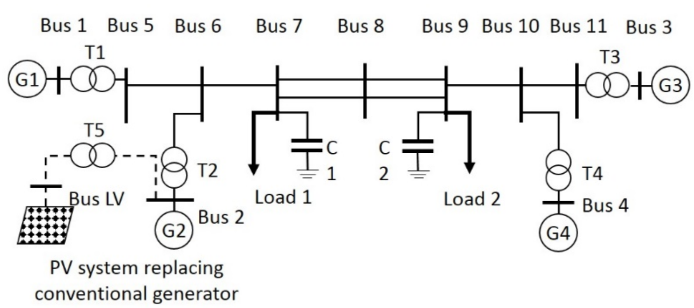

Figure 6: Four-machine, 11-bus power system

G1 is considered as reference machine and the operating performance characteristics investigated with PV system replacing conventional generating station G2. G2 consists of 7 units and each unit is replaced by PV generator with the same rating to investigate the system dynamic behavior. The PV generator is assumed to generate the same active and reactive power generated from the disconnected conventional generating unit. Table 1 presents the main parameter of the used PV system unit parameters.

TABLE 1: PV SYSTEM PARAMETERS

PV Module	Number of modules connected in series: 20 Number of modules connected in parallel: 140 Output power: 0.45 KW. Power factor: 0.95 lag Open circuit voltage in STC: 43.8 V Short Circuit current:5A MPPT voltage: 35 V. MPPT current: 4.6 A
DC voltage controller	Capacitor in each array: 0.0175 µ Farad Nominal voltage: 1000 V Rated power:10 MW
Current controller	$T_1 = T_2 = 0.001\ s, T_3 = 0.003\ s, T_{mpp} = 3\ s$

There is no effect on the steady state operating condition with replacing the conventional generator by PV system at the same active and reactive power output. A three phase fault is used to investigate the system dynamic behavior which strongly depends on the system transient behavior following the fault and system inertia. Without connecting the PV system, the worst case with minimum CCT of 298 milliseconds associated with fault at bus 6 and the corresponding critical generator is G4.

The effects of the PV model is investigated with and without reactive current control. Fig. 7 shows the change in terminal voltage at bus 7 and Fig. 8 presents the variation of Grid frequency to a three phase fault of 0.2 second duration at Bus 10 with replacement of traditional generating units at Bus 2 by equivalent PV generating system.

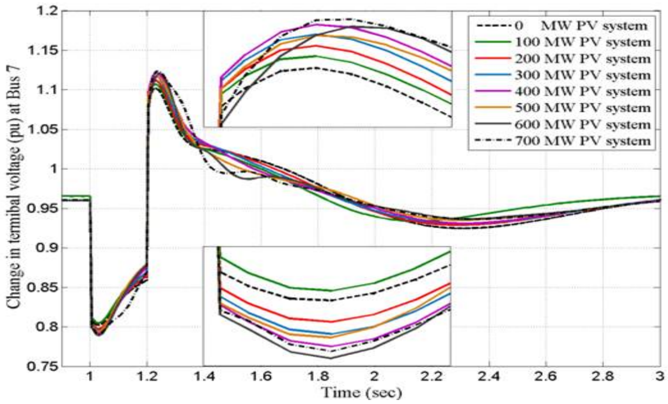

Figure 8: Change in terminal voltage at bus 7

The results indicate that the terminal voltage is slightly varied with increasing the PV system integration level while the frequency is strongly affected with completely replacement of the traditional power station G2 by equivalent PV system generating units. This is due to the reduction of system inertia where the frequency variation strongly dependent on the system inertia.

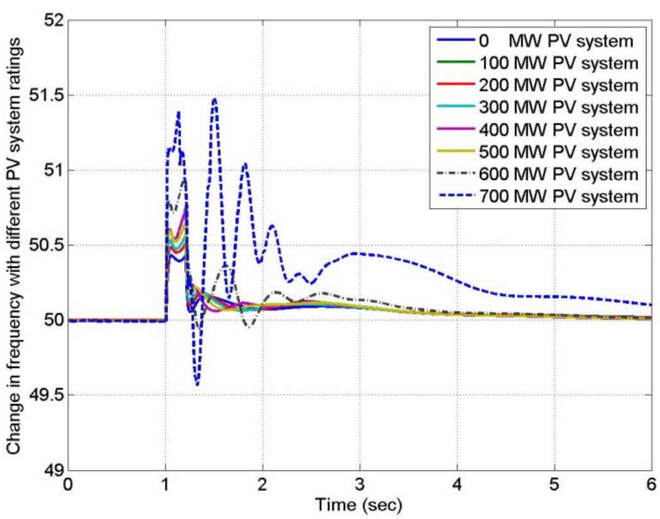

Figure 9: Frequency variation with replacing G2 by PV units

Figure 9 presents the minimum CCT associated three phase faults at the bus 6 which is the critical fault location in the system with replacing each conventional generating unit by equivalent PV system unit. The results also reflect the deterioration of system stability with increasing the level of PV system replacement where the system transferred from transiently stable to transiently unstable region with complete replacement of G2 by PV system.

To investigate the effect of PV system location on the system dynamic, 100 MW unit of G2 is replaced by PV system units at

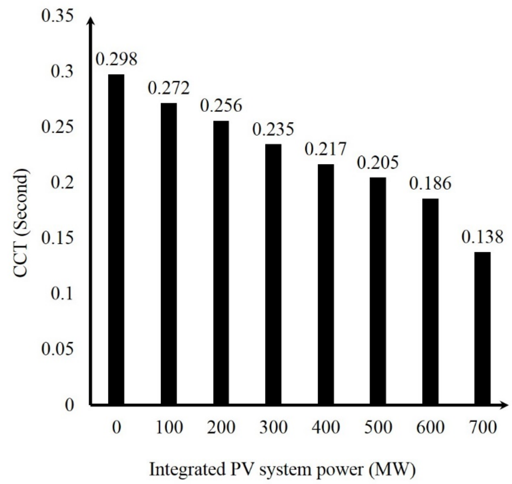

Figure 7: CCT with replacing G2 by PV system units

all busses. Fig. 10 shows the variation of system frequency and Fig. 11 presents the terminal voltage of load connected at bus 7.

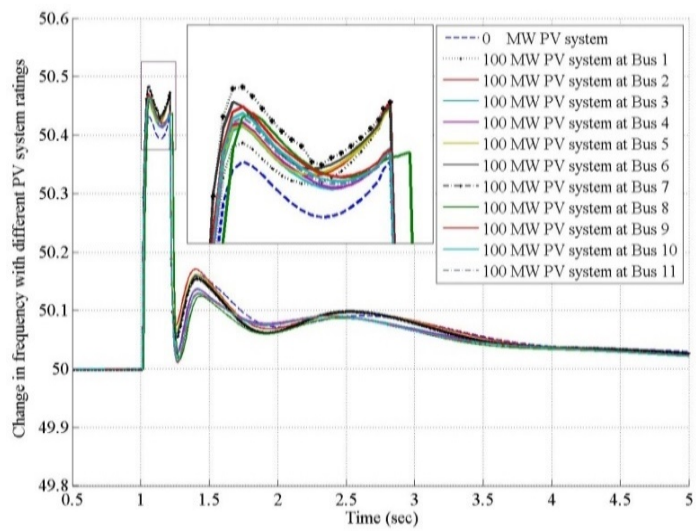

Figure 10: Frequency variation with connecting PV unit at all busses

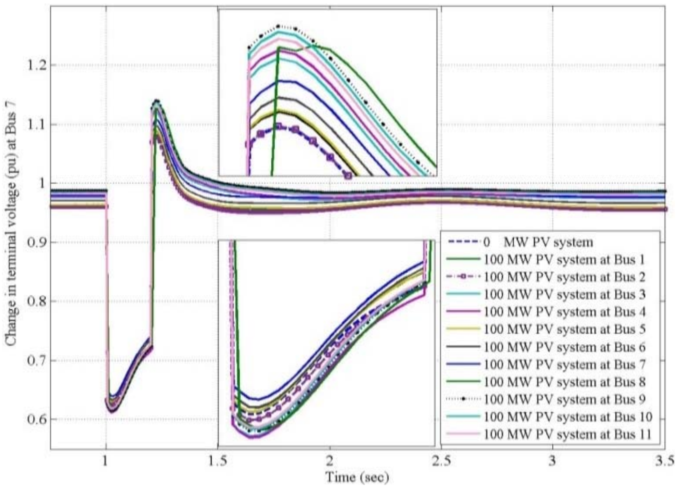

Figure 11: The terminal voltage at bus 7

The change in the location of the 100 MW PV unit had a small effect on frequency variation while the terminal voltage at bus 7 is more sensitive to the location of the PV system. The best location is bus 2 while the worst is bus 9. The effect of PV system location on the minimum CCT illustrated in Fig. 12. The CCT is significantly affected by the location of PV system. Based on the results, connecting the PV system at bus 1, bus 2 and bus 5 decreases the CCT while it is increased with connecting at other busses with a three phase fault at critical fault location. Therefore, the power system transient stability depends on the location of replacement of traditional generating unit by PV system.

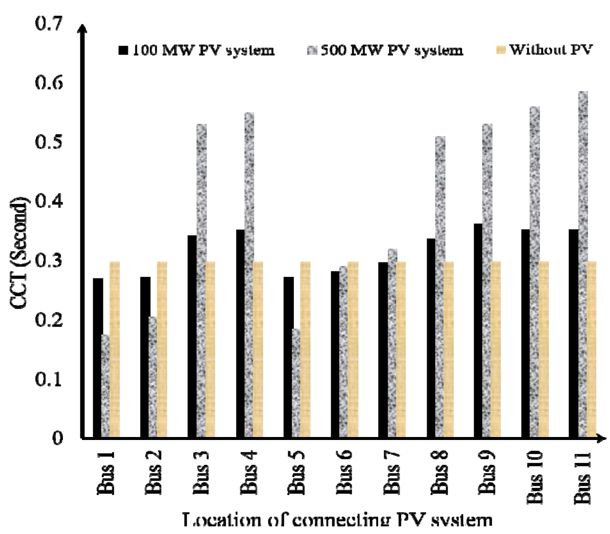

Figure 12: CCT with connecting PV system at different locations

VI. CONCLUSION

The effect of gradually replacing conventional generator with PV system on power system dynamic stability is investigated. Detailed model of PV system provided in DigSILENT software is used with assuming that the PV system has the capability to supply the reactive power using associated controller and integrated reactive power sources. The model integrated by a controller to regulate the active and reactive power outputs according to the DC side output of the PV system considering the output of PV array and the terminal voltage of the DC side capacitor. Impacts of connecting PV system on transient stability and voltage profiles have been investigated. The best location of connecting PV system can be selected based on CCT considering voltage profiles at all busses. The results show the system transient stability depends on the location of replacement of traditional generating units by PV system. With allocating the PV system at the optimal location, the CCT is significantly increased. The voltage profiles are less in case of connecting PV system compared with connecting steam generation units but with insignificant change.

REFERENCES

[1] Sara Eftekharnejad, Vijay Vittal, Gerald Thomas Heydt, Brian Keel, and Jeffrey Loehr, “Impact of Increased Penetration of Photovoltaic Generation on Power Systems”, IEEE Transactions on Power System, vol. 28, no. 2, May 2013.

[2] P. P. Dash and M. Kazerani, "Dynamic modeling and performance analysis of a grid-connected current-source inverter-based photovoltaic system," IEEE Transactions on Sustainable Energy, vol. 2, pp. 443-450, 2011.

[3] H. C. Seo, C. H. Kim, Y. M. Yoon, and C. S. Jung, "Dynamics of gridconnected photovoltaic system at fault conditions," in Transmission & Distribution Conference & Exposition: Asia and Pacific, 2009, pp. 1-4.

[4] Yazdani, A.; Dash, P.P., "A Control Methodology and Characterization of Dynamics for a Photovoltaic (PV) System Interfaced With a Distribution Network," in Power Delivery, IEEE Transactions on , vol.24, no.3, pp.1538-1551, July 2009.

[5] M. Liserre, R. Teodorescue, and F. Blaabjerg, “Stability of photovoltaic and wind turbine grid-connected inverters for a large set of grid impedance values,” IEEE Trans. Power Electron., vol. 21, no. 1, pp. 263–272, Jan. 2006.

[6] M. Yagami, S. Ishikawa, Y. Ichinohe, K. Misawa, and J. Tamura, Tamura, “Transient stability assessment of synchronous generator in powersystem with high-penetration photovoltaics (part 2) ,” International Conference on Electrical Machines and Systems, Oct. 26-29, 2013, Busan, Korea.

[7] DIgSILENT PowerFactory. [Online]. Available: http://www.digsilent.de

[8] Yun Tiam Tan; Kirschen, D.S., "Impact on the Power System of a Large Penetration of Photovoltaic Generation," Power Engineering Society General Meeting, 2007. IEEE , vol., no., pp.1,8, 24-28 June 2007

[9] Villalva MG, Gazoli JR, Filho ER. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Trans. Power Electron 2009;24(5):1198–208.

[10] Wei Xu, Chaoxu Mu, and Jianxun Jin, “ Novel Linear Iteration Maximum Power Point Tracking Algorithm for Photovoltaic Power Generation”, IEEE Trans on applied superconductivity, vol. 24, no. 5, October 2014.

[11] P. Kundur, Power System Stability and Control. New York: McGraw-Hill, 1994.