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VOLTAGE STABILITY ASSESSMENT IN A DISTRIBUTED PHOTOVOLTAIC SYSTEM USING VOLTAGE STABILITY INDEX

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***ABSTRACT*:** Distributed Generation (DG) plays a role of a small electric power generator or storage which is not a part of a large central power system. At present scenario due to the numerous advantages, Distribution Generation (DG) has now been integrated with grid. Integration with grid will ensure more reliable and durable power system. However, stability problem in power system arises in numerous ways depending upon configuration of the system and operating mode. In Distributed Generation (DG), voltage stability problem occurs commonly due to reactive power deficiency. The voltage instability might lead to voltage collapse and in due course of time power block outs may occur. In a Photovoltaic based DG, the problem of voltage instability problems are controlled by controlling the real and reactive power with help of compensating devices. In this paper a grid connected 100kW Photovoltaic system is implemented using MATLAB/Simulink and Voltage Stability Index (VSI) of 33 radial bus distribution system is continuously evaluated in order to assess the stability problem.

Key words: Distributed Generation (DG), Voltage Stability Index (VSI), Photovoltaic System (PV)

I. INTRODUCTION

At present scenario, the future of deregulation confronted by the electric utilities. Constructive environment for the entry of distributed assets will be created only when there is necessary to provide adequate power quality and reliability. Advancement in recent technologies has encouraged the entry of Power generation and energy storage at the distribution level. Distributed utility uses both distributed resources and load management, in order to achieve its goal. DG has advantageous sites like; provides market participants the opportunity to make response according to the market condition which is changing with the variation of time, it also provides reliability, flexibility in price and quality with the merits of serving as a substitute of grid investment. Moreover the DG system is more attractive than most types of central power plants as it has small size and short construction lead times. It also an environmental friendly as the emission from DG technology is less than coal power station.

Different Distributed generation technologies are being developed under different phases. This includes turbines, gas turbines, diesel engines, photovoltaic systems (PV), gas-fired IC engines, wind energy conversion systems (WECS), and fuel cell systems. Also distributed generator such as fuel cells and photovoltaic's have quite low maintenance cost because, there is no moving parts. Numerous advantages are resulted when integrating the Distributed Generation into a utility. These advantages are named as, relieved transmission and distribution congestion, peak shaving, line loss reduction, reduced environmental impacts, voltage support and increased overall energy efficiency. Unfortunately, as the penetration level of the PV system increases the power system might fall into the state of instability. This

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is due to inability of the power system to supply the reactive power or extract more reactive power by the system itself. This condition has contributed to the growing importance of the problems associated with stability assessment in the grid connected distributed PV system. Hence voltage stability of the DG system has to be continuously monitored by evaluating the voltage stability index values at different nodes or buses. In the stability analysis of a Distributed photovoltaic system location of distributed generator also plays an important factor.

Advantageous side of the DG is the improved service reliability and quality, better voltage regulation and have lesser transmission and distribution losses [3]. This paper presents evaluation of voltage stability index in a distributed PV system. Voltage stability index have been evaluated in order to investigate the strength and condition of each nodes or buses. Voltage stability index values helps to indentify the weak/or strong buses of the distributed PV system so that corrective action can be made if any of the buses reaches the state of critical condition. In this paper voltage stability index value of a 100kW grid connected distributed PV system has been evaluated for 33 radial node or bus distribution system.

II. VOLTAGE STABILITY

Voltage stability is the ability of a power system to maintain steady state voltage at all buses in the system under normal operating condition and after the occurrence of a disturbance [1]. The main factor contributing to voltage instability is usually the voltage drops that limit the capacity of transmission networks to transfer power between buses. Increased voltage drops could be associated with the change of rotor angles. Voltage instability occurs when load dynamics try to restore power consumption beyond the capability of the transmission system and the connected generation.
With the increased loading and exploitation of the existing power structure, the probability of occurrence of voltage collapse are significantly greater than before and the identification of the nodes which prone to the voltage fluctuations have attracted more attention for the transmission as well as the distribution systems. For operating a power system in a safe and secure manner, all unsecure operating states must be identified well in advance to facilitate corrective measures to overcome the threat of possible voltage collapse.

2.1 VOLTAGE STABILITY INDICES

Voltage stability is considered as the potential of a power system in maintaining its buses voltage amplitude against the increment of the load demand. Many different indices have been introduced to evaluate the power systems security level from the point of voltage static stability. By considering the radial distribution networks properties, the following index is used for the present paper. **Chakravorty** and **Das** (Chakravorty and Das, 2001) proposed a method that computes the voltage stability index of nodes (k = 2,3,…,n) as follow.

$$SI_k = |E_0|^4 - 4\{P_k X_k - Q_k R_k \}^2 - 4\{P_k R_k + Q_k X_k \}|E_0|^2 \quad (1)$$

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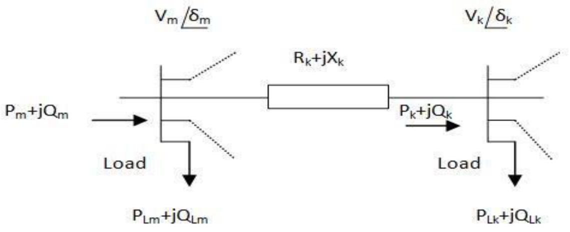

Figue1: Line section model of radial distribution system

The system is reduced to equivalent circuit with following equation to calculate the equivalent impedance from main substation to buses to find each value of SI. Figure shows the electrical equivalent for proposed method

$$R_k + jX_k = \frac{[(P_1 + jQ_1) - (P_k + jQ_k)] \cdot E_0^2}{(P_1^2 + Q_1^2)}$$

(2)

Where,

E_0 and $V_k \angle \delta$ are voltage of main substation and node k respectively

$S_1 = P_1 + jQ_1$ is apparent power of substation feeder

$S_k = P_k + jQ_k$ is apparent power of node k.

For secure and stable operation must be $SI_k > 0$ for all nodes. The node with minimum value of voltage stability index could be shown that it is more sensitive to the voltage collapse.

III. PV SYSTEM MODELLING

A solar cell is a p-n semiconductor junction, when exposed to the light; a current is generated (DC current).The generated current change linearly with the solar irradiance. A solar cell is a building block of a solar panel. By connecting solar cells in series and parallel combinations a PV module is formed. A single solar is modelled by utilizing a current source, a diode and two resistors. This model is called as single diode model of solar cell.

The PV mathematical model of a single diode model used to simplify PV array is represented by the equations (2.1) – (2.4)

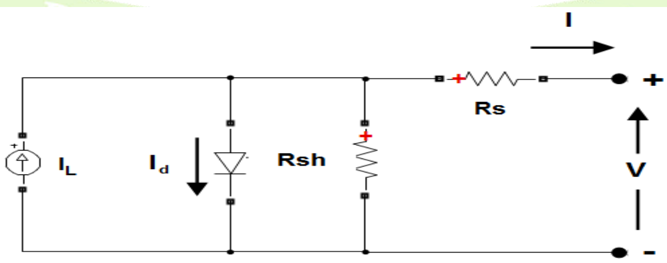

Figure 2: Equivalent circuit of PV Cell

$I_D = I_O [\exp (q(V + I R_s)/KT)) – 1]$

(3)

While, the solar cell output current:

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$$I = I_L - I_D - I_{sh} \quad (4)$$

$$I = I_L - I_O\,[\exp\,(q(V + I\,R_S)/KT)) - 1] - (\,V + IR_S\,)/\,R_{sh} \quad (5)$$

Where:
I : Solar cell current (A)
I_L: Light generated current (A) [Short circuit value assuming no series/ shunt resistance]
I_O: Diode saturation current (A)
q : Electron charge (1.6×10-19 C)
K : Boltzman constant (1.38×10-23 J/K)
T : Cell temperature in Kelvin (K)
V : solar cell output voltage (V)
R_s: Solar cell series resistance (Ω)
R_{sh}: Solar cell shunt resistance (Ω)

In this paper 330 Sun Power modules (SPR 305) are used. PV array consists of 66 strings of parallel connected modules with each strings having 5 series connected module. Each module produces a power of 305.2W (66*5*305.2W=100.7kW). It is considered that all panels are identical and are subject to the same meteorological conditions. The electrical characteristics of PV modules used in the simulation are listed in the table 1.

Parameter	**Specifications**
STC Power Rating	305 W
Peak Efficiency	18.7%
Number of Cells	96
Imp	5.58 A
Vmp	54.7 V
Isc	5.96 A
Voc	64.2 V
Temp. Coefficient of Power	0.38% /K
Temp. Coefficient of Voltage	0.177 V/K
NOCT	45°C

Table 1. Specification of SPR 305 Module

The IV and PV characteristics of PV module with different irradiations levels are shown in figure 1. When irradiance and cell temperature changes, the current-voltage and power-voltage characteristics changes. As the temperature is rising the efficiency is falling. This indicates the necessity of voltage, or current regulation power electronic circuits (MPPT), and a system to enable the maximization of the generated power.

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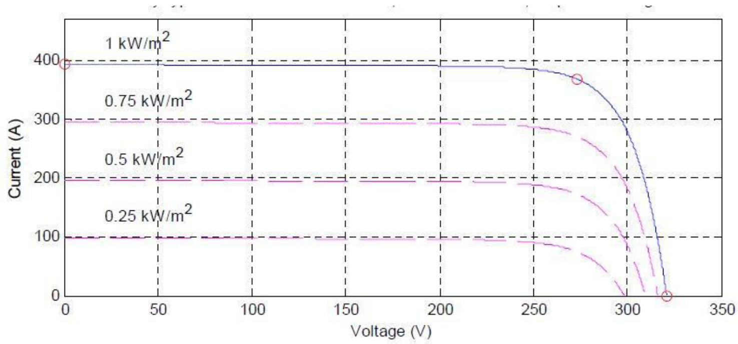

Figure 3. V-I characteristics with different irradiation level

Red dots on blue curves indicate module manufacturer specifications (Voc, Isc, Vmp, Imp) under standard test conditions (25 degrees Celsius, 1000 W/m^2).

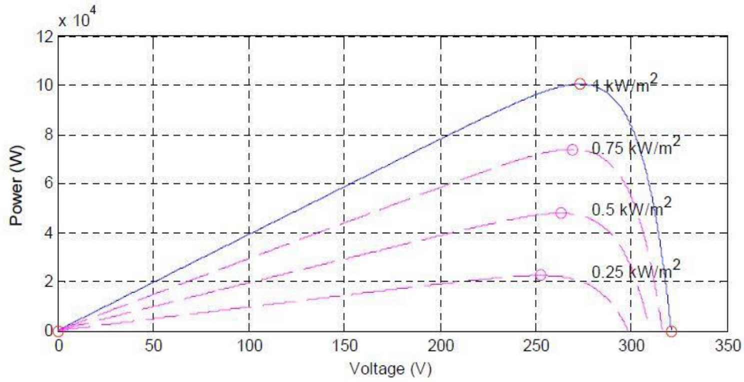

Figure 4: P-V characteristics for different irradiation level

3.1 MAXIMUM POWER POINT TRACKING

PV modules output power varies with changes in direction of the sun, solar radiation level and temperature. Also for a given operating condition there is only one maximum power point in the PV characteristics of the PV modules. It should be essential that the PV module operates close to this point. The process of operating PV module at this condition is called as maximum power point tracking (MPPT). The utilization of the solar PV module gets improved by maximization of PV power. Since the output power of PV cell depends upon various parameters like solar radiation, temperature and load, the output characteristic is nonlinear. To achieve the best performance under changing external environmental condition it is essential that PV system should work at maximum power point. Maximum power extracted from the PV cell is transferred to the load by using MPPT.

3.2 VARIOUS MPPT ALGORITHMS

Different maximum power point tracking (MPPT) algorithms have been implemented and these algorithms are distinguished from each other based on the factors like cost, complexity and number of sensors used. Most commonly used MPPT algorithms are listed below.

1) *Perturb and Observe (P&O) method:* The operating voltage of PV cell is perturbed in this method. This method is easy to implement and is not accurate and fast enough, since temperature and solar radiation effects are not been considered [10].

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2) *Incremental Conductance (IC) method*: In this method slope of the PV curve is used for determining the MPP. The slope of the PV is positive on the left of MPP and negative on the right of MPP. This method is an accurate and fast but is complex and the hardware requirements are more.
3) *Fractional Open Circuit Voltage method and Fractional Short Circuit Current method.* In fractional open circuit voltage method the MPP voltage with respect to VOC is monitored and in the case of Fractional Short Circuit Current method, the MPP current with respect to ISC is monitored. Due to the approximation of a constant ratio these methods have lower efficiency and the accuracy under varying weather conditions cannot be guaranteed.

3.3 Proposed MPPT Algorithm

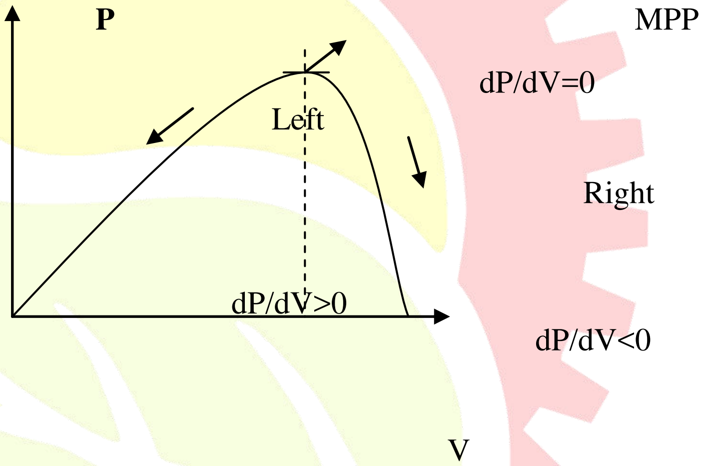

Figure 5: P-V Curve of solar module

In the proposed MPPT algorithm, the array terminal voltage is adjusted according to the MPP voltage is based on the incremental and instantaneous conductance of the PV module. The basic concept of Incremental conductance on a PV curve of a solar module is shown in figure. The slope of the P-V module power curve is zero at The MPP, increasing on the left hand side of the MPP and decreasing on the right hand side of the MPP. The basic equations of this method are as follows.

$$dP/dV=0 \text{ at MPP}$$
$$dP/dV>0 \text{ left of MPP}$$
$$dP/dV<0 \text{ right of MPP}$$
$$dP/dV = d(VI)/d(V)= I + V*dI/dV$$

(6)

The *dP/dV* is used as Maximum power point identifier factor. By, The IC method is proposed by utilizing this factor for effectively tracking the MPP of PV array. PWM control signal of the boost converter regulated by the MPPT until the desire condition: $(dI/dV) + (I/V) = 0$ is achieved. The Flow chart of incremental conductance MPPT is shown in figure. The voltage reference of PV array is adjusted by increasing or decreasing a constant value ($\Delta V=\delta$) to the previous reference voltage with the help of control signals produced by the IC method. MPP is achieved by a fixed step size ($+\ \delta$) without considering the gap between the operating point of PV and MPP location.

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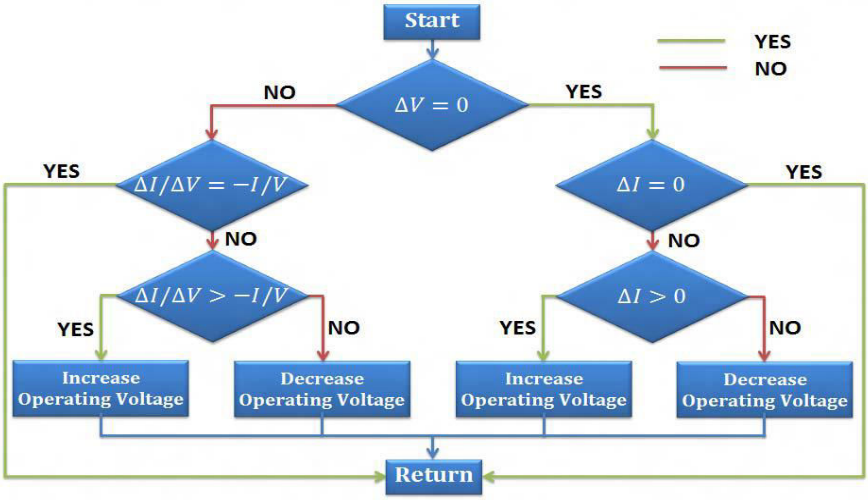

Figure 6. Flow chart of Incremental conductance method

3.4 BOOST CONVERTER

DC-DC converters used to convert an unregulated dc voltage to a regulated dc output voltage. The converter is used as a switching mode regulator. PWM at a fixed frequency is used for achieving the regulation and BJT, MOSFET or IGBT is generally used as a switching device. There are different types of dc- dc converters are used to meet variety of application specific demands such as buck, boost, buck-boost and cuk topologies. DC–DC converter used in the MPPT scheme should have a low input current ripple. Buck converter produces high current ripples on the PV module side and hence larger value of input capacitance is required on the module side. On the other side, boost converters have low ripple on the PV module side, so in this simulation work, boost converter is used.

The steady-state voltage and current relations of the boost converter operating in continuous current mode are

$$V_D = \frac{Vpv}{1-D} \quad (7)$$

$$I_D = \eta_b(1-D)\, I_{pv} \quad (8)$$

Where:

ηb: Efficiency of the boost converter
D: Dc-dc converter duty cycle
Ipv: PV array output current
Vpv: PV array output voltage
ID: Dc bus current (inverter side)
VD: Dc bus voltage (inverter side)

5-kHz boost converter increases the voltage of PV module (272 V DC at maximum power) to 500 V DC. Switching duty cycle is optimized by the MPPT controller that uses the "Incremental Conductance" technique.

A PWM boost converter with the following parameters is used for maximum power point tracking.

PARAMETERS	VALUE
Duty cycle D	0.5

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Inductor Lin	5mH
Capacitor Cin	100µF
Capacitor Cout	12000µF
Switching Frequency Fs	5000 Hz
Output voltage Vout	500V

Table 2. Design parameter of boost converter

3.5 INVERTER MODELLING

PV module is interfaced with grid through an inverter. Two major tasks are involved in inverter interfacing a PV module with the grid. One of the tasks is to ensure that the PV module is operated at the maximum power point (MPP). The other is to inject sinusoidal current into the grid. Various inverter topologies and controllers are used for interfacing the PVG and utility in a grid connected PV system.

3.5.1 Voltage source inverters (VSI)

The DC side of VSI realized as a constant voltage source and the output current is varying with load. For this reason an inductance is normally connected with a grid so that high current is not supplied when there is no voltage or phase match between grid and inverter.The three-level VSC regulates DC bus voltage at 500 V and keeps unity power factor. The control system has two control loops: an external control loop which regulates DC link voltage to +/- 250 V and an internal control loop which regulates Id and Iq grid currents (active and reactive current components). Id current reference is the output of the DC voltage external controller. Iq current reference is set to zero in order to maintain unity power factor. Vd and Vq voltage outputs of the current controller are converted to three modulating signals Uref_abc used by the PWM three-level pulse generator. The control system uses a sample time of 100 µs for voltage and current controllers as well as for the PLL synchronization unit. The VSC converts the 500 V DC to 260 V AC and keeps unity power factor and a 10-kvar capacitor bank filtering harmonics produced by VSC. A 100-kVA three-phase coupling transformer is used to step up the 260 V AC to 25kV AC of utility level.

IV. MATLAB-SIMULINK Environment

By using the characteristic equations (3), (4) & (5) Simulink model of PV array is implemented as shown in figure 7. The PV array modelling uses the parameters correspond to SPR 305 module. The parameters of SPR 305 module is listed in the table. The MATLAB/ Simulink model for incremental conductance method is shown in the figure 8.

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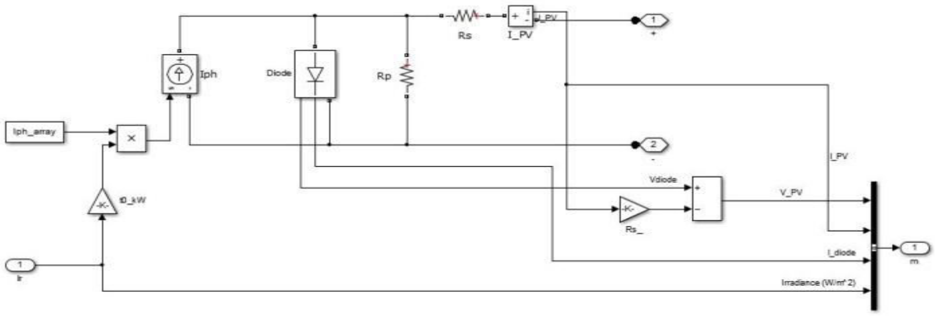

Figure 7. The MATLAB/ Simulink model for PV Array

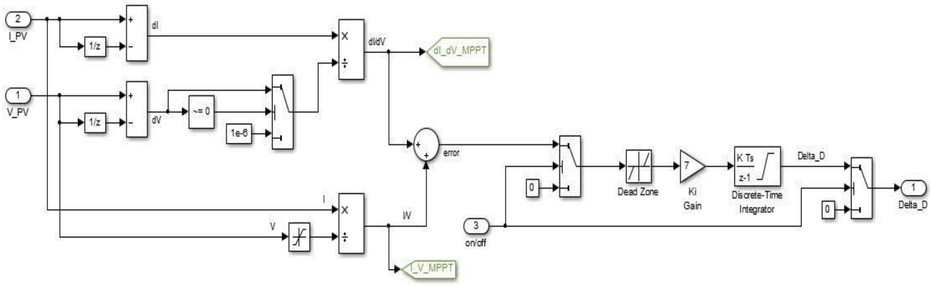

Figure 8. Simulink model of Incremental Conductance Mppt Controller

SIMULINK model of PV array, MPPT, Boost Converter and Inverter is shown in figure 9.

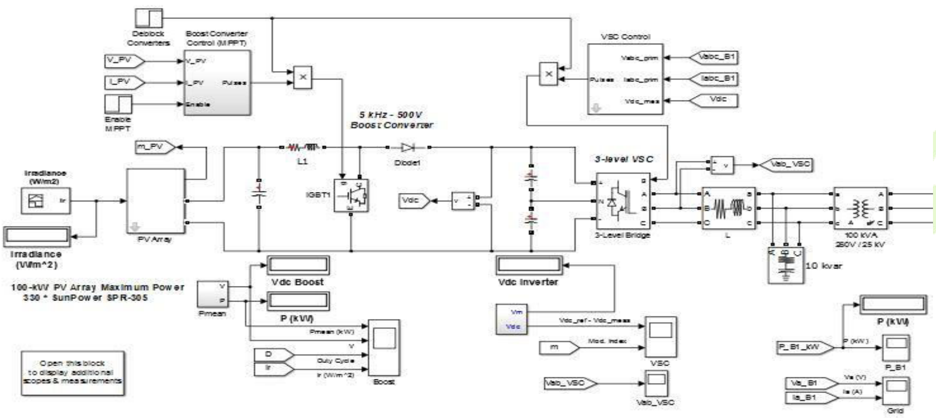

Figure 9. SIMULINK model of PV array, MPPT, Boost Converter and Inverter

The SIMULINK diagram of complete photovoltaic grid connected system shown figure 10. The gird model has PV array is connected to a 50Hz, 25kV grid through a DC/DC boost converter and DC/AC inverter. The 500 V obtained from DC/DC converter is applied to a dc to ac inverter. A 10-kvar capacitor bank filter is inserted after the VSC in order to eliminate harmonics produced by VSC.

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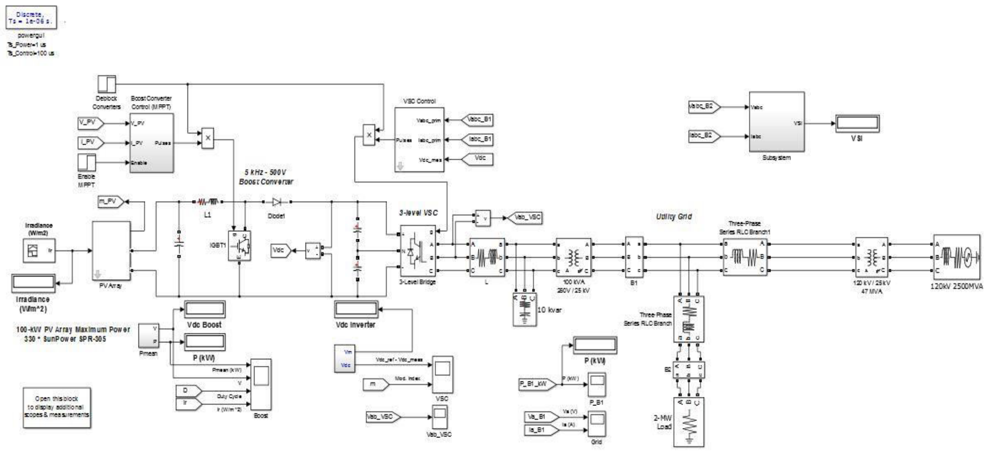


Figure 10. Complete photovoltaic grid connected system

V. SIMULATION RESULTS

The model shown in figure 10 was simulated using MATLAB/ Simulink. The change in irradiation level that falls on the PV solar panel is shown in figure 11. Depending on the variation in irradiation level the voltage and current changes. Signal builder is used for plotting the variation in irradiation level.

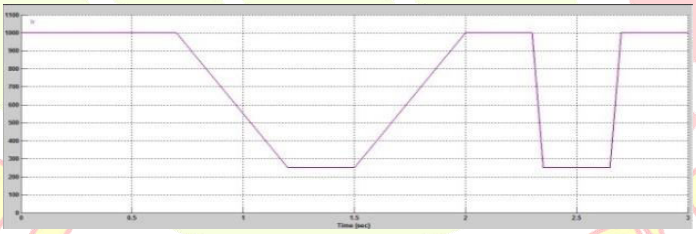
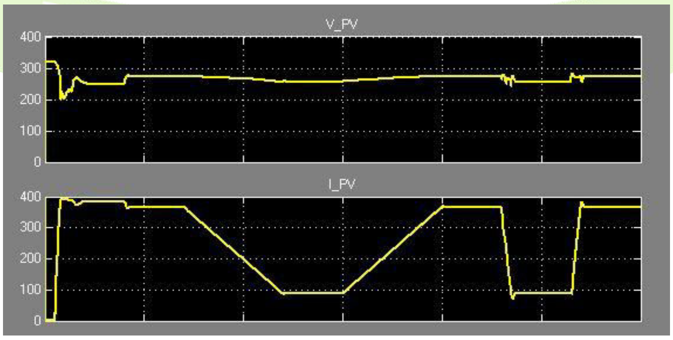


Figure 11. Variation of solar irradiation

The simulation was run with the MPPT controller using the incremental conductance algorithm and 5 kHz boost converter. The output voltage, current and power of PV panel is shown in the figure 12.



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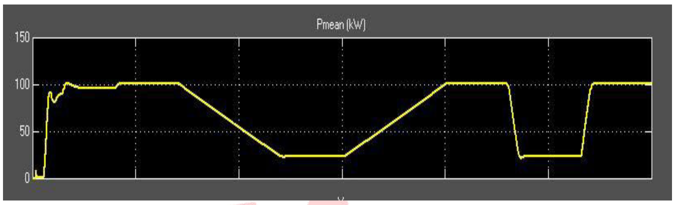

Figure 12. Output voltage, current and power of PV array

Load flow analysis is done for determining the node voltages and then the proposed voltage stability indicator (VSI) values are determined for radial distribution system with 33 nodes on 25 kV. The line data and nominal load data of 33 node radial distribution system are taken from [9].

The values of VSI indicator for each node of 33 bus systems are presented in table 4.

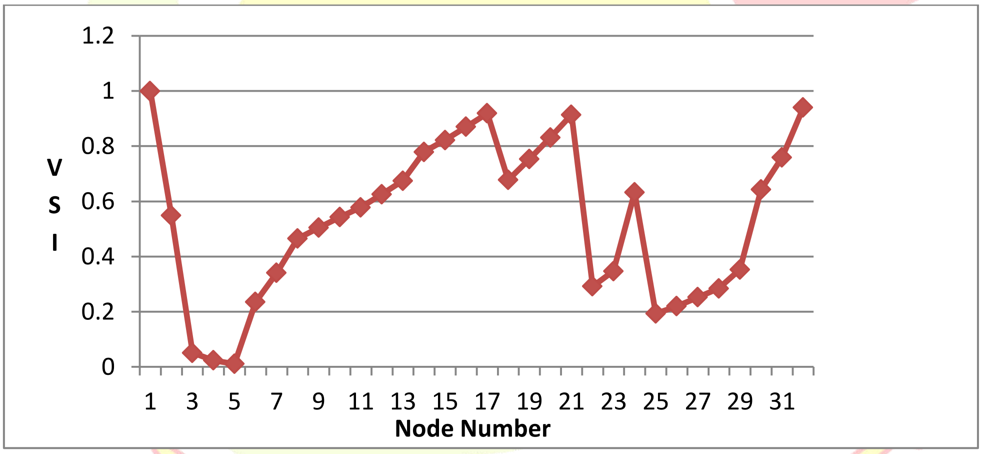

Figure 13. VSI of each node of the proposed system

From table 4, the voltage stability index (VSI) values of each of the 33 bus radial distribution system are arranged based on the critical value. It also helps to identify the bus which is likely to get voltage collapse. From figure 13 it is evident that the node 6, 5 and 4 has minimum values, respectively. Therefore, the buses 6, 5 and 4 are identified as a weakest bus in this system and hence these buses are most likely to get collapse. The figure 13 shows the variation of VSI for different load conditions.

Node Number	VSI
6	**0.01104**
5	**0.02386**
4	**0.05151**
26	0.19338
27	0.22008

7	0.23533
28	0.25282
29	0.28440
23	0.29211
8	0.34080
24	0.34728
30	0.35315

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9	0.46527	20	0.75294
10	0.50452	32	0.75957
11	0.54297	15	0.77896
3	0.54859	16	0.82187
12	0.57811	21	0.83152
13	0.62618	17	0.87006
25	0.63250	22	0.91387
31	0.64276	18	0.91929
14	0.67448	33	0.93989
19	0.67733	2	0.99971

Table 4. VSI of 33 node system

VI. CONCLUSION

The MATLAB/ Simulink model of a 100kW distributed PV system has been modelled and integrated with a grid for investigating the voltage stability of the system. The voltage stability index (VSI) is evaluated for assessing the effect of high penetration level in a distributed PV system. In this paper, voltage stability index (VSI) of a 33 bus radial distribution system is computed. The stability of a grid connected PV system is determined for different load conditions. Also, the stability of the system is continuously monitored by evaluating the stability index (VSI) value at each node. The node that has least index has been identified as a weakest bus or node. In this paper, the nodes 6, 5, and 4 has the least values respectively. Hence these nodes identified as weakest ones and are considered to be in critical condition. So, the weakest nodes are considered for improving the voltage stability of the system.

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