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Modeling of Photovoltaic System Interconnected with Radial Distribution System using MATLAB/SIMULINK

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Abstract*— The global electrical energy consumption is steadily rising and consequently there is a demand to increase the power generation capacity. A significant percentage of the required capacity increase can be based on renewable energy sources. The need for a cleaner environment and the continuous increase in power demand makes renewable energy production, like solar and wind increasingly interesting energy production and solar energy could be a solution for the ever increasing power demands. One of the major advantages of PV technology is that it has no moving parts therefore, the hardware is very robust, it has long life time and low maintenance requirements and most importantly it is one solution that offers environmentally friendly power generation. Maximum Power Point Trackers (MPPTs) play a vital role in photovoltaic systems because they increase the efficiency of the solar photovoltaic system by increasing the power output. A PV array has an optimum operating point, known as the maximum power point, which varies according to cell temperature and insulation level and array voltage. A MPPT is needed to operate the PV array at the optimal point enabling the system to extract the maximum amount of energy available. MPPT algorithms are necessary because PV arrays have a non-linear voltage-current characteristic with a unique point where the power produced is maximum. The output power from the solar panel varies with solar irradiation, temperature and so on. To increase the power extracted from the solar panel, it is necessary to operate the photo voltaic system at the maximum power point. The system implements two of the most popular MPPT methods to extract maximum power, they are perturb & observe and incremental conductance methods. In this paper, the MATLAB/SIMULINK arrangement of perturb & observe (P&O) and incremental conductance (INC) MPPT algorithm which is responsible for driving the dc-dc boost converter to track Maximum Power Point (MPP) is proposed. The system includes PV array, MPPT, buk-booster converter, 3ø Inverter, Step-up Transformer, LC filter. The overall PV model system has good efficiency with the best performance under the incremental conductance algorithm. This system is connected to electric utility to measure the performance. In this paper, the objective such as optimal location and sizing of DG units are analyzed through simulation to check the system performance in reducing the power losses, increase in voltage profile and reliability. For analyzing the performance of PV array an IEEE test system is considered. Simulation results confirmed the effectiveness of the proposed control strategies and their capability under different case study

***Index Terms*— Distributed Generation, Incremental Conductance, Perturb & Observe, Power Losses, PV array, Radial Distribution System, Reliability and Voltage Profile.**

I. INTRODUCTION

Solar photo voltaic energy is now-a-days one of the most important available resources because is free, abundant and pollution free and distributed all over the world. The PV generation systems have two major problems-the conversion efficiency of electric power generation is low and the amount of electric power generation is low, the amount of electric power generated by solar arrays change continuously with weather conditions. Moreover, the solar cell V-I characteristics is non-linear and varies with irradiation and temperature.

In general, there is a unique point on the V-I or V-P curve, called the Maximum Power Point (MPP), at which the entire PV system operates with Maximum efficiency and produces its maximum output power [1 - 4]. The location of the MPP is not known, but can be located, either through calculation models or by search algorithms. Therefore, Maximum Power point Tracking (MPPT) techniques [9] are needed to maintain the PV array's operating point at its MPP. The perturb & observe (P&O)[12-14], incremental conductance (INC)[16-18] method are the most known methods to track the MPP by updating repeatedly the operating voltage of the PV array varying the duty cycle of the power converter with a fixed step size. Even though the solar energy is present throughout the day but the solar irradiation levels vary continuously due to sun intensity on the solar panel varies continuous due to the variation in direct and diffused radiation falling on the solar panel and also because of the unpredictable shadows cast by clouds, birds, trees etc. The common inherent drawbacks of photovoltaic systems are their intermittent natures that make them unreliable. However, by incorporating maximum power tracking algorithms, the photovoltaic systems power transfer efficiency and reliability can be improved significantly as it can continuously maintain the operating point of the solar panel at the MPP pertaining to that irradiation and temperature and so on.

The output power of a PV cell is indeed a non linear function of the operating voltage and this function has a maximum power point corresponding to a particular value of voltage. In order to operate at the MPP, an energy power converter [20-22] must be connected at the output of a PV array, such converter forces the output voltage of the PV array is equal to the optimal value.

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Although they are several methods existing in MPPT, it appears that no attempt has been made to use PV system as a DG in radial distribution system for improvement in voltage profile, reliability and mitigation of losses. Therefore, in this paper, modeling and simulation aspects of PV system is developed to interconnect with radial distribution system for achieving the above objectives.

The effectiveness of the proposed system is tested on IEEE 15 bus radial distribution system, the reliability and load data is given in appendix. The impacts will be evaluated by means of optimal location and sizing by placing at different locations in a distribution system. Furthermore, the proposed analysis aimed at quantifying the distributed generation impact on total power losses, voltage profile and reliability.

II. SYSTEM MODELING

The general block diagram of grid connected photo voltaic system is presented in Fig.1. It consists of PV array, MPPT, DC-DC Converter, Inverter, Step-up Transformer and LC Filter.

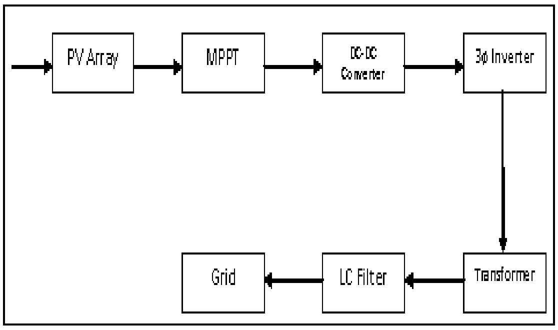

Fig.1 Block Diagram representation of PV System

The model of PV array with MPPT control is simulated in MATLAB/SIMULINK which is presented in Fig.2.

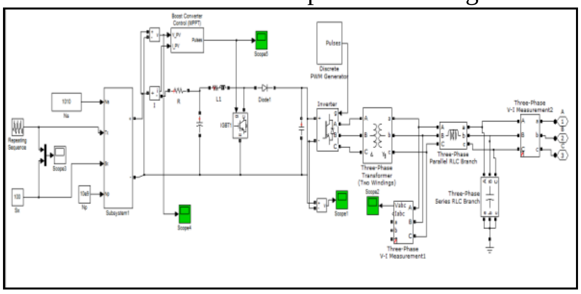

Fig. 2 Simulink model of Photo Voltaic System

III. MAXIMUM POWER POINT TRACKING

A typical solar panel converts only 30 to 40 percent of the incident solar irradiation into electrical energy. Maximum power point tracking technique is used to improve the efficiency of the solar panel. According to maximum power transfer theorem, the power output of a circuit is maximum when the source impedance matches with the load impedance. In the source side a buk-boost converter [19, 23] is connected to a solar panel in order to enhance the output voltage. By changing the duty cycle of the boost converter appropriately the source impedance is matched with that of the load impedance. Several approaches have been proposed for tracking the MPP [5-8]. Among these methods, the Perturb & Observe and Incremental Conductance methods are widely used although they have some problem such as the oscillation around MPP and confusion by rapidly changing atmospheric conditions [10, 11]. In general, these tracking approaches used a fixed iteration step size which is determined by the accuracy and tracking speed requirements.

A. Perturb & Observe Method

The most common used MPPT algorithm is the P&O method and is also known as hill-climbing algorithm due to its simplicity of implementation. However, it has some drawbacks like oscillations around the MPP in steady state operation and also low response speed at the event of changes in solar irradiance. Based on the algorithm of P&O [15] the simulink diagram is developed as shown in Fig.3.

A maximum power point tracker is designed by the combination of Perturb & Observe algorithm which triggers the duty cycle of the DC-DC converter. By changing the duty cycle of converter, the PV panel is made to deliver the maximum power at that irradiance to the load. The MATLAB/SIMULINK model of Perturb & Observe algorithm to track the maximum power output, along with a DC-DC boost converter is shown in Fig. 3.

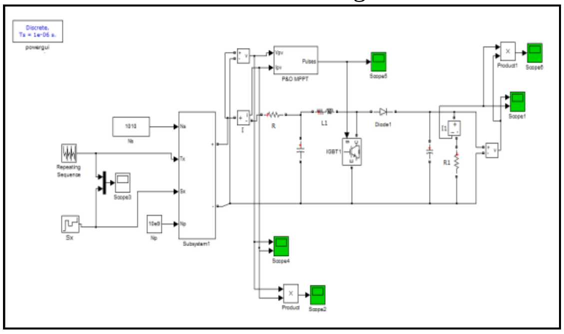

Fig. 3 MATLAB/SIMULINK model of Perturb & Observe algorithm

P & O algorithm is based on the calculation of the PV array output power and the power change by sensing both the PV current and voltage. The controller operates periodically by comparing the present value of the power output with the previous value to determine the change on the solar array voltage or current. The algorithm reads the value of current and voltage at the output solar PV module. Power is calculated from the measured voltage and current. The magnitude of power and voltage at $(k+1)^{th}$ instant are measured again and power is calculated from the measured values.

If the magnitude of power is increasing, the perturbation will continue in the same direction in the next cycle, otherwise the perturbation direction is reversed. When the MPP is reached, the system then oscillates around the MPP. In order to minimize the oscillation, the perturbation step size should be reduced such that when the operating point is away from the MPP, the step change in duty cycle should be large, when it nears the MPP, the step change in should reduce. The simulation output of P& O MPPT algorithm at varying irradiance condition is shown in Fig. 4.

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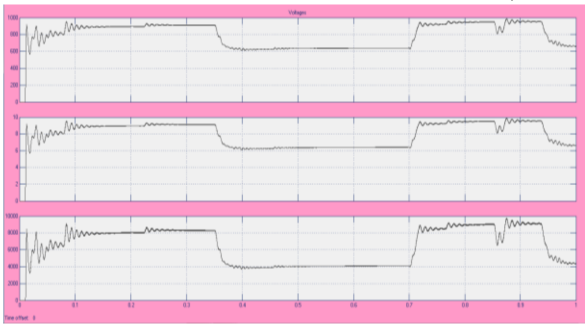

Fig. 4 Voltage, Current, Power Output of P&O MPPT Algorithm

The change in the duty cycle adjusted by the MPPT controller to extract the maximum power from the module is shown with time (t) Seconds in Fig. 5.

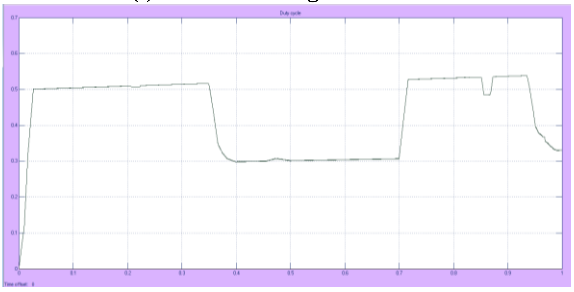

Fig. 5 Change in Duty Cycle of P & O MPPT Algorithm

B. Incremental Conductance Method

Based on the flow chart for incremental conductance MPPT algorithm [19] a simulink block is developed as shown in Fig. 6. The PV array terminal voltage can be adjusted relative to the MPP voltage by measuring the incremental conductance (I/V) and instantaneous conductance (ΔI/ΔV). Once the MPP is reached, the operation of the PV array is maintained at this point unless a change in ΔI is noted. In case of $dP/dV > 0$, the voltage is increased and in case of $dP/dV < 0$, the voltage is decreased to select the MPP.

A maximum power point tracker is designed by the combination of incremental conductance algorithm which triggers the duty cycle of the DC-DC converter. By changing the duty cycle of converter, the PV panel is made to deliver the maximum power at that irradiance to the load. The MATLAB/SIMULINK model of incremental conductance algorithm to track the maximum power output, along with a DC-DC boost converter is shown in Fig. 6.

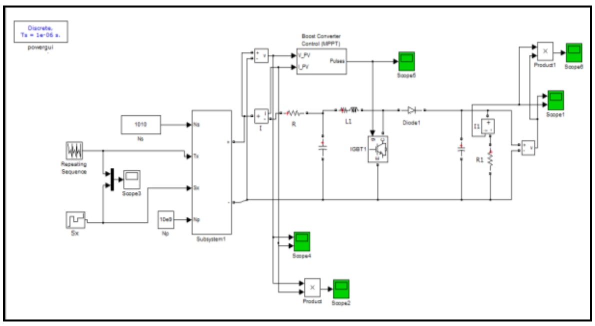

Fig. 6 MATLAB/SIMULINK model of Incremental Conductance Algorithm

The voltage, current and power output of the incremental conductance MPPT algorithm under varying irradiance and temperature condition is shown in Fig. 7.

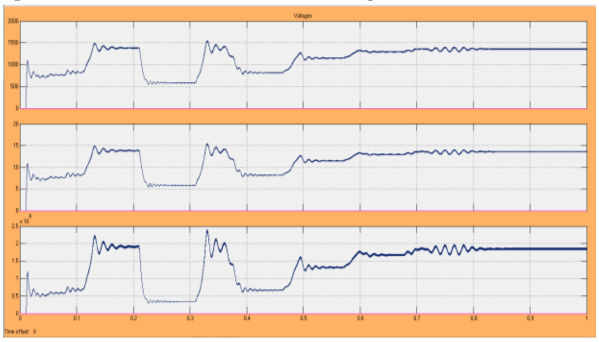

Fig. 7 Voltage, Current, Power Output of Incremental Conductance MPPT Algorithm

The MPPT controller adjusts the duty cycle of the boost converter on the event of any change in the irradiance to deliver maximum power possible. The variation of duty cycle in fixed step size corresponding to the change in insulation and temperature is shown with time (t) sec in Fig. 8.

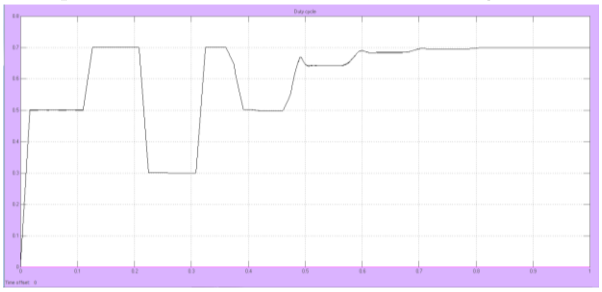

Fig.8 Variation of Duty Cycle

Even though the P&O and INC method tracks the maximum power under varying atmospheric condition, the INC method tracks the maximum power efficiency than P & O method. Hence the comparison of P&O and INC MPPT of power tracking is shown in Fig. 9.

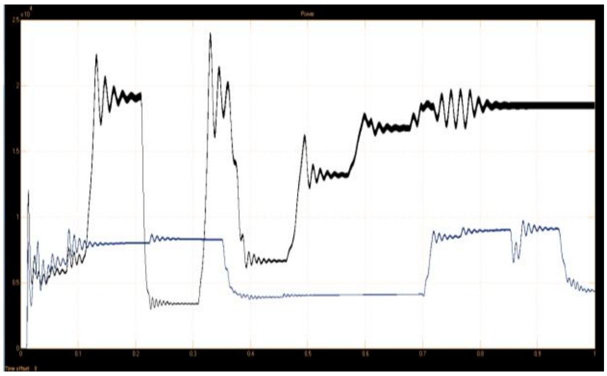

Fig. 9 Output Power comparison of P&O and INC MPPT

IV. ALLOCATION AND SIZING OF DISTRIBUTED GENERATION

The installation of DG units at non optimal places can result in an increase in system losses, implying in an increase in costs and therefore, having an effect opposite to the desired. For that reason, the use of an methodology capable of analyzing the influence on some system characteristics of DG allocation and sizing can be very useful.

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Given a set of possible expansion alternatives, the evaluation of a DG allocation and sizing strategy should be made through a SIMULINK program for distribution networks with the representation of generators.

In this paper, the DG locations and sizing will be considered based on the voltage profile. Divide the network into three subzones; the voltages are analyzed at each and every node. The location of DG is attained based on the corresponding lowest voltage values at the particular node point. The particular location where voltage profile is minimum said to be optimal location. In each subzone, a small amount of DG (10-20% of the feeder load) strategically allocated could cause a significant improvement in voltage profile and reduction in power losses. The system reliability indices in the presence of DG are evaluated using analytical method for reliability indices calculation in radial networks adopted to handle multiple generation sources at distribution level.

V. IMPACT OF DG ON VOLTAGE PROFILE, POWER LOSSES AND RELIABILITY

Interconnecting a DG to the distribution feeder [24] can have significant effects on the system such as power flow, voltage profile and reliability. A DG installation changes traditional characteristics of the distribution system. Most of the distribution systems are designed such that the power flows in one direction. The installation of DG introduces another source in the system. When the DG power is more than the downstream load, it sends power upstream reversing the direction of power flow and at some point between the DG and substation the real power flow is zero due to the back flow of power from DG.

The installation can impact the overall voltage profile of the system. Inclusion of DG can improve feeder voltage of distribution networks in area where voltage dip or blackouts are of concern for utilities. The voltage issues related to installation of DG on IEEE test system have been discussed.

One of the major potential benefits offered by DG is the reduction in electrical line losses. The loss can be significant under heavy load conditions. With the inclusion of DG, line loss in the distribution system can be reduced.

Distribution system reliability is an important factor in systems planning and operation. The reliability indices such as SAIFI, SAIDI, CAIDI and AENS are used to evaluate reliability of the system. The calculation of reliability indices can be examined for the proposed test system by using MATLAB program and can be improved by proper allocation of DGs.

The DG can also improve the reliability of the system by serving as a backup generation for some customers in case of interruptions from the utility.

The location for the placement of DGs is a key importance. The impact of installing DG as backup at various locations on the distribution circuit is also explored in this paper.

VI. SIMULATION RESULTS

The implementation of the proposed method is done in MATLAB/SIMULINK and IEEE test system is utilized for testing the performance of the system. The standard IEEE 15 bus radial distribution system is shown in Fig.10.

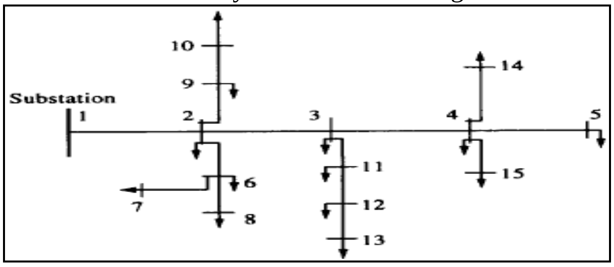

Fig. 10 Single Line diagram of IEEE 15 bus system

The proposed methodology aims at evaluating the impact of location of DG units at various buses for reduction in power losses, improvement in voltage profile and reliability in distribution network. The simulink model shown in Fig. 11 is developed for the above test system with DGs placed at optimal locations i.e., 5, 7 and 13 are the selected nodes based on the minimum voltage profile at each subzones. In the above case study, the DG is modeled with PV array to efficiently consider the performance of the radial distribution system. The flat voltage profile is 1.0 p.u. for the system at node 1. The range of the voltage is taken from 0.95 to 1.05 p.u. The repair time and switching time is 4 hrs and 0.1 hrs respectively. The total load of the system is 1577 KW. In appendix the table 3 and 4 shows the reliability and load data of IEEE 15 bus radial distribution system considered for analysis.

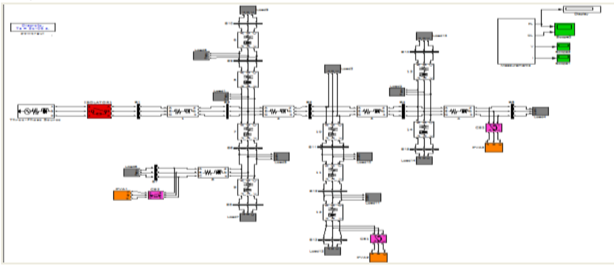

Fig. 11. The Simulink model of IEEE 15 bus Radial Distribution with 3 DGs

The optimal location and sizing of DG units are given in Table 1. In order to consider the effects of DG placement in the test system, the results are compared with the base case and presented in Table 2.

Table. 1 Optimum location and sizing of one DG unit in 15 bus system

Location	Size (KW)
5	500
7	600
13	400

Table. 2 Comparison of Results before and after DG in 15 bus system

Parameter	Base Case	DG with PV array
P_{Loss} (KW)	361.8	66.27
V_5(p.u.)	0.8610	0.9777

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V_7(p.u.)	0.8651	0.9780
V_{13}(p.u.)	0.8562	0.9994
SAIFI(inter./customer)	5.4951	5.4951
SAIDI(hrs/customer)	21.9803	17.0292
CAIDI(hrs)	4.000	3.099
AENS(kwh/cust.year)	115.2735	1.2489

It can be seen from the table that determination of optimal location and sizing of DG have a considerable effect on loss minimization, improvement in voltage profile and reliability.

The DG causes an impact in power losses due to its proximity to the load centers. DG units are allocated in such a way that they provide a higher reduction in losses. From table it can be obtained that the active power losses are reduced from 361.8KW to 66.27KW represented through graph as shown in Fig. 12. The simulation result of power losses before and after DG for all 15 buses is shown in Fig. 13.

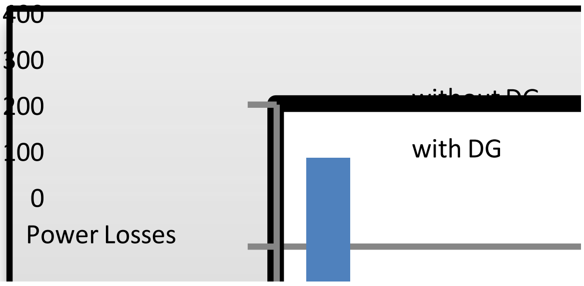

Fig. 12 The variation of total power losses before and after DG

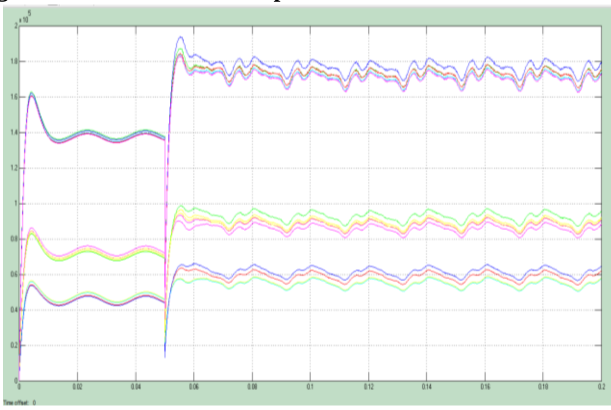

Fig. 13 Simulation Result of Power losses for proposed test system

The variation of voltage levels with and without DG is shown in Fig. 14 and the simulation result is shown in Fig. 15.

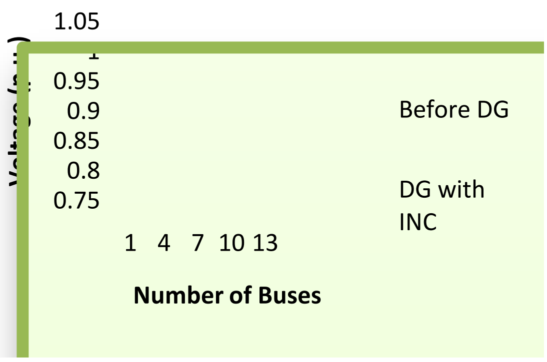

Fig. 14 The variation of Voltage levels with and without DG for the 15 bus system

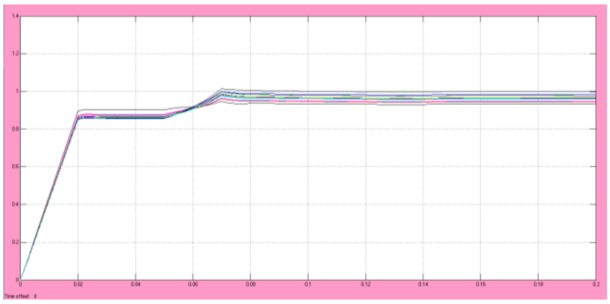

Fig. 15 The simulation result of Voltage levels with and without DG

Significant improvements in the reliability indices can also be observed as the DG unit is placed away from the substation and closer to the end of the line. Table 2 summarizes the improvement in reliability indices when DG of various sizes is moved from the distribution substation towards the end of the line. The variation of these indices is shown in Fig. 16.

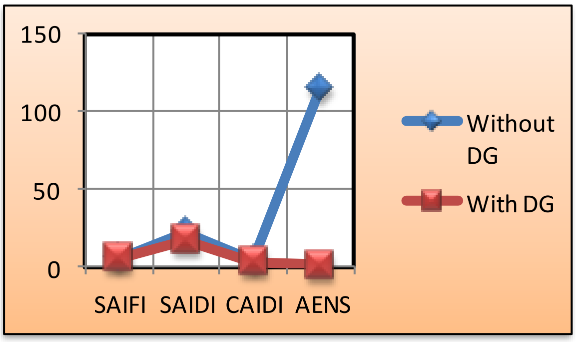

Fig. 16. Distribution System Reliability Indices before and After DG

VII. CONCLUSION

As renewable energy systems become more widespread PV systems are more likely to be found in a grid connected scheme. In this paper, the PV array system is modeled using MATLAB/SIMULINK. The model consists of PV array, the buck-converter model and the MPPT control model. When the PV array is used as a source of power supply it is necessary to use the MPPT to get the maximum power point from the PV array. The MPPT is implemented by using a boost converter, to operate under continuous conduction. The simulation results show that the model behaves appropriately with the characteristics of the system. Further, the model is simulated with MPPT algorithms namely Perturb & Observe and Incremental Conductance methods which improve the performance of the PV system. The result indicates that the proposed control system is capable of tracking the PV array maximum power and thus improves the efficiency of the PV system.

To obtain the performance of the PV array it is interconnected with IEEE 15 bus radial distribution system. From the results, it is observed that DG can reduce the power losses while simultaneously improving the voltage profile and reliability of the system.

The DG rating and location are important factors for improving the system performance. Therefore, these factors

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have been considered very carefully in order to determine the best location of DG. The improvement in reliability indices is maximum with DG at feeder end. Power losses decreases as location of DG from feeder end increases. The location of DGs attained on the corresponding lowest voltage profile at the particular node point in various sub zones. The proposed system is arrived at an optimal location by keeping into account these factors.

APPENDIX

Table 3. The Load and Reliability data of Fig. 13

Load Point	λ (f/yr)	Repair Time (r hrs)	No. of customers	Load (KW)
1	0.2749	4	6	0
2	0.2749	4	9	56.7
3	0.2749	4	12	90
4	0.3049	4	40	180
5	0.4669	4	67	56.7
6	0.2749	4	4	180
7	0.3009	4	25	180
8	0.4789	4	20	90
9	0.2929	4	25	90
10	0.2749	4	40	56.7
11	0.3149	4	15	180
12	0.3269	4	15	90
13	0.3009	4	28	56.7
14	0.2869	4	10	90
15	0.2869	4	12	180

Table 4. Line Data for Fig. 13

Branch No	Sending End Node	Receiving end node	R(ohms)	X(ohms)
1	1	2	1.35309	1.32349
2	2	3	1.17024	1.14464
3	3	4	0.84111	0.82271
4	4	5	1.52348	1.02760
5	2	9	2.01317	1.35790
6	9	10	1.68671	1.13770
7	2	6	2.55727	1.72490
8	6	7	1.08820	0.73400
9	6	8	1.25143	0.84410
10	3	11	1.79553	1.21110
11	11	12	2.44845	1.65150
12	12	13	2.01317	1.35790
13	4	14	2.23081	1.50470
14	4	15	1.19702	0.80740

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