A Probabilistic Approach for Power Loss Minimization in Distribution Systems

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***Abstract*—The number of Wind Power Distributed Generators are increasingly integrated in power systems because of having environmentally friendly and technically sound characteristics. It is prevalent that the non-optimal size and placement of Distributed Generation (DGs) can cause high power loss and unexpected voltage profile variation on feeder. This research study focusses on the probabilistic approach to design of Distributed Generation (DGs) and its impact on medium voltage (MV) feeders. Monte Carlo simulation based probabilistic power flow considering stochastic nature of wind and solar power generation and uncertainty of load variation are employed. The proposed method is simple that used open source MATLAB software including MATPOWER tools to analyse and design low voltage and medium voltage feeder. This method can furnish several choices to utilities/owners to place WT-DGs and PV-DGs at different suitable nodes. The method will be tested on different case study using Indian practical 22-bus and IEEE 69-bus network and the effect of DGs on the system voltage profile and loss are investigated accordingly.**

***Index Terms*— Distributed Generations (DGs); Medium voltage (MV) feeder; Probabilistic approach; MCS; MATPOWER.**

I. INTRODUCTION

Distributed generation (DGs) are extensively used in modern power system due to possessing inherent environmentally characteristics. In the last few decades, to combat with the global warming and reduce the greenhouse gas emission numerous national and international policies has been taken to increase the penetration of nonrenewable and renewable DGs worldwide. DGs not only have environmental related merits but also it emphasizes to regulate energy related policies, decline peak demand cost, rescheduling of network up gradation, lowering the transmission and distribution costs and reduce loss, diversify the resources and significantly enhance the quality of services to customer side [1].

The power generation from DGs must be such an extent that will not exceed the demand of distribution area. At beginning the distribution systems designed in such a way that power will flow from substation to load center. So the conductor size also decreases from sending to receiving end. If DGs with higher ratings than required are installed will cause reverse power flow and that might cause excessive power losses in lower sized conductors [2, 3]. Hence, the total amounts of the load (MW) influence the size selection of DGs at distribution area.

A lot of research study had carried out based on distribution line losses which mainly considered the feeder losses minimization [4–12]. In these studies, the losses were considered for single generation and load case. The methodologies regarding these researches were based on Analytical methods and these methods were non iterative hence time saving [4, 5]. Those methodologies and techniques were employed to find the location and size of single DG unit. The multiple DG integration creates nonlinear effect on power system operation [6]. Consequently, different multiple DG placement techniques were inaugurated [7]. It is not so easy find a proper analytical solution that can be applied for multiple DG sitting and sizing.

The researches that described above were considering deterministic models of power production and loads. More precisely, it was assumed the conditions of extreme loading and consequently extreme voltage level instead of actual feeder voltage was gained. Another strong demerit of these calculations was that they did not consider the uncertainties in the load forecasting and in solar radiation and wind velocity availability. Moreover, due to the stochastic nature of weather the power generation by wind is also is random in nature. Hence, the probabilistic analysis rather than deterministic at the time of operational planning and planning is more perfect [13].

This paper proposes a way to find the optimal ratings of Distributed Generations (DGs) that decrease the power loss and improve the voltage profile on distribution feeder. This study analyzes the impact of WT-DG on the MV feeder with probabilistic approach based on statistical information of the load and wind variation. Monte Carlo simulation along with Weibull probability distribution function is used to predict wind variation and normal probability distribution function is used to estimate load demand with certain standard deviation. The power flow is solved by using MATPOWER [14, 15] tools in MATLAB. The method will be tested on study cases that illustrate the selection of WT size based on technical constraints and desired objectives. Power Summation method from MATPOWER perform the power flow solution, hence practical 22-bus, IEEE 69-bus radial test network is used as a case files.

II. Probabilistic Modeling of Wind Speed, Solar Radiation and Load Generation

Using standard probability density function the random samples are generated in MATLAB environment. There is a drawback to generate the random samples from wind or solar radiation variations statistical model, since it contains some zero samplings. That is, wind speed bellow cut-in or above cut-out and for solar radiation when weather conditions are bad. So, it does not match with any available standard distribution model. There is a way to avert this problem: separate the statistical data into two, the first one will contain the zero-value velocity or radiation and second one will contain non-zero velocity or radiations. The non-zero wind variation is then modelled as a Weibull distribution and solar variation modelled as normal distribution that has the closest cdf with the empiric one from the wind speed and solar radiation variation statistical model. A total of 10,000 random samplings will be generated (Fig. 1).

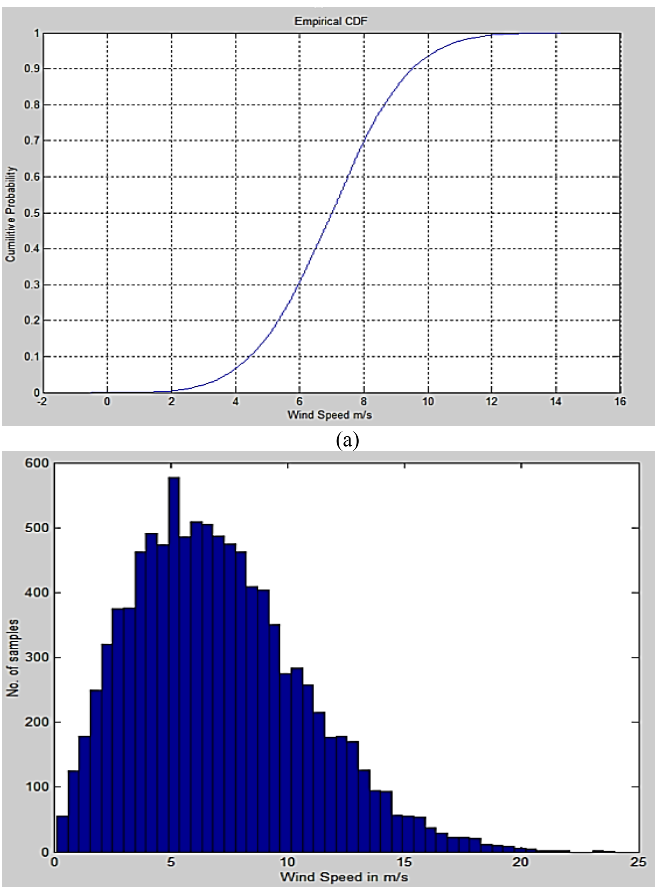

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Figure 1. (a) cdf of wind speed variation in m/s. (b). Histogram of randomly generated wind speed (ms^{-1}) with 10 thousand samples.

A. Designing of of WT-DG based on Stochastic DG Output

The available variable AC power generation from WT is directly proportional to the wind speed variations. Then the generated outputs from the WT pass to the Power Conditioning Unit (PCU) that is made from inverters, converter and related control and protection module. It is essentially imperative to increase WT generated power from available wind velocity since it is a capital-intensive technology that have less operating cost. If capacity factor and power coefficient assumed constant, then the power output from wind turbine is assumed to be proportional to the wind velocity variations. In this study an Ideal WT has been considered which generated power varies with the variation of wind considering the remaining factors are constants (for example: such as waking effect, temperature, pressure, height of tower etc.).

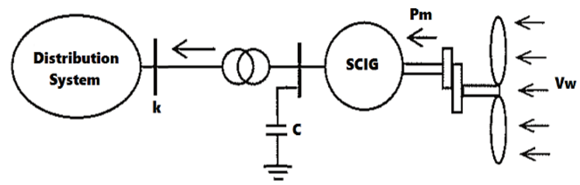


Figure 2. A fixed speed wind generator connected to bus k.

A variable speed wind turbine generation system has connected to the node-*k* of a distribution feeder through a step-up transformer (fig. l). To support reactive power demand by the generator an additional shunt capacitor has connected. The mechanical power (P_m) generated from WT fed into the generator which again convert it to electrical power and supply to the distribution system at node-*k*. The available mechanical power *P* generated by the WT can be written as follows:

$$P_m = \frac{1}{2}\rho A V_{wind} C_p(\lambda, \beta) \qquad (1)$$

Where, ρ, A, V_{wind}, C_p are density of the air, rotor swept area, velocity of wind and power coefficient or performance coefficient which depends on tip speed ratio (λ) and blade pitch angle (β). The value of C_p is 0.35 (approx.), Maximum theoretical is 0.593 (Betz number). If ρ, A, C_p are constant then available wind power will be,

$$P_{available} \propto v^3 \qquad (2)$$

The generation of wind power is highly related to the velocity of the site. Different methods were developed to model the wind behaviour such as: data mining algorithms time-series model [16] or clustering approach [17]. In this work, the variation of wind speed, i.e., V_{wind} is modelled as a Weibull PDF (fig.1) and its characteristic function which relates the wind speed and the output of a WT as follows:

$$pdf(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \qquad (3)$$

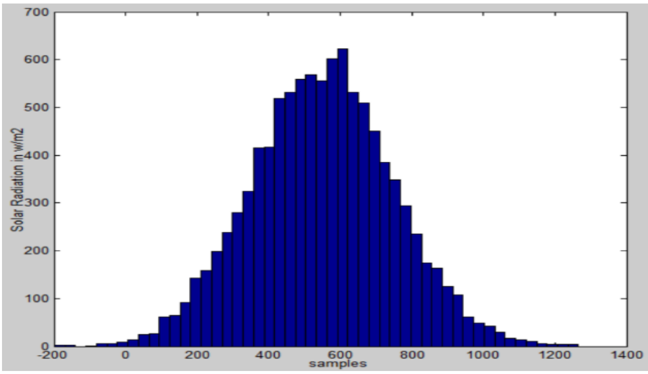
Where, k and c are the shape and scale factor of the Weibull k PDF of wind speed, respectively [18]. The power generated from the wind turbine generator is determined as follows:

$$P_i^w = \begin{cases} 0 & ; v_{out} < v_{wind} < v_{in} \\ P_i^w, r\left(\frac{v_{wind} - v_{in}}{v_{rated} - v_{in}}\right) & ; v_{in} \le v_{wind} \le v_{rated} \\ P_i^w, r\,; & ; v_{rated} \le v_{wind} \le v_{rated} \end{cases} \qquad (4)$$

Where, $P^{w}_{i,r}$ is the rated power of WT connected in node-i, P^{w}_{i} is the generated power of WT of node-i, v_{out} is the cut-out speed and v_{in} is the cut-in speed. , v_{rated} is the rated speed of the WT.

B. *Solar Radiation and PV Array Data*

Normal distribution function has been taken to using equation (6) as the similar steps to determine the random samplings of non-zero load variation. 10,000 random samplings will be considered. Where**,** Average solar radiation (μ) = 550 w/m^2 and standard deviation (δ) = 200 w/m^2.



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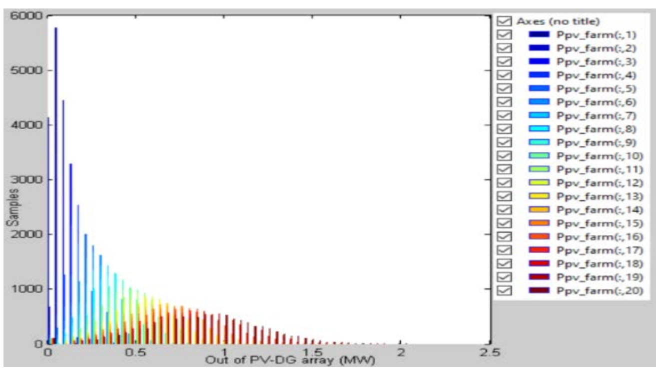

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Figure 3. (a) Histogram of solar radiation, (b) Solar power from PV-DG array.

Maximum and minimum solar radiation is 1265.7 w/m^2 and 198.45 w/m^2 respectively. Here, we have considered commercially available PV-module with 10% efficiency polycrystalline solar cell. Conversion efficiency of solar panel has taken 80% and standard radiation of solar PV is 1000 Watt under test condition. Rating of the solar array has calculated as following way:

$$P_{rated}^{Array} = n_{conv} A_{panel} N_{module} P_{rated}^{module} \qquad (5)$$

Where, n_{conv}, A_{panel}, N_{module}, and P_{rated}^{module} are conversion efficiency solar panel, panel area total no. of the module, module rating respectively.

C. *Modelling of Load Consumptions*

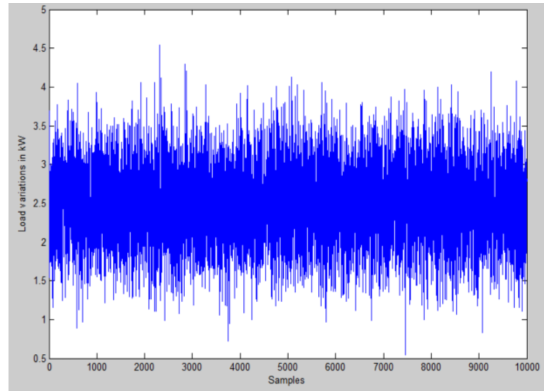


Figure 4. Randomly generated Load variation (kW).

The load will be modeled as a Normal distribution function as the similar steps to determine the random samplings of non-zero wind variation. 10,000 random samplings will consider. For Normal Distribution function:

$$(x) = \frac{1}{\delta\sqrt{2\pi}}\, e^{-\frac{1}{2}\left(\frac{x-\mu}{\delta}\right)} \qquad (6)$$

Here, μ and δ are the mean and standard deviation of the Normal PDF, respectively.

D. *Load Flow Calculations*

In this research work, the customer load variations and electric power productions are taken to be mutually independent. To get the random change of load profiles and power generation at every node of the distribution system the Monte Carlo Simulation was carried out where the MCS samples are same as the sample values of the experiment. Hence, the MCS based probabilistic power flow provides the results that are in terms of power flows in different sections of feeder and node voltage profiles in the system can be considered statistically and this statistical method can be used. Since, it is highly accurate so, MCS are using extensively in different power system problem solution. Though the computational time is higher but does not a matter for planning purposes [5]. In this work, Power Summation Method (PSM) for radial network from MATPOWER [15] simulation tools with MATLAB is used for distribution systems.

III. Consideration of Case Studies

A. *Probabilistic Load Flow Algorithm*

All the system data with constraints are considered in this step such as: load data, standard deviation of load, maximum and minimum allowed voltage in the system, expected average of the wind speed and solar radiations, related parameters of Normal pdf, Weibull pdf etc. After input of all these data, the probabilistic data for wind speed, solar radiation hence the power, load demand are generated . The flow chart regarding DG size selection has given in fig. 5. It should be keept in mind that MCS neither give any info regarding sequence of wind speed generation and load nor any correlation in-between. Also it was considered that overall results were unchanged when 10 thousands random sampling had generated.

B. 22-bus Practical Distribution Test System

The data for the 22-bus agricultural test system is given in [19], (Fig. 6), which belongs to a slight part of Eastern Power Distribution system in India with 11 kV base voltages. It has total of 662.311 kW real power load and 667.40 kVAr reactive power loads comprised with 21 branches and 22-buses in Figure 4.14. This practical test system is rated with voltage 11 kV, Vmax =1.1 pu and Vmin = 0.9 pu along with base 10 MVA complex power rating. Without any DG or reactive compensation, the feeder has 17.74 kW losses in Fig. 6.

The flow chart regarding WT generator size selection has given in fig. 5. It should keep in mind that MCS neither give any info regarding sequence of wind speed generation and load nor any correlation in-between. Also it was considered that overall results were unchanged when 10,000 random samples were generated.

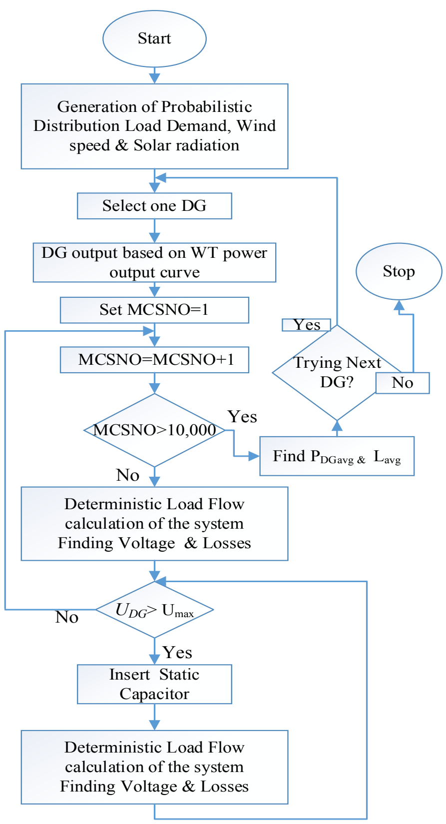


Figure 5. Algorithm of Probabilistic load flow using MCS with MCSNO=10,000.

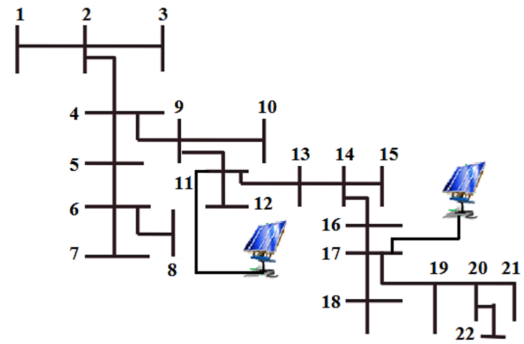


Figure 6. PV-DG connected at node-17 and node-11.

C. 69-bus RadialTest System

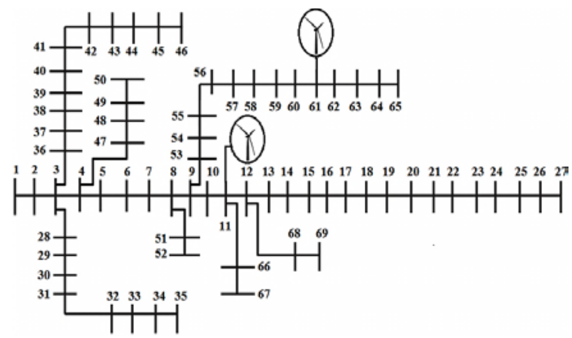
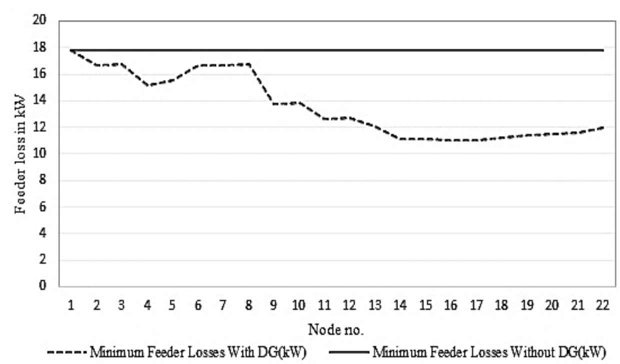


Figure 7. WT-DG connected at each node to get minimum loss point.

IV. RESULTS AND DISCUSSIONS

Connecting WT-DG and feeding the power at each node except node-1 (slack bus), the node-17 gives the minimum 11.40 kW loss with 358 kW average output if we use 600 kW WT. Here it can be used two 300 kW WT-DG at node-17 which are commercially available. So, the total capacity of WT is 300*2=600kW that corresponds to 90.59% (PG/Pload=600/662.311) of wind penetration.



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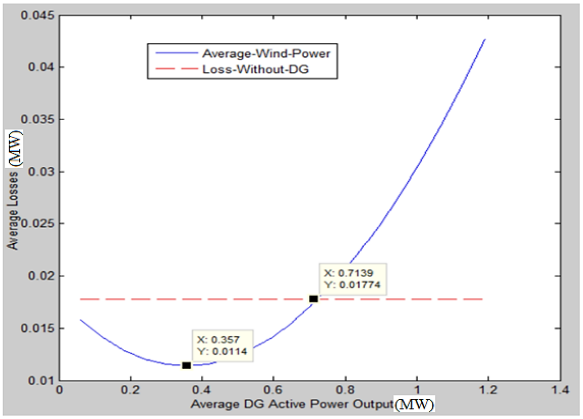

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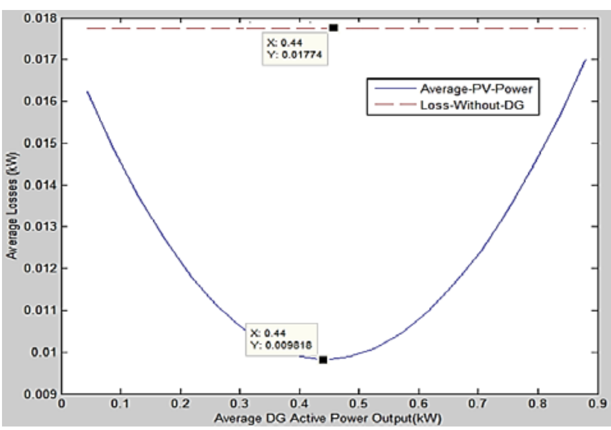
Figure 8. (a) Feeder losses when connecting WT-DG in different nodes (b) Average Loss as a function of Average DG output power.

Since, available output of WT is 358 kW; the capacity factor of WT will be 59.67% (358/600). Then second minimum loss node is node-16 with 11.42 kW output. Hence, 35.74% power will be saved after connecting WT-DG at node-17 without using any capacitive compensation. The minimum loss node is found as descending node-17, 16, 14, 15, 18, 19, 20, 21, 22, 13, 11, 12, 9, 10, 4, 5, 6, 7, 2, 8, 3, 1 (fig. 8). Keeping WT fixed at node-17 the lowest losses found at node-11. Consequently, the feeder losses further reduced to 10.92 kW given in Table-1. Voltage at WT-DG connected point (Node-17) became $V_{17} = 1.001$ pu for single DG but without DG it was 0.9743 pu. Node-22 is minimum voltage node with 0.9729 pu but after connecting DG at node-17 the minimum become node-8 with 0.9976 pu.



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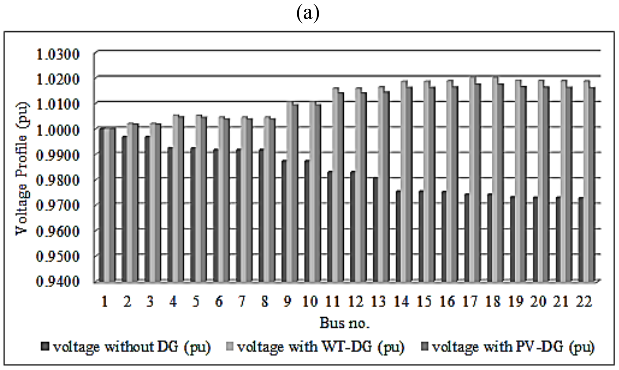

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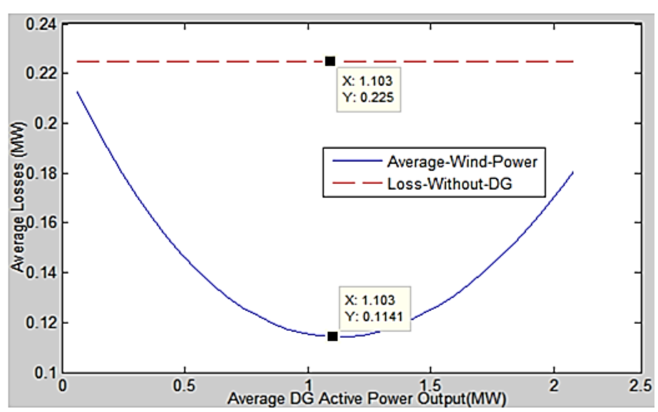
Figure 9. (a) Feeder losses when connecting PV-DG at various nodes (b) comparison of voltage profile with and without DGs.

The 22-bus distribution feeder also has been investigated with PV-DG and that showed same minimum loss node as WT-DG. Voltage profiles and losses have given in Table I. It is noticeable that PV-DG always reduce the feeder losses regardless the average DG output and its size in fig. 9(a). PV-DG gives better real power generation and loss reduction with respect to WT-DG with same rating considering the above condition. Using single node placement, the minimum real power losses reduced to 9.82 kW which is nearly 14% feeder losses reduction than WT-DG. To meet the load of 22-bus radial system it would be needed three thousand solar modules with 200 W module rating or 50 kW twelve arrays can be used to satisfy about 600 kW. Besides the voltage profile improvement of PV-DG is better than WT-DG within the ±6% allowable voltage limit.

TABLE I. FEEDER LOSSES AND VOLTAGE PROFILE AT DGS CONNECTION POINT

DG	Connecting point	Feeder Losses (kW)	DG output (kW)	DG Size (kW)	Voltage at DG connection point (pu)	
WT 22-bus	17	11.40	358	600	V_{17}=1.0010	
	17,11	10.92	2*179	600	V_{17}=1.0023	V_{11}=1.016
PV 22-bus	17	9.82	440	1000	V_{17}=1.0059	
	17,11	9.66	2*220	1000	V_{17}=1.0033	V_{11}=1.003
WT 69-bus	61	117.80	1410	2300	V_{61}=0.9690	
	61,11	114.10	2*710	2300	V_{61}=0.9779	V_{11}=0.9992
PV 69-bus	61	95.19	1724	3500	V_{61}=0.9729	
	61,11	90.67	1724	3500	V_{61}=0.9824	V_{11}=1.0012

Same procedures have been applied on 69-bus radial distribution systems to find the minimum loses node on the feeder. The node-61 gives the minimum 117.8 kW that is the lowest feeder loss and minimizes around 47.64 % Besides, WT will furnish around 1.41 MW if 2.3 MW WT-DG is connected at node-61. For multiple DG connection the node-61 and node-11 have given minimum 114.1 kW feeder losses. 69-bus radial system also investigated with PV-DG following same steps. It is found that PV-DGs have better feeder loss minimization and voltage improvement than WT-DGs (fig. 10). The summarized results have given in Table-1.



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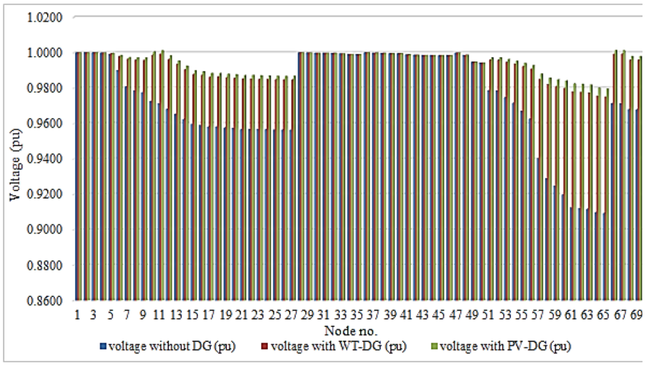

(b)

Figure 10. (a) Average feeder losses with WT-DG connected at different nodes (b) voltage profile improvement with and without DGs.

Voltage level has improved significantly after connecting DGs on 69-bus radial distribution system. The voltage at node-11 is V_{11} = 0.9713 pu and at node 61 it was V_{61} = 0.9123 pu except any DGs incorporation. After connecting WT-DGs and PV-DGs these became V_{11} = 0.9992 pu, V_{61} = 0.9779 pu and V_{11} = 1.0012 pu, V_{61} = 0.9824 pu respectively (fig. 9). Voltage become near to 1 pu after connecting PV-DG except from node-14 to 27. Still changes of voltage level are in allowable limit.

Table II shows about \$80,622 and \$66,175 per year can possible to save by just suitable placement of PV-DG's and WT-DGs respectively in 69-bus distribution networks. In case of 22-bus test system these losses reduction is approximately \$4796 and \$4006 annually. Hence, it is a quite clear evident that without using any further reactive compensation it is possible to reduce feeder losses in a remarkable amount. Though stochastic load variation and generation have been considered but for taking comprehensible snapshot of loss minimization nominal load (100%), light (50%), and peak (160%) load is taken to operate 5260, 2000 & 1500 hours respectively (8760 hours) and energy cost is \$0.06/ kWh has been considered for cost calculation.

TABLE II. ANNUAL COST SAVING WITHOUT CONNECTING REACTIVE COMPENSATIONS

Test system	Load condition	Losses without DG (kW)	Losses with DG (kW)	Savings ($)
22 - bus with WT-DG	Nominal load	17.74	10.92	4,006.10
	Light load	4.33	2.69	
	Peak load	46.79	28.38	
Total cost ($)		10,329.44	6,323.35	
22 - bus with PV-DG	Nominal load	17.74	9.66	4,796.44
	Light load	4.33	2.35	
	Peak load	46.79	24.47	
Total cost ($)		10,329.44	5,532.99	
69 - bus with WT-DG	Nominal load	225	114.1	66,175.44
	Light load	51.61	27.24	
	Peak load	652.5	311.6	
Total cost ($)		133,498.20	67,322.76	
69 - bus with PV-DG	Nominal load	225	90.67	80,621.75
	Light load	51.61	22.1	
	Peak load	652.5	240.1	
Total cost ($)		133,498.20	52,876.45	

V. CONCLUSION

This work incorporated a MCS based probabilistic planning technique to implement optimal allocation and sizing of wind and solar based DGs in medium voltage distribution feeders. The stochastic nature of wind speed and solar radiations were modeled using Weibull and normal probability density function respectively. The randomness in load variation was modeled with normal pdf. These two models comprise the probabilistic generation-load model. The probabilistic load flow (PLF) has performed to determine the optimal location by minimum feeder loss and size has determined from DG array for that optimal location.

It has been clearly observed that PV-DG showed the better power loss minimization than the WT-DG. Connecting DGs at optimal location around forty-five percent reduced in 22-bus system and sixty percent minimized in 69-bus systems. An array of DG was used with every sample of MCS that suggested the name plate ratings of DG and its average output based on location and generation-load model. Results showed that multiple DG placement reduce more feeder loss than single placement. The proposed probabilistic generation-load model has incorporated the uncertainties and provided real snapshot of distribution systems and can be used for placement of other type of DGs.

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