Incorporation of probabilistic solar irradiance and normally distributed load for the assesment of ATC

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***Abstract*- In deregulated electricity market determination of available transfer capability (ATC) in advance becomes necessary to use whole existing transmission network efficiently and economically. This work considers optimal power flow (OPF) based method to estimate ATC when probabilistic solar power is injected into the system as active power source. Novel voltage sensitivity indices are considered for the optimal placement of solar power generation into the transmission network. Probabilistic demand is incorporated by considering load variations as normally distributed random variables. Monte Carlo sampling (MCS) and Latin Hypercube sampling (LHS) techniques are considered to extract samples from the normally distributed load samples. Simulation result shows a significant reduction in ATC values occur when probabilistic load is taken into account, as compare to the steady load.**

Keywords— Available Transfer Capability (ATC); Beta Probability Distributed Function (PDF); Latin Hypercube sampling; Optimal Power Flow (OPF); Solar irradiance modelling; Probabilistic load; IEEE 24 RTS;

I. INTRODUCTION

In late nineties deregulation of electrical industries have been started to improve the power systems operations such as generation, transmission, distribution etc. In deregulated electricity market it becomes important to provide reliable electricity supply at a cheaper rate to the consumers. Hence it becomes important to utilize power system operations effectively and economically. In deregulated environment, ATC plays an important role in utilizing transmission network effectively and also helps in congestion management, unit commitment, overloading, stability etc. According to North American Electric Reliability Council (NERC) Report [1], 'Available transfer Capability (ATC) is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses.' which can be explained mathematically as given below,

$$ATC=TTC-TRM-\{CBM+ETC\} \tag{1}$$

Where,

TTC: Total Transfer Capability
CBM: Capacity Benefit Margin
TRM: Transmission Reliability Margin
ETC: Existing Transfer Commitments

Due to restructuring in power system operations a competitive and innovative electricity market is developed which supports alternative methods for electricity generation such as wind, hydro, solar etc. Sporadic nature of renewable energy resources is a cause of concern, it requires comprehend study on various power system operations. This work presents determination of ATC values for a solar power integrated transmission network.

In past few years many researchers have proposed different approaches for ATC determination such as DC power flow method, sensitivity based approach, optimal power flow based approach etc. A simple approach for the ATC assessment of transmission system is explained in [2]. In competitive electricity market to calculate ATC an AC distribution factor based approach is explained in [3]. ATC determination for Multi-transactions in deregulated electricity market using ACPTDF is represented in [4]. In [5] ATC evaluation for the wind power incorporated systems is explained. ATC calculation for the restructured electricity market using a bifurcation methodology is described in [6]. Probabilistic nature of wind is considered for the evaluation of ATC in [7]. In [8] A Monte Carlo method for total transfer capability calculation is explained. Probabilistic evaluation of ATC based on MCS approach with progressive simulation is explained in [9]. Modelling of photovoltaic modules and impact of solar power generation on distribution network is presented in [10-11]. Determining of PV penetration for distribution scheme with time varying load models is given in [12]. A comparison of voltage sensitivity indices is explained in [13].

In this work for the assessment of ATC an OPF based approach is considered. In OPF based approach we can subject a large number of equality and inequality constraints. To harness solar power, 20,000 samples of solar radiation are considered. These samples are generated by using Beta probability distributed function [12]. MCS technique is considered for the levelling procedure, these 20,000 samples are divided into 11 different solar radiation levels. Variation in demand for 24 hours is considered as normal probability distribution function for the ATC determination. Two different procedures MCS and LHS [14] are used for the sampling of probabilistic nature of demand. ATC values for three different methodologies without probabilistic load, with probabilistic load using MCS and LHS are obtained. IEEE 24 bus system [15] is considered for the testing of proposed work. To calculate ATC a single bilateral transaction between bus number 23 i.e. seller bus and bus number 15 i.e. buyer bus is considered.

The next section presents problem formulation for optimal power flow with different constraints. Section III presents solar power generation modelling. Simulation results of the proposed methodology are presented and explained in segment IV. And finally section V concludes the work.

II. ATC CALCULATION METHODOLOGY

A. Objective function for OPF problem

$$Min\, Y(x, \alpha, \beta, \xi_{SOLAR}) \tag{2}$$

$$e\,(x, \alpha, \beta, \xi_{SOLAR}) = 0 \tag{3}$$

$$f\,(x, \alpha, \beta, \xi_{SOLAR}) \leq 0 \tag{4}$$

Where,

Y represents the objective function, e shows the equality constraints and f shows the inequality constraint, x represents the state vector, α shows the control variables, β represent fixed variables, ξ_{SOLAR} represent control variables for solar power generation.

B. Formulation of ATC calculation problem

A single bilateral transaction is considered for the ATC calculation. This problem can be formulated by given objective function.

$$Max\, \lambda \tag{5}$$

Objective function can be optimized by considering given equality and inequality constraints

(i) Equality Constraints: Power injection at the various buses can be considered as the equality constraints. From the load flow solution, mathematical expression for real and reactive power injection at any bus *i,* is given below:

$$P_i - \sum_{j=1}^{n}\left[V_i V_j * \{G_{ij}\, cos(\delta_{ij}) + B_{ij}\, sin(\delta_{ij})\}\right] = 0 \tag{6}$$

$$Q_i - \sum_{j=1}^{n}\left[V_i V_j * \{G_{ij}\, sin(\delta_{ij}) - B_{ij}\, cos(\delta_{ij})\}\right] = 0 \tag{7}$$

Where P_i is the injected real power and Q_i is the injected reactive power at any bus *i*. G_{ij} and B_{ij} shows the conductance and susceptance matrix for the transmission line between bus *i* and bus *j*.

$$P_i = P_{Gi} + P_{Wi} - P_{Di} \tag{8}$$

$$Q_i = Q_{Gi} - Q_{Di} \tag{9}$$

(ii) Inequality constraints: Various number of inequality constraints for OPF based load flow solution can be represented as:

Voltage limits:

$$V_{i\,min} < V_i < V_{i\,max} \tag{10}$$

$$V_{j\,min} < V_j < V_{j\,max} \tag{11}$$

Angle limits:

$$\delta_{i\,min} < \delta_i < \delta_{i\,max} \tag{12}$$

$$\delta_{j\,min} < \delta_j < \delta_{j\,max} \tag{13}$$

Inequality constraints limits for active and reactive power injection at bus *I* are shown as:

$$P_{Gi\,min} < P_{Gi} < P_{Gi\,max} \tag{14}$$

$$Q_{Gi\,min} < Q_{Gi} < Q_{Gi\,max} \tag{15}$$

Active and reactive power flow limits for the transmission line between bus *i* and bus *j* are represented as:

$$P_{ij\,min} < P_{ij} < P_{ij\,max} \tag{16}$$

$$Q_{ij\,min} < Q_{ij} < Q_{ij\,max} \tag{17}$$

Where,

P_{Gi} and Q_{Gi} denotes the active and reactive power at any bus *i* respectively, P_{Di} and Q_{Di} represents the active and reactive power load at any bus *i* respectively, V_i and δ_i denotes the voltage and angle constraints at bus *i*, V_j and δ_j denotes voltage and angle constraints at bus *j*, $P_{Gi\,max}$ and $P_{Gi\,min}$ are the maximum and minimum limits of real power injection at any bus i, $Q_{Gi\,max}$ and $Q_{Gi\,min}$ are the limits for maximum and minimum reactive power injection at any bus *i*, $P_{ij\,max}$ and $P_{ij\,min}$ are the limits for maximum and minimum active power flow between bus *i* and bus *j*, $Q_{ij\,max}$ and $Q_{ij\,min}$ are the limits for maximum and minimum reactive power flow between bus *i* and bus *j* respectively.

To calculate ATC, the change in active power generation and load demand at a seller bus and buyer bus in (8) can be calculated by considering generation and load at corresponding buses as-

$$P_{Gm} = \lambda P_{Gm}^{o} \tag{18}$$

$$P_{Dn} = \lambda P_{Dn}^{o} \tag{19}$$

Where, P_{Gm} *and* P_{Dn} are active power generation and load corresponding to the bus m and n. m and n are the seller bus and buyer bus respectively.

Maximum power (P_{Dn}) can be transfer between seller bus m and buyer bus n by maximizing loadability factor lambda (λ). To maximize λ number of equality and inequality constraints have to be satisfied. And thus ATC can be determined by using following equation:

$$ATC = \lambda_{max} P_{Dn}^{o} - P_{Dn}^{o} \tag{20}$$

III. SOLAR POWER GENERATION MODELLING

As solar irradiance is an intermittent source of energy, output power of photovoltaic module is not constant. This solar output power is further considered for the evaluation of ATC. To calculate output power of photovoltaic module mathematical modelling of solar irradiance has to be done.

A. Mathematical modelling of probabilistic solar radiation

Probabilistic solar irradiance can be studied using different probability distribution function such as Beta and Weibull probability distribution function. Among all probability distribution function Beta probability distribution function follows solar irradiance more accurately. So Beta probability distribution function is considered for the expressing solar irradiance as represented in figure 1. The mathematical expression of probabilistic solar irradiance model can be characterised as the Beta probability distribution function with solar irradiance *s in watt/meter^2* as random variable, is given by:

$$f_b(s) = \frac{s^{\alpha-1}(1-s)^{\beta-1}}{\Gamma(\alpha) * \Gamma(\beta)} * \Gamma(\alpha+\beta) \tag{21}$$

Where,

$f_b(s)$ is the Beta probability distribution Function of s, *s* is the solar radiation in watt/m^2, α and β are the parameters of Beta probability distribution function, which are determined by using the following equations:

$$\alpha = \mu * \left[\frac{(1-\mu)*\mu}{\sigma} - 1\right] \tag{22}$$

$$\beta = (1-\mu) * \left[\frac{(1-\mu)*\mu}{\sigma} - 1\right] \tag{23}$$

Where,

μ and σ are the mean and standard deviation of probabilistic solar irradiance respectively.

B. Photo-Voltaic Module specification and modelling

$$P_{PV} = N * FF * V_y * I_y \tag{24}$$

$$FF = \frac{V_{mpp} * I_{mpp}}{V_{oc} * I_{sc}} \tag{25}$$

$$V_y = V_{oc} - K_v * T_{cy} \tag{26}$$

$$I_y = s * [I_{sc} + K_i(T_{cy} - 25)] \tag{27}$$

$$T_{cy} = T_A + s * \left(\frac{N_{OT} - 20}{0.8}\right) \tag{28}$$

Where,

P_{PV}: Output power of PV module in KW
N: Number of PV module
FF: Fill Factor
V_{mpp}: Maximum power point (mpp) voltage in Volts
I_{mpp}: mpp current in Ampere
V_{oc}: Open circuit voltage (Volts)
I_{sc}: Short circuit current (Ampere)
K_v: Voltage temperature coefficient
K_i: Current temperature coefficient
T_{cy}: Cell temperature
T_A: Ambient temperature
N_{OT}: Normal operating temperature of the cell

Table I: Single PV module specification

V_{mpp}	I_{mpp}	V_{oc}	I_{sc}	K_v	K_i	T_A	N_{OT}	N
31.6	8.23	37.9	8.67	0.128	.003631	30	45	5000

A. Sampling and leveling of solar irradiance

Incoming solar radiation depend on various factors of weather condition. All these factors make solar radiation highly unpredictable and uncertain. To convert this probabilistic nature to deterministic nature, sampling process is used. In this work Monte Carlo sampling technique is considered for the sampling of solar radiation which extracts 20,000 solar irradiance samples from Beta probability distribution function.

For the calculation of ATC OPF based approach is considered which subjects to a large number of equality and inequality constraints. Due to these constraints evaluation time for the ATC calculation is increased. So ATC calculation for 20,000 solar radiation samples is a complex task. To make this process simpler a levelling procedure is considered, in which 20,000 solar radiation samples are divided into 11 levels. First Solar output power is calculated for each of these levels and then ATC is evaluated for every level. The different solar radiation levels are given in the table 2. Total solar power is calculated by considering 5000 PV modules and this solar output power is injected into the system on the basis of novel voltage sensitivity index (NVSI).

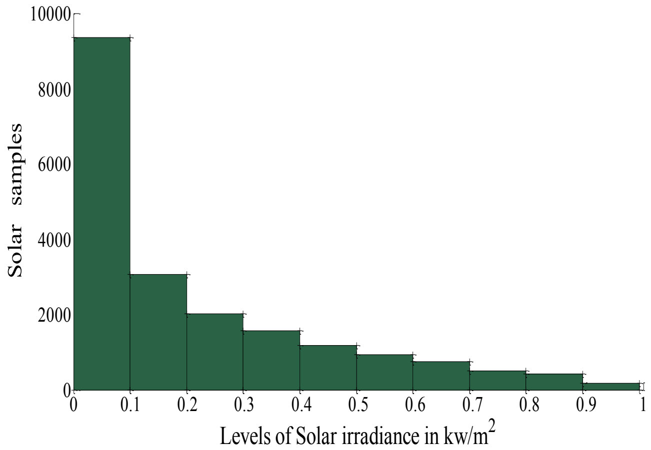

Fig.1. Distribution of 20,000 solar irradiance samples

B. Optimal location of solar power plant using NVSI

For the optimal location of PV based solar plant the behaviour of transmission network needs to be considered. There are number of techniques such as fast voltage sensitivity index (FSVI), novel voltage sensitivity index (NVSI) etc. [16]. NVSI approach is considered for finding optimal location of

PV solar plant. Mathematical expression for NVSI is given below:

$$NVSI = \frac{2X\sqrt{P_2^2+Q_2^2}}{2Q_2X-|V_1|^2} \quad (29)$$

In this expression X shows the reactance of the transmission line. P_2 and Q_2 represents active and reactive power at the receiving end. $|V_1|$ represents voltage magnitude at sending end.

With NVSI approach sensitivity indices are calculated for all the transmission lines. To get information about optimal location of solar plant high value of NVSI is considered. A high value of NVSI represents a stable transmission line having a maximum value of loadability factor compared to other transmission lines. This approach results into two locations which are further considered for the optimal placement of solar plant. By repeatedly injecting solar power at both these buses ATC is calculated. Bus respect to the highest ATC is considered for the optimal location of solar power plant.

IV. PROBABILSTIC LOAD MODELLING AND SAMPLING

In power system operations active power demand and reactive power demand are two most uncertain quantities. For the modelling of probabilistic load normal probability distribution function is considered as it provides most accurate demand variations at each bus. Steady state values of demand at each bus is considered as mean value and standard deviations of active power demand and reactive power demand have been taken of 8% and 0.02% respectively. Values of standard deviations are chosen such that demand should always positive.

Mathematical model of active load and reactive load can be represented as,

$$f(P_{Di}) = \left(\frac{1}{\sigma_{P_{Di}}\sqrt{2\pi}}\right) exp - \left(\frac{(P_{Di}-\mu_{P_{Di}})^2}{2\sigma_{P_{Di}}^2}\right) \quad (30)$$

$$f(Q_{Di}) = \left(\frac{1}{\sigma_{Q_{Di}}\sqrt{2\pi}}\right) exp - \left(\frac{\left(Q_{di}-\mu_{P_{Di}}\right)^2}{2\sigma_{QDi}^2}\right) \quad (31)$$

Computation time for ATC determination using OPF based approach is more as a large number of constraints are considered. So only 300 samples of probabilistic load are generated using normal probability distribution function.

Probabilistic demand sampling

Probabilistic demand sampling is the method in which values are randomly select from sample space. Two different methods are used for the sampling which are:

A. Monte Carlo sampling

Monte Carlo sampling (MCS) process is the conventional process to extracts samples from a large sample space. In this process random numbers are used to draw a sample from a probability distribution function. This process is entirely random i.e., any selected sample may fall anywhere within the sample space of the input probability distribution variables.

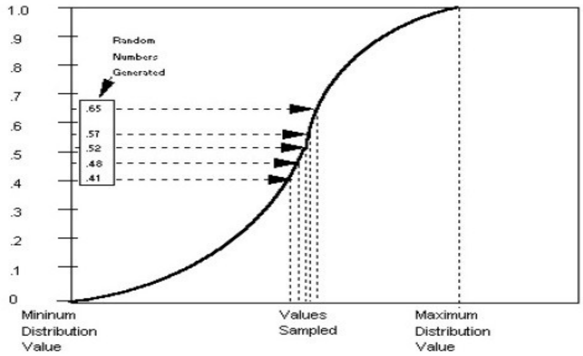

Fig.2. extraction of samples considering MCS

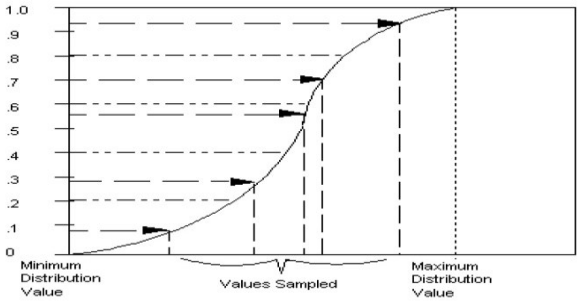

Fig.3. extraction of samples considering LHS

B. Latin hypercube sampling

Latin Hypercube sampling (LHS) process considers stratification of the input probability distribution variables. It simply divides sample space into equal parts on the probability scale (0 to 1.0). A sample is then randomly select from each part of the input probability distribution function. LHS technique is forced to signify samples in each part, and thus, is enforced to re-form the input probability distribution function.

V. SIMULATION AND RESULTS

IEEE 24 bus RTS is considered for the study and evaluation of the proposed methodology. Simulation of the proposed approach is done in MATLAB environment, and CONOPT solver of GAMS (distribution 23.4) is called from MATLAB for solving the OPF problem.

In the first step NVSI are calculated for 38 transmission lines of IEEE 24 bus RTS which are shown in Figure 3. It shows line 13 is having highest sensitivity index. This transmission line is connected between bus no. 8 and bus no. 10. To get exact location of the solar plant, ATC is evaluated by placing solar plant at both the buses one after another; bus showing the maximum ATC is the optimal location for the solar plant.

Hourly based solar irradiance data of one typical meteorological year (TMY) is considered for the purpose of this work. The test data for an Indian city named Lucknow is taken from the National Solar Radiation Database (NSRDB) [17]. Actual power output of the photo voltaic array can be obtained by multiplying mean power to the probability of occurrence for each solar irradiance level. Simulation results for the output power of 5000 PV modules for each solar irradiance level is shown in the table 2. Calculated PV power is injected into the bus 8 and bus 10, one by one. For the calculation of ATC a single bilateral transaction between bus 23 as seller bus and bus 15 as buyer bus is taken into consideration. OPF based problem is solved by using GAMS. Maximum value of loadability factor for ATC calculation is obtained by using MATLB environment.

Three different cases are considered for the determination of ATC. First level in every case shows the non-availability of solar power it is also considered as the base level. In first case steady state demand is taken into account at each bus of IEEE 24 RTS. Calculated values of ATC are shown in table III and ATC comparison for PV at two buses of line 13 is shown in figure 7. From these two curves it is clear that as solar output power is varies the ATC values for different levels also varies and ATC values for solar placement at 10^{th} bus is more compare to 8^{th} bus. So bus no. 10 is most suitable for the integration of solar power.

Probabilistic nature of load which is normally distributed is considered for the other two cases. These two cases are differentiated according to the two sampling techniques used to extract 300 load samples for each solar radiation level. Case II considers MCS process while as case III considers LHS process. Probabilistic load at bus 1 using MCS and LHS is shown in the figure 8 and 10 respectively. As LHS process covers all the sample space of normally distributed function, it provides a better approximation of probabilistic load. So LHS technique gives more accurate result for the ATC calculation compare to the MCS process.

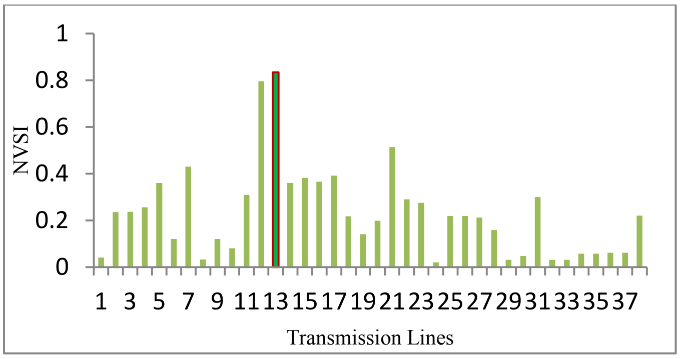

Fig.5. NVSI values for every line

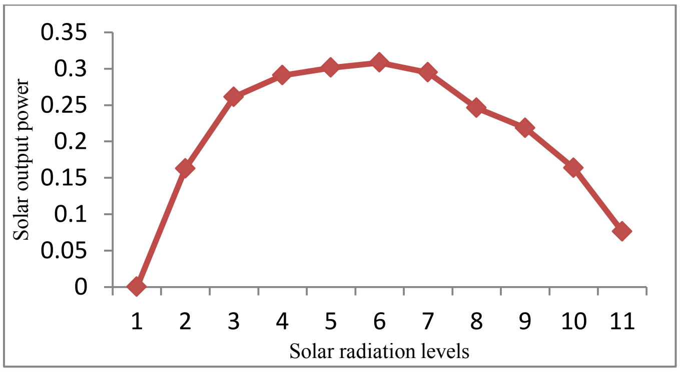

Fig.6.Output power for every solar radiation level

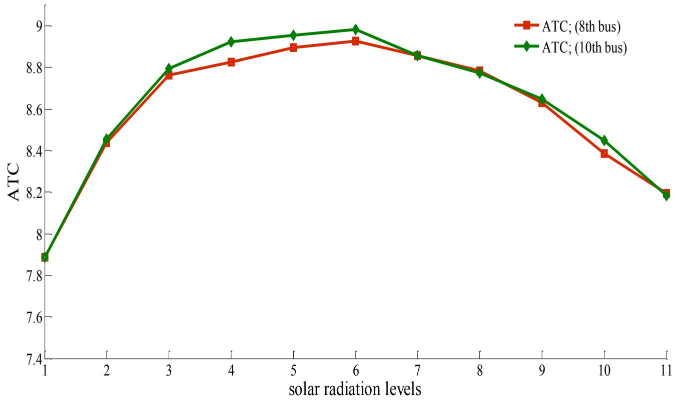

Fig.7. ATC comparison: PV at two buses of line 13

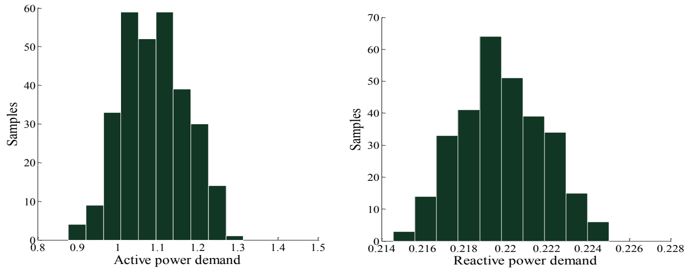

Fig.8. normally distributed load at bus 1 using MCS sampling

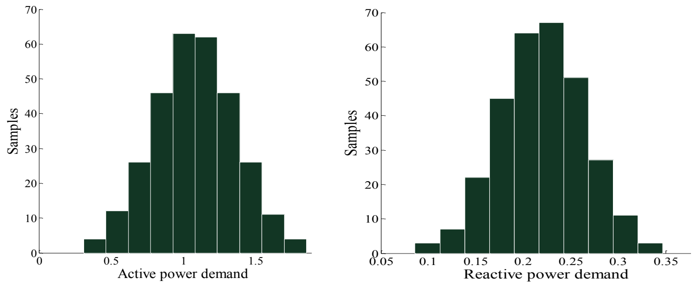

Fig.9. normally distributed load at bus 1 using LHS sampling

Table II solar radiation levels and corresponding power outputs

Radiation levels	***Solar radiation range Kw/m^2***	***mean power (pu)***	***Probability of occurrence***	***Actual output power (Pu)***
1	0	0	-	0
2	0 - 0.1	0.3442	0.4670	0.1607
3	0.1 – 0.2	1.6901	0.1535	0.2595
4	0.2 – 0.3	2.8157	0.1016	0.2859
5	0.3 – 0.4	3.9356	0.0784	0.3086
6	0.4 – 0.5	5.0210	0.0623	0.3128
7	0.5 – 0.6	6.0399	0.0487	0.2941
8	0.6 – 0.7	7.0601	0.0349	0.2464
9	0.7 – 0.8	8.0882	0.0267	0.2164
10	0.8 – 0.9	9.0210	0.0188	0.1696
11	0.9 – 1.0	9.8480	0.0080	0.0793

Table III calculated ATC values

Solar radiation Levels	*ATC Without probabilistic load (case I)*	*ATC with probabilistic load*	
		Monte Carlo Sampling (case II)	*Latin Hypercube Sampling (case III)*
1	7.8870	7.607853	7.432101
2	8.4548	8.169962	7.833921
3	8.7950	8.473976	8.026051
4	8.9220	8.660727	8.089041
5	8.9557	8.631727	8.110408
6	8.9827	8.664843	8.126436
7	8.8571	8.55999	8.096694
8	8.7739	8.491286	7.993456
9	8.6496	8.406792	7.939784
10	8.4498	8.182426	7.835329
11	8.1835	7.914689	7.605158

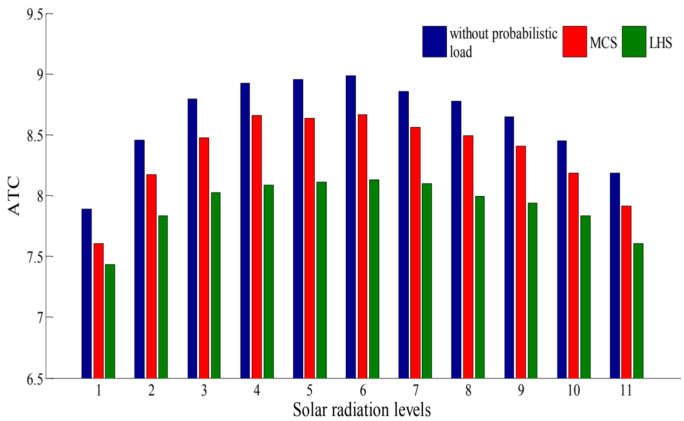

Fig.10. Comparison of ATC for all the three case

Simulation result of ATC for all the three cases when solar power is integrated at 10^{th} bus is present in table III. A comparison graph for calculated ATC values is also present in figure 10. From this graph we can observe that a significant reduction of ATC is occurs when probabilistic nature of load is considered. As LHS process gives most approximated probabilistic load model, ATC values for this case are less compare to MCS process.

VI. Conclusion

Probabilistic nature of solar irradiance and load are taken into account for the assessment of ATC which is carried out on IEEE 24 bus reliability test system. In this work three different cases are considered for the determination of ATC. First case considered probabilistic nature of solar irradiance while load variations are fixed at each bus. In case II and case III probabilistic nature of solar radiation and load demand both are taken into account. Case II uses MCS for extraction of load samples while in case III considers LHS. Simulation results for all three cases concludes that as injected solar power increases ATC values are also increases, if optimally placed. A significant reduction in ATC values occurs from case I to case II, a further reduction in case III. LHS process gives more accurate load model so results obtained in case III are more accurate in compare to case II.

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