International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8 Issue-3, September 2019

Transmission Congestion Management Considering Modeling of Solar Photovoltaic Distributed Generator in Deregulated Power System

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Abstract**:** ***This paper presents an effective methodology for transmission congestion management (TCM) in deregulated power system considering random nature of solar photovoltaic distributed generator (SPVDG). Solar photovoltaic power generation has gained popularity worldwide. Its' optimal sitting in the grid can provide congestion relief and reduce line losses etc. However, to maximize the potential benefits of this renewable energy source, its' stochastic power output which mainly depends on solar irradiance needs due consideration. In this paper, seasonal variations of solar irradiance have been modeled using beta probability density function to determine expected power output of SPVDG over various seasons of one year. TCM problem has been formulated as a non-linear programming with the objective of social welfare maximization of electricity market subject to equality and inequality constraints incorporating seasonal load demand variations. The optimal siting of SPVDG integration in the grid has been discussed. The proposed methodology has been simulated by incorporating practical data of a real-life SPVDG in standard IEEE 30-bus, IEEE 118-bus and practical Indian Utility 62-bus systems. Simulation results show the benefits of proposed methodology on market indices. The effectiveness of proposed approach is also discussed in comparison with existing methodology of distributed generation modeling***

Keywords**:** ***Beta probability density function, locational marginal pricing, solar photovoltaic distributed generator, transmission congestion.***

I. INTRODUCTION

Transmission congestion management (TCM) plays an important role in the deregulated environment of power sector [1]. Congestion in transmission network creates market inefficiency, increases power losses and cost of energy. The various TCM schemes have been adopted in different electricity market models worldwide which can be briefly summed as pricing methods [2]-[4], re-dispatch [5]-[6], counter-trading [7], load auctions [8], reactive power support [9]-[10], load curtailment [11], deploying flexible AC transmission system (FACTS) devices [12]-[13], demand management [13]-[14], and distributed generation (DG) [15]-[19]. Nodal pricing/locational marginal pricing (LMP) mechanism [1], [10], [15] is adopted in several United States (U.S). Zonal pricing, a variant of nodal pricing is implemented by Australian and Scandinavian electricity markets for market clearing [1]-[2]. Nodal/LMP and zonal pricing methods indicate the location for installation of new generators and/or transmission expansion to manage congestion in the network. These financial tools act as deterrent for market constituents to re-schedule their generation/demand schedules but network congestion still exists posing threat to system security. Re-dispatching of hydro-thermal combination and all-thermal generators for alleviation of TCM in a pool based electricity market is used in [5]-[6]. References [12]-[14] have used FACTS devices and employed demand response technique for cost effective congestion management. However, the cost of reactive power and the impact of load variations have not been included in [5]-[6],[12]-[14]. The reactive power management is an integral component of transmission management [9]-[10].

The load side management has emerged as quite effective technique for congestion management. Distributed generation (DG) technology is one of the most effective tools of load management [15]-[21]. DG constitutes harnessing small and medium amount of power (few kW ~ few MW) from renewable energy resources like solar, wind, biomass and small/mini hydro plants etc. In this work, solar photovoltaic distributed power generator (SPVDG) is explored as DG technology for TCM for pool based market. The operating cost of solar power plants mainly comprises small operation & maintenance cost while fuel cost is zero [15]-[19]. Numerous literatures are available on the optimal siting and sizing of DG in power system with different objective functions. In deregulated electricity markets, the optimal placement and sizing of DG is important for TCM and social welfare (SW) maximization [17]-[18], [20].

Manuscript published on 30 September 2019

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Singh et al. [18] have used Z-bus based contribution factors for optimal placement of DG in the network to maximize SW. However, authors have used DC modeling and considered only real power generation cost for load instance in the optimization problem. LMP is widely used tool for DG integration in system for TCM [3]-[4], [15], [18]. Kumar and Gao [4] have used real power nodal price based zonal approach for optimal siting of DG in pool and hybrid electricity markets. Ramesh and Kumar [21] have used transmission line relief sensitivity index as tool for optimal placement of DG. Peesapati et al. [19] have presented a multi-objective TCM approach with solar, biomass and wind based DGs. But, the variability of the DG outputs has not been taken onto account in [15]-[16], [18]-[19] and the authors have committed the rated capacities of DGs in market dispatch.

However the power production of renewable DGs like wind and solar power is stochastic due to their dependence on random variables such as temperature, irradiance level and wind speed [20]. Hence analysis of such DGs requires probabilistic approach before committing their generation in electricity markets. Solar generation is mainly function of irradiance falling on photovoltaic (PV) panels. In this paper, seasonal variations in solar irradiance over the span of one year have been modeled using beta probability density function (PDF). Randomness of solar irradiance can be best modeled with beta PDF than other probability distribution functions like lognormal, weibull, gamma and logistics functions [22]-[24]. The problem has been formulated as non-linear optimization of TCM with an objective to maximize the SW of electricity market over the year incorporating the probabilistic seasonal output of SPVDG. The proposed approach has been applied for IEEE 30-bus, IEEE 118-bus and practical Indian Utility 62-bus systems. The results show the benefits of proposed methodology on SW, its components, merchandising surplus (MS) and losses.

The novelty of the present paper lies in the fact that the effects of seasonal variations of solar generation output using beta pdf, and seasonal variations in load demand changes have been incorporated in the TCM problem. Moreover, full AC modeling of power system is used which includes the reactive power generation cost in addition to real power generation cost and demand benefit in the objective function. The mechanism for optimal placement of SPVDG in the system based on market operations over the year has been discussed in the present work and contributes to the planning part of power system.

The rest of paper is organized as follows: Modeling of SPVDG is detailed in Section II. Section III provides formulation of TCM problem in electricity market. Results and discussion are presented in Section IV. Conclusions are drawn in Section V.

II. MODELING OF SPVDG

Solar PV power generation depends on site climatic conditions like irradiance, ambient temperature, dust, humidity and wind speed, characteristics of PV modules, regular cleaning and maintenance of plant [24]-[25]. Therefore it is vital to analyze the output of solar power plant apropos site conditions. In order to simplify the SPVDG modeling equations, the variation of site irradiance, temperature and characteristics of PV modules are considered only to determine the expected power output of plant. Thus modeling of SPVDG consists of two parts: solar irradiance modeling and power generation function for PV array.

A. Solar irradiance modeling

Solar irradiance and hence power output varies with the time of day and season of a year. In this work, one year is divided into four seasons as per prevailing conditions of Indian subcontinent. During any t th season, for i th time interval the solar irradiance is modeled by beta pdf, $f_b^t\left(s^t\right)$ as given below [20], [26].

$$f_b^t(s^t) = \begin{cases} \dfrac{\Gamma(\alpha^t+\beta^t)}{\Gamma(\alpha^t)\,\Gamma(\beta^t)} *(s^t)^{(\alpha^t-1)} *(1-s^t)^{(\beta^t-1)}, \\ for\ 0 \le s^t \le 1,\ \alpha^t \ge 0,\ \beta^t \ge 0 \\ \\ 0, \qquad otherwise \end{cases} \tag{1}$$

Where $\Gamma(.)$ is gamma function, β^t and α^t are parameters of beta distribution function and s^t is solar irradiance in kW/m^2 during t th season. β^t and α^t are calculated from mean (μ^t) and standard deviation (σ^t) of random variable solar irradiance, s^t from [20], [26].

B. Power generation function for PV array

The power $P_o^t\left(s^t\right)$ generated by PV array corresponding to solar irradiance s^t during t th season is calculated as [20], [24], [26]:

$$P_o^t(s^t) = N * FF * V^t(s^t) * I^t(s^t) \tag{2}$$

Where N is total number of PV modules in array forming SPVDG and F is the fill factor. $I^t(s^t)/V^t(s^t)$ are current/voltage of solar PV module during t th season and can be obtained from the characteristic parameters of PV modules and equations given in [20], [24], [26]. Once the beta pdfs of solar irradiance are generated for specified time intervals, the expected power output, $P_{pvi}^t(s^t)$ of SPVDG for any i th time interval during t th season can be obtained from the integration of product of $P_o^t(s^t)$ and $f_b^t(s^t)$ over $s_{\min}^t$ to $s_{\max}^t$ as:

$$P_{pvi}^t(s^t) = \int_{s_{\min}^t}^{s_{\max}^t} P_o^t(s^t) * f_b^t(s^t)\,ds \tag{3}$$

C. Algorithm for calculation of SPVDG output

The methodology adopted to determine the expected power output of SPVDG as function of site climatic conditions is summarized in following steps:

step 1. The hourly historical data of irradiance of SPVDG site under study is taken for one year.

step 2. The year is divided into four seasons as per prevalent site conditions. Then mean irradiance for each hour of the season is calculated and plotted versus time (7:00 to 18:00 hours). Observing the variation of irradiance with time, the time intervals are specified from the plot, such that one mean value of irradiance pertains for each specified time interval. The mean μ^t and standard deviation σ^t of irradiance are calculated using Microsoft Excel.

step 3. Beta probability density function is applied to model stochastic solar irradiance using (1). The parameters β^t and α^t of beta distribution function are obtained from [20], [26].

step 4. The power outputs of SPVDG are calculated for each specified time interval (3).

step 5. The weights w_i^t of each time interval of a day for each season are calculated. The expected SPVDG power outputs, P_{PV}^t (MW) during any t th season is obtained from (4).

Seasonal expected power output of SPVDG,

$$P_{PV}^t = \left(w_i^t * P_{pvi}^t\right) / \sum_i w_i^t \quad \forall i \in time\,intervals, t \in T \tag{4}$$

Where T is set of seasons.

Steps 3-5 are coded with MATLAB programming.

step 6. Repeat steps 1-5 to determine expected power outputs for all seasons of the year.

III. TCM PROBLEM FORMULATION IN ELECTRICITY MARKET WITH SPVDG PLACEMENT IN SYSTEM

In this work, a double auction pool based electricity market followed by Pennsylvania-New Jersey-Maryland (PJM) has been considered for analysis. GENCOs and DISCOs submit their supply and demand bids to ISO. The seasonal variations in load demand and SPVDG power output affect the generation and demand schedules; as a result SW changes in each season. In the proposed approach, ISO prepares a generation and demand schedules with an objective of social welfare maximization over the year considering non-linear load flows as equality constraints and transmission line loadings as inequality constraints. SW function as given in [18] is multiplied with fractional weight of respective season to maximize SW over a set of seasons of the year. The sum of weights equals to one. Hence mathematically TCM problem has been formulated as non-linear optimization problem with the objective of maximization of SW over the year.

A. Objective function

$$Max\ SSW = \sum_{t=1}^{T} ws^t * \left[\begin{array}{l} \sum\limits_{i=1}^{N,t} \left\{ B_i^t \left(P_{di}^t \right) \right\} \\ - \sum\limits_{i=1}^{N,t} \left\{ C_i^t \left(P_{gi}^t \right) + C_{qi}^t \left(Q_{gi}^t \right) \right\} - C(SPVDG) \end{array} \right] \tag{5}$$

Where SSW is annualized value of SW in \$, $B_i^t(P_{di}^t) / C_i^t(P_{gi}^t)$ are demand benefit function of DISCO/ cost function of GENCO for real power demand (P_{di}^t) /generation (P_{gi}^t) at i th bus during t th season in \$/hr and can be obtained from their demand bids and supply bids respectively [18]. $C_{qi}^t(Q_{gi}^t)$ is cost of reactive power generation of GENCO at i th bus during t th season in \$/hr and can be obtained from reactive power capability curve of generator [9-10]. The cost of SPVDG, $C(SPVDG)$ can be obtained from its supply bid as:

$$C(SPVDG) = a_{PVk}^t (P_{PVk}^t)^2 + b_{PVk}^t P_{PVk}^t \quad \$/hr \tag{6}$$

a_{PVk}^t, b_{PVk}^t are coefficients of cost function of SPVDG in \$/MWh^2, \$/MWh respectively during t th season.

The non-linear load flows as equality constraints, transmission line loadings as inequality constraints, bounds on variables and capability curve constraints are referred from [9]-[10], [18]. But with placement of SPVDG at k th bus in system, real power equation gets modified. Real power constraints at i th bus during t th season are given in (7) – (8).

$$P_{gi}^t - P_{di}^t = V_i^t \sum_{j=1}^{N} V_j^t \{G_{ij} \cos(\delta_i^t - \delta_j^t) + B_{ij} \sin(\delta_i^t - \delta_j^t)\}$$
$$\forall i = 1, 2, ...N; i \neq k, t \in T \tag{7}$$

$$P_{gk}^t + P_{PVk}^t - P_{dk}^t =$$
$$V_k^t \sum_{j=1}^{N} V_j^t \{G_{kj} \cos(\delta_k^t - \delta_j^t) + B_{kj} \sin(\delta_k^t - \delta_j^t)\};$$
$$t \in T, k \text{ is SPVDG bus} \tag{8}$$

Where $G_{ij} + j B_{ij}$ is bus admittance matrix element for i th row and j th column, N is set of system buses, and V_i^t / δ_i^t are bus voltage magnitude / angle at i th bus during t th season.

SPVDG power output constraint is

$$0 \leq P_{PVk}^t \leq P_{pv\max}^t \quad \forall k \in N, t \in T \tag{9}$$

Where $P_{PVk}^t / P_{pv\max}^t$ is solar power generation at k th bus during t th season/rated capacity of SPVDG.

B. Locational marginal price (LMP)

LMPs are by-products of market dispatch solution, determined as Lagrangian multipliers of real and reactive power constraints [9]-[10], [15].

The difference of LMPs between two nodes of transmission line gives a measure of its congestion.

C. Consumer payment (CP)

Consumer payment, at any node i, during t th season is the amount to be paid by the consumer for purchase of electricity at that node [15] and is calculated as:

$$CP_i^t = \lambda_{pi}^t * P_{gi}^t + \lambda_{qi}^t * Q_{gi}^t \quad \$/hr \tag{10}$$

λ_{pi}^t, λ_{qi}^t are Lagrangian multipliers of real power and reactive power constraints respectively at i th bus. CP is one of the selection criterions for optimal placement of DG in the system [15], [18]. DG supplies the loads locally thereby relieving the transmission line from hitting any of its limits.

D. Congestion rent (CR) and Merchandising surplus (MS)

Congestion rent (CR) is calculated as difference in SW value of TCM problem without and with taking into account congestion constraints [18]. CR in \$/hr can be determined as

$$SW_5^{wo,t} - SW_5^t \tag{11}$$

$SW_5^{wo,t}$, SW_5^t are the values of SW of the TCM problem as given by (5), without and with taking into account line flow limit constraints.

Merchandising surplus (MS) is defined as the difference of buyer payments and seller revenues and the annualized value can be calculated in \$/hr as:

$$MS = \sum_{t=1}^{T} ws^t * \begin{pmatrix} \sum_{i=1}^{N,t}\left(\lambda_{pi}^t * P_{di}^t + \lambda_{qi}^t * Q_{di}^t\right) \\ \\ -\sum_{j=1}^{N,t}\left(\lambda_{pj}^t * P_{gj}^t + \lambda_{qj}^t * Q_{gj}^t\right) \end{pmatrix} \quad \forall i \in N,\, t \in T$$

(12)

It occurs due to congestion in the network. The annualized values of SW and MS in \$/hr are multiplied with 8760 (number of hours in a year) to obtain the annual values of SW and MS in \$.

IV. RESULTS AND DISCUSSION

The proposed methodology has been simulated on IEEE 30-bus, IEEE 118-bus and a practical Indian utility 62-bus systems. The TCM problem has been solved with “A Modeling Language for Mathematical Programming” (AMPL) software employing KNITRO solver [27]. Interior/Direct algorithm has been used for solving non-linear optimization TCM problem and implemented on computer with configuration OS-WIN7, CPU i3@2.30 GHz (4CPUs), 2 cores, RAM-4GB.

A. IEEE 30-bus system

IEEE-30 bus system consists of 6 GENCOs, 21 DISCOs and 41 transmission lines. The cost coefficients of SPVDG bid, supply and demand bids of GENCOs and DISCOs respectively are as given in [18]. The generation power limits are taken from [18], [28]. Minimum real power generation limit is assumed to be zero. The annual seasonal variations can be divided into four seasons namely winter (December-February), summer (March-June), rainy (July-September) and post-monsoon (October-November). Seasonal load demands on various buses of IEEE-30 bus system assumed in this work are shown in Fig. 1. Load demands are assumed to be constant during a particular season.

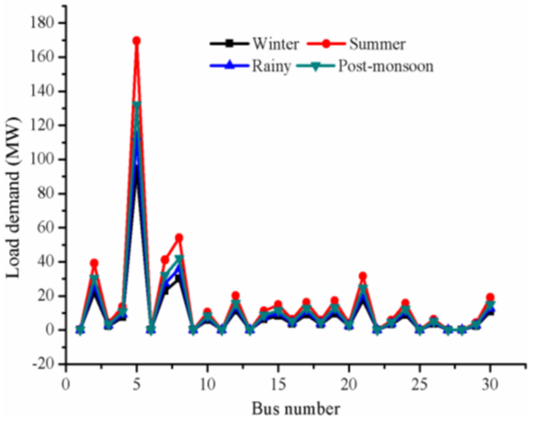

Fig. 1. Seasonal load demands on IEEE-30 bus system

B. Expected power output of SPVDG

For the present work, a SPVDG of capacity 24 MWp (228600 modules of 105 kWp each made of thin film CdTe type) situated at Sri Muktsar Sahib (Punjab State), India is considered for analysis. The site latitude and longitude are 30.47°N and 74.37°E, respectively, which has average annual horizontal solar insulation of 4.73 kWh/m^2/day. The data sources for analysis are taken from Meteonorm [29]. Solar irradiance data of one year is used for analysis. Following the algorithm given in sub-section C of Section II, the time intervals of one day during summer and rainy seasons are specified as 7:00-9:00, 9:00-11:00, 11:00-14:00, 14:00-16:00 and 16:00-18:00 hours while for winter and post-monsoon seasons are specified as 8:00-11:00, 11:00-14:00 and 14:00-17:00 hours. The beta pdfs are obtained during each specified time interval of each season using (1). As an example, beta pdf of solar irradiance during interval 11:00-14:00 hours in summer season is shown in Fig. 2. The mean ambient temperatures during winter, summer, rainy and post-monsoon are 13.43°C, 28.13 °C, 29.67 °C and 21.6 °C respectively as calculated from historic data.

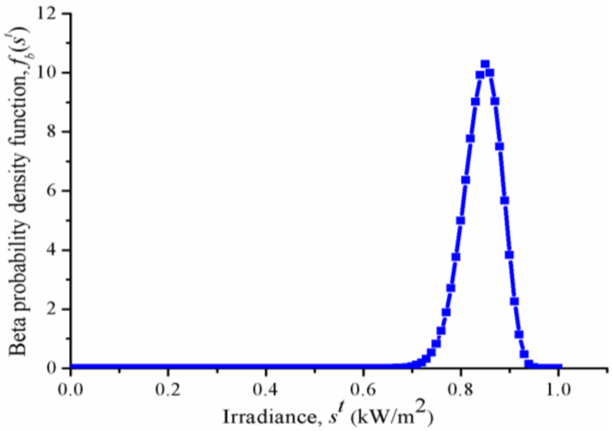

Fig. 2. Beta PDF of irradiance during 11am-2pm in summer season

The expected power outputs of SPVDG during specified time intervals of four seasons of one year are calculated using (2) – (3) and are given in Table-I.

Table-I: Expected power output (MW) of SPVDG during specified time intervals of four seasons of one year.

	Time interval (hours)				
Season	**7:00-9:00**	**9:00-11:00**	**11:00-14:00**	**14:00-16:00**	**16:00-18:00**
Summer	6.0484	13.4518	17.2443	13.9811	6.6248
Rainy	5.4938	12.4798	15.5051	12.8334	5.8047
	Time interval (hours)				
Season	**8:00-11:00**	**11:00-14:00**	**14:00-17:00**	-	-
Winter	6.1776	11.1324	6.2872	-	-
Post-monsoon	8.6952	13.4669	7.2334	-	-

The variation of expected power output corresponding to expected value of irradiance in summer season during sunshine hours is shown in Fig. 3.

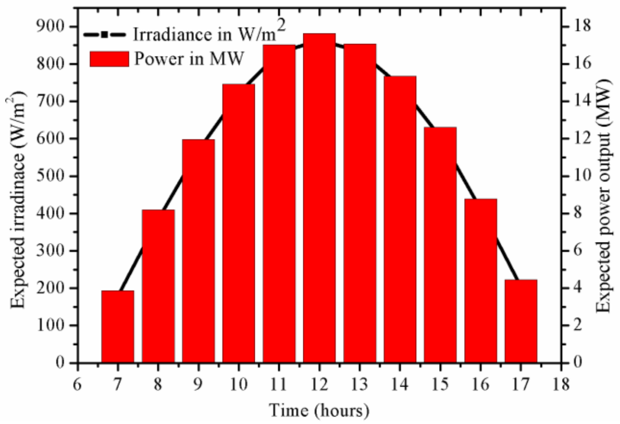

Fig. 3.Variation of expected irradiance and expected power output during 7:00-17:00 hours in summer

The expected power outputs of SPVDG obtained from (4) for winter, summer, rainy and post-monsoon seasons are 7.866MW, 11.995MW, 10.8853MW and 9.7985MW, respectively.

C. TCM with SPVDG

For base case analysis, TCM problem is solved without SPVDG. The weights taken for winter, summer, rainy and post-monsoon seasons are 25%, 33.3%, 25% and 16.7%, respectively. The system becomes congested in all the seasons except summer season, due to the line number 2 connecting bus 1 and bus 3 hitting its line loading limit. SW, demand benefits, GENCO costs of real and reactive powers, congestion rent, during various seasons, and Annual SW and MS are obtained for base case, as shown in Table-III. The various annualized values are obtained by taking weighted sum of corresponding seasonal values. The congestion rent in summer season is nil (Table-III). This is due to the reason that, high demand in summer season requires more power to be purchased from costlier generators (for example generator at bus number 5), which causes change in pattern of power flow over the transmission lines. Hence, line 1-3 operates within the rated capacity in this season.

The optimal location for SPVDG placement in system is decided based on weighted LMPs and weighted CPs of real power. The highest priority locations obtained by weighted LMPs is bus 30, whereas by weighted CPs is bus 5. Three top locations obtained by these methods for SPVDG placement in system are tabulated in Table-II.

Table-II: Ranking of buses for SPVDG placement based on weighted LMPs and weighted CP.

Ranking	**Bus No.**	**LMP method ($/MWh)**	**Bus No.**	**CP method ($/hr)**
1	30	48.83	5	5864.92
2	29	45.88	8	1704.99
3	26	44.43	7	1490.10

The proposed TCM problem is solved with SPVDG placed at bus 30 (optimal location given by weighted LMP) and bus 5 (given by weighted CPs). The expected power outputs of SPVDG as determined in sub-section B of Section IV for each season are committed in electricity market. The various indices of electricity market obtained for each season and calculated for the year are tabulated in Table-III.

Table-III: Social welfare, its components and congestion rent without SPVDG and with SPVDG placed at bus 30 and bus 5.

Parameters		**Base Case (without SPVDG)**	**SPVDG placed at bus 30 (weighted LMP-based approach)**	**SPVDG placed at bus 5 (weighted CP-based approach)**
Social welfare ($/hr)	Winter	7978.74	8075.72	8061.09
	Summer	11260.33	11543.42	11452.70
	Rainy	9038.38	9182.30	9156.55
	Post-monsoon	10004.14	10200.64	10112.49
	Annualized value	9674.66	9861.97	9806.94
Demand benefit ($/hr)	Winter	17004	17004	17004
	Summer	27741.75	28195.13	27902.01
	Rainy	20404.80	20404.80	20404.80
	Post-monsoon	23636.66	23805.6	23638.74
	Annualized value	22537.52	22716.72	22591.24
GENCO cost of real power ($/hr)	Winter	8994.89	8662.53	8676.76
	Summer	16393.75	16203.78	16001.39
	Rainy	11319.81	10851.20	10875.65
	Post-monsoon	13560.55	13240.99	13160.89
	Annualized value	12802.4	12485.54	12414.43
GENCO cost of reactive power ($/hr)	Winter	30.36	29.77	30.18
	Summer	87.68	88.07	88.07
	Rainy	46.61	44.75	46.04
	Post-monsoon	71.98	70.02	71.41
Congestion Rent ($/hr)	Winter	71.96	66.36	73.24
	Summer	0.0	0.0	0.0
	Rainy	75.51	68.53	77.74

	Post-monsoon	52.67	62.90	56.49
	Annualized value	45.66	44.23	47.18
Annual SW **(k$)**	-	84750.02	86390.86	85908.82
Annual MS **(k$)**	-	15161.79	13790.06	14913.5

D. Effectiveness of Proposed Methodology

The results in Table-III show that annual SW of value 86390.86 k$ is maximum with SPVDG placed at bus 30. Also, annual MS of market participants decreases significantly to value 13790.06 k$ from 15161.79 k$ in base case indicating overall reduction in transmission congestion. Moreover, the results obtained in Table-III show that demand benefits have been improved and GENCO costs of real and reactive power and congestion rent have been reduced by the placement of SPVDG in the system. The percentage improvement in SW is highest in summer season. This is due to the reason that summer season witness more sunny hours and load demand. This means the SPVDG brings maximum improvement in the market, when it was desperately needed. This depicts self-healing feature of SPVDG integrated electricity market.

The availability of solar power output varies from season to season and is definitely less than the rated capacity of SPVDG. Although, modeling SPVDG by its rated capacity (as projected in some earlier approaches [15]-[16], [18]-[19]) would give apparently improved results, but the same are not practically attainable. In this regard, the proposed methodology of modeling SPVDG gives more accurate results. Hence, the ISO and utilities can be benefited from the proposed approach of TCM of electricity markets.

The improvement in these market indices is more prevalent for SPVDG location at bus 30 (LMP method) than bus 5 (CP method). It shows that CP method is not able to provide the optimal location for SPVDG placement, as CP at any bus is proportional to load demand at that bus, which is not a correct economic signal for congestion management. Fig.4 show the variation in annual SW and annual MS due to SPVDG placement at optimal (bus 30) and sub-optimal locations (bus 29 and bus 26) determined from LMPs. Similarly, Fig.5 shows the variation of line power flow losses during different seasons with SPVDG placement at different locations. Highest improvement is obtained by placing SPVDG at bus 30, which proves the importance of placing SPVDG at optimal location given by LMP method.

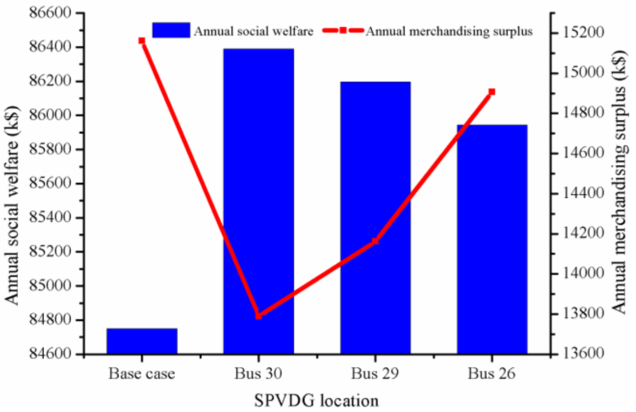

Fig.4. Variation of annual SW and MS with SPVDG placement at optimal and sub-optimal locations

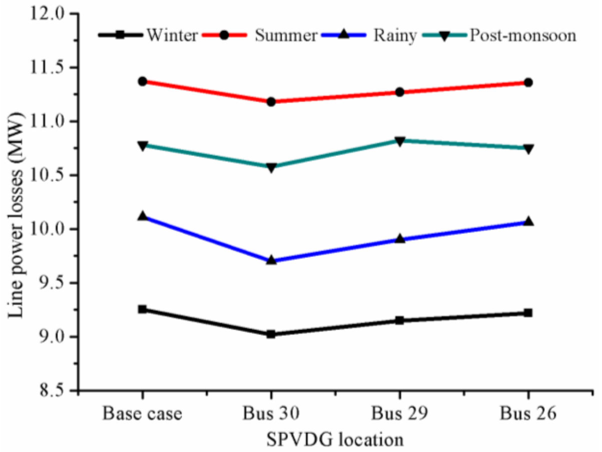

Fig.5. Seasonal variation in line power losses with different SPVDG locations

In the nutshell, it can be concluded that the improvement in market indices are governed by weight assigned to each season (which in turn depends upon the duration of a particular season), availability of power from SPVDG, and location of SPVDG.

The proposed TCM methodology is compared with an existing TCM approach [18], as given in Table-IV. The optimal location of SPVDG placement by proposed approach is bus 30, but by [18] is bus 3. This is due to the incorporation of AC modeling, reactive power cost and seasonal variations of load in the proposed approach. The optimal location in proposed approach is decided based on performance of market operations over the year.

In Table-IV, the SW, demand benefit, GENCO costs of real and reactive power, DG cost and CR obtained in proposed TCM approach are compared with that of [18].

Table -IV: Comparison of results of proposed approach with [18]

	Base Cases		**After DG Placement**	
	Without DG placement [18]	**Proposed approach-Base case**	**With DG placed [18]**	**Proposed approach-SPVDG placed at optimal location**
Social welfare ($/hr)	8438.4	9674.66	9073.5	9861.97
Demand benefit ($/hr)	17,004.0	22,537.52	17,004.0	22716.72
GENCO cost of real power ($/hr)	8565.6	12802.4	6130.5	12485.54
GENCO cost of reactive power ($/hr)	-	60.46	-	59.65
DG cost ($/hr)	-	-	1800.0	309.56
Congestion rent ($/hr)	222.2	45.66	-	44.23

The comparison of results given in Table-IV shows that value of SW with proposed approach has increased to 9861.97 $/hr from 9073.50 $/hr in [18], and demand benefit with proposed approach has increased to 22,716.72 $/hr from 17004.0 $/hr in [18] with SPVDG placement at optimal location. The cost of generation has gone higher and CR is not completely eliminated in proposed approach due to reason that only expected power output of SPVDG for various seasons are committed in proposed approach. Expected power output is quite lower than DG capacity of 60 MW taken in [18]. CR in proposed approach has decreased significantly from 222.2 $/hr [18] to 45.66 $/hr in the base case itself due to AC modeling as reactive power support in system helps in reducing network congestion.

E. IEEE 118-bus system and Indian Utility 62-bus system

The proposed approach is also implemented on IEEE 118-bus system [28] and Indian Utility 62-bus system [30]. In IEEE 118-bus system, the congested system conditions are simulated by considering maximum line loadability limit of 125MVA. In Indian utility 62-bus system, the number of lines which hit the limits during winter, summer, rainy and post-monsoon seasons are 16, 30, 20 and 25, respectively, out of the total 89 transmission lines. Due to increase in scale of these systems, the maximum capacity of SPVDG is taken as 50MWp, which provides 16.385 MW (32.77%), 24.985MW (49.97%), 22.675 MW (45.35%), and 20.415MW (40.83%) power output during winter, summer, rainy and post-monsoon seasons, respectively. The optimal locations obtained for SPVDG placement based on weighted LMP method are bus 59 and bus 53respectively for IEEE 118-bus and Indian utility 62-bus systems. The results obtained in these systems also demonstrate the effectiveness of proposed methodology, as discussed in sub-section D of Section IV. The reductions in seasonal CR obtained in these systems are shown in Fig.6 and Fig.7, respectively.

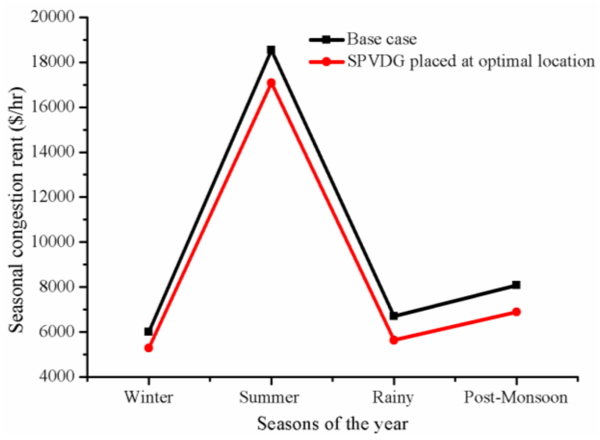

Fig.6. Seasonal variation of CR with and without SPVDG placement in IEEE 118-bus system

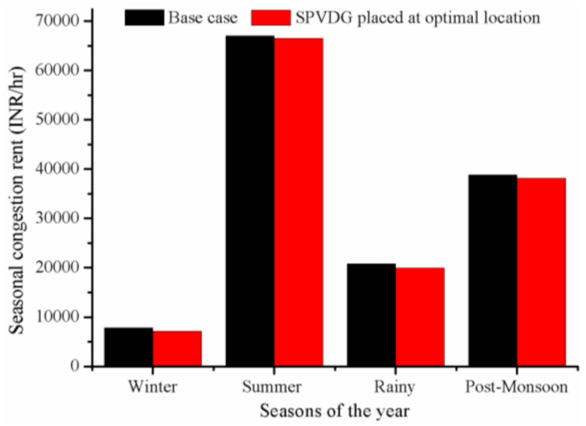

Fig.7. Seasonal variation of CR with and without SPVDG placement in Indian Utility 62-bus system

V. CONCLUSION

In this paper, an effective TCM methodology for pool based electricity market integrated with SPVDG in deregulated environment is presented. In the proposed methodology, the problem of stochastic power output of SPVDG due to its dependence on solar irradiance is addressed by modeling the randomness of irradiance with beta pdf. TCM incorporates seasonal variations of expected power outputs as determined from beta pdf as well as seasonal variations of load demands. Simulation of proposed methodology on IEEE 30-bus, IEEE 118-bus and practical Indian utility 62-bus system and comparison with existing TCM approach give following concluding points:

1) Due to the dependency of solar power output on irradiance, the expected power output available during various seasons is much less than the rated capacity of SPVDG. Hence, modeling of SPVDG by its rated capacity (as done in some earlier approaches) in TCM problem, cannot give accurate results. This proves the effectiveness of proposed methodology.
2) TCM results are largely influenced by the location of SPVDG placement and availability of its power output. SW of electricity market increases whereas MS and CR decrease with optimal location of SPVDG in the system.
3) Due to incorporation of the effect of reactive power and losses (AC modeling of power system), the TCM results are quite different than the DC approach.

ACKNOWLEDGMENT

Anu Singla is thankful to I. K. Gujral Punjab Technical University, Kapurthala, India for providing her an opportunity to pursue Ph.D programme in Electrical Engineering. Authors are grateful to the authorities of Punjab Energy Development Agency, Chandigarh, India for sharing technical detail of SPVDG incorporated in the present work.

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