Simultaneous sitting PVU and DSTATCOM in distribution grid considering the effect of geographical conditions

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Abstract

This paper proposes a model to allocate photovoltaic unit (PVU) and distribution static compensator (DSTATCOM) that incorporate the operation effect of PVU in sizing and sitting problem. The model is based on the dynamic assessment of PVU production and the effect of it on placement of PVU and DSTATCOM. Geographical conditions are interfered in placement problem of PVU and DSTATCOM simultaneously. The model is verified in a multi-objective form. The multi-objective problem is formulated based on voltage stability, liability, power loss and total cost of PVU and DSTATCOM. This problem is solved by employing optimization techniques and the results of optimization processes are tested in different scenarios. Uncertainty in network loads is an inevitable task that should be considered in network planning. Uncertainty in the presented model has been defined as a set of divided parts in the presented model. The proposed model has been evaluated on two test systems, 30 bus and 69 bus. The obtained results indicate that the presented model can be employed to study the intermittent behavior of PVU in placement problem.

Keywords: photovoltaic, placement model, operation effect, DSTATCOM.

1. Introduction

Various types of renewable intermittent energy sources are being used in distribution systems as dispersed generation. PVUs are mostly non-dispatchable and controllable units with intermittent generation. Output power of PVUs is mainly dependent on solar irradiation and environmental temperature. In practice, the location of this kind of distributed generation (DGs) should be determined based on a mixed combination of technical and environmental perspectives. PVU has effects on voltage variation, energy efficiency and improvement of technical index of power system [1]. However, the system performance might be threatened if the capacity and the connection to the grid point are not determined carefully. [2]. The intermittent nature of PUVs in energy production has been considered in previous research works in which the operational problems are the main concern, but for the PVUs placement goals fewer contributions have been developed [3]. The right place for connecting PVU to the grid is always determined through solving an intricate problem with non-linear and mixed-integer multi-objective problem. The multi-objective problem mathematically models and incorporates different objectives into a merged one. By employing a solution methodology, usually a heuristic optimization method, a Pareto-optimal solutions for the best possible tradeoffs among the objectives is achieved indicating more attractive places for PVUs installation [4].

DSTATCOM is a converter-based compensator that is utilized to correct bus voltage. DSTATCOM provides the additional reactive current to reduce the voltage variations [5]. DSTATCOM can be employed simultaneously with PVU to improve power system performance.

1.1. Literature review

DG allocation in power system has been studied in numerous papers. A method to reduce the disadvantages of DGs in the power system on protection relays has been presented in [6]. DG placement is formulated as an optimization problem while short circuit currents are considered as constraints of optimization problem. In [7], three criteria, including real power losses, voltage variations, and voltage stability index are considered to formulate the size and location determination of DGs. Simultaneously placement of DG and capacitor banks (CB) considering the stochastic nature of DG has been presented in [8]. The results obtained by this paper show that the operation and positive behavior of DG is mainly dependent on the type of DG.

In [9] DG allocating is done with an aim of congestion mitigation. The reactive capability of wind turbines in DG allocation has been proposed in [10]. The effect of double fed induction generator (DFIG) and squirrel-cage induction generator (SCIG) compensation on voltage stability has been studied. This paper has concluded that the configuration of wind units can affect advantages of DGs on power grids. Voltage profile, energy not supplied (ENS), economic profit, transfer capacity and load balancing have been considered in [11].

In [12], a new method for placement of DG and tie-switch assignment have been surveyed. The obtained results show that using the proposed method power losses and voltage quality are improved. Simultaneous network reconfiguration and DG allocation have been presented in [13]. The proposed plan decreases power losses, flattens voltage profile and assists the load balancing purposes in a distribution system. Fuzzy-ant colony optimization (ACO) is employed to solve the optimization problem and compared with fuzzy-genetic algorithm (GA) and fuzzy-particle swarm optimization method (PSOM).

1.2. Motivation and purpose

A model has been presented in this paper for simultaneous planning PVU and DSTATCOM in a distribution network. In this model the impact of uncertainty of PVUs power generation on location determination problem has been considered. Depending on solar irradiation and environmental temperature, generation of PVU will vary continuously. Inflexible production pattern of PVU can affect placement and sizing alternatives. The presented planning model in this paper is employed to improve economic and operational targets as voltage stability, loadability, power loss and total installation costs of PVU and DSTATCOM. The proposed technique has been tested on two standard systems, 33 and 69 buses, and the results are used to show the reliability of the employed model. Different from the previous studies, the proposed model deals with a number of issues, including a) dynamic generation modeling of PVU and employing of it in placement and sizing of PVU and DSTATCOM, b) consideration of four important objectives in distribution networks, c) uncertainties in bus load. Also, an attempt is made to overcome the probabilistic nature of PVU generation. To show the effectiveness of the presented method four scenarios have been adopted and simulated.

2. Generation pattern of PVU

As shown in Figure 1, generation characteristic of a PVU is dependent on geographical conditions. Solar irradiation and environmental temperature are two important parameters that directly affect the generation pattern of PVU.

The voltage of PVU can be written as follows [14, 15]:

$$V_{PVU} = V_{max}^{PVU} + OCV(T_o - T_o^{ref}) \quad (1)$$

where V_{PVU} and V_{max}^{PVU} are photovoltaic panel voltage at the maximum power point and maximum voltage of photovoltaic panel at the reference operating position. OCV is temperature coefficient for open circuit voltage (V/˚C). T_o and T_o^{ref} are photovoltaic panel operating temperature (˚C) and photovoltaic panel temperature at reference operating position (25 ˚C).

The current created by the PVU is formulated as follows:

$$I_{PVU} = I_{SC}\left\{\frac{I_{TS}}{I_{ref}} - \Psi_1\left[exp\left(\frac{V_{max}^{PVU}}{\Psi_2 V_{OC}^{PVU}}\right) - 1\right]\right\} + SCC(T_o - T_o^{ref}) \quad (2)$$

$$\Psi_1 = (1 - \frac{I_{max}^{PVU}}{I_{SC}})\, exp(\frac{V_{max}^{PVU}}{\lambda_2 V_{OC}}) \quad (3)$$

$$\Psi_2 = \left(\frac{V_{max}^{PVU}}{V_{OC}} - 1\right)[ln(1 - \frac{I_{max}^{PVU}}{I_{SC}})]^{-1} \quad (4)$$

$$T_o = T_a + \frac{T_{NOC-20}}{800} I_{TS} \quad (5)$$

where I_{SC} is short circuit current of photovoltaic panel (A). I_{TS} is irradiance on a tilted surface (W/m2) and I_{ref} is irradiance at reference operating position (1000 W/m2). V_{OC}^{PVU} is open circuit voltage of photovoltaic panel and SCC being temperature coefficient for short circuit current (A/˚C). I_{max}^{PVU} is the maximum current of PVU at the reference operating conditions (A) and V_{max}^{PVU} is maximum voltage of PVU at the reference operating conditions (V).

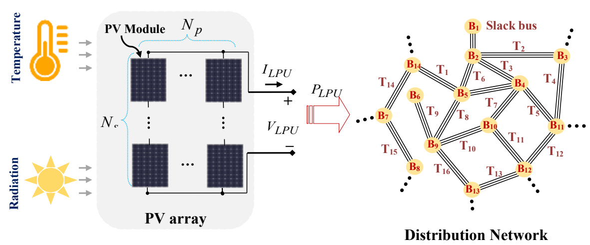

Figure 1: PVU installed in a distribution network

3. Model of DSTATCOM

As shown in Figure 2, the injection voltage of DSTATCOM can be written as follows [5, 16]:

$$V_D = |V_D|(cos\,\rho_D + jsin\,\rho_D) \quad (6)$$

$$P_M^{inj} = |V_M|^2 G_{MD} + |V_M||V_D|[G_{MD}\,cos(\rho_M - \rho_D) + B_{MD}\,sin(\rho_M - \rho_D)] \quad (7)$$

$$Q_M^{inj} = -|V_M|^2 B_{MD} + |V_M||V_D|[G_{MD}\,sin(\rho_M - \rho_D) - B_{MD}\,cos(\rho_M - \rho_D)] \quad (8)$$

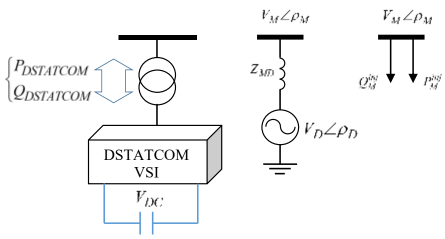

Figure 2: DSTATCOM model

4. Mathematical formulation of problem

The main target is to specify the optimal location and size of DG and DSTATCOM to maximize voltage stability index and system loadability and minimize the total system loss and investment cost of DG and DSTATCOM.

The presented model has been formulated as follows:

$$MinF(C_v^{PM}, C_p^{PM}, f_p^{PM}) = Min(F_{VS}^{PM}, F_{CL}^{PM}, F_{LP}^{PM}, F_{TC}^{PM}) \quad (9)$$

subject to

$$\Psi(C_v^{PM}, C_p^{PM}, f_p^{PM}) = 0 \text{ (equality constraints)} \quad (10)$$

$$\Gamma(C_v^{PM}, C_p^{PM}, f_p^{PM}) > 0 \text{ (inequality constraints)} \quad (11)$$

where C_v^{PM}, C_p^{PM}, f_p^{PM} are condition vector, control, and fixed parameters of the model, respectively.

4.1. Voltage stability criterion

Based on Ref. [17], voltage stability index can be defined as following referring to Figure 3:

$$F_{VS} = \sum_{\Omega=1}^{n_b-1}(2\,V_{\Omega+1} - V_{\Omega}) \quad (12)$$

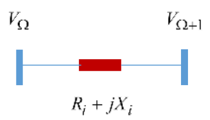

Figure 3: Two buses of system

n_b is the total number of buses. The higher value of FVS shows more stable voltage performance.

4.2. Loadability index

The second aim of DG and DSTATCOM placement is to maximize system loadability without any voltage and loading violation in presence of DG uncertainty [18]. Loadability criterion is formulated as follows:

$$F_{CL} = \sum_{d=1}^{365}\sum_{j=1}^{n_l}\frac{S_j^d}{S_i^{max}} \quad (13)$$

where S_i^d is the apparent power for *j*th line on the nth day of one year. n_l is the number of lines.

4.3. Power loss index

Complex power S_{ij} from ith node to jth node and S_{ji} from *j*th node to *i*th node can be written as follows [19]:

$$S_{ij} = V_i I_{ij}^{*} \quad (14)$$

$$S_{ji} = V_j I_{ji}^{*} \quad (15)$$

where V_i and V_j are voltage in bus *i* and *j*, respectively. Also, I_{ij} is the current flowing between bus *i* and *j*. Real power loss in kth branch is presented as:

$$S_L(k) = S_{Lij}(k) + S_{Lji}(k) \quad (16)$$

Total power loss for one year considering the generation variation of DG is:

$$F_{LP} = \sum_{d=1}^{365}\sum_{k=1}^{n_l} S_L(k) \quad (17)$$

where n_l is the total number of branches.

4.4. Total cost of DG and DSTATCOM

The total cost of the problem is written as follows:

$$F_{TC} = C_{DG} + CD \quad (18)$$

where C_{DG} and CD are the aggregated costs of DG and DSTATCOM, respectively.

4.4.1. Total costs of DG

The investment cost of DG can be expressed as follows [20]:

$$C_{IC,DG}^{Annual} = \sum_{i=1}^{N} C_{IC,DG_i} \times S_{DG_i} \times CRF \quad (19)$$

where $C_{IC,DG}^{Annual}$ and C_{IC,DG_i} are annual initial investment cost of DGs and initial cost of installation for ith DG in $/KVAr, respectively. S_{DG_i} is capacity of *i*th DG in KVA, and N is the number of DGs to be installed in the distribution network.

CRF is the rate of capital return that has been formulated as follows:

$$CRF = \frac{i_r(1+i_r)^z}{(1+i_r)^z - 1} \quad (20)$$

where i_r and z are annual interest rate and lifetime of *i*th DG.

The fuel cost is calculated as follows:

$$C_{Fuel,DG} = \sum_{i=1}^{N} C_{Fuel,DG_i} \times S_{DG_i} \quad (21)$$

In the above equation, C_{Fuel,DG_i} is fuel cost of ith DG in $/KVA. Operating and maintenance cost is directly related to the capacity of the DGs, and it can be written:

$$C_{O\&M,DG} = \sum_{i=1}^{N} C_{O\&M,DG_i} \times S_{DG_i} \quad (22)$$

$C_{O\&M,DG_i}$ is operating and maintenance cost of ith DG in $/KVA. With respect to the defined costs, the function of the annual cost of DG is as follows:

$$C_n^i = C_{IC,DG}^{Annual} + (8760 \times (C_{Fuel,DG} + C_{O\&M,DG})) \quad (23)$$

4.4.2. Total cost of DSTATCOM

The total investment cost of installed DSTATCOM, CD, is presented as follows:

$$CD = \frac{i_r(i_r+1)^z}{(i_r+1)^z-1} \times \sum_{i\in\Lambda} IC_i \tag{24}$$

$$IC_i = CO_i^{FD} \times S_i^{FD} \times 1000(US\$) \tag{25}$$

where CO_i^{FD} is the cost function of ith DSTATCOM. S_i^{FD}represents the capacity of the DSTATCOM in MVAr and Λ is the set of all candidate locations for installation. The cost function for a DSTATCOM can be written as follows [21]:

$$CO_i^{FD} = 0.000375(S_i^{FD})^2 - 0.3041(S_i^{FD}) + 162.4\ (U\$/kVAR) \tag{26}$$

5. Uncertainty in the placement problem

It is assumed that the loads in the system have an uncertainty. In this state, the system performance range is divided into a set of scenarios. As the number of scenarios increases, modeling accuracy will increase. In this section, the normal distribution is used to fit the uncertainty of the load, where each constrained area is called a scenario. To calculate the total value of the objective function, the effects of each scenario must be considered. To do this, each scenario must be applied separately to the network [9, 20, 22]. Then, the values of the objective function should be calculated separately for each scenario. The general objective function in this condition can be written as follows:

$$Min\ F = \{\beta_1\left(\sum_{s=1}^{N_s}\frac{-F_{VS}^s}{F_{SC,max}}p_s\right) + \beta_2\left(\sum_{s=1}^{N_s}\frac{-F_{CL}^s}{F_{CL,max}}p_s\right) + \beta_3\left(\sum_{s=1}^{N_s}\frac{F_{LP}^s}{F_{LP,max}}p_s\right) + \beta_4\left(\sum_{s=1}^{N_s}\frac{F_{TC}^s}{F_{TC,max}}p_s\right)\} \tag{27}$$

where F_{VS}^s, F_{CL}^s, F_{LP}^s and F_{TC}^s are the values of functions in sth scenario.

6. Numerical studies

6.1. Computational process

The computational process of the problem has been depicted in Figure 4. In the first stage, an initial particle of particle swarm optimization algorithm (PSOM) is generated. For each particle, AC-PF is carried out for 365 days during a year based on the mandatory generation of photovoltaic dispersed generation unit (PDGU), considering two main parameters, irradiation and temperature. Then, four main objective function F_{VS}, F_{CL}, F_{LP} and F_{TC} are calculated, and global optimal values are fined. The algorithm is repeated until the stopping criterion is met.

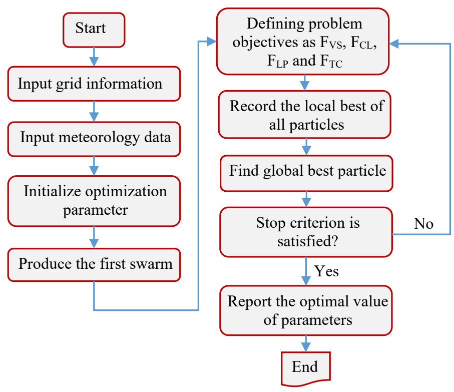

Figure 4: The computational process of problem

6.2. Implementation of the proposed method on test system

Based on the presented technique, the comparison studies are applied on two test systems. The first test system is a 33-bus distribution system with 3.7 MW and 2.3 MVAR [23]. The single line diagram (SLD) of 33 bus test system has been depicted in Figure 5. The second test system is a 69 bus IEEE distribution system with 3.802 MW and 3.696 MVAR [24]. The SLD of 69-bus test system has been shown in Figure 6.

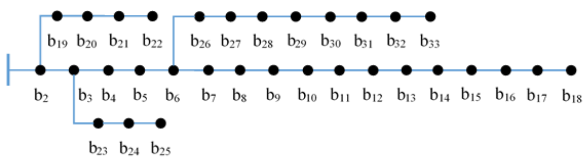

Figure 5: SLD of 33-bus test system

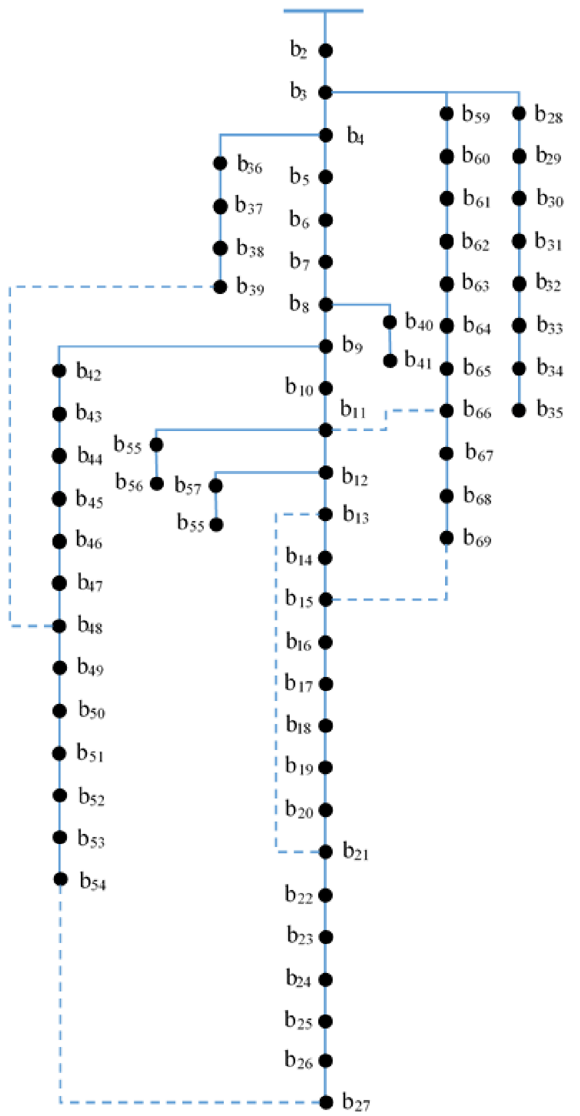

Figure 6: SLD of 69-bus test system

Four candidate bus is selected in each test system for placement of DG. Photovoltaic units are installed in locations with suitable radiation. Solar irradiation and temperature data for 365 days of one year for four candidate bus of 33-bus and 69-bus test system have been given in Figure 7 and Figure 5. In these figures, irradiation, temperature and days are located in X, Y and Z axes, respectively [25].

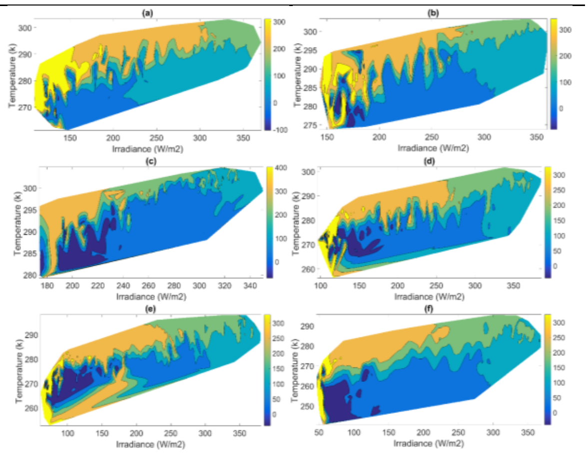

Figure 7: The contour diagram of irradiation, temperature and days of one year for four candidate buses for 33-bus IEEE test system; (a) bus 22, (b) bus 33, (c) bus 18, (d) bus 25, (e) bus 12, (d) bus 31.

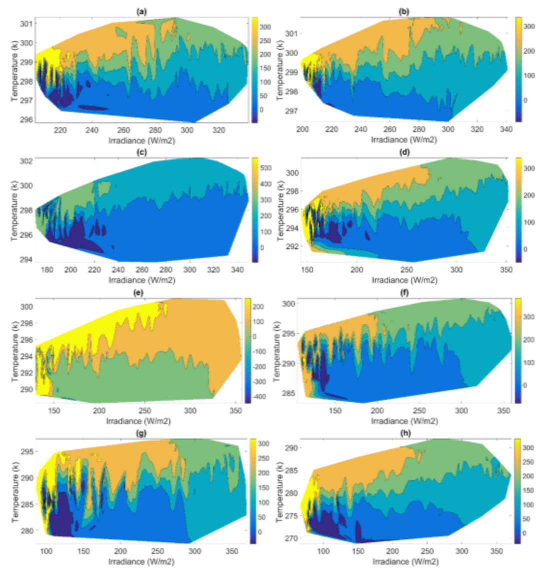

Figure 8: The contour diagram of irradiation, temperature and days of one year for four candidate buses for 33-bus IEEE test system; (a) bus 22, (b) bus 33, (c) bus 18, (d) bus 25, (e) bus 12, (d) bus 31.

To evaluate the proposed method, four scenarios have been considered as follows:

- Scenario 1 (S1): System without using DG and DSTATCOM

- Scenario 2 (S2): System is considered with DG units

• Scenario 3 (S3): System is considered with DSTATCOM units

• Scenario 4 (S4): System is considered with DG and DSTATCOM units

The characteristics of the used photovoltaic and DSTATCOM unit have been given in Table 1.

Table 1: The specification of the used DG

Parameters and specifications	Value
Investment cost ($/KW)	1440
Annual operation and maintenance cost ($/KW)	14.4
Lifetime (year)	25

6.2.1. Case study 1: 33-bus test system

The presented method is applied on the 33-bus test system. The problem of PVU and DSTATCOM placement consists of five basic steps. In the first step, system data is inserted. Load power flow is carried out in the second step. The objective function is formed in the third step and optimization problem is solved using PSOM in step 4. The report of the optimal points set is done in step 5.

The report of the optimal points set for the optimal location of PVU and DSTATCOM for the 33-bus test system is given in Table 2.

The value of the system's objective functions is extracted during the optimization process and is shown in Figure 9 to Figure 12 for four different scenarios for the two PSOM and PSOM-nonlinear time-varying evolution (NTVE) optimization algorithms.

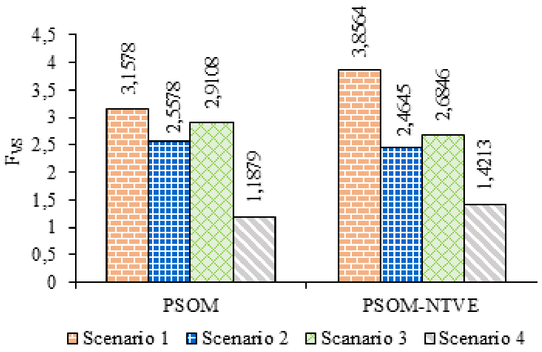

Figure 9: Comparison of FVS values

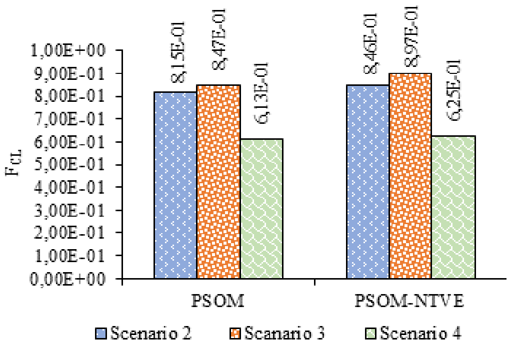

Figure 10: Comparison of FCL values

Table 2: Comparison of parameters for different scenarios

	S1	S2	S3	S4
PVU location	-	18	-	31
PVU capacity (KW)	-	475.4	-	184.9
DSTATCOM location	-	-	12	18
DSTATCOM capacity (KVAr)	-	-	2462.4	6.754

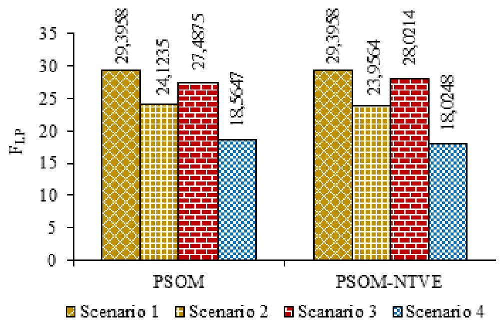

Figure 11: Comparison of FCL values

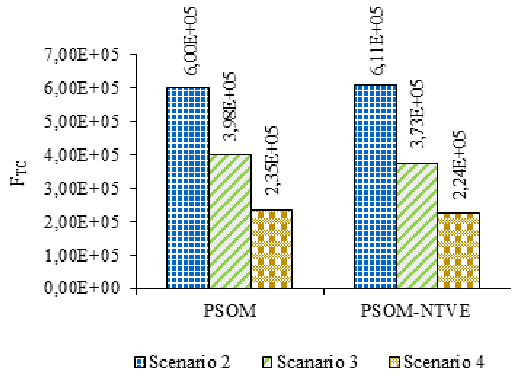

Figure 12: Comparison of FTC values

Also, comparison of voltage profile in two scenarios, scenario 1 and 4, has been shown in Figure 13.

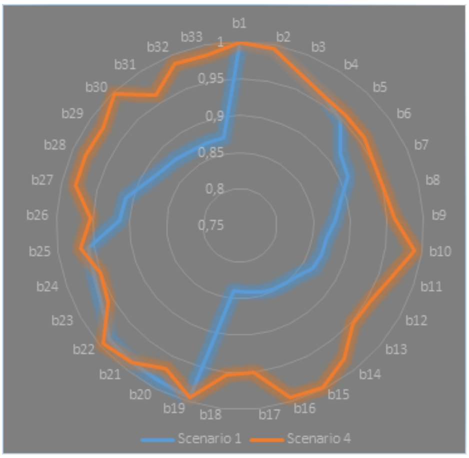

Figure 13: Voltage profile in two scenarios for the 33-bus system

6.2.2. Case study 2: 69-bus test system

The report of the optimal points set for the optimal location of PVU and DSTATCOM for the 69-bus test system is given in Table 3.

The value of the system's objective functions is extracted during the optimization process and is shown in Figure 14 to Figure 17 for four different scenarios for the two PSOM and PSOM-NTVE optimization algorithms.

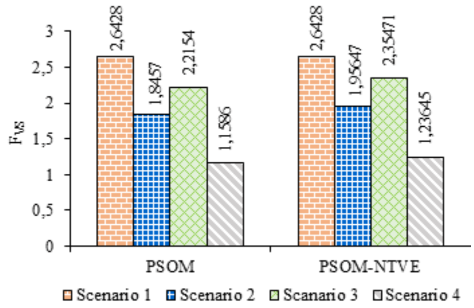

Figure 14: Comparison of FVS values

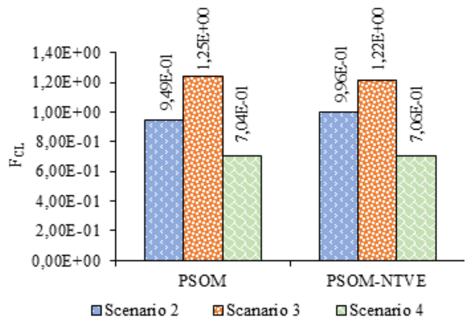

Figure 15: Comparison of FCL values

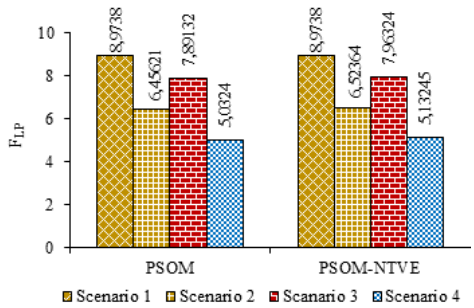

Figure 16: Comparison of FLP values

Table 3: Comparison of parameters for different scenarios

	S1	S2	S3	S4
PVU location	-	69	-	54
PVU capacity (KW)	-	524.5	-	272.3
DSTATCOM location	-	-	17	22
DSTATCOM capacity (KVAr)	-	-	3621.7	12.458

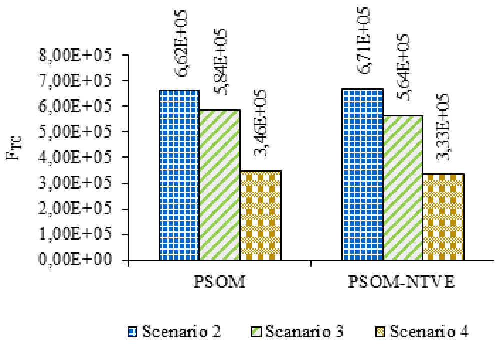

Figure 17: Comparison of F_{TC} values

Comparison of voltage profile for 69 bus system in two scenarios, scenario 1 and 4, has been shown in Figure 18.

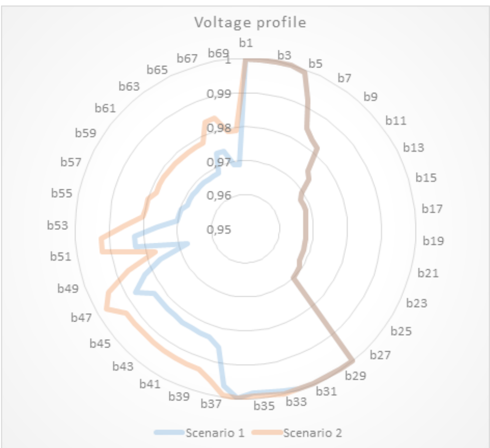

Figure 18: Voltage profile in two scenarios for 69-bus system

6.3. Considering uncertainty in the proposed placement problem

As previously mentioned, uncertainty in the estimation of network load is an inevitable task. Therefore, the network design taking into account the load uncertainty, leads to network optimization and robustness of it in uncertainty of load. To consider uncertainty, it is assumed that the load in bus- 32 has a normal distribution function as shown in Figure 19 and Figure 20. According to Figure 19 and Figure 20, a total of 7 scenarios are considered for assessment of load uncertainty.

Table 4: The results in the state of uncertainty in load bus for two test system

	30-bus test system	69-bus test system
PVU location	32	25
PVU capacity (KW)	195.64	284.87
DSTATCOM location	17	52
DSTATCOM capacity (KVAr)	7.2545	13.218
FVS	1.6245	1.7513
FCL	0.6579	0.7893
FLP	19.6547	6.3254
FTC	2.4828×10^5	3.6195×10^5

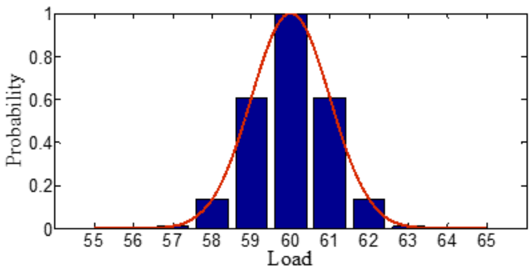

Figure 19: The normal distribution function for bus load in 30-bus test system

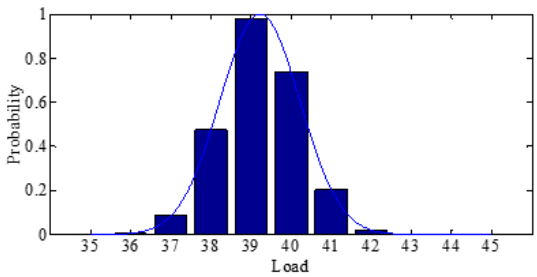

Figure 20: The normal distribution function for bus load in 69-bus test system

The results of the proposed method have been given in Table 4. The results have been presented for two test systems, the 30-bus and 69-bus test system.

7. Conclusion

A model to simultaneous plan of PVU and DSTATCOM has been presented in this paper considering the effect of the operational behavior of PVU. This model is based on real output of PVU. The generation of PVU in this model varies with geographical data and therefore can cover the intermittent nature of PVU. In this model four target functions are considered, voltage stability, loadability, power loss and total cost of DG and DSTATCOM. The method presented in this paper can improve technical and economical parameters of the distribution network. The generation of PVU depends on two important parameters. It is concluded that simultaneous placement and sizing of PVU and DSTATCOM depends on two factors: solar irradiation and environmental temperature. The considered problem is formulated as a multi-objective optimization and that optimization process is done to extract the acceptable solution. Four scenarios are designed to compare the different aspects of the problem. Simulation studies are performed and two test systems, 33-bus test system and 69- bus test system, are considered to evaluate the presented method. The results show the impact of the presented method on improvement of distribution grid.

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Nomenclature

PVU	Photovoltaic unit	$S_L(k)$	Real power loss in *k*th branch
DSTATCOM	Distribution static compensator	C_{DG}	Total cost of DG
DG	Distributed generation	CD	Total cost of DSTATCOM
CB	Capacitor bank	$C_{IC,DG}^{Annual}$	Annual initial investment cost of DGs
DFIG	Double fed induction generator	C_{IC,DG_i}	Initial cost of installation for *i*th DG in $/KVAr
SCIG	Squirrel-cage induction generator	S_{DG_i}	Capacity of *i*th in KVA
ENS	Energy not supplied	N	Number of DGs installed in distribution network
ACO	Ant colony optimization	CRF	Rate of capital return
GA	Genetic algorithm	i_r	Annual interest rate
PSOM	Particle swarm optimization method	z	Long life of *i*th DG
PDGU	Photovoltaic dispersed generation unit	C_{Fuel,DG_i}	Fuel cost of *i*th DG in $/KVA
SLD	Single line diagram	$C_{O\&M,DG_i}$	Operating and maintenance cost of *i*th DG in $/KVA
V_{PVU}	Photovoltaic panel voltage at the maximum power point	CO_i^{FD}	Cost function of *i*th DSTATCOM
$V_{\max}^{PVU}$	Maximum voltage of photovoltaic panel at the reference operating position	S_i^{FD}	DSTATCOM size in MVAr
OCV	Temperature coefficient for open circuit voltage (A/°C)	Λ	Collection of all candidate locations
T_o	Photovoltaic panel operating temperature (°C)	F_{VS}^s	Value of function in *s*th scenario
T_o^{ref}	Photovoltaic panel temperature at reference operating position (25 °C)	F_{CL}^s	Value of function in *s*th scenario
I_{SC}	Short circuit current of photovoltaic panel (A)	F_{LP}^s	Value of function in *s*th scenario
I_{TS}	Irradiance on a tilted surface (W/m2)	F_{TC}^s	Value of function in *s*th scenario
I_{ref}	Irradiance at reference operating position (1000 W/m2)	n_b	Total number of buses
V_{oc}^{PVU}	Open circuit voltage of photovoltaic panel and SCC is temperature coefficient for short circuit current (A/°C)	V_m	Voltage of *m*th bus
C_v^{PM}	Condition vector parameters of model	V_{m+1}	Voltage of (*m*+1)th bus
C_p^{PM}	Control parameters of model	R_i	Resistance of line
f_p^{PM}	Fixed parameters of model	X_i	Impedance of line
S_i^d	Apparent power for *j*th line and *n*th day for one year	Ω	Counter
n_b	Number of lines	Ψ	Equality constraints

S_{ij}	Complex power from *i*th node to *j*th node	Γ	Inequality constraints
V_i	Voltage in bus *i*	G_{MD}	Conductance
I_{ij}	Measurement current between bus *i* and *j*	B_{MD}	Susceptance