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Proper Allocation of Renewable Distribution Generators in Distribution Systems using Evolutionary Programming

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Abstract: In this project, an evolutionary programming (EP) based technique has been presented for the optimal placement of distributed generation (DG) units energized by renewable energy resources (wind and solar) in a radial distribution system. To handle the uncertainties associated with load and renewable resources, probabilistic techniques have been used. Two operation strategies, namely "turning off wind turbine generator" and "clipping wind turbine generator output", have also been adopted to restrict the wind power dispatch to a specified fraction of system load for system stability consideration. To reduce the search space and thereby to minimize the computational burden, a sensitivity analysis technique has been employed which gives a set of locations suitable for DG placement. For the proposed EP based approach, an index based scheme has also been developed to generate the population ensuring the feasibility of each individual and thus considerably reducing the computational time. The developed technique has been applied to a 12.66-kV, 69-bus distribution test system. The solutions result in significant loss reduction and voltage profile improvement.

Keywords: Distributed Generation, Renewable Energy Resources, Evolutionary Programming, Sensitivity Analysis.

I. INTRODUCTION

The Integration of distributed generation (DG) with distribution system offers several technical and economical benefits to utilities as well as to customers [1]–[14]. However, mere inclusion of DGs may not guarantee the improvement in system performance. Depending on the size, location and penetration level, DG may have negative impacts on the performance of distribution network [1]–[5]. Hence, a proper allocation of DG units in the distribution system plays a crucial role. For DG placement in the distribution systems, various issues, such as reduction of system power loss [3]–[12], improvement in system voltage profile[1],[10], diminution of harmonic pollution[10], maximization of DG capacity[13] minimization of investment [14], [15] etc., have been aimed at by researchers in their single or multi-objective problem formulations. Different optimization techniques, such as Primal-Dual Interior- Point method [3], mixed integer nonlinear programming [4], [5], evolutionary programming (EP) technique [6], analytical approach [7]–[9], trade-off method [10], [11], Hereford Ranch algorithm [12], linear programming technique [13], genetic algorithm (GA) technique [14], heuristic approaches [15], Classical Second Order method [16], Tabu Search approach [17], and Decision Theory approach [18] have been exploited to solve the optimization problems for DG placement.

Placement of such DGs requires some special techniques to handle their intermittent outputs. For a system with wind turbines (WTs), Chiradeja and Ramakumar [1] developed mathematical expressions for the probability density functions (PDFs) of system voltage profile using convolution technique based probabilistic approach. Wang and Nehrir [7] considered wind turbine generators (WTGs) as variable power DGs. Using hourly-simulated outputs from WTs, they derived an analytical expression to find out the optimal position of WTGs in the distribution systems with uniformly distributed time varying loads. to handle the uncertainties associated with renewable resources based DG units, Carpinelli et al. [10], Celli et al. [14], and Celli and Pilo [18] considered a set of scenarios of power production from such DG units with their occurrence probabilities. Then, out of various sizing alternatives, they selected the best alternative corresponding to optimal expected value of objective function. Atwa and El-Saadany [4] and Atwa et al. [5] proposed a mixed integer non-linear programming based approach to determine the optimum capacity and location of renewable resources based DG units in the distribution system so as to minimize the annual energy loss. They combined together the probabilistic models for wind speed and load to develop the generation load model and incorporated this combined model into deterministic optimal power flow equations to compute the annual energy loss.

However, all the methods [1], [4], [5], [7], [10], [14], [18] do not consider the correlation between load and renewable resources [19], [20]. Also, these methods are unable to restrict the wind power dispatch to a certain percentage of system load which is necessary for maintaining the system stability [20]–[23] This paper attempts to overcome aforesaid issues and presents an EP based approach for the optimal placement of photovoltaic arrays (PVAs) and WTGs in a radial distribution system. Suitable probabilistic models have been employed to represent the uncertainties associated with load and renewable resources. To restrict the wind power dispatch to a certain fraction of system load, two operation strategies have also been adopted and simulated. The developed formulation has been tested on a 69-bus distribution system with encouraging results. This paper begins with the mathematical modeling and formulation of DG placement problem. Then, an EP based algorithm is presented for solving the formulated optimization problem. Finally, the results with test system are presented and relevant conclusions are derived.

II. MATHEMATICAL MODELING

Following assumptions have been made to develop the mathematical model for optimal placement of PVAs and WTGs in a distribution system:

- Since the determination of optimal numbers and capacities of PVAs and WTGs to be placed is a problem of long-term expansion planning, their numbers and sizes are known a priori. In general, the number and size of renewable energy resources based DGs are governed mainly by economic consideration in addition to the renewable resource at the site, electric utility rates, requirements for interconnections, legal and environmental issues, etc.
- Depending on the control status, the DG buses can be modeled either as voltage-controlled buses or as constant active- and reactive-power buses [24]. In this work, both PVAs and WTGs are assumed to be operated at constant power factors, hence, DG buses are treated as the constant active- and reactive-power buses.
- The distribution system under consideration is balanced [3]–[10], [12], [14]–[17]. Various steps involved in the developed approach are as follows:

A. Sensitivity Analysis

The optimal placement of DGs in the distribution systems is a combinatorial optimization problem. Search for the best combination amongst the various possible combinations for DG allocation is computationally arduous even for a small distribution system. The search space, however, can be compacted by reducing the number of candidate locations for DG placement using a suitable sensitivity analysis technique [6], [25]. Hence, to identify suitable candidate/sensitive locations for DG integration, the proposed method starts with calculation of sensitivity of active power loss with respect to active- and reactive- power injections in the distribution system. The sensitivity of P_L active power loss in the system due to injected power is defined as

$$\text{Sensitivity of } P_L = \frac{\partial P_L}{\partial S} = \frac{P_L^{S+\Delta S} - P_L^{S}}{\Delta S} \quad (1)$$

where S denotes the injected active- or reactive-power, ΔS denotes the increment in S , and $P_L^{S+\Delta S}$ and P_L^{S} represent the value of P_L with injected power S+ΔS and S, respectively. After calculating the sensitivity of active power loss with respect to active- and reactive-power, the buses are arranged in the descending order of sensitivity values obtained and a desirable number of most sensitive buses (say N_C candidate locations) are selected as the possible candidates for DG placement.

B. Modeling of Location of DG Units

The allocation matrix A^P representing the placement of N_P PVA types at N_C candidate locations is given as

$$A^P = [a_{m,n}^{p}]_{m=1 to N_p, n=1 to N_c} \quad (2)$$

where $a_{m,n}^{p}$ is the (m,n)th element of A^P to represent the number of the mth PVA type at the nth candidate location.

Similarly, the allocation matrix A^W for N_W WTG types at N_C candidate locations is written as

$$A^W = [a_{m,n}^{W}]_{m=1\ to\ N_W, n=1\ to\ N_c} \quad (3)$$

Where $a_{m,n}^{W}$ is the (m,n)th element of A^W to represent the number of the mth WTG type at the nth candidate location.

C. Modeling of Renewable Resources and Load Data

The load and renewable resources, mainly solar radiation, are strongly correlated. To nullify the effect of correlation and to be able to treat those independently, the study period is divided into several segments (say NT segments), each referred to as time frame [19], [20]. For each time frame, solar irradiance is considered as a random variable and is assumed to follow a Beta distribution [19], [20]. Over t^{th} time frame, the PDF for solar irradiance is given as

$$f_v(v) = \frac{k^t}{c^t}\left(\frac{v}{c^t}\right)^{k^t-1} e^{-\left(\frac{v}{c^t}\right)^{k^t}} \quad (4)$$

With $\alpha^t > 0$ and $\beta^t > 0$

Where f_s(s) is Beta distribution for solar irradiance during the tth time frame with α^t and β^t as parameters; s_{max}^{t} is the maximum solar irradiance during the tth time frame; τ and denotes Gamma function. Similarly, for each time frame, random wind speed is assumed to follow a Weibull distribution [19], [20]. For the tth time frame, the PDF for wind speed is given as

$$f_v(v) = \frac{k^t}{c^t}\left(\frac{v}{c^t}\right)^{k^t-1} e^{-\left(\frac{v}{c^t}\right)^{k^t}} \quad (5)$$

For v>0, c^t>1 and k^t>0

Where $f_v(v)$ is Weibull PDF for wind speed during the tth time frame; and c^t and k^t denote scale and shape parameters, respectively, of Weibull PDF in the tth time frame. Beta and Weibull distributions are continuous PDFs, while proposed method requires discrete forms of these PDFs for each time frame. Hence, in the next step, the discrete forms of these distributions are generated. Let be the discrete form of and given as [20]

$$s^t = [\{s_r^t, P(s_r^t)\} : r = 1\ to\ NS^t] \quad (6)$$

Using a similar approach, discrete form of wind speed PDF $f_v(v)$ is given as [20]

$$V^t = [\{v_r^t, P(v_r^t)\} : r = 1\ to\ NV^t] \quad (7)$$

Where v_r^t is the rth level of wind speed; $P(v_r^t)$ is probability associated with v_r^t; and NV^t is the number of discrete states in the model V^t . The load data is generally available in discrete form. For each time frame, the probabilistic load model is obtained by reordering the load values, picking the different load levels, counting their occurrences and calculating the corresponding probabilities. For the t[th] time frame, the probabilistic load model L^tcan be given by [20]

$$L^t = [\{l_r^t, P(l_r^t)\}: r = 1 \text{ to } NL^t] \quad (8)$$

where $l_r^t$is the r[th] state of load as a fraction of peak load; $P(l_r^t)$ is probability associated with l_r^t and can be calculated using (10); and $NL^t$is the number of discrete states in the model L^t

$$P(l_r^t) = \frac{\text{number of occurences of load level } l_r^t}{\text{total number of load points during tth time frame}} \quad (9)$$

D. Modeling of Injected Power from DG Units

The matrix $p^p(A^p, s_i^t)$ representing the real power injection into the system from PVAs corresponding toA^p and can be expressed as

$$p^p(A^p, s_i^t) = [a_{m,n}^p \cdot f_m^p(s_i^t)]_{m=1 \text{ to } N_p, n=1 \text{ to} N_C} \quad (10)$$

Where f_m^p is a function of solar irradiance to calculate the real power output from the m[th] PVA type and is described in the Appendix. Using (10), matrix $Q^P(A^P, s_i^t)$ representing the reactive power injection into the system from PVAs corresponding to A^P and s_i^t is given as

$$Q^P(A^P, s_i^t) = [a_{m,n}^p \cdot f_m^p(s_i^t). \tan(\emptyset_{m,n}^p)]_{m=1 \text{ to } N_P, n=1 \text{ to } N_C} \quad (11)$$

where $\emptyset_{m,n}^p$ is the power factor angle of the m[th] PVA type at the nth location. Fluctuations in the wind speed and thereby active power generation from WTGs causes imbalance between the generation and demand. This imbalance may lead to the frequency and voltage variation and subsequently, may affect the safety and stability of the system. Therefore, to avoid such serious problems, the dispatched wind energy is limited to a specific percentage of system demand [20]–[23].

The ratio of dispatched wind power to total system load is known as wind power dispatch to load ratio (WPDLR).The WTs can broadly be classified into two categories [26], [27], namely, pitch regulated WTs and stall regulated WTs. In case of pitch regulated WTs, their blades are physically rotated about their longitudinal axis to control the rotor torque and power from the wind side, while in case of stall regulated WTs, their blade angle is fixed but the aerodynamic performance is designed in such a way that they stall at high wind speeds. In the presented work, the following two control/operation strategies are adopted to simulate the realistic situation to keep WPDLR within a specified value:

- Turning off WTG and
- Clipping WTG output.

In "Turning off WTG" control strategy, WTGs are turned off one at a time until WPDLR is within the prescribed limit. This practice is adopted in the fixed pitch WTGs (stall regulated). In "Clipping WTG output" control strategy, the output from all the WTGs is proportionally reduced until WPDLR is maintained within the prescribed limit. This control scheme is possible in the variable pitch WTGs (pitch regulated). In this work, parameter $x_{m,n}$ represents the applied control strategy for the m[th] WTG type at the nth candidate location as shown in (12)

$x_{m,n} = 0 \; or 1$ if control strategy= turning off WTG
$0 < x_{m,n} < 1$ if control strategy =clipping WTG Output
For m=1 to N_W, n=1 to N_C (12)

In the present work, above mentioned control strategies are considered separately by using the control parameters . In case of "Turning off WTG" strategy, turning off process of the WTGs is started from the least sensitive location until WPDLR is within the specified limit. In case of "Clipping WTG output" strategy, the output from different WTs is uniformly curtailed to keep WPDLR within the imposed limit. Considering the above mentioned control strategies, the matrix representing the real power injection into the system from WTGs corresponding to $A^W, v_j^t \text{ and } l_k^t$ and can be expressed as

$$P^W(A^W, v_j^t, l_k^t) = [x_{m,n}(v_j^t, l_k^t). a_{m,n}^W \cdot f_m^W(v_j^t)]_{m=1 \text{ to } N_W, n=1 \text{ to } N_C} \quad (13)$$

Where f_m^W is a function of wind speed to calculate the real power output from the m[th] WTG type and is described in the Appendix. $P^W(A^W, v_j^t, l_k^t)$ depends upon A^W, v_j^t and x; and the control parameters x depend on both the wind power (thus on wind speed) and the load level satisfying (14); hence, $P^W(A^W, v_j^t, l_k^t)$ is represented as a function of A^W, v_j^t and l_k^t in (13):

$$\sum_{m=1}^{N_W} \sum_{n=1}^{N_C} x_{m,n}(v_j^t, l_k^t). a_{m,n}^W \cdot f_m^W(v_j^t) \leq WPDLR . l_k^t . \sum_{i=1}^{N_B} P_i^{load} \quad (14)$$

Where N_B is the number of buses in the system and P_i^{load} is the peak active load at the i[th] bus of the system. Using (14), matrix $Q^W(A^W, v_j^t, l_k^t)$ representing the reactive power injection into the system from WTGs corresponding to $A^W, v_j^t \text{ and } l_k^t$ and is given as

$$Q^W(A^W, v_j^t, l_k^t) = [x_{m,n}(v_j^t, l_k^t). a_{m,n}^W \cdot f_m^W(v_j^t). \tan(\emptyset_{m,n}^W)]_{m=1 \text{ to } N_W, n=1 \text{ to } N_C} \quad (15)$$

Where $\emptyset_{m,n}^W$ is the power factor angle of the m[th] WTG type at the nth location having the same number of columns as the number of candidate locations, the allocation matrices for PVAs and WTGs, given by (2) and (3), respectively, can be combined to obtain a single matrix A representing the allocation of PVAs and WTGs at different candidate locations in the system as

$$\mathbf{A} = \begin{bmatrix} A^P \\ A^W \end{bmatrix} \quad (16)$$

Combining (10) and (13), a single matrix for the net real power injection into the system corresponding to A , $s_i^t, v_j^t$and l_k^t can be obtained as

$$P^I(A, s_i^t, v_j^t, l_k^t) = \begin{bmatrix} P^P(A^P, s_i^t) \\ P^W(A^W, v_j^t, l_k^t) \end{bmatrix} \quad (17)$$

Similarly, (13) and (15) can also be combined to obtain a single matrix $Q^I(A, s_i^t, v_j^t, l_k^t)$for the net reactive power injection into the system corresponding to A , s_i^t, v_j^t and l_k^t, as

$$Q^I(A, s_i^t, v_j^t, l_k^t) = \begin{bmatrix} Q^S(A^s, s_i^t) \\ Q^W(A^W, v_j^t, l_k^t) \end{bmatrix} \quad (18)$$

The net real- and reactive-power injection vectors, as in (17) and (18), respectively, have the following features:

- Total active- and reactive-power injection in the system at candidate locations can be calculated by column-wise sum of vectors P^I and Q^I, respectively,
- Total active- and reactive-power generation from different DG types can be obtained by row-wise sum of vectors P^I and Q^I respectively.

E. Combining the Developed Models to Analyze the System

In this step, first the load flow solution is obtained for each time frame taking into account the previously developed models for the net power injections at candidate locations and for load; and then the solutions are used to analyze the system over the study period. For a branch, as shown in Fig. 1, relations for active power flow, reactive power flow and bus voltages can be given as

$$P_{pq} = P_q^F + P_q^L - P_q^I + \frac{G_{pq}}{2}(V_p^2 + V_q^2) + \frac{R_{pq}}{V_p^2}\{(P_{pq} - V_p^2\frac{G_{pq}}{2})^2 + (Q_{pq} + V_p^2\frac{B_{pq}}{2})^2\} \quad (19)$$

$$Q_{pq} = Q_q^F + Q_q^L - Q_q^I - \frac{B_{pq}}{2}(V_p^2 + V_q^2) + \frac{X_{pq}}{V_p^2}\{(P_{pq} - V_p^2\frac{G_{pq}}{2})^2 + (Q_{pq} + V_p^2\frac{B_{pq}}{2})^2\} \quad (20)$$

$$V_q^2 = V_p^2 - 2\{\left(P_{pq} - V_p^2\frac{G_{pq}}{2}\right)R_{pq} + (Q_{pq} + V_p^2\frac{B_{pq}}{2}) X_{pq}\} + \frac{R_{pq}^2 + X_{pq}^2}{V_p^2}\{(P_{pq} - V_p^2\frac{G_{pq}}{2})^2 + (Q_{pq} + V_p^2\frac{B_{pq}}{2})^2\} \quad (21)$$

where $P_q^F = \sum_{\forall j|i=q} P_{ij}$ and $Q_q^F = \sum_{\forall j|i=q} Q_{ij}$ with (22) and (23) at the bottom of the next page. Here $P_{pq}(Q_{pq})$ are the sending end active (reactive) power flows; $R_{pq}(X_{pq})$ are the series resistance (reactance); $G_{pq}(B_{pq})$ and are the shunt conductance (susceptance) of a branch connected between buses P and q. $P_q^I(Q_q^I)$ are the active (reactive) power injections and $P_q^L(Q_q^L)$ are the total active (reactive) load at bus q . $P_q^F(Q_q^F)$ are the sum of active (reactive) power flows through all the downstream branches connected to bus q .V_q is the magnitude of voltage at bus q . Q_q^{Load} is the peak reactive load at bus q of the system. Corresponding to a given solar irradiance state, wind speed state, load state and allocation matrix, the load profile can be generated satisfying (22), while active and reactive power injections at candidate locations in the system can be obtained using (23). The system power losses, voltage magnitudes and line loadings can, then, be calculated using load flow studies by solving (19) to (21) iteratively [27].

Let $P_{loss}(A, s_i^t, v_j^t, l_k^t)$ be the system active power loss corresponding to $P^I(A, s_i^t, v_j^t, l_k^t)$ and $Q^I(A, s_i^t, v_j^t, l_k^t)$ which themselves are dependent on A, s_i^t, v_j^t *and* l_k^t . Matrix A, given by (16), represents a considered allocation alternative of DGs, while s_i^t, v_j^t *and* l_k^t , and are the states of independent random variables. Therefore, $P_{loss}(A, s_i^t, v_j^t, l_k^t)$ is also a state of a random variable with the associated probability as

$$P(P_{loss}(A, s_i^t, v_j^t, l_k^t)) = P(s_i^t).P(v_j^t).P(l_k^t). \quad (24)$$

$P_q^L = l_k^t P_q^{Load}$ and $Q_q^L = l_k^t Q_q^{Load}$

$$P_q^I = \begin{cases} \sum_{m=1}^{N_P+N_W} [(m,n)th \text{ element of } P^I(A, s_i^t, v_j^t, l_k^t)] & \text{if nth sensitive location} = q \\ 0 & \text{otherwise} \end{cases}$$

$$Q_q^I = \begin{cases} \sum_{m=1}^{N_P+N_W} [(m,n)th \text{ element of } Q^I(A, s_i^t, v_j^t, l_k^t)] & \text{if nth sensitive location} = q \\ 0 & \text{otherwise} \end{cases}$$

For the t[th] time frame, the expected values of system active power loss, P_{Loss}^t , can be given as

$$P_{Loss}^t = \sum_{i=1}^{Ns^t} \sum_{j=1}^{NV^t} \sum_{k=1}^{NL^t} P_{Loss}(A, s_i^t, v_j^t, l_k^t).$$

$$P(P_{Loss}(A, s_i^t, v_j^t, l_k^t)) = \sum_{i=1}^{Ns^t} \sum_{j=1}^{NV^t} \sum_{k=1}^{NL^t} P_{Loss}(A, s_i^t, v_j^t, l_k^t).P(S_i^t)P(V_j^t).P(l_k^t) \quad (25)$$

And then, the expected active energy loss, AE_{Loss}^E , over the study period is calculated as

$$AE_{Loss}^E = \sum_{t=1}^{NT} P_{Loss}^t . H^t \quad (26)$$

where H^t is the number of hours associated with the t[th] time frame. For the calculation of expected voltage magnitude, V_q^E of bus q over the study period, the following expression is used

$$V_q^E = \sum_{t=1}^{NT} \sum_{i=1}^{Ns^t} \sum_{j=1}^{NV^t} \sum_{k=1}^{NL^t} P_{Loss}(A, s_i^t, v_j^t, l_k^t)P(S_i^t).(P(V_j^t).P(l_k^t). \quad (27)$$

where $V_q(A, s_i^t, v_j^t, l_k^t)$ is the voltage magnitude of bus q corresponding to , A, s_i^t, v_j^t *and* l_k^t . The expected loading, S_{pq}^E of a branch connected between p buses q and over the study period is computed as

$$S_{pq}^E = \sum_{t=1}^{NT} \sum_{i=1}^{Ns^t} \sum_{j=1}^{NV^t} \sum_{k=1}^{NL^t} S_{pq}(A, s_i^t, v_j^t, l_k^t).P(S_i^t)P(V_j^t).P(l_k^t) \quad (28)$$

With $S_{pq}(A, s_i^t, v_j^t, l_k^t) = \sqrt{\{p_{pq}(A, s_i^t, v_j^t, l_k^t)\}^2 + \{Q_{pq}(A, s_i^t, v_j^t, l_k^t)\}^2}$

where $S_{pq}(A, s_i^t, v_j^t, l_k^t)$ is the loading of a branch connected between buses p and q corresponding to A, s_i^t, v_j^t *and* l_k^t. $P_{pq}(A, s_i^t, v_j^t, l_k^t)$ and $Q_{pq}(A, s_i^t, v_j^t, l_k^t)$ are the real and imaginary parts, respectively, of $S_{pq}(A, s_i^t, v_j^t, l_k^t)$.

TABLE I: Base Case Results For 69-Bus Distribution System

Energy losses		Energy from Sub-Station	
Active (MWh)	Reactive (MVARh)	Active (MWh)	Reactive MVARh)
71.83	32.26	6028.15	4859.38

III. RESULTS AND DISCUSSION

The developed algorithm is applied on a 12.66-kV, 69-bus distribution test system to find out the optimal positions of DG units. The test system is assumed to be situated near Kandla Port (State: Gujrat, Country: India) and data for solar irradiance, ambient temperature and wind speed for this site are obtained from [33] and [34], respectively. The data for distribution test system are obtained from [35]. This system has a peak load of 1.1079 MW. The study period of one year is divided into 12 months and each month is further subdivided into 24 segments, each referring to a particular hourly interval (for example: 08:00–09:00 hours) of the entire month. Thus, there are total 288 (12 24) segments over a year the number of hours associated with each segment is numerically equal to the number of days in the month under consideration. The historical data of solar irradiance, wind speed and load are also divided into 288 segments and for each segment, appropriate PDFs are developed using the respective historical data. Considering IEEE load profile [36], the obtained base case load flow results are presented in Table I. Base case values of minimum and maximum voltage magnitudes and line loadings are used as the limiting values for (33) and (34), respectively. The values of penalty terms K_V *and* K_S and are taken as 100 in order to assign equal weights to both. In order to select the buses suitable for DG placement, sensitivity analysis is performed for the choosen distribution system using the approach as described in [25].

The active power loss sensitivities with respect to active- and reactive-power injections at different buses of test system are shown in Fig. 1. Bus numbers 54, 53, 52, 51, 50, 49, 48, 47, 46, 27, 25, 24, 23,22, 21, 20, 19, 18, 17, 16, 15, 14, 45, 13, 58, 57, 12, 44, 56, 55, 11, 43, 10, 42, 9, 41, 40, 8, 7, 6, 39, 38, 35, 34, 5, 33, 37, 69, 68, 67, 66, 65, 32, 64, 31, 30, 63, 62, 61, 60, 36, 4, 29, 59, 28, 3, and 2 have descending order of active power loss sensitivities with respect to both active- and reactive-power injections. Top 25 buses are selected as the candidate buses for placement of PVAs and WTGs in the following two configurations:

- 1 PVA and 1 WTG, each of 0.25 MW size;
- 2 PVAs and 2 WTGs, each of 0.125 MW size.

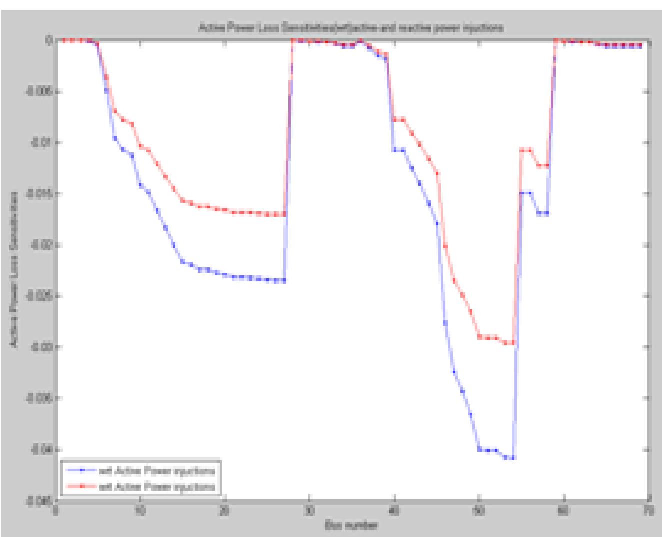

Fig.1. Active power loss sensitives with respect to active and reactive power injections at different buses in 69-distribution system.

For PVA, photovoltaic (PV) modules, each of rating=75W_p, V_{oc}=21.98V,I_{SC}=5.32A, V_{MPP}=71.32V, I_{MPP}=4.76A,C_V=14.40 mV/°C, And N_{OT}=43°C and for WTG,WTs, each of V_{Cut-in}=2.5 m\s,V_{rated}=11.0m\s and $V_{Cut-out}$=21.0m\s are considered [20]. The value of WPDLR is varied from 0% to 40% in steps of 10% in order to analyze the impact of dispatched wind power on the system performance. When the value of WPDLR becomes zero, WTGs cannot share any load. Hence, for this case (WPDLR=0), only PVAs are allocated in the system. In each configuration, the WTGs are operated at constant lagging power factor of 0.8, while the PVAs are operated at unity power factor. The value of WPDLR and control strategies for WTGs have been varied to determine the optimal locations of candidate PVAs and WTGs. The obtained Results are given in Table II. The optimal locations of DGs vary with the value of WPDLR, applied control strategy and the number of DG units to be located. For comparing the performance and the optimality of solution obtained by proposed algorithm, the developed formulation has also been solved by two other techniques, namely, 1) GA, and 2) Exhaustive search method.

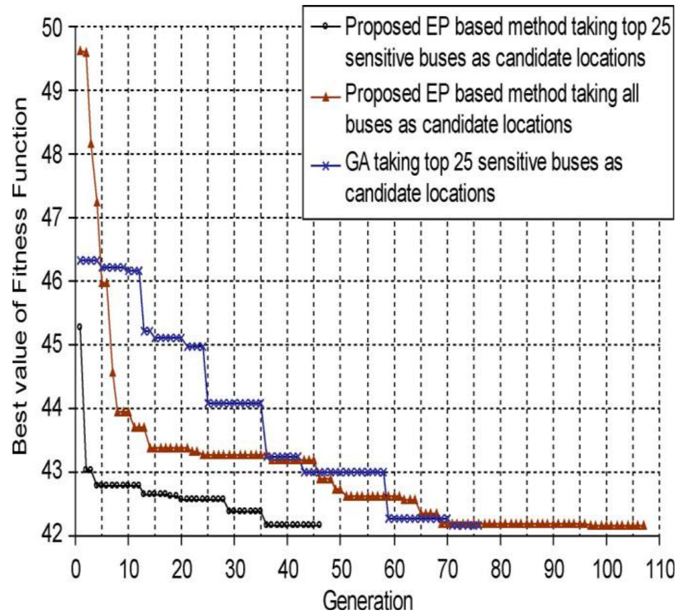

Fig.2. Convergence characteristics of different evolutionary algorithms for placement of 2 PVAs and 2 WTGs in 69-bus distribution system with WPDLR=0.4 by "Clipping WTG Output" control strategy.

TABLE II: Optimal Location of PVAS and WTGS In 69-Distribution System

Control Strategy	WPDLR	1PVA and 1 WTG		2 PVA and 2 WTG	
		PVA at Bus no.	WTG at Bus no.	PVAs at Bus no.	WTGs at Bus no.
Clipping WTG Output	0.0	53	-	53,54	-
	0.1	51	53	53,54	51,53
	0.2	54	50	52,54	50,53
	0.3	53	50	50,53	50,53
	0.4	53	50	53,54	50,52
Turning off WTG	0.0	53	-	53,54	-
	0.1	53	53	54,54	53,53
	0.2	53	53	52,54	52,53
	0.3	54	50	53,53	50,51
	0.4	53	50	51,54	50,53

All these methods are applied to allocate 2PVAs and 2 WTGs at top 25 sensitive locations of 69- bus distribution test system with WPDLR=0.4 by "Clipping WTG Output" control strategy.

TABLE III: Comparison of Results by Different Methods for Placement of 2 PVAS and 2 WTGS In 69-Bus Distribution System with WPDLR=0.4 and "Clipping WTG Output" Control Strategy

Candidate locations		All busess	25 sensitive buses		
Method		Proposed EP method	Proposed EP method	GA	Exhaustive Search method
Optimal locations	PVAs at bus no.	53,54	53,54	53,54	53,54
	WTGs At bus no	50,52	50,52	50,52	50,52
Population size		20	20	20	-
No. of Generations To converge		107	46	76	105625
Computational time(in minutes)		109	32	137	3698

To validate the use of sensitivity analysis, the proposed EP based method is also applied to 69-bus distribution test system with WPDLR=0.4 under "Clipping WTG output" control strategy and considering all the 69 buses as possible candidate locations to place 2 PVAs and 2 WTGs. As the computational time and the number of generations taken to converge vary for different methods and also change for different runs of the same method, all the programs for evolutionary algorithms are executed for 10 times and the average of the best fitness in each generation is calculated. The average convergence characteristics of different evolutionary computation methods are plotted in Fig.2. From the Figure it can be seen that the proposed EP based method converges rapidly towards optimal solution. A comparison of different methods for solving the developed formulation in terms of best/optimal solution, population size, average number of generations and average computational time taken for convergence is given in Table III. From Table III, it is evident that all the methods result in same optimal locations for DG units.

TABLE IV: Performance of 69-Bus Distribution System By Allocating 1 PVA and 1 WTG

Control strategy	WPDLR	Energy losses	Energy From substation	Energy Generated from	
				PVA MWH	WTG MWH
Clipping WTG output	0.0	65.69	5773.01	249	0.00
	0.1	51.16	5349.88	249	408.59
	0.2	44.81	5097.26	249	654.86
	0.3	42.58	4966.20	249	783.69
	0.4	42.17	4918.61	249	830.87
Turning Off WTG	0.0	65.69	5773.01	249	0.00
	0.1	61.40	5656.88	249	111.83
	0.2	56.04	5497.50	249	265.85
	0.3	48.17	5226.76	249	528.72
	0.4	43.79	5028.30	249	722.80

However, there is significant difference in the computational time and number of generations taken to converge. When all the buses are considered as candidate locations for DG placement, the proposed EP based method takes 107 generations to converge in 109 min. However, when the search space is reduced by taking only the top 25 sensitive locations as candidate locations for DG placement, the proposed EP based method takes approximate 57% less generations to converge in approximate 72% less time as compared to the previous one.

TABLE V: Performance of 69-Bus Distribution System By allocating 2 PVAs and 2 WTGs

Control Strategy	WPDLR	Energy losses	Energy From Substation	Energy Generated from	
				PVA MWH	WTG MWH
Clipping WTG Output	0.0	65.69	5773.01	249	0.00
	0.1	51.14	5349.86	249	408.59
	0.2	44.70	5097.16	249	654.86
	0.3	42.53	4966.15	249	783.69
	0.4	42.15	4918.60	249	830.87
Turning Off WTG Output	0.0	65.69	5773.01	249	0.00
	0.1	58.43	5576.90	249	188.84
	0.2	48.64	5261.63	249	494.33
	0.3	44.27	5069.58	249	682.00
	0.4	42.59	4962.51	249	787.40

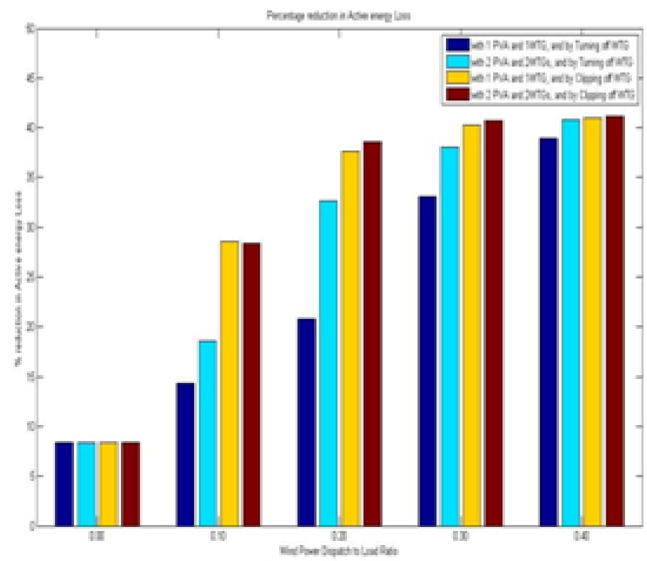

Fig. 3. Percentage reduction in active energy losses for 69-bus distribution system for different DG placement schemes.

This proves the appropriateness of sensitivity analysis techniques to reduce the search space and the computational burden without compromising with the quality of solution. It can also be observed from Table II that, though top 25 sensitive locations of 69-bus distribution test system are considered as candidate locations for DG placement, the optimal locations of PVAs and WTGs for different cases are limited to top 5 sensitive buses (i.e., Bus number 54, 53, 52, 51, and 50) only. The expected energy losses and expected energy contributions from sub-station and DG units for the two configurations with different control strategies and with different values of WPDLR are presented in Tables IV and V. For the sake of comparison, the obtained results for active energy loss corresponding to different placement schemes are compared with the base case value, and the percentage reductions in active energy losses are calculated and shown in Fig.3. In this figure, the energy losses reduce with increase in the value of WPDLR. Corresponding to WPDLR=0.40, around 40% reduction in active energy loss can be achieved. However, this reduction in Active energy loss varies depending upon the number the number of DGs units placed and control strategies employed. Referring to Tables IV and V, for all the cases, the total energy generated by PVAs is constant and is equal to 249MWh, as there is no restriction on the amount of solar energy dispatched. When only PVAs are located , (WPDLR=0.0) system performance is identical; and approximately 9% reduction in active energy loss and about 4% reduction in active energy drawn from sub-station are observed for all the cases.

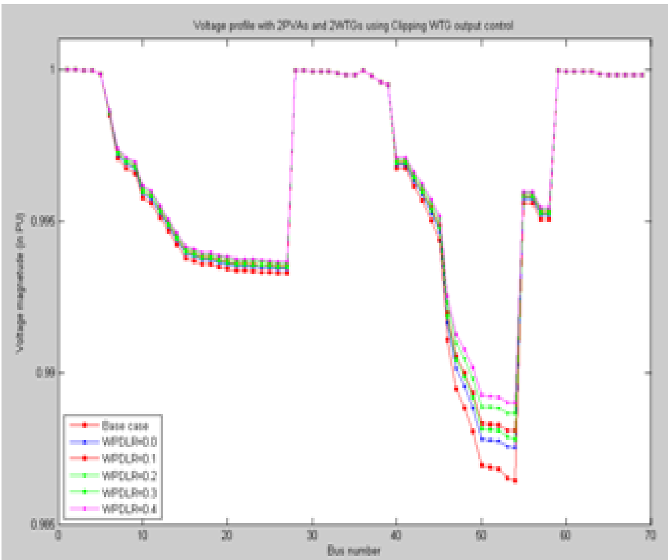

Fig.4. Voltage profile for 69-bus distribution system with 2 PVAs and 2WTGs using "Clipping WTG output" control strategy.

The active energy from WTGs increases with increase in the value of WPDLR. However, the WTG output under "Clipping WTG output" control mode is more in comparison to that under "Turning off WTG" control mode. Whenever the available wind power exceeds its permissible dispatch limit, the two strategies control the wind power dispatch in entirely different manners. Corresponding to WPDLR=0.4and "Turning off WTG" control strategy, 1 WTG injects 722.8MWh energy, while 2 WTGs inject 787.4MWh energy. With single WTG employing "Turning off WTG" control mode, it is turned off to maintain the value of WPDLR within the specified limit and consequently, it is unable to deliver any power to the system. In case of multiple WTGs using "Turning off WTG" control strategy, turning off process of WTGs is started from the least sensitive location until the value of WPDLR is within the permissible limit, while WTGs are operated in the remaining locations. This results in more energy generation from WTGs in case of multiple WTGs as compared to case of single WTG On the other hand, corresponding to WPDLR=0.4 and "Clipping WTG output" control strategy, the total energy generated by WTGs is constant and is equal to 830MWh, Hence, the energy generated from WTGs under "Clipping WTG control mode. output" control strategy is constant regardless of the number of WTGs and always higher than that from WTGs under "Turning off WTG" control strategy. That is why, for a chosen value of WPDLR, "Clipping WTG Output" control mode enhances the system performance in a better manner as compared to "Turning off WTG "control mode.

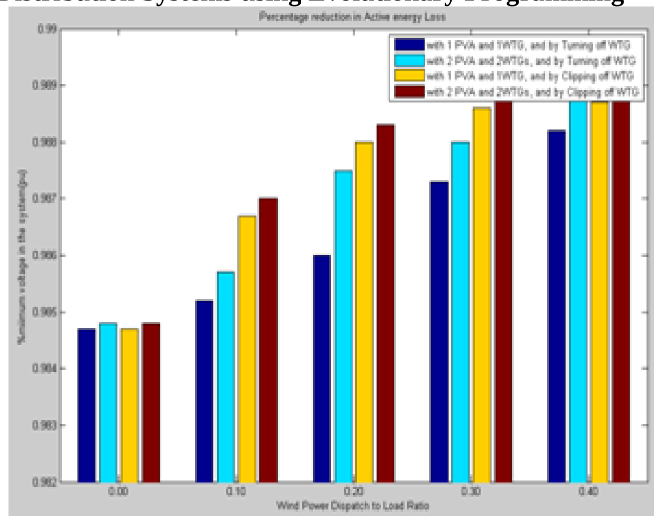

Fig.5. Minimum voltages for 69-bus distribution system for different DG placement schemes.

The expected voltage profile of the 69-bus distribution system after placing 2 PVAs and 2 WTGs and using "Clipping WTG Output" control strategy is shown in Fig. 4. For the sake of comparison, base case voltage profile is also shown in this figure. It is evident from this figure that the maximum voltage level in the system remains unchanged. However, significant improvement in the voltage magnitudes of bus number 7 to 27 and 40 to 58 is observed in comparison to their base case values. Similar voltage profiles are also calculated for other cases and a comparison of minimum voltages obtained by different placement schemes is presented in Fig. 5. voltage magnitude is raised with increase in the value of WPDLR. Corresponding to WPDLR=0.4 , the minimum voltage magnitude in the system lies between 0.9882pu to 0.9890pu depending on the DG configuration and employed control strategy for WTGs. Since the active energy injected by WTGs under "Clipping WTG output" control strategy is always higher than that under "Turning off WTG" control strategy, for a chosen value of WPDLR, "Clipping WTG output" control mode improves the voltage profile of system in a better way as compared to "Turning off WTG" control mode. It can be seen from Fig. 5 that corresponding to WPDLR=0.1, the minimum voltage in the system is below 0.986pu in case of "Turning off WTG" control strategy, while it is close to 0.987pu in case of "Clipping WTG output" control strategy.

Now, comparing the two configurations of DG units, though the individual total capacity of each DG type (PVA and WTG) is same for both the configurations, the allocation of several smaller units is more beneficial for the improvement in voltage profile of the system as compared to the allocation of few large units. This is because the allocation of several DG units simultaneously raises the voltage levels of buses at which they are connected and substantially improves the system voltage profile. When few DG units are located, the improvement in the voltage level is limited to a few nearby buses only. It can also be seen from Fig. 6 that corresponding to and "Turning off WTG" control strategy, the minimum voltage in the system is approximately 0.986pu with placement of 1 PVA and 1 WTG, while it is close to 0.9875pu with the placement of 2 PVAs and 2 WTGs.

IV. CONCLUSION

In this paper, an EP based approach has been developed and presented for finding the optimal locations of PVAs and WTGs in a radial distribution system. The active energy loss have been minimized considering the constraints on bus voltages, line loadings, number of DGs to be placed and dispatched wind power. The developed approach has following features:

- The allocation vectors for DGs have been represented in two dimensions so as to calculate power injections and DG outputs in a simple manner.
- "Turning off WTG" and "Clipping WTG output" control/ operation strategies have been simulated to keep the dispatched wind power within a specified percentage of system load.
- Using probabilistic techniques, the uncertainties associated with load and renewable resources have been modeled and the expected values of various variables of interest have been calculated.
- To reduce the search space and thereby to minimize the computational burden, a sensitivity analysis technique has been employed to select the candidate buses for DG allocation.
- To solve the developed formulation, being a combinatorial optimization problem with non-monotonic solution surfaces, an EP based algorithm has been developed as classical optimization techniques are not well suited to solve this type of problems.

The proposed technique has been applied to a 69-bus distribution test system. Optimal DG placement results in reduced energy losses and improved voltage profile in the system. From the results obtained, the following observations have also been made:

- There are variations in the optimal locations of DGs with the number of DG units, the value of WPDLR and applied control strategy for wind turbines.
- The system performance improves with increase in the value of wind power dispatch to load ratio.
- For a distribution system with wind turbines, "Clipping WTG output" control mode enhances system performance in a better way in comparison to "Turning off WTG" control mode.
- Allocation of several DG units of smaller size is more beneficial compared to few DG units of large size for improvement in system performance.

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