GA based optimal planning of VAR sources using Fast Voltage Stability Index method

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Abstract: This paper presents a novel approach for reactive power planning of a connected power network. Reactive power planning is nothing but the optimal usage of all reactive power sources i.e., transformer tap setting arrangements, reactive generations of generators and shunt VAR compensators installed at weak nodes. Shunt VAR compensator placement positions are determined by a FVSI (Fast Voltage Stability Index) method. Optimal setting of all reactive power reserves are determined by a GA (genetic algorithm) based optimization method. The effectiveness of the detection of the weak nodes by the FVSI method is validated by comparing the result with two other well-known methods of weak node detection like Modal analysis and the *L*-index method. Finally, FVSI based allocation of VAR sources emerges as the most suitable method for reactive power planning.

Key words: active power loss, FVSI method, genetic algorithm, operating cost, reactive power planning, weak nodes

1. Introduction

Reactive power planning has been one of the most challenging problem to the power system engineers. Expansion of a transmission network is not always possible because of several reasons like cost, right of way etc. Again maintaining good quality of voltage for distribution of power to the consumer is also an important aspect. Sometimes a situation of system collapse is observed even with the slight increase in reactive power demand. Hence, it becomes absolutely necessary for the proper co-ordination and planning of all reactive power sources present in the network. In this paper, main concerns are proper planning and coordination of control variables like transformer tap changers, shunt VAR compensators, generators reactive VAR in an interconnected power system for minimum active power loss as well as minimum operating cost.

A linear programming based optimization method is presented in [1] for optimal reactive power generation of large scale electric power networks. The solution of the reactive power

problem by optimal placement of a capacitor is discussed in [2]. A modal analysis technique is described in [3] for the determination of weak nodes of a connected power network. The reactive power problem is solved in [4] by injecting reactive power at weak buses of a connected power system. Application of evolutionary programming in reactive power planning is discussed in [5]. A hybrid expert system and simulated annealing based algorithm for the planning of reactive power sources is presented in [6]. A technique for the determination of reactive margin is presented in [7]. Heuristic modal for secured operation of a power system is developed in [8]. A binary search technique and special heuristics are applied for optimal VAR planning in the case of a large scale power system in [9]. Static security constraints and non-probabilistic uncertainties in load values are considered for optimal reactive power planning in [10]. Two rule based modules are used for voltage profile improvement to alleviate voltage limit violations and for minimization of active power loss in [11]. Comparative analysis of some evolutionary algorithms on reactive power planning for IEEE 30 bus system is discussed in [12]. Reactive power planning along with a voltage stability problem is presented in [13]. A modified interior power method is applied for optimal reactive power control in [14]. A GA based optimization algorithm is used for the allocation of static VAR compensators for a reactive power planning problem in [15]. A simulated annealing (SA) based optimization method is used to solve a multi-objective VAR planning problem in [16]. The effect of SVC's on an interconnected power system under normal and contingencies are investigated in [17]. Comparison of different evolutionary algorithms are presented in [18] for optimal reactive power flow. Heuristic methods are combined with optimization algorithms for voltage and reactive power control in [19]. An artificial bee colony based optimization technique for the optimal power flow problem and simultaneous reduction of active power loss in a large power network is described in [20]. Chance constrained programming based reactive power planning is investigated in [21]. How various optimization techniques can be used to overcome the different problems associated to reactive power planning is discussed in [22]. Solution for the security constrained reactive power planning problem is discussed in [23]. The Genetic algorithm based solution methodology is adopted for the power system network expansion planning in [24]. A successive linear programming technique is applied in [25] for a reactive power dispatch problem. A general quantum Genetic algorithm is used in [26] for reactive power and voltage control. Different strategies for simultaneous reduction of active power loss and improvement of a voltage profile is presented in [27]. A particle swarm based optimization technique for reactive power planning is presented in [28]. A Covariance matrix based evolutionary strategy for reactive power planning as well as enhancement of voltage stability is presented in [29]. Reactive power expansion planning is presented in [30]. An idea for optimal VAR planning in distribution feeders are presented in [31] where the locations of capacitors are determined by a heuristic approach. An AC modal of a Transmission Expansion Planning problem along with the reactive power planning solution technique is presented in [32]. A principle of the Genetic algorithm is described in [33]. In the present paper, the authors have proposed a new approach for the solution of the reactive power problem based on the detection of a weak bus by the FVSI method. The GA based optimization technique is then applied to determine the optimal setting of VAR sources.

2. Problem formulation

The objective of the reactive power planning problem is to minimize the active power loss and the overall operating cost that includes cost due to energy loss and the investment cost of shunt VAR compensators installed at weak buses. Three approaches as Modal analysis, *L*-index and FVSI method of weak node detection are presented. Also the improvement of voltage stability is addressed along with the effective planning of the reactive power sources in the present work. Hence in the present work, reactive power planning is a multi-objective problem and different objective functions and constraints are formulated as follows:

2.1. Minimization of active power loss

Minimization of the active power loss in the transmission lines can be formulated as follows:

Minimize
$$F_1 = P_{\text{loss}} = \sum_{k=1}^{m} g_k \left[V_i^2 + V_j^2 - 2V_i V_j \cos\left(\delta_i - \delta_j\right) \right], \tag{1}$$

where P_{loss} denotes active power loss, m is the number of lines, g_k is the conductance of branch k connected between i-th and j-th bus. V_i and V_j are the voltage magnitudes of the i-th and j-th buses. δ_i and δ_j are the voltage phase angles of the i-th and j-th bus respectively. X is the vector of dependent variables.

$$X = [P_G^i, V_L^1, \dots V_L^n, Q_g^1 \dots Q_g^k], \tag{2}$$

where P_G^i is active power generation at i-th bus, V_L^i is the voltage of the i-th load bus, where $i = 1, 2, 3, \dots, n$. n is the number of load bus. Q_g^i is the reactive power output of the i-th generator. where, $i = 1, 2, \dots, k$. where k is the number of generator bus.

The vector of the control variables are represented as:

$$U = [P_g^1 \dots P_g^b, V_g^1 \dots V_g^b, Q_c^1 \dots Q_c^q, t_n^1 \dots t_n^t]. \tag{3}$$

P_g^i is the active power generation at i-th bus that remains unchanged as given by standard IEEE 30 bus test system. V_g^i is the voltage of the voltage controlled bus, where $i = 1, 2, \dots, b$. Here, b is the total number of the generator bus. Q_c^i is the shunt capacitor value installed at the i-th weak bus, where $i = 1, 2, \dots, q$. q is the total number of shunt VAR compensators or the total number of weak nodes. t is the total number of tap changing transformer.

Now in the present problem, the main objective is to reduce the active power loss by proper coordination of the control variables as represented by Equation (3). Transformer tap setting arrangements and controlling of VAR output of generators do not require investment of additional cost but installation of shunt VAR compensators at weak nodes add extra cost to the operating cost.

Hence objective of the reactive power planning problem becomes minimization of the cost which is the sum of the cost due to energy loss and the installation cost of shunt VAR compensators. Therefore, the objective function can be expressed as:

Minimize
$$F_1 = C_1 + C_2, \tag{4}$$

where C_1 is the cost due to the energy loss, C_2 is the cost of the shunt capacitor. Fixed installation cost of capacitor $=1000$ \$, energy cost $= 0.06$ \$/KWh, capacitor cost/ kvar $= 3$ \$, energy rate $= 0.06 \times 100000 \times 8760$,
where

$$C_1 = P_{\text{loss}} \times \text{Energy rate}. \tag{5}$$

2.2. Voltage profile improvement

For the secured operation of the power system and to provide a quality service to the consumer, maintaining a steady voltage profile even under increased loading condition is one of the challenging criteria for the power generation companies. The objective function can be formulated as:

Minimize
$$F_2 = \sum_{i=1}^{n_b} \left| V_i - V_{\text{specified}} \right|, \tag{6}$$

where, n_b is the total number of buses and $V_{\text{specified}}$ is the specified bus voltage. $V_{\text{specified}}$ is taken as 1.0 p.u. The above mentioned objective functions are to be minimized under the following quality and inequality constraints.

2.3. Equality constraints

These constraints are load flow equations as described below:

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{n_b} V_j \left[G_{ij} \cos\left(\delta_i - \delta_j\right) + B_{ij} \sin\left(\delta_i - \delta_j\right) \right] = 0, \quad i = 1, 2, \ldots, n_b, \tag{7}$$

$$Q'_{Gi} - Q_{Di} - V_i \sum_{j=1}^{n_b} V_j \left[G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j) \right] = 0, \quad i = 1, 2, \ldots, n_b. \tag{8}$$

Here $Q'_{Gi} = Q_{Gi} + Q_{ci}$ and Q_{ci} is shunt VAR compensation at the weak nodes provided by shunt VAR compensation, where n_b is the total number of buses, P_{Gi} and Q_{Gi} are active and reactive power generation at the i-th bus, P_{Di} and Q_{Di} are active and reactive power demand at the i-th bus, G_{ij} and B_{ij} are the transfer conductance and susceptance between i-th bus and j-th bus respectively.

2.4. Inequality constraints

Generator Constraints: The generator voltage magnitudes and reactive power outputs are constrained by design specifications. The lower and upper limits of generator voltage magnitude and reactive power outputs are given below:

$$V_{Gi}^{\min} \leq V_{Gi} \leq V_{Gi}^{\max}, \quad i = 1, 2, 3, \ldots., k, \tag{9}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}, \quad i = 1, 2, 3, \ldots., k. \tag{10}$$

Shunt VAR compensator constraints: Reactive power output of a shunt VAR compensator must be restricted within their lower and upper limits as follows:

$$Q_{ci}^{\min} \leq Q_{ci} \leq Q_{ci}^{\max}, \quad I = 1, 2, 3, \ldots., q. \tag{11}$$

Transformer constraints: The upper and lower values for the transformer tap settings are limited by physical considerations and these are given below:

$$T_i^{\min} \leq T_i \leq T_i^{\max}, \quad i = 1, 2, 3, \ldots., t. \tag{12}$$

Security constraints: These include the constraints on voltage magnitudes at *pq* buses and transmission line loadings. Voltage of each *pq* bus must be within its operating limits. Line flow through each transmission line must be within its capacity limits. These are described as follows:

$$V_{Li}^{\min} \leq V_{Li} \leq V_{Li}^{\max}, \quad i = 1, 2, 3, \ldots., n, \tag{13}$$

$$S_{li} \leq S_{li}^{\max}, \quad i = 1, 2, 3, \ldots., m. \tag{14}$$

3. Determination of weak nodes

Weak nodes or the weak buses are determined by following methods:

3.1. Weak nodes detection by *L*-index method

The *L*-index method is an approximate measure of closeness of the system to voltage collapse. The buses with the high *L*-index value are the vulnerable buses of the system and require VAR support to maintain a voltage profile when subjected to increased load demand. Though voltage stability enhancement can be done by minimizing *L*-index values at each bus of the power system but in the present work the *L*-index values are used only for the detection of weak nodes.

In the proposed work, weak buses are ranked according to their *L*-index values and some weak buses (here four buses) are selected according to high *L*-index values. Now the VAR support to the system will be provided by installation of a shunt VAR compensator at these

buses. These along with the transformer tap setting arrangements and generators form control vector as shown in Table 1. A Genetic algorithm based optimization technique is applied for the optimal setting of the variables present inside the control vector. The *L*-index value of the jth bus is defined as:

$$L_j = \left| 1 - \sum_{i=1}^{k} F_{ji} \frac{V_i}{V_j} \right|, \quad \text{where} \quad j = 1, 2, 3, \ldots, n, \tag{15}$$

where

$$F_{ji} = -[Y_1]^{-1}[Y_2], \tag{16}$$

where, k is the number of *pv* buses and n is the number of *pq* buses. Y_1 and Y_2 are the sub matrix of the system *Y*-bus obtained after segregating the *pq* and *pv* buses as

$$\begin{bmatrix} I_{pq} \\ I_{pv} \end{bmatrix} = \begin{bmatrix} Y_1 & Y_2 \\ Y_3 & Y_4 \end{bmatrix} \begin{bmatrix} V_{pq} \\ V_{pv} \end{bmatrix}. \tag{17}$$

3.2. Weak nodes detection by modal analysis method

A modal analysis method [3] uses reduced Jacobian matrix J_R to analyze the system and provide both a relative proximity of the system to voltage instability, as well as the mechanism or key contributing factors to instability. We know that

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \dfrac{\partial P}{\partial \theta} & \dfrac{\partial P}{\partial V} \\ \dfrac{\partial Q}{\partial \theta} & \dfrac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}, \tag{18}$$

If active power *P* is kept constant in Equation-(18) then

$$\begin{bmatrix} 0 \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}, \tag{19}$$

$$\Delta Q = J_R \Delta V , \tag{20}$$

where J_R is the reduced Jacobian system matrix and

$$J_R = \left[J_{QV} - J_{Q\theta} J_{PQ}^{-1} J_{PV} \right]. \tag{21}$$

The reduced Jacobian J_R gives direct relation between incremental changes of bus voltage magnitudes with the changes in reactive power injections. The modes of the power network can be defined by the eigenvalues and eigenvectors of J_R. Assume $J_R = \xi \wedge \eta$, where ξ is the

right eigenvectors matrix of J_R, η is the left eigenvector matrix of J_R, $\wedge$ is the diagonal eigenvalue matrix of J_R

$$J_R^{-1} = \xi \wedge^{-1} \eta .$$ (22)

Incremental changes in reactive power and voltage are related by Equation (20). Substituting Equation (22) into Equation (20), we get

$$\Delta V = \xi \wedge^{-1} \eta \Delta Q \quad \text{or} \quad \Delta V = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta Q ,$$ (23)

where λ_i is the ith eigen value, ξ_i is the ith column right eigen vector of J_R, η_i is the ith row left eigen vector of J_R. λ_i, ξ_i and η_i define the ith mode of the system.

The left and right eigenvectors corresponding to the critical modes in the system can provide information concerning the mechanism of voltage instability, by identifying the elements participating in these modes. The bus participation factor measuring the participation of the kth bus to the ith mode can be given as:

$$P_{ki} = \xi_{ki} \eta_{ik} .$$ (24)

Bus participation factors corresponding to the critical modes can predict areas or nodes in the power system susceptible to voltage instability. Buses with large participation factors are defined as critical buses of the connected power network.

3.3. Weak nodes detected by Fast Voltage Stability Index (FVSI) method

A Fast Voltage Stability Index of lines is also used for the detection of weak nodes of a connected power system. The Fast Voltage Stability Index of a line can be approximately determined by

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} ,$$ (25)

where Z is the line impedance, X is the line reactance, Q_j is the reactive power at the receiving end, V is the sending end voltage.

The line that exhibits FVSI closed to 1.00 implies that it is approaching its instability point. If FVSI goes beyond 1.00, one of the buses connected to the line will experience a sudden voltage drop leading to system collapse. FVSI values for all lines are calculated and the end nodes of lines are detected as vulnerable nodes for lines having high FVSI values.

4. Genetic algorithms (GA) in brief

In the present work, a Genetic algorithm is used as the optimization algorithm for reactive power planning. GA is used to determine the optimum magnitude of VAR sources. All the

VAR sources are the control variables and appeared within a solution string in GA as shown in Fig. 1. Initially, sets of solution strings are created randomly in such a manner so that all the control variables have to be between their maximum and minimum limits as defined. Hence, in the initialization process of GA, a population vector consisting of several control variables is generated. Then the objective function is computed for every individual of the population. A biased roulette wheel [33] is created from the values obtained after computing the objective function for all the individuals of the current population.

Table 1. Solution vector consisting of control variables

Q_g^1	...	Q_g^k	Q_c^1	...	Q_c^q	t_n^1	...	t_n^t

Thereafter the usual Genetic operation such as Reproduction, Cross-over and Mutation takes place. Two individuals are randomly selected from the current population for reproduction. Then crossover takes place with a probability close to one (here 0.8). Finally mutation with a specific probability (very low) completes one Genetic cycle and individuals of the same population with improved characters are created in the next generation. The objective function is then again calculated for all the individuals of the new generation and all the genetic operations are again performed and the second generation of the same population size is produced. This procedure is repeated till the final goal is achieved.

5. Results and discussion

A GA based optimization algorithm is applied on the IEEE 30 bus test system to solve the multi objective reactive power planning problem for different increased loading conditions. Here the GA based optimization algorithm is used for the proper co-ordination of the VAR generation of the generators, transformer tap setting arrangements and the reactive power of the shunt VAR compensators installed by modal analysis or the *L*-index method. The connection diagram of the IEEE 30 bus test system is shown in Fig. 1.

Variation of active power loss with the number of iterations for the base reactive loading, 125% of the base and 150% of the base reactive loading is shown in Fig. 2, Fig. 3 and Fig. 4 respectively. Variation of operating cost with iteration for the base, 125% of the base and the 150% of the base reactive loading is shown in Fig. 5, Fig. 6 and Fig. 7 respectively. Active power loss and operating cost for different loading conditions by the three different methods of weak node detection is shown in Table 2. In the proposed method, maintaining a voltage profile within the acceptable limit is one of the important criteria. Maximum and minimum voltage magnitudes in different loading conditions for all the three methods of weak node detection is shown in Table 3. It is clear from Table 3 that by the effective planning of VAR sources a satisfactory voltage profile is maintained even under different increased loading cases. In Table 3, V_{min} is the voltage of the weakest node and V_{max} is the voltage of the least weak node detected by the particular method of weak bus detection. Voltages of the most and

least weak nodes of the three methods i.e., an *L*-index, modal analysis and FVSI methods are given in Table 3. The values of V_{min} and V_{max} are computed for different loading conditions when a GA based optimization technique is applied considering the modal analysis, *L*-index and FVSI method of weak node detection. From Table 2, it is observed that active power loss and operating cost is less in the FVSI method of detection than other two methods under all loading conditions. Again from Figs. 2-7, it is clear that if shunt VAR compensator locations are determined by the FVSI method and GA is then applied for the optimal setting of the reactive power sources including the shunt capacitor gives the most satisfactory result not only in terms of reduced active power loss but also in terms of system operating cost. This is observed for all loading conditions as shown in the Figs. 2-7, where GA based characteristics for different modes of weak node detections are plotted. Table 4 shows the value of reactive power sources obtained after applying the GA to the FVSI method of weak node detection.

It is to be mentioned that 19, 18, 26, 14 are the weak buses detected by Modal analysis and 28, 12, 26, 24 are the weak nodes detected by the *L*-index method. According to the FVSI method, weak nodes are 7, 17, 24 and 30 respectively.
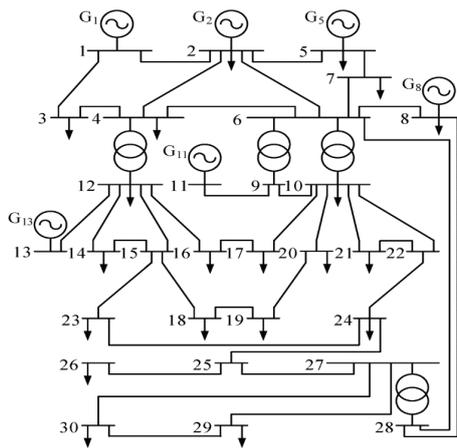

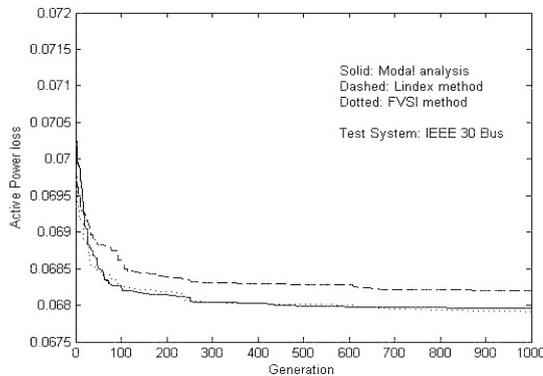
Fig. 1. Connection diagram of IEEE 30 bus test system

Fig. 2.Variation of active power loss with generation for base reactive loading using GA
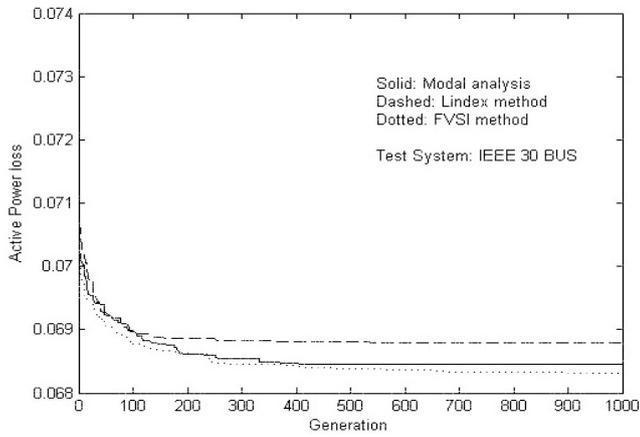
Fig. 3. Variation of active power loss with generation for 125% base reactive loading
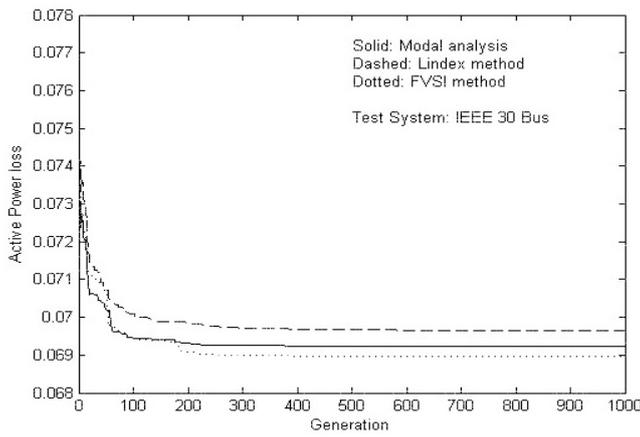

Fig. 4. Variation of active power loss with generation for 150% base reactive loading using GA
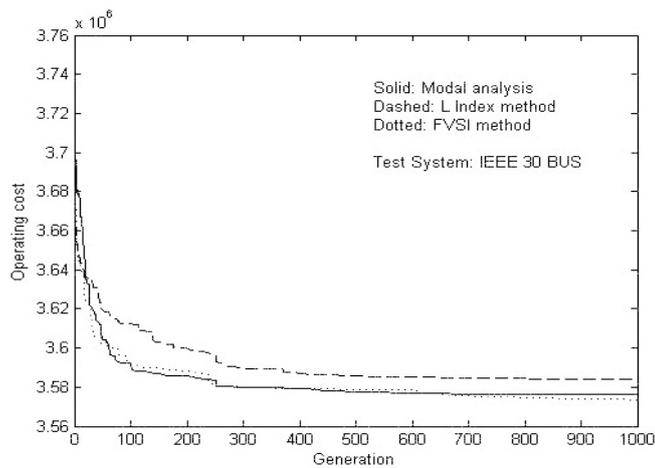

Fig. 5. Variation for operating cost with generation for base loading with GA
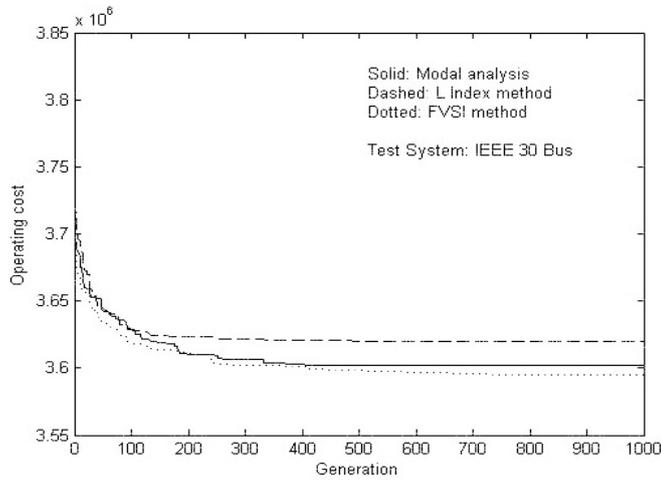
Fig. 6. Variation of operating cost with generation for 125% of base loading with GA
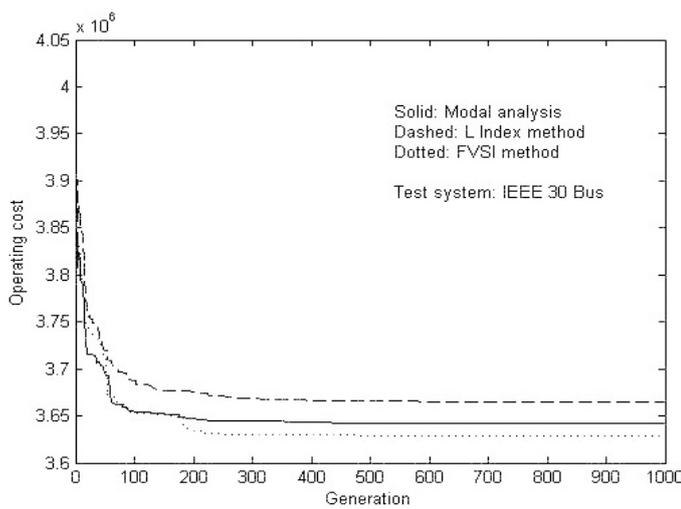

Fig. 7. Variation of operating cost with generation for 150% of base loading with GA

Table 2. Active power loss and operating cost for different loading in IEEE 30 bus system

Reactive system loading in p.u.	*L*-index method		Modal analysis method		FVSI method	
	active power loss in p.u. with GA	operating cost in ($) with GA	active power loss in p.u. with GA	operating cost in ($) with GA	active power loss in p.u. with GA	operating cost in ($) with GA
Qd	0.0681	3.5886×10^6	0.0680	3.5763×10^6	0.0679	3.5733×10^6
1.25 *Qd*	0.0688	3.6197×10^6	0.0684	3.6017×10^6	0.0683	3.5945×10^6
1.5 *Qd*	0.0696	3.6442×10^6	0.0692	3.6422×10^6	0.0690	3.6287×10^6

Table 3. Maximum and minimum voltage magnitude for different reactive loading
in IEEE 30 bus test system

Reactive System loading in p.u.	*L*-index method		Modal analysis method		FVSI method	
	V_{max} (GA) in p.u.	V_{min} (GA) in p.u.	V_{max} (GA) in p.u.	V_{min} (GA) in p.u.	V_{max} (GA) in p.u.	V_{min} (GA) in p.u.
Qd	1.0924 (24)	1.0030 (28)	1.0940 (14)	1.0154 (19)	1.0960 (30)	1.0073 (7)
1.25 *Qd*	1.0930 (24)	1.0010 (28)	1.0949 (14)	1.0012 (19)	1.0936 (30)	1.0071 (7)
1.5 *Qd*	1.0915 (24)	0.9995 (28)	1.0865 (14)	0.9993 (19)	1.0913 (30)	1.0072 (7)

Table 4. Optimum values of the variables under different loading conditions using Genetic algorithm

Reactive system loading in p.u.	FVSI method		
	Q generation (p.u.)	OLTC Positions (p.u.)	Shunt VAR compensators (p.u.)
Qd	$Qg(2) = 0.1492$ $Qg(5) = 0.2303$ $Qg(8) = 0.2286$ $Qg(11) = 0.0183$ $Qg(13) = 0.2056$	tn(11) = 0.9 tn(12) = 0.9102 tn(15) = 0.9 tn(36) = 0.9	Sh(28) = 0.0894 Sh(12) = 0.0750 Sh(24) = 0.0295 Sh(26) = 0.0479
1.25 *Qd*	$Qg(2) = 0.1914$ $Qg(5) = 0.2731$ $Qg(8) = 0.2993$ $Qg(11) = 0.0529$ $Qg(13) = 0.2532$	tn(11) = 0.9 tn(12) = 0.9 tn(15) = 0.9 tn(36) = 0.9	Sh(28) = 0.1116 Sh(12) = 0.1106 Sh(24) = 0.0359 Sh(26) = 0.0555
1.5 *Qd*	$Qg(2) = 0.2288$ $Qg(5) = 0.3214$ $Qg(8) = 0.2999$ $Qg(11) = 0.1677$ $Qg(13) = 0.27$	tn(11) = 0.9063 tn(12) = 0.9034 tn(15) = 0.9 tn(36) = 0.9	Sh(28) = 0.1371 Sh(12) = 0.1420 Sh(24) = 0.0428 Sh(26) = 0.0776

6. Conclusions

This paper shows a new method of reactive power planning where weak nodes of capacitor placement is determined by the FVSI method. The program on a Genetic algorithm is developed by the authors in the MATLAB 13a environment and is then applied for optimal setting of all VAR sources including the shunt VAR compensators. GA based allocation of VAR sources with the FVSI method of weak node detection gives a better result than all other methods of weak node detection. It is observed that active power loss and system operating cost

are lesser in the FVSI method than in other two methods such as modal analysis and the *L*-index method. It is also to be mentioned that substantial reactive power support is available for maintaining good quality of voltage at all the nodes even at increased loading conditions. Therefore, the main contribution of this present work is the determination of the proper method of weak node detection and the authors have also established that the maximum benefit can be achieved if VAR sources are allocated on this basis. So, this FVSI based optimal allocation of VAR sources by the Genetic algorithm can be a new tool for reactive power planning.

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