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FVSI based Reactive Power Planning using Differential Evolution

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Abstract

This paper proposes an application of Fast Voltage Stability Index (FVSI) to Reactive Power Planning (RPP) using Differential Evolution (DE). FVSI is used to identify the weak buses for the RPP problem which involves experimental process of voltage stability analysis based on the load variation. The point at which FVSI close to unity indicates the maximum possible connected load and the bus with minimum connected load is identified as the weakest bus at the point of bifurcation. The proposed approach has been used in the IEEE 30-bus system. Simulation results show considerable reduction in system losses and improvement of voltage stability with the use of FVSI for the RPP problem.

Keywords: Power systems, Reactive Power Planning, Fast Voltage Stability Index, Differential Evolution.

Introduction

The Reactive Power Planning (RPP) is one of the most complex problems of power systems as it requires the simultaneous minimization of two objective functions. The first objective deals with the minimization of operation cost by reducing real power loss and improving the voltage profile. The second objective minimizes the allocation cost of additional reactive power sources. RPP is a nonlinear optimization problem for a large scale system with lot of uncertainties.

During the last decades, there has been a growing concern in the RPP problems for the security and economy of power systems [1-9]. Conventional calculus based optimization algorithms have been used in RPP for years [1-4]. Conventional optimization methods are based on successive linearization and use the first and second differentiations of objective function. Since the formulae of RPP problem are hyper quadric functions, linear and quadratic treatments induce lots of local minima. Over the last decade, new methods based on artificial intelligence have been used for RPP which selects the weak buses randomly or heuristically [5-8].

This paper proposes an application of FVSI to identify the weak buses for the RPP problem using DE [8, 9, 16]. DE is a mathematical global optimization method for solving multidimensional functions.

The main idea of DE is to generate trial parameter vectors using vector differences for perturbing the vector population [8, 10, 11]. DE uses population of solutions, which can move over hills and across valleys to discover a globally optimal point. Since, DE uses the fitness function information directly, not derivatives, therefore can deal with non-smooth, non-continuous and non-differentiable functions. RPP is one of such problems. DE uses probabilistic transition rules to select generations, not deterministic rules, so it can search a complicated and uncertain area to find the global optimum which makes DE, a more flexible and robust than the conventional methods.

The slow variation in reactive power loading towards its maximum point causes the traditional load flow solution to reach its non convergence point. Beyond this point, the ordinary load flow solution does not converge, which in turn forces the system to reach the voltage stability limit prior to bifurcation in the system. The margin measured from the base case solution to the maximum convergence point in the load flow computation determines the maximum loadability at a particular bus in the system. Solvability of load flow can be achieved before a power system network reaches its bifurcation point [13, 15].

In this paper, maximum loadability is estimated through voltage stability analysis. Voltage stability analysis is conducted using the stability index, FVSI [9, 16]. The reactive power at a particular bus is increased until it reaches the instability point at bifurcation. At the instability point, the connected load at the particular bus is determined as the maximum loadability. The maximum loadability for each load bus will be sorted in ascending order with the smallest value being ranked highest. The highest rank implies the weak bus in the system that has the lowest sustainable load.

The proposed approach has been used in the RPP problems for the IEEE 30-bus system [3] which consists of six generator buses, 21 load buses and 41 branches of which four branches, (6,9), (6,10), (4,12) and (28,27) are under load tap-setting transformer branches. The reactive power source installation buses are buses 30, 26, 29 and 25 which are identified based on the FVSI technique. There are totally 14 control variables.

Problem formulation

List of Symbols

N_l = set of numbers of load level durations

N_E = set of branch numbers

N_c = set of numbers of possible VAR source installment buses

N_i = set of numbers of buses adjacent to bus i including bus i

N_{PQ} = set of PQ - bus numbers

N_g = set of generator bus numbers

N_T = set of numbers of tap - setting transformer branches

N_B = set of numbers of total buses

h = per - unit energy cost

d_l = duration of load level *1*

g_k = conductance of branch k

V_i = voltage magnitude at bus i

θ_{ij} = voltage angle difference between bus i and bus j

e_i = fixed VAR source installment cost at bus i

C_{ci} = per - unit VAR source purchase cost at bus i

Q_{ci} = VAR source installed at bus i

Q_i = reactive power injected into network at bus i

G_{ij} = mutual conductance between bus i and bus j

B_{ij} = mutual susceptance between bus i and bus j

G_{ii}, B_{ii} = self conductance and susceptance of bus i

Q_{gi} = reactive power generation at bus i

T_k = tap - setting of transformer branch k

N_{Vlim} = set of numbers of buses inwhich voltage overlimits

N_{Qglim} = set of numbers of buses inwhich reactive power

Generation overlimits

The objective function in RPP problem comprises two terms [6]. The first term represents the total cost of energy loss as follows:

$$W_C = h \sum_{l \in N_l} d_l P_{loss,l} \tag{1}$$

Where, $P_{loss,l}$ is the network real power loss during the period of load level *1*. The $P_{loss,l}$ can be expressed in the following equation in the duration d_l :

$$P_{loss} = \sum_{\substack{k \in N_E \\ k \in (i,j)}} g_k (V_i^2 + V_j^2 - 2V_i V_j \cos\theta_{ij}) \tag{2}$$

The second term represents the cost of VAR source installments which has two components, namely, fixed installment cost and purchase cost:

$$I_C = \sum_{i \in N_C} (e_i + C_{Ci} \left|Q_{Ci}\right|) \tag{3}$$

The objective function, therefore, can be expressed as follows:

$$\begin{aligned}
&\min f_C = I_C + W_C \\
&s.t \\
&0 = P_i - V_i \sum_{j \in N_i} V_j (G_{ij} \, Cos\theta_{ij} + B_{ij} \, Sin\theta_{ij}) \quad i \in N_{B-1} \\
&0 = Q_i - V_i \sum_{j \in N_i} V_j (G_{ij} \, Sin\theta_{ij} - B_{ij} \, Cos\theta_{ij}) \quad i \in N_{PQ} \\
&Q_{Ci}^{\min} \le Q_{Ci} \le Q_{Ci}^{\max} \quad i \in N_C \\
&Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \quad i \in N_g \\
&V_i^{\min} \le V_i \le V_i^{\max} \quad i \in N_B \\
&T_k^{\min} \le T_k \le T_k^{\max} \quad i \in N_T
\end{aligned} \tag{4}$$

Where, reactive power flow equations are used as equality constraints; VAR source installment restrictions, reactive power generation restrictions, transformer tap-setting restrictions and bus voltage restrictions are used as inequality constraints. Q^{min}_{ci} can be less than zero and if Q_{ci} is selected as a negative value, say in the light load period, variable inductive reactance should be installed at bus i. The transformer tap setting T_k, generator bus voltages V_g and VAR source installments Q_c are control variables so they are self restricted. The load bus voltages V_{load} and reactive power generations Q_g are state variables which are restricted by adding them as the quadratic penalty terms to the objective function. Equation (4) is therefore changed to the following generalized objective function:

$$\begin{aligned}
&\min F_C = f_C + \sum_{i \in N_{V\lim}} \lambda_{Vi} (V_i - V_i^{\lim})^2 \\
&\qquad + \sum_{i \in N_{Qg\lim}} \lambda_{Qgi} (Q_{gi} - Q_{gi}^{\lim})^2 \\
&s.t \\
&0 = P_i - V_i \sum_{j \in N_i} V_j (G_{ij} \, Cos\theta_{ij} + B_{ij} \, Sin\theta_{ij}) \quad i \in N_{B-1} \\
&0 = Q_i - V_i \sum_{j \in N_i} V_j (G_{ij} \, Sin\theta_{ij} - B_{ij} \, Cos\theta_{ij}) \quad i \in N_{PQ}
\end{aligned} \tag{5}$$

Where, λ_{vi} and λ_{Qgi} are the penalty factors which can be increased in the optimization procedure; $V^{lim}{}_i$ and $Q^{lim}{}_{gi}$ are defined in the following equations:

$$V_i^{\lim} = \begin{cases} V_i^{\min} & if \quad V_i < V_i^{\min} \\ V_i^{\max} & if \quad V_i > V_i^{\max} \end{cases}$$
$$Q_{gi}^{\lim} = \begin{cases} Q_{gi}^{\min} & if \quad Q_{gi} < Q_{gi}^{\min} \\ Q_{gi}^{\max} & if \quad Q_{gi} > Q_{gi}^{\max} \end{cases} \qquad (6)$$

weak bus identification

The Fast Voltage Stability Index is used to identify the weak buses. The characteristics of the FVSI are same with the existing techniques proposed by Moghavemmi et al. [14] and Mohamed et al. [12] whereby, the discriminant of quadratic equation is greater than or equal to zero. The maximum threshold is set to unity as the maximum value beyond this limit, system bifurcation will be experienced.

FVSI Formulation: The FVSI is derived from the voltage quadratic equation at the receiving bus on a two-bus system [16]. The general two-bus representation is illustrated in Figure 1.

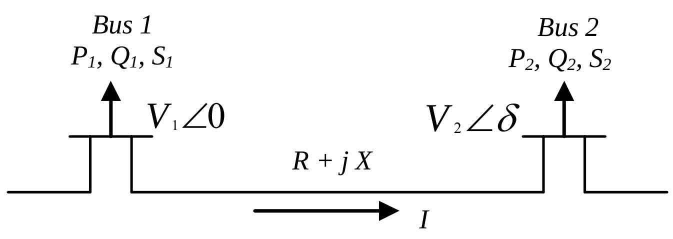


Figure 1: Two-bus power system model

From the figure, the voltage quadratic equation at the receiving bus is written as,

$$V_2^2 - \left(\frac{R}{X}Sin\delta + Cos\delta\right)V_1V_2 + \left(X + \frac{R^2}{X}\right)Q_2 = 0 \qquad (7)$$

Setting the discriminant of the equation to be greater than or equal to zero yields

$$\left[\left(\frac{R}{X}Sin\delta + Cos\delta\right)V_1\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_2 \geq 0 \qquad (8)$$

Rearranging (8),

$$\frac{4Z^2Q_2X}{V_1^2\left(R \cdot Sin\delta + X \cdot Cos\delta\right)^2} \leq 1 \qquad (9)$$

Since δ is normally very small, then, $\delta \approx 0$, $R \, Sin \, \delta \approx 0$ and $X \, Cos \, \delta \approx X$.

Taking the symbols i as the sending bus and j as the receiving bus, FVSI can be defined by,

$$FVSI_{ij} = \frac{4Z^2 Q_j}{V_i^2 X} \tag{10}$$

Where, Z is the line impedance, X is the line reactance, Q_j is the reactive power at the receiving end, and V_i is the sending end voltage.

Determining the maximum loadability for Weak Bus Identification

The following steps are implemented.

1. Run the load flow program for the base case.
2. Evaluate the FVSI value for every line in the system.
3. Gradually increase the reactive power loading by 0.01pu at a chosen load bus until the load flow solution fails to give results for the maximum computable FVSI.
4. Extract the stability index that has the highest value
5. Choose another load bus and repeat steps 3 and 4.
6. Extract the maximum reactive power loading for the maximum computable FVSI for every load bus. The maximum reactive power loading is referred to as the maximum loadability of a particular bus.
7. Sort the maximum loadability obtained from step 6 in ascending order. The smallest maximum loadability is ranked the highest, implying the weakest bus in the system.
8. Select the weak buses as the reactive power installation site for the RPP problem.

Differential Evolution (DE)

DE is a mathematical global optimization method for solving multidimensional functions. The main idea of DE is to generate trial parameter vectors using vector differences for perturbing the vector population [8, 10, 11].

Main Steps of the DE Algorithm

Initialization: All the parameter vectors in a population are randomly initialized and evaluated using the fitness function.

Mutation: DE generates new parameter vectors by adding the weighted difference between two parameter vectors to a third vector. For each target vector $x_{i,G}$, i = 1,2,…,NP, a mutant vector is generated according to:

$$\underline{v}_{i,G+1} = x_{r1,G} + F\,(x_{r2,G} - x_{r3,G}) \tag{11}$$

Where $\underline{v}_{i,G+1}$ is a mutant vector; $r1, r2$ and $r3$ are the randomly selected, mutually different vectors; F is a real constant factor [0 - 2] which controls the amplification of the differential variation.

Recombination: The mutated vector's parameters are then mixed with the parameters of another predetermined vector, the target vector, to yield the trial vector,

$$\underline{u}_{i,G+1} = (\underline{u}_{1i,G+1}, \underline{u}_{2i,G+1}, \ldots, \underline{u}_{Di,G+1}) \tag{12}$$

Where,

$$\underline{u}_{ji,G+1} = \begin{cases} \underline{v}_{ji,G+1} & \text{if } (randb(j) \le CR) \text{ or } j = rnbr(i) \\ x_{ji,G} & \text{if } (randb(j) > CR) \text{ and } j \ne rnbr(i) \end{cases}$$

$$j = 1, 2, \ldots, D. \tag{13}$$

randb(j) is the j^{th} evaluation of a uniform random number generator with outcome [0 - 1], *CR* is the crossover constant [0 - 1] which has to be determined by the user, *rnbr(i)* is randomly chosen index from 1…D

Selection: If the trial vector yields a lower cost than the target vector, the trial vector replaces the target vector. Otherwise, the target vector is passed to the next iteration.
numerical results

Simulation results have been obtained by using MATLAB 7.3 (R2006b) software package on a 2.93 GHz, Intel® Core™2 Duo Processor. IEEE 30-bus system [3] has been used to show the effectiveness of the algorithm. The network consists of 6 generator-buses, 21 load-buses and 41 branches, of which four branches, (6, 9), (6, 10), (4, 12) and (28, 27) are under load-tap setting transformer branches. The possible VAR source installment buses are 25, 26, 29 and 30 based on the maximum loadability. The maximum loadability and FVSI values for the IEEE 30 bus system are given in Table I.

Table I: bus ranking and fvsi values.

Rank	Bus	Qmax (p.u)	FVSI
1	30	0.25	0.9857
2	26	0.2999	0.9755
3	29	0.34	0.9969
4	25	0.49	0.9850
5	15	0.51	0.9805
6	27	0.59	0.9847
7	10	0.62	0.9949
8	24	0.62	0.9887
9	14	0.76	0.9863
10	18	0.78	0.9976
11	23	0.81	0.9852
12	20	0.87	0.9922
13	19	0.90	0.9795

14	12	0.90	0.9980
15	16	0.98	0.9999
16	17	0.98	0.9936
17	22	1.11	0.9970
18	28	1.15	0.9931
19	9	1.19	0.9969
20	6	1.39	0.9989
21	4	1.39	0.9947
22	3	1.56	0.9937
23	21	1.60	0.9859
24	7	1.79	0.9996

The parameters and variable limits are listed in Tables II and III. All power and voltage quantities are per-unit values and the base power is used to compute the energy cost.

Table II: parameters.

S_B (MVA)	h ($/puWh)	e_i($)	C_{ci} ($/puVAR)
100	6000	1000	30,00,000

Table III: limits.

Q_c		V_g		V_{load}		T_K	
min	max	min	max	min	max	min	max
-0.12	0.36	0.9	1.1	0.95	1.05	0.95	1.05

Three cases have been studied. Case 1 is of light loads whose loads are the same as those in [3]. Case 2 and 3 are of heavy loads whose loads are 1.25% and 1.5% as those of Case 1. The duration of the load level is 8760 hours in both the cases [6].
Initial Power Flow Results

The initial generator bus voltages and transformer taps are set to 1.0 pu. The loads are given as,

Case 1: $P_{load} = 2.834$ and $Q_{load} = 1.262$

Case 2: $P_{load} = 3.5425$ and $Q_{load} = 1.5775$

Case 3: $P_{load} = 4.251$ and $Q_{load} = 1.893$

Total initial generations and power losses are given in Table IV.

Table IV: initial generations and power losses.

	P_g	Q_g	P_{loss}	Q_{loss}
Case 1	3.00944	1.35997	0.17562	0.33143
Case 2	3.84665	2.19512	0.30415	0.85062
Case 3	4.72234	3.15382	0.47134	1.49382

Table V: optimal generator bus voltages.

Bus	1	2	5	8	11	13
Case 1	1.1000	1.0947	1.0529	1.0992	1.1000	1.1000
Case 2	1.1000	1.1000	1.0923	1.1000	1.1000	1.1000
Case 3	1.1000	1.1000	1.0892	1.0984	1.0999	1.0995

Table VI: optimal transformer tap settings.

Branch	(6,9)	(6,10)	(4,12)	(28,27)
Case 1	1.0427	0.9500	1.0108	0.9667
Case 2	1.0134	0.9500	0.9902	0.9862
Case 3	1.0151	0.9504	0.9746	0.9912

Table VII: optimal var source installments.

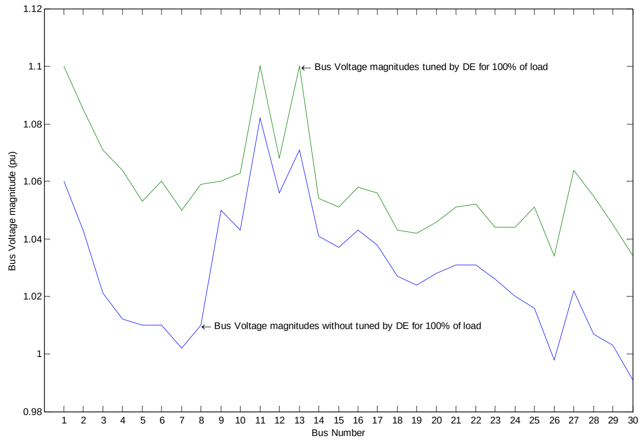
Bus	26	28	29	30
Case 1	0	0	0	0
Case 2	0.052876	0.031113	0.021918	0.031951
Case 3	0.088826	0.031312	0.028756	0.048701

Table VIII: optimal generations and power losses (pu).

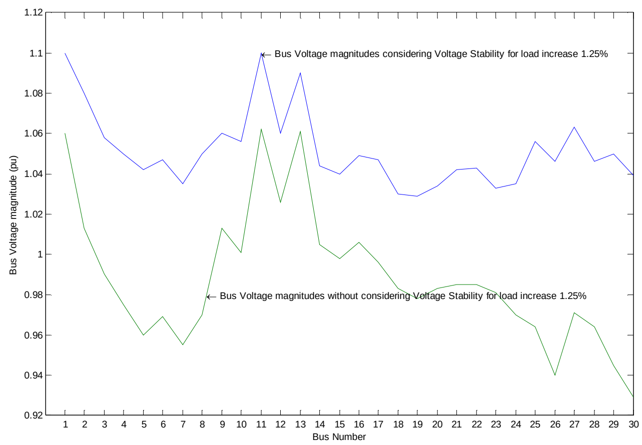
	P_g	Q_g	P_{loss}	Q_{loss}
Case 1	2.99444	1.29668	0.160436	0.26768
Case 2	3.80911	1.86788	0.266236	0.66124
Case 3	4.65957	2.66657	0.408582	1.20417

Table IX: cost comparison.

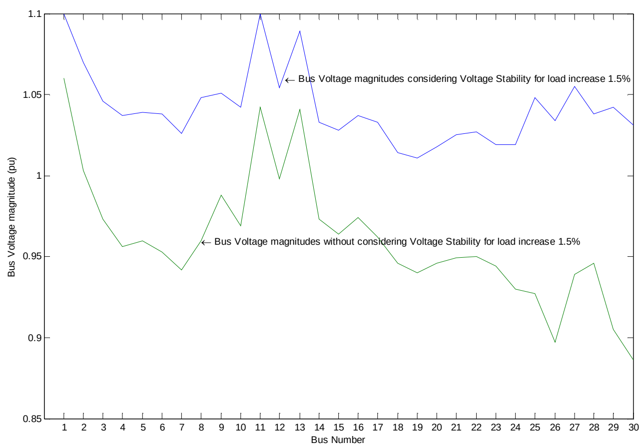
	P_C^{save} %	W_C^{save}($)	f_C($)
Case 1	8.645	7,98,071.04	$8.4325*10^6$
Case 2	12.4656	19,92,759.84	$1.4411*10^7$
Case 3	13.3148	32,98,560.48	$2.2072*10^7$



Voltage Profile of the system for Case 1



Voltage Profile of the system for Case 2



Voltage Profile of the system for Case 3

Optimal results and comparison

The optimal generator bus voltages, transformer tap settings, VAR source installments, generations and power losses are obtained as in Tables V - VIII.

The real power savings, annual cost savings and the total costs are calculated as,

$$P_C^{save}\% = \frac{P_{loss}^{init} - P_{loss}^{opt}}{P_{loss}^{init}} \times 100\%$$
$$W_C^{save} = hd_l(P_{loss}^{init} - P_{loss}^{opt}) \quad (14)$$
$$f_C = I_C + W_C$$

Table IX gives the cost comparison. From the comparison, the FVSI based RPP gives more savings on the real power, annual cost and the total cost for the cases 1, 2 and 3 respectively.

Figures 2, 3 and 4 show the Voltage Profile of the system for 100%, 125% and 150% of the loads respectively. From the plots, the bus voltage magnitudes are better for the FVSI based RPP using DE, than the bus voltage magnitudes without considering the voltage stability and DE. Also, most of the voltage magnitude and reactive power violations are eliminated while using the FVSI for the RPP.

Conclusion

FVSI based approach has been developed for solving the weak bus oriented RPP problem. Based on FVSI, the locations of reactive power devices for voltage control are determined. The individual maximum loadability obtained from the load buses will be sorted in ascending order with the smallest value being ranked highest. The highest rank implies the weakest bus in the system with low sustainable load. These are the possible locations for reactive power devices to maintain stability of the system. The application studies on the IEEE 30-bus system shows that the proposed approach gives more savings on real power, annual and the total costs for different loading conditions. Also, the voltage profile of the system has been improved while considering the FVSI based RPP using DE, than the bus voltage magnitudes without considering the voltage stability and DE. Hence, with the proposed approach a proper planning can be done according to the bus capacity to avoid voltage collapse of the system

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