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Soft computing technique based reactive power planning using NVSI

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This paper proposed an application of New Voltage Stability Index(NVSI) to Reactive Power Planning(RPP) using Soft Computing Technique based Differential Evolution(DE).NVSI is used to identify the weak buses for the Reactive Power Planning problem which involves process of experimental by voltage stability analysis based on the load variation. The Formulation of a New Voltage Stabilty Index(NVSI),which is originates from the equation of a two bus network,neglecting the resistance of transmission line,resulting in appreciable variations in both real and reactive loading.The proposed approach has been used in the IEEE 30-bus system.Results show considerable reduction in system losses and improvement of voltage stability with the use of New Fast Voltage Stability Index for the Reactive Power Planning problem.

Keywords: Power system, Reactive Power Planning, New Fast Voltage Stability Index, Differential Evolution

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1. Introduction

The Reactive Power Planning (RPP) is one of the most complex problems of power system as it requiers 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 system [1]-[7].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]-[7].

This paper proposes an application of NVSI to identify the weak buses for the RPP problem using soft computing technique based Differential Evolution(DE) [15]. DE is a mathematical global optimization method for solving multi dimensional functions.The main idea of DE is to generate trial parameter vectors using vector differences or perturbing the vector population [8], [10], [11],[17].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-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

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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, new line stability index (NVSI) has been proposed.This method does not consider the resistance [18] of the transmission line. The weak bus and weak line are identified by analyzing the results obtained through the line stability indices using proposed method.Gradually increase the real and reactive power loading [19] at one load bus until it reaches the instability point at bifurcation. At the instability point, the connected load at the particular bus is determined as the maximum loadabilty. 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 NVSI technique. There are totally 14 control variables.

2. Nomenclature

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 bus

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}, Bii= 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 in which voltage over limits

N_{Qglim}= set of numbers of buses in which VAr over limits

3. Problem Formulation

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

$$W_C = h\sum_{1\in N_1} d_1 P_{loss,1} \tag{1}$$

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

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

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

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

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

$$\mathrm{M_{in} f_c} = \mathrm{I_C} + \mathrm{W_C}, \tag{4}$$

Subjected to

(i) Real power balance equation:

$$0=\mathrm{P_i} - V_i \sum_{j\in N_l} V_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \; i\in N_{B-l} \tag{5}$$

(ii)Reactive power balance equation

$$0=\mathrm{Q_i} - V_i \sum_{j\in N_l} V_j \left(G_{ij}\sin\theta_{ij} + B_{ij}\cos\theta_{ij}\right) \; i\in N_{PQ} \tag{6}$$

(iii)Slack bus real power generation limit:

$$P_s^{\min} \le P_s \le P_s^{\max} \tag{7}$$

(iv)Generator reactive power generation limit:

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \quad i \in N_{PV} \tag{8}$$

(v)Generator bus voltage limit:

$$V_{gi}^{\min} \le V_{gi} \le V_{gi}^{\max} \quad i \in N_B \tag{9}$$

(vi)Capacitor bank reactive power generation limit:

$$Q_{ci}^{\min} \le Q_{ci} \le Q_{ci}^{\max} \quad i \in N_C \tag{10}$$

(vii)Transformer tap setting limit:

$$t_k^{\min} \le t_k \le t_k^{\max} \quad i \in N_T \tag{11}$$

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_{ci}^{min} 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:

$$\text{Min} \quad F_C = F_C + \sum_{i \in N_{Qg\lim}} \lambda_{Vi} \left(V_i - V_i^{\lim}\right)^2 + \sum_{i \in N_{V\lim}} \lambda_{Qgi} \left(Q_{gi} - Q_{gi}^{\lim}\right)^2 \tag{12}$$

Subjected to

$$0 = \mathrm{P_i} - V_i \sum_{j \in N_l} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}\right) \quad i \in N_{B-l}$$

$$0 = \mathrm{Q_i} - V_i \sum_{j \in N_l} V_j \left(G_{ij} \sin\theta_{ij} + B_{ij} \cos\theta_{ij}\right) \quad i \in N_{PQ}$$

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

$$V_i^{\lim} = \begin{cases} V_i^{\min} & if \quad V_i \prec V_i^{\min} \\ V_i^{\max} & if \quad V_i \succ V_i^{max} \end{cases}$$

$$Q_{gi}^{\lim} = \begin{cases} Q_{gi}^{\min} & if \;\; Q_{gi}^{\min} \prec Q_{gi}^{\min} \\ Q_{gi}^{\max} & if \;\; Q_{gi}^{\max} \succ Q_{gi}^{\max} \end{cases}$$

4. NVSI Formulation

The NVSI is derived from the voltage quadratic equation at the receiving bus on a two-bus system [12],[14],[18]. The general 2-bus representation is illustrated in Figure 1.

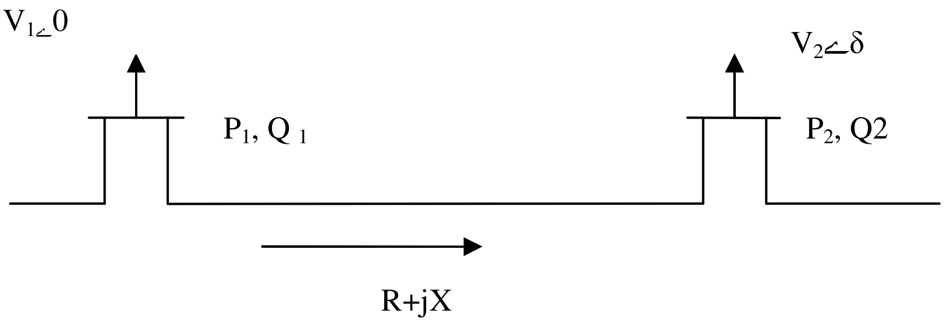

Figure 1.Model of two bus system

From fig 1. Current flowing between bus 1 and 2 is

$$I = \frac{\mathrm{V}_2 < 0 - V_2 < \delta}{R + j\,X} \tag{13}$$

$$I^* = \frac{\mathrm{V}_1^* - V_2^*}{R - jX} \tag{14}$$

Comparatively resistance of transmission line is negligible. This equation may be rewritten as

$$I^* = \frac{\mathrm{V}_1^* - V_2^*}{jX} \tag{15}$$

And the receiving end power

$$S = V_2 I^* \tag{16}$$

Incorporating in equation (16) in and solving

$$P_2 = \frac{V_1 V_2}{X} \sin\delta \tag{17}$$

$$Q_2 = \frac{V_2^2}{X} + \frac{V_1 V_2}{X} \sin\delta \tag{18}$$

Eliminating $\boldsymbol{\delta}$ from equations yields

$$(V_2^2)^2 + (2Q_2X - V_1^2)V_2^2 + X^2(P_2^2 + Q_2^2) = 0 \tag{19}$$

This is an equation of order of two V_2.This condition have at least one solution is

$$(2Q_2X - V_1^2) - 4X^2(P_2^2 + Q_2^2) \geq 0 \tag{20}$$

$$\frac{2X\sqrt{(P_2^2 + Q_2^2)}}{2Q_2X - V_1^2} \leq 1 \tag{21}$$

Taking suffix "i" as the sending bus and "j" as the receiving bus, NVSI can be defined by

$$NVSI_{ij} \frac{2X\sqrt{(P_j^2 + Q_j^2)}}{2Q_jX - V_i^2} \tag{22}$$

Variable definition follows

Z = Line Impedance
X = Line Reactance
Q_j = Reactive power at the receiving end
V_i = sending end voltage
θ = line impedance angle
$\boldsymbol{\delta}$ = angle difference between the supply voltage and receiving voltage
P_i = sending end real power

5. Differential Evolution (DE)

Differential Evolution is first proposed over 1994-1996 by Storn and Price at Berkeley.DE is a mathematical global optimization method for solving multi dimensional functions. The main idea of DE is to generate trial parameter vectors using vector differences for perturbing the vector population [8],[10], [11].

5.1 Main Steps of the DE Algorithm

5.1.1 Initialization

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

5.1.2 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:

$$V_i^{G+1} = X_{r1}^G + F(X_{r2}^G - X_{r3}^G) \tag{23}$$

Where, V_i^{G+1} is a mutant vector; r_1, r2 and r_3 are the randomly selected, mutually different vectors; F is a real constant factor [0 - 2] which controls the amplification of the differential variation.

5.1.3 Recombination

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

$$\mathbf{V_i^{G+1}} = \begin{cases} \mathbf{V_{j,i}^{G+1}, \text{if } rand_{j,i}(0,1) \leq CR \text{ or } j = k} \\ \mathbf{X_{j,i,}^{G} \quad otherwise} \end{cases} \tag{24}$$

rand(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, rand(i) is chosen randomly, the index from 1…D

5.1.4 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 iteration and the numerical results.

6. Simulation Results

Simulation results have been obtained by using MATLAB 7.5 (R2007b) 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 buses for possible VAR source installation based on max load buses are 25, 26, 29 and 30. The maximum loadability and FVSI values for the IEEE 30 bus system are given in Table I.

Table I.Bus ranking and NVSI values

Rank	Bus	Q_{max} (p.u)	NVSI
1	30	0.256	0.9886
2	26	0.27	0.9649
3	29	0.30	0.9926
4	25	0.44	0.9738
5	15	0.46	0.9708
6	27	0.51	0.9886
7	10	0.56	0.9847
8	24	0.58	0.9768
9	14	0.70	0.9794
10	18	0.73	0.9866

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_g	
min	max	min	max	min	max	min	Max
- 0.12	0.35	0.9	1.1	0.96	1.05	0.96	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 cases [6].

6.1. Initial Power Flow Results

The initial generator bus voltages and transformé 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} = 3.542 and Q_{load} = 1.577
Case 3 : P_{load} = 4.251 and Q_{load} = 1.893

Table IV. Initial generations and power losses

	P_g	Q_g	P_{loss}
Case 1	3.008	1.354	0.176
Case 2	3.840	2.192	0.314
Case 3	4.721	3.153	0.461

Table V. Optimal generator bus voltages.

Bus	1	2	5	8	11	13
Case 1	1.10	1.09	1.05	1.09	1.10	1.10
Case 2	1.10	1.10	1.09	1.10	1.10	1.10
Case 3	1.10	1.10	1.08	1.09	1.09	1.09

Table VI. Optimal transformer tap settings.

Branch	(6,9)	(6,10)	(4,12)	(28,27)
Case 1	1.0433	0.9540	1.0118	0.9627
Case 2	1.0133	0.9460	0.9872	0.9862
Case 3	1.0131	0.9534	0.9737	0.9712

Table VII. Optimal var source installments.

Bus	26	28	29	30
Case 1	0	0	0	0
Case 2	0.0527	0.030	0.022	0.031
Case 3	0.0876	0.029	0.027	0.047

Table VIII. Optimal generations and power losses

	P_g	Q_g	P_{loss}	Q_{loss}
Case 1	2.989	1.288	0.160	0.256
Case 2	3.808	1.867	0.260	0.632
Case 3	4.659	2.657	0.392	1.170

Table IX.Cost comparison

	DE using FVSI		DE using NVSI	
	$PCsave_{\%}$	W_C^{save}(\$)	$_{PC}save_{\%}$	W_C^{save}(\$)
Case-1	8.644	7, 98,070.94	9.65	7, 99,080.05
Case-2	12.452	19, 92,758.84	17.19	19, 98,759.88
Case-3	13.311	32, 98,528.48	14.96	33, 90,532.16

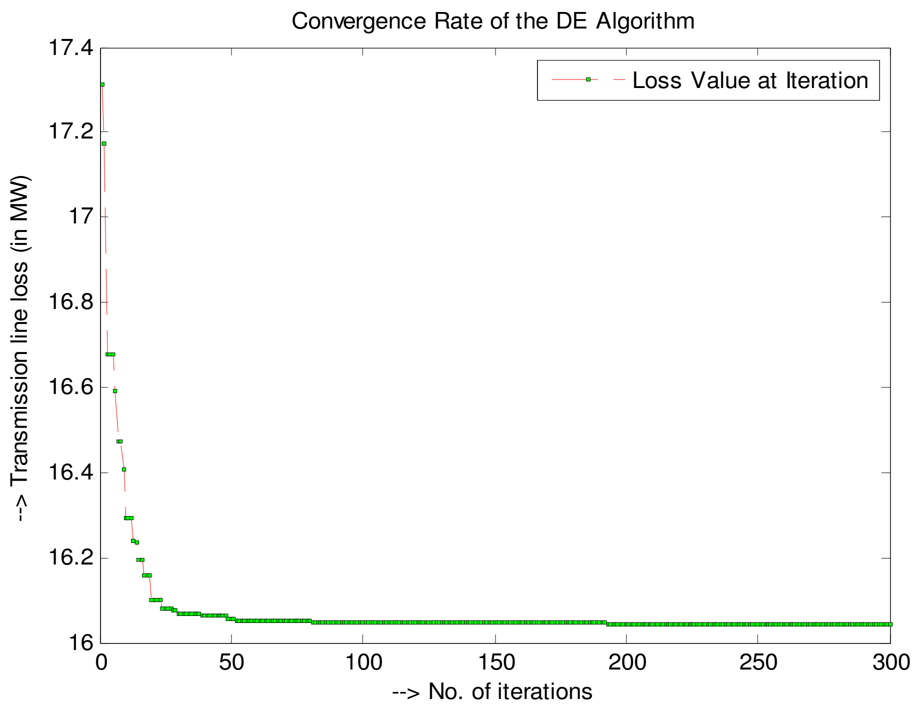

Figure 2. Converence Rate of DE-NVSI for normal loading

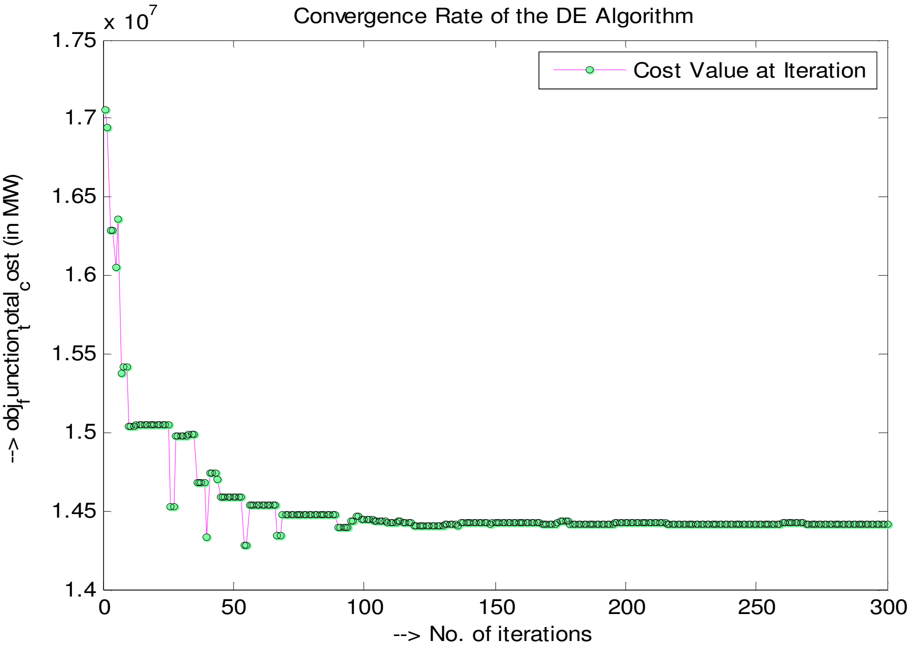

Figure 3.The convergence characteristic for Normal loading in terms of cost

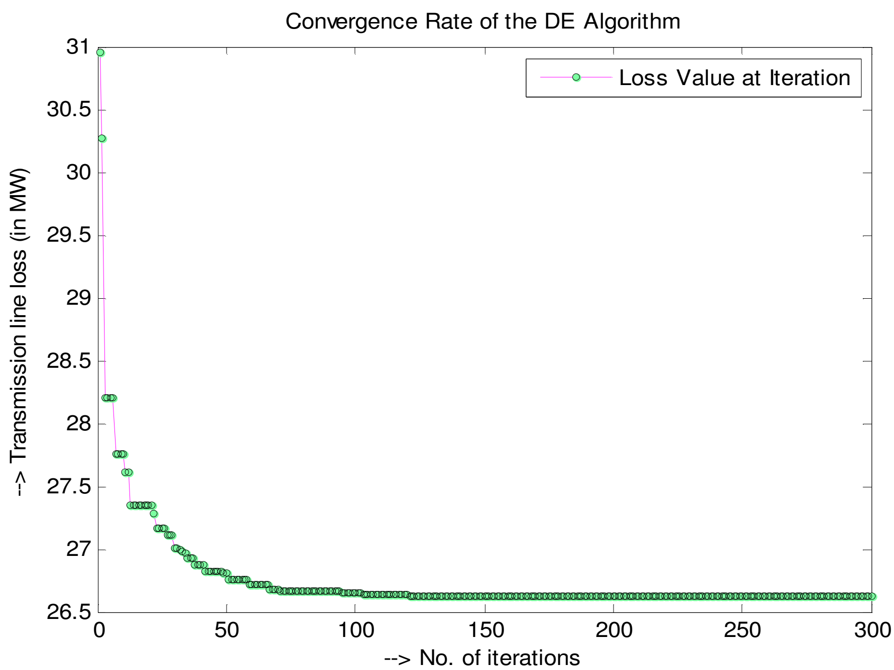

Figure 4. Converence Rate of DE-NVSI for 1.25% loading

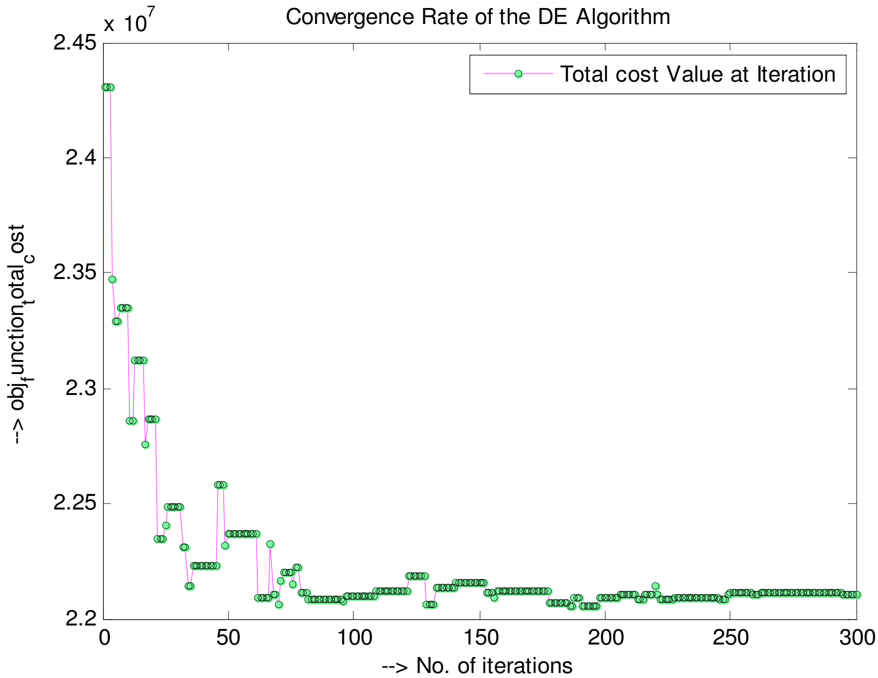

Figure 5.The convergence characteristic for 1.25 % loading in terms of cost

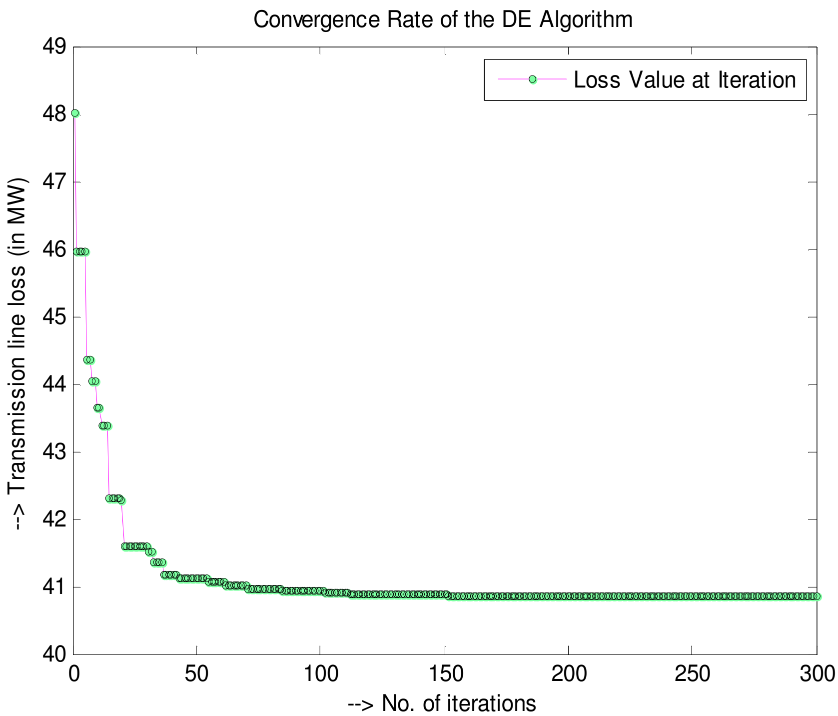

Figure 6. Converence Rate of DE-NVSI for 1.5% loading

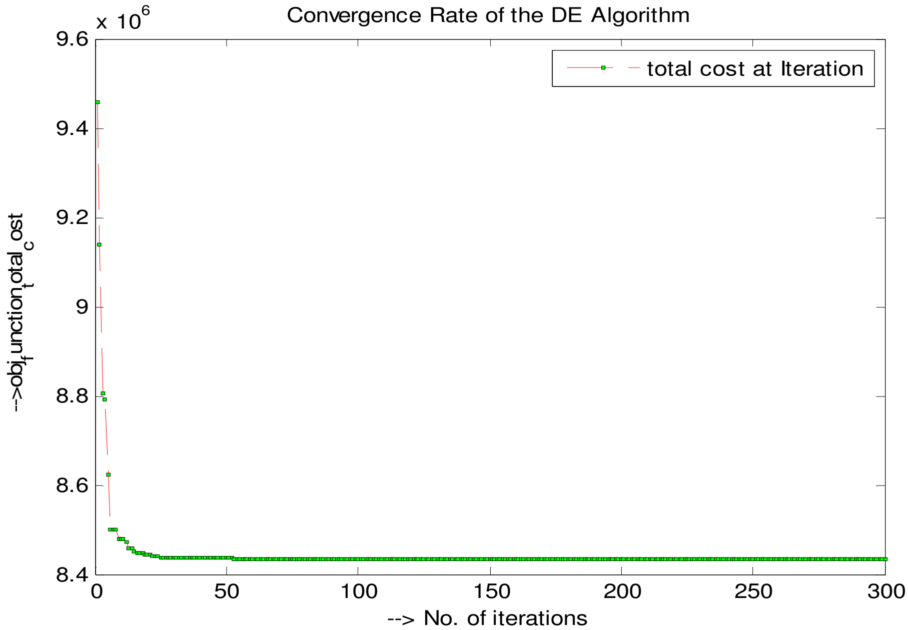

Figure 7.The convergence characteristic for 1.5% loading in terms of cost

6. Optimal results and comparaison

The optimal generator bus voltages, transformer tap settings, VAR source installments, generations and power losses are obtained as in Tables V - VII. The real power savings, annual cost savings and the total costs are calculated as,

$$P_C^{Save}\% = \frac{P_{loss}^{\text{int}} - p_{loss}^{opt}}{P_{loss}^{\text{int}}} \times 100\% \quad (25)$$

$$W_C^{Save} = hd_l(P_{loss}^{\text{int}} - p_{loss}^{opt})$$

$$F_C = I_C + W_C$$

Table IX gives the cost comparison. From the comparison, the NVSI 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, 4, and 6 show the Convergence Rate of DE (using NVSI) with VAR. For Normal, 1.25% and 1.5 % loading.Fig.3, 5 and 7 show the convergence characteristic in terms of cost for normal, 1.25% and 1.5% loading. It can be seen that from Table VIII, the Transmission loss is considerably less and more saving using DE with NVSI Comparing DE with FVSI.

7. Conclusion

NVSI based approach has been developed for solving the weak bus oriented RPP problem. Based on NVSI, 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 Differential Evolution using NVSI approach gives more savings on real power, annual and the total costs for different loading conditions comparing DE using FVSI. The proposed approach a proper planning can be done according to the bus capacity to avoid voltage collapse of the system

References

[1] A. Kishore and E.F. Hill, Static optimization of reactive power sources by use of sensitivity parameters, *IEEE Transactions on Power Apparatus and Systems*, PAS-90, pp.1166-1173.1971.

[2] S.S. Sachdeva and R. Billiton, Optimum network VAR planning by nonlinear programming, *IEEE Transactions on Power Apparatus* and System, PAS-92, pp.1217- 1225,1973.

[3] K.Y.Lee, Y.M.Park and J.L.Ortiz, A united approach to optimal real and reactive power dispatch, *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-104, No.5, pp.1147–1153,1985.

[4] Y.Y. Hong, D.I. Sun, S.Y. Lin and C.J. Lin, Multi-year multi-case optimal VAR planning, *IEEE Transactions on Power Systems*, PWRS-5, No.4, pp.1294-1301,1990.

[5] Kenji Iba, Reactive Power Optimization by Genetic Algorithm, *IEEE Transactions on Power Systems*, Vol. 9, No, 2, pp. 685 – 692,1994.

[6] L.L.Lai, Application of Evolutionary Programming to Reactive Power Planning Comparison with non linear programming approach, *IEEE Transactions on Power Systems*, Vol. 12, No.1, pp.198 – 206,1997.

[7] Wenjuan Zhang, Fangxing Li, Leon M. Tolbert, Review of Reactive Power Planning: Objectives, Constraints, and Algorithms, *IEEE Transactionson Power Systems*, Vol. 22, No. 4,2007.

[8] Zouyiqin, Optimal Reactive Power Planning Based on Improved Tabu Search Algorithm, International Conference on Electrical and Control Engineering, June 25-June 27 ISBN: 978-0-7695-4031-3,2010.

[9] D.E.Goldberg.Gentic Algorithm in Search, optimization and machine learning, Adition Wesley, New York, 1989.

[10] JaniRonkkonen, SakuKukkonen, Kenneth V. Price, Real-Parameter Optimization with Differential Evolution, *IEEE Proceedings*, pp. 506-513,2005.

[11] H. Yahia, N. Liouane, R. Dhifaoui, Weighted Differential Evolution Based PWM Optimization for Single Phase Voltage Source Inverter, *International Review of Electrical Engineering*, Vol. 5, Issue. 5, pp. 1956 –1962,2010.

[12] A. Mohamed and G.B. Jasmon, Voltage contingency selection technique for security assessment, *IEE Proc.*, vol. 136, pp. 24-28,1989.

[13] P.W. Sauer, R.J. Evans, and M.A. Pai, Maximum unconstrained loadability of power systems, *IEEE* Int. Symp. Circuits and Systems, vol. 3, pp. 1818-1821,1990.

[14] M. Moghavemmi and F.M. Omar, Technique for contingency monitoring and voltage collapse prediction, *IEE Proc. Generation, Transmission and Distribution*, vol. 145, pp. 634-640,1998.

[15] A.C.G. Melo, S. Granville, J.C.O. Mello, A.M. Oliveira, C.R.R. Dornellas, and J.O. Soto, Assessment of maximum loadability in a probabilistic framework, *IEEE Power Eng. Soc.* Winter Meeting, vol. 1, pp. 263-268,1999.

[16] I.Musirin, and T.K.A.Rahman, Novel Fast Voltage Stability Index(FVSI) for Voltage Stability Analysis in Power Transmission system, Proc. Of Student Conference on Research and Development, Shah Alam, Malaysia, July 2002.

[17] KkitPo Wong, Zhao Wong, Differntial Algorithm, An Alternative approach to Evolutionary Algorithm, *IEEE Transaction on Power systems*, Vol.12.No.3, 2005.

[18] Thierry Van Custem, Costas Vourans, Voltage Stabilty of Electrical Power Systems, Springer, pp.20-23,2008.

[19] R.Kanimozhi and K.Selvi, A Novel Line Stabilty Index for Voltage Stability Analysis and Contigency Ranking in Power Systems using Fuzzy Based Load Flow, *J.Electrical Engineering Technolology* Vol.8, No.4.pp.694-703,2013.