Voltage Security Enhancement with Corrective Control Including Generator Ramp Rate Constraint

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Abstract: - Corrective action for voltage stability is one of the issues which the electrical utilities care most about. This paper deals with the development of optimization model that is capable of performing corrective control action. Though the preventive control approach is preferred for the secure operation of the system, corrective control can also be carried out as it is considered economical. Corrective control actions would maintain voltage stability of the system in case of severe and unforeseen contingencies. Under the corrective control strategy, control actions are not taken until the contingency actually occurs. But a contingency plan is prepared in advance for the identified severe cases. Corrective control is activated when a contingency has occurred endangering voltage stability. The objective of this paper is to achieve maximum voltage stability margin in the contingency state while satisfying system and equipment constraints. Also the generator ramp rate constraints are taken into account for the system's corrective control capabilities after the outage has occurred. Particle Swarm Optimization (PSO) algorithm is applied to solve this optimization problem. The effectiveness of this algorithm is demonstrated through the Voltage Security Enhancement in the IEEE 30-bus and IEEE 57-bus test systems.

Key-Words: - L-index, ramp rate, Particle swarm optimization (PSO), Optimal power flow (OPF)

1 Introduction

Corrective action is an indispensable part of the on-line voltage stability monitoring system. It is to stabilize an unstable power system, directing the system trajectory onto a new stable equilibrium point shortly after a severe contingency, such as the tripping of a heavily loaded transmission line or the outage of a large generating unit. It can be formulated as a static nonlinear optimization problem which can be solved by the OPF. Generator ramp rates can significantly restrict the speed with which active power is rerouted in the network. Hence they are taken as the additional control variable constraint of the optimization problem for the corrective action. The use of ramp rate constraint to simulate the unit state and generation changes is an effective and acceptable approach in theoretical developments of industrial processes. This constraint ensures that output from each unit is within ramping range. The corrective control is activated when a contingency has occurred endangering voltage stability. Most of the security constrained OPF problems has assessed the voltage security based on the indices which depends on load bus voltage magnitudes. However voltage instability problems have been shown to occur in systems where voltage magnitudes never decline below acceptable limits. To measure the severity level of voltage stability problems, a lot of performance indices have been proposed [1]. They could be used on-line or off-line to help the operators to determine how close the system is to collapse. In general, these indices aimed at defining a scalar magnitude that can be monitored as system parameters change with fast computation speed. They include sensitivity factors [2,3], second order performance index [4,5], voltage instability proximity index[6], singular values and eigen values [7,8,9] and so on. A methodology of control against voltage instabilities based on singular value decomposition is developed and presented in [10]. One of the disadvantages of this methodology is that large amount of CPU time is required in singular value decomposition. Song et al presented a new concept of reactive reserve based contingency constrained OPF for enhancement of voltage stability margin by increasing the minimum eigen value of load flow

Jacobian so as to maintain desired voltage profile[11]. A nonlinear least square optimization algorithm for voltage stability margin improvement using L-index method is presented in [12]. A voltage stability index called L-index based on the power flow solution is discussed in [13]. This index ranges from 0 to 1. The bus with the highest L-index will be the most vulnerable bus in the system. The modal analysis technique to compute the voltage stability level of the system is developed in [14]. The corrective control for the voltage stability of complex power systems based on Primal- Dual Interior point method is discussed in [15]. The control actions to counter the ill effects of sudden disturbances are dealt in [16]. Wang et al solved both preventive and corrective control problems for satisfying a certain level of the voltage stability margin, but the condition at the base solution after applying the controls is not taken into account. A sensitivity based heuristic tool to determine corrective action, so as to help the system operator in the reactive power flow control problem is stated in [17]. The corrective action for coupling optimization and dynamic simulation of voltage instabilities with an iterative approach is presented in [18]. Several evolutionary algorithm based techniques have been proposed to solve OPF and voltage security enhancement problems [19-22]. In this paper, PSO algorithm is used to solve the corrective control of voltage security enhancement problem formulated as an optimization system, with the minimization of the maximum L-index as the objective function. The PSO algorithms are insensitive to scaling of the design variables. They are easily parallelized for concurrent processing and are derivative free. It has very few algorithms parameters and is very efficient in global search algorithms [23-27].

2 Voltage Security Enhancement

There are various methods of determining the voltage collapse proximity indicator. One such method is the L-index of the load buses in the system proposed in [13]. It is based on load flow analysis and its value ranges from 0 (no load condition) to 1 (voltage collapse). The bus with the highest L index value will be the most vulnerable bus in the system. The L-index calculation for a power system is briefly discussed below:

Consider a N-bus system in which there are N_g generators. The relationship between voltage and current can be expressed by the following expression:

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{1}$$

where I_G, I_L and V_G, V_L represents currents and voltages at the generator buses and load buses.

Rearranging the above equation we get,

$$\begin{bmatrix} V_L \\ V_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{2}$$

where $$F_{LG} = -[Y_{LL}]^{-1}[Y_{LG}] \tag{3}$$

$$K_{LG} = -[Y_{LL}]^{-1}[Y_{GL}] \tag{4}$$

The L-index of the j-th node is given by the expression,

$$L_j = \left| 1 - \sum_{i=1}^{N_g} F_{ji} \frac{V_i}{V_j} \angle\left(\theta_{ij} + \delta_i - \delta_j\right) \right| \tag{5}$$

where V_i voltage magnitude of i-th generator

V_j Voltage magnitude of j-th generator.

θ_{ij} Phase angle of the term F_{ji}.

δ_i Voltage phase angle of i-th generator unit.

δj Voltage phase angle of j-th generator unit.

N_g Number of generating units

The values of F_{ji} are obtained from the matrix F_{LG}. The L indices for a given load condition are computed for all the load buses and the maximum of the L indices gives the proximity of the system to voltage collapse. It was demonstrated that when a load bus approaches a voltage collapse situation, the L-index approaches one. Hence for a system-wide voltage stability assessment, the L-index is evaluated at all load buses and the maximum value of the L indices gives an indication of how far the system is from voltage collapse. Contingencies such as transmission line or generator outages often result in voltage instability in power system. The system is said to be secured if none of the contingencies causes voltage instability in the system. The maximum L-index of the system under a contingency gives a measure of severity of that contingency.

3 Ramp rate Constraint

While considering the corrective action formulation, ramp constraints or coupling constraints are of the general form:

$$h(u, u_w) \geq 0 \tag{6}$$

Corrective control action involves changing the control variables of the system in response to contingency occurrence within pre-specified limits. This process is also known as post contingency corrective rescheduling. The use of ramp rate constraints to simulate the unit state and generation changes is an effective and acceptable approach in the view of theoretical developments. In practical systems, the operating range of all on-line unit is restricted by their ramp rate limits due to physical operating limitations. These constraints recognize that the range of adjustment of certain control is determined by their setting at the time of contingency. They act as a 'bridge' between the base and the post contingency case. In the algorithm they are modelled as

$$\underline{\Delta} \le u - u_w \le \overline{\Delta} \qquad w = 1, \ldots, k \tag{7}$$

where $\underline{\Delta}$ and $\overline{\Delta}$ are the lower and upper ramp rate limits. The ramp rate of the generator is usually defined as the percentage of the generator capacity.

where k-1...c represents the post contingency state.

u_0 is the preventive control variable.

T_k is the assumed time for corrective control.

$du/dt|_{max}$ represents the ramp rate of corrective control.

4 Mathematical Problem Formulation

Enhancing voltage stability under contingency can be achieved through minimizing the voltage stability indicator L-index values at every bus of the system and consequently the global power system L-index. This is achieved through rescheduling of control variables. L-index gives a scalar number to each load bus. This index uses information on a normal power flow and is in the range of zero (no load case) to 1 (voltage collapse).

This is mathematically stated as

$$\text{Minimize } L^{\max} \tag{8}$$

Subject to

4.1 Equality Constraints

$$P_i - V_i \sum_{j=1}^{N_B} V_j (G_{ij} Cos\theta_{ij} + B_{ij} Sin\theta_{ij}) = 0, i \in N_B - 1 \tag{9}$$

$$Q_i - V_i \sum_{j=1}^{N_B} V_j (G_{ij} Sin\theta_{ij} - B_{ij} Cos\theta_{ij}) = 0, i \in N_{PQ} \tag{10}$$

The equality constraints are satisfied by running the power flow program.

4.2 Inequality Constraints

The inequality constraints are the physical and operating limits which must be satisfied by corrective control solution. These constraints are

Voltage limit

$$V_i^{\min} \le V_i \le V_i^{\max}; i \in N_B \tag{11}$$

Generator reactive power limit

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max}; i \in N_B \tag{12}$$

SVC reactive power generation limit

$$Q_{ci}^{\min} \le Q_{ci} \le Q_{ci}^{\max} \; ; i \in N_c \tag{13}$$

Transformer tap setting limit

$$t_k^{\min} \le t_k \le t_k^{\max} \; ; k \in N_T \tag{14}$$

Transmission line flow limit

$$S_l \le S_l^{\max} \; ; l \in N_l \tag{15}$$

Ramp rate constraint

$$\left| u_k - u_o \right| \le T_k * \frac{du}{dt} \Big|_{\max} \tag{16}$$

From the above formulation it is found that the voltage security enhancement problem is a combinatorial non-linear optimization problem. The active power generation (P_{gi}) and generator terminal bus voltages (V_{gi}) are the control variables and they are self restricted by the optimization algorithm. The active power generation at the slack bus (P_{sl}), load bus voltage (V_{load}) and reactive power generation (Q_{gi}) are the state variables and are restricted by adding a quadratic penalty term of the objective function.

5 Particle Swarm Optimization (PSO)

The PSO is a population based optimization algorithm. Its population is called a swarm and each individual is called a particle. The PSO algorithm works on the social behavior of particles in the swarm. It finds the global best solution by simply adjusting the trajectory of each individual toward its own best location and toward the best particle of the entire swarm at each time step [23,24]. The particle updates its velocity and position with the following equations

$$V_i^{k+1} = W * V_i^k + C_1 * rand()_1 * (pbest_i - S_i^k) + C_2 * rand()_2 * gbest_i - S_i^k)$$

$$W = W_{\max} - \frac{W_{\max} - W_{\min}}{iter_{\max}} * iter \tag{18}$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \tag{19}$$

Usually the constant weighting factor or the acceleration coefficients $C_1, C_2 = 2$, control how far a particle moves in a single iteration. The inertia weight W is used to control the convergence behavior of the PSO. The suitable selection of the inertia weight provides a balance between global and local exploration, and the exploitation of results in a lesser number of iterations on an average to find a sufficient optimal solution. As originally developed, W_{max} and W_{min} are often set to 0.9 and 0.4. *rand( )*$_1$ and *rand( )*$_2$ are two separately generated uniformly distributed numbers in the range [0,1]. $pbest_i$ is the best previous position of the ith particle. $gbest_i$ is the global best position among all the particles in the swarm. *iter* is the current iteration number. $iter_{max}$ is the maximum iteration number. The velocity of the particle on each dimension is clamped to the range [$-V_{max}$, V_{max}] to reduce the possibility of the particle leaving the feasible space. It determines the resolution or fitness, with which the regions between the present position and the target position are searched. If V_{max} is too high, particles may fly past good solutions. If V_{max} is too small, particles may be trapped in local optima, unable to move far enough is only one population in an iteration that moves towards the global optimal point to reach the better position in the problem space [25-27].

5.1 PSO Algorithm

Step 1: Initial search points and velocities are randomly generated for each of the three variables between their upper and lower bounds.

Step 2: The objective for each set of particles is evaluated based on the fitness function. If the constraints are violated, penalty is added.

Step 3: Assign the particle's position to the pbest position, and its fitness to the pbest fitness. Identify the best among the pbests as the gbest.

Step 4: New velocities and new search points (directions) are formulated using the equations (17) to (19).

Step 5: Objectives corresponding to the new search points and velocities are evaluated.

Step 6**:** Compare the best current fitness evaluation with the population's gbest. If the current value is better than the gbest, reset the gbest to the current best position and fitness value.

Step 7**:** If the iteration reaches the maximum number, then exit. Otherwise go to step 4.

5.2 PSO implementation

5.2.1 Representation

Each individual in the PSO population represents the candidate solution. The elements of that solution consist of all the optimization variables of the problem. With direct representation of the solution variables, the computer memory required to store the population is reduced.

5.2.2 Evaluation function

The function of each individual in the population evaluated according to its 'fitness', which is defined as the non-negative figure of merit to be maximized. It is associated mainly with the objective function. In this problem, the objective is to maximize voltage stability margin; i.e, minimize the L^{max} while satisfying the equality and inequality constraints equation (9) to (16). For each individual, the equality constraints are satisfied by running the Newton-Raphson algorithm, and the constraints on the state variables are taken into consideration by adding the penalty function to the objective function. Since the PSO maximizes the fitness function, the minimization objective function f is transformed into a fitness function to be maximized as

Fitness = k/f where k is a large constant

6 Simulation Results

The proposed PSO-based approach was applied to the IEEE 30-bus and IEEE 57-bus test systems for voltage security enhancement, under normal and contingency states. The real and reactive loads are scaled up according to predetermined weighting factors to analyze the system under a stressed condition. The L-indices for a given load condition are computed for all the load buses and the maximum of the L-indices gives the proximity of the system to a voltage collapse. Generation excitation, static VAR compensators and transformer tap settings are considered as control variables for voltage stability improvement. The details of the IEEE test data are taken from [28].

6.1 Case 1 PSO-OPF for base case

The IEEE 30- bus system has 6 generator buses, 24 load buses and 41 transmission lines of which four branches are (6-9),(6-10),(4-12) and (28-27) with tap setting transformers. The upper and lower voltage limits at all buses except the slack bus are taken as 1.10 p.u and 0.95 p.u respectively. The slack bus voltage is fixed at its specified value of 1.06 p.u. The PSO based algorithm was tested with different parameter settings and the best results are obtained with the following setting

No: of generations	:	50
Population size	:	50
C_1	:	2
C_2	:	2
W_{max}	:	0.9
W_{min}	:	0.4

The optimal values of the control variables from the algorithm are given in the Table 1. The algorithm took 77 sec to reach the optimal solution. Corresponding to these control variables, it was found that there was no limit violation. The convergence characteristics are given in Figure 1.

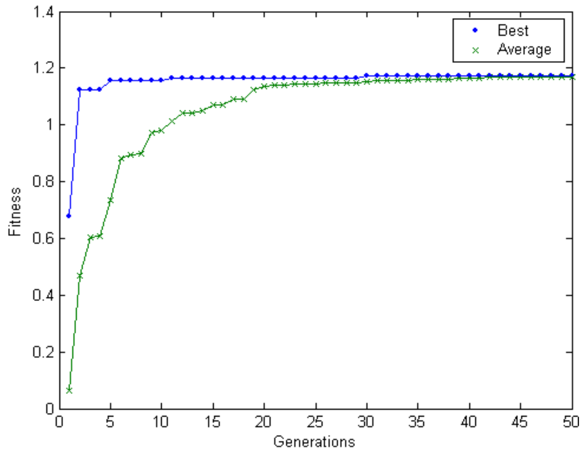

Fig.1 Convergence diagram of IEEE 30-bus system

Table 1 Results of PSO-OPF optimal control variables

Control variables	Variable setting
P_1	165.8568
P_2	55.8505
P_5	28.0625
P_8	19.4378
P_{11}	20.0513
P_{13}	12.5989
V_1	1.0500
V_2	1.0393
V_5	1.0019
V_8	1.0368
V_{11}	1.1000
V_{13}	1.0363
T_{11}	0.9828
T_{12}	1.1
T_{15}	0.9587
T_{36}	1.0612
Q_{C10}	3.3842
Q_{C12}	0.9679
Q_{C15}	2.1739
Q_{C17}	1.2539
Q_{C20}	2.1675
Q_{C21}	1.0973
Q_{C23}	4.0890
Q_{C24}	5
Q_{C29}	2.5253
Cost($/hr)	802.1137
L^{max}	0.1192

6.2 Case (ii) Contingency state scheduling

The PSO algorithm reaches a minimum L-index value of 0.1192 for the base case. To analyze the system under disturbance, contingency analysis was conducted for all the lines. From the contingency analysis, the first five severe line outages L-index values are determined. After identifying the severe contingency lines the ramp constraint values are included and the L-index values are determined. With the inclusion of generator ramp rate constraint the voltage security enhancement values are tabulated in Table 2. From the table, it is found that the L-index value decreases rapidly in the corrective control approach without any violations. This shows that the voltage stability is improved after the application of this algorithm. As an illustration the optimal values with corrective control for line outages 1-2, 9-10, 4-12 and 6-7 are given in Table 3. In order to analyze the system under stressed conditions, active and reactive powers of each bus are multiplied by 1.25. Corresponding to this setting, the L-indices of all the load buses are computed. From the contingency analysis, line outage 1-2 and 9-10 with the L^{max} values of 0.3041 and 0.2768 has been found to be severe. The PSO algorithm was applied to enhance the voltage stability under contingency state. The voltage stability enhancement values before and after the contingencies are stated in Table 4. From the table, it is found that the value of L^{max} decreases and voltage stability is improved after the application of the algorithm.

Table 2 Results of PSO-based optimal control variables

Control variables	Contingency (line 1-2 outage) Corrective control
P_1	131.1165
P_2	68.4393
P_5	24.2967
P_8	35
P_{11}	17.7414
P_{13}	20.4728
V_1	1.05
V_2	1.0058
V_5	0.9731
V_8	0.9884
V_{11}	0.9979
V_{13}	0.9534
SVC_1	4.576
SVC_2	4.875
SVC_3	1.7027
SVC_4	1.9457
SVC_5	2.6125
L^{max}	1.2080
Cost($/hr)	853.4595

Table 3 Results of optimization under contingency state for IEEE 30-bus system for base case loaded condition

Contingency line	L^{max} value (Before optimization)	L^{max} value (After optimization)
1-2	0.2862	0.1805
9-10	0.2052	0.1708
4-12	0.1993	0.1604
6-7	0.1898	0.1403

Table 4 Results of optimization under contingency state for IEEE 30-bus system for 125% loaded condition

Contingency line	L^{max} value (Before optimization)	L^{max} value (After optimization)
1-2	0.3041	0.2017
9-10	0.2768	0.2355

6.3 IEEE 57-bus test system

The IEEE 57-bus system has 7 generators, 50 load buses, 80 transmission lines, 5 synchronous condensers and 17 tap changing transformers**.** The base load of the system is 1272 MW and 298 MVAR. The PSO based algorithm was tested with different parameter settings and the best results are obtained with the following setting:

No: of generations : 70
Population size :50
C_1 :2
C_2 :2
W^{max} :0.9
W^{min} :0.4

The optimal settings for the base case are listed in Table 5. The single line contingency analysis is performed in IEEE 57-bus system. Based on the contingency study line outage (46-47) was identified as severe case with L^{max} value of 0.4778 respectively. Buses 30, 31, 32, 33 and 34 were selected for reactive power injection. The result of the PSO-based algorithm for voltage security enhancement is summarized in Table 6. From the table it is found that voltage stability level of the system has improved after the application of the proposed algorithm. This shows the effectiveness of the proposed algorithm in solving the contingency constrained voltage security problems. Figure 2 represents the convergence diagram.

Table 5 Control variable settings for IEEE 57-bus system

control variables	Variable settings
P_1	477.6638
P_2	377.5064
P_3	15.4749
P_6	87.1025
P_8	133.2654
P_9	71.9430
P_{12}	550
V_1	1.06
V_2	1.06
V_3	1.0502
V_6	1.0585
V_8	1.0600
V_9	1.0461
V_{12}	1.0417
T_{19}	1.0038
T_{20}	1.0392
T_{31}	1.100
T_{35}	1.100
T_{36}	1.100
T_{37}	1.0256
T_{41}	1.0439
T_{46}	1.1000
T_{54}	1.1000
T_{58}	1.0988
T_{59}	1.100
T_{65}	1.100
T_{66}	1.100
T_{71}	1.100
T_{73}	1.0984
T_{76}	10561
T_{80}	1.0988
Q_{30}	4.1045
Q_{32}	4.3871
Q_{31}	5
Q_{33}	2.4363
Q_{34}	5
L^{max}	0.2456

Table 6 System Performance for IEEE 57-bus test system

Line outage	Before optimization	After optimization
46-47	0.4778	0.3801
25-30	0.3242	0.2985

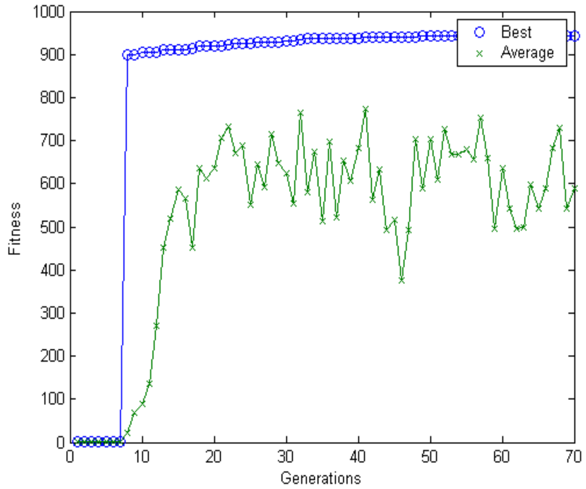

Fig.2 Convergence diagram of IEEE 57-bus system

Table 7 Comparison of optimal values in previous work in the literature

Method	Optimal Value ($/hr)
Gradient Approach[28]	802.43
Hybrid Evolutionary Programming[19]	802.62
Refined GA[20]	804.019
Improved Evolutionary Programming [21]	802.465
Proposed method	802.1137

7 Conclusion

The voltage security enhancement problem is solved by PSO algorithm with minimization of L^{max} value as the objective function. The algorithm was proposed to identify the optimal control variable setting under normal and contingency state. The proposed algorithm was demonstrated on IEEE -30 bus and IEEE 57-bus test system with generator ramp rate limits as an additional constraint. Results show that the PSO algorithm is well suited for obtaining the best solution and is effective for voltage security enhancement in the normal and contingency states.

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