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Approach for Solving Voltage Collapse Critical point Considering SVC Control and Load Increase Uncertainties Using Particle Swarm Optimization [1]

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Abstract: This paper presents a approach for solving voltage collapse critical point based on Particle Swarm Optimization (PSO). The proposed method is formulated as AC Optimal Power Flow (OPF) for maximizing expectation of the distance to voltage collapse, which also takes the generator capacity, transmission lines capability, tap position of On-load tap changer (OLTC), node voltage security constraints, steady control characteristic of Static Var Compensator (SVC), load static voltage characteristic and load increase uncertainties into account. Then, the mixed-integer nonlinear optimisation problem is solved by PSO. The test results show that the proposed approach are rationality and feasibility, it also investigates the effect of SVC and load model to voltage collapse margin.

Key-Words: - Power system, Voltage collapse, Optimal power flow, Particle swarm optimisation, SVC, Load static voltage characteristic, Uncertainties

1 Introduction

Voltage collapse typically occurs on power systems which are heavily loaded, faulted and/or have reactive power shortages. Voltage collapse is a system instability in that it involves many power system components and their variables at once. Indeed, voltage collapse often involves an entire power system, although it usually has a relatively larger involvement in one particular area of the power system. Although many other variables are typically involved, some physical insight into the nature of voltage collapse may be gained by examining the production, transmission and consumption of reactive power. Voltage collapse is typically associated with the reactive power demands of loads not being met because of limitations on the production and transmission of reactive power. Limitations on the production of reactive power include generator and SVC reactive power limits and the reduced reactive power produced by capacitors at low voltages. The primary limitations on the transmission of power are the high reactive power loss on heavily loaded lines, as well as possible line outages that reduce transmission capacity. Reactive power demands of loads increase with load increases, motor stalling, or changes in load composition such as an increased proportion of compressor load.

For a particular operating point, the amount of additional load in a specific pattern of load increase that would cause a voltage collapse is called the loading margin to voltage collapse. Loading margin is the most basic and widely accepted index of voltage collapse. An operation point of a power system not only is a stable equilibrium of differential and algebraic equations (DAE), but also must satisfy all the of static constraints at the equilibrium, such as upper and lower bunds of generators, voltage of all bus and transfer capability of all transmission lines. Since many voltage collapse accidents have been occurred over the last three decades [1], voltage security problems have been dominated and the consideration of the problem has been required in Volt/Var Control (VVC) problem [2], [3]. First one is to calculate the distance between the current operating point and the voltage collapse point. The calculation can be realized by drawing P-V or Q-V curves using the continuation power flow (CPFLOW) technique [4]. The authors has been developed a practical CPFLOW and verified it with practical power systems [5]. Another one is optimal power flow (OPF), in this method, system static security constrains are easily considering. An alternative

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approach for determination the margins is based on the use of OPF, Interior method (IP) algorithm is used to solve it . [6],[7]. But IPmethods has difficulty to handle discrete problem. In [8], a particle swarm optimization for reactive power and voltage control considering voltage security assessment is proposed, however, it not takes steady control characteristic of Static Var Compensator (SVC), load static voltage characteristic and load increase uncertainties into account. As well known, these factors are very important to voltage collapse .This paper presents a approach for solving voltage collapse critical point based on Particle Swarm Optimization (PSO). The proposed method is formulated as A AC Optimal Power Flow (OPF) for maximizing expectation of the distance to voltage collapse, which also the generator capacity, transmission lines capability, tap position of On-load tap changer (OLTC), node voltage security constraints, steady control characteristic of Static Var Compensator (SVC), load static voltage characteristic and load increase uncertainties into account. Then, the mixed-integer non-linear optimisation problem is solved by PSO. The test results show that the proposed approach are rationality and feasibility, it also investigates the effect of SVC and load model to voltage collapse margin

2 Formualtion of OPF Based Voltage Collapse Critical Point Model Considering SVC Control and Load Increase Uncertainties

2.1 Power flow control model of SVC

Since the early eighties, advances in Flexible AC Transmission Systems (FACTS) controllers in power systems have led to their application in improving stability of power networks. Several studies analyzing the application of FACTS controllers for voltage and angle stability have been reported in the literature. The effect of the SVC controller on the economic operation and voltage stability [9]

The steady state V-I characteristics of SVC is shown in Fig.1.

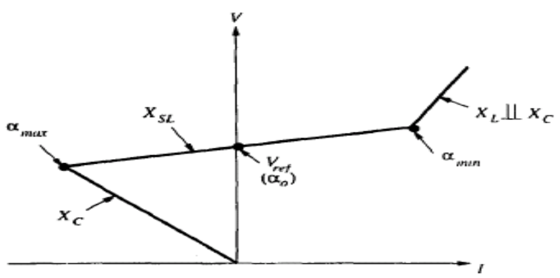

Fig.1 Typical steady state V-I characteristics of SVC

Each phase of this FACTS controller typically made up of a thyristor-controlled reactor (TCR) in parallel in parallel with a fixed capacitor bank; the system is the shunt connected to the bus through a step-up transformer bank to bring the voltage up to the required transmission levels. By controlling the firing angle α of the thyristor , the device is able to control the bus voltage magnitude, as changes on α basically result on change in the current and ,hence , the amount of reactive consumed by the inductor L; for α =90^0 the inductor L is "fully on", whereas for α =180^0 the inductor L is "fully off". The continuous switching operations of the TCR generate certain harmonic pollution on the waveforms that have to taken into account for the design and operation of the controller.

The basic control strategy is typically to keep the transmission bus voltage within certain narrow limits defined by a control droop X_{SL} and the α limits (90^0< α <180^0). The power flow state control model of SVC can be summarized in the following per-unit equations:

$$V_l - V_{REF} + X_{SL} V_k B_e = 0$$
$$Q_{SVC} - V_k^2 B_e = 0$$
$$\pi X_C X_L B_e + \sin(2\alpha) - 2\alpha + \pi(2 - \frac{X_L}{X_C}) = 0 \quad (1)$$

Where V_l is stands for the controlled bus voltage magnitude; V_k is represents the TCR and fixed capacitor voltage magnitude; V_{REF} is the control set point and X_{SL} is stands for the droop; Q_{SVC} is the controlled reactive power; B_e is the equivalent susceptance of the TCR and fixed capacitor combination; and X_L, X_C correspond to the fundamental frequency reactance of L and C, respectively.

2.2 Load model and increases uncertainties

Because of the use of aggregate methods to represent loads, standard PQ models may not accurately reflect the characteristic of the system in all cases. In this section, different static load models that express the active and reactivepowers of loads as a function of the voltage magnitude at the load bus are considered. Several voltage dependent load models have been analyzed in voltage stability studies, for example [10]. In this paper, an ZIP load model is introduced in the various OPF formulations [11]. This model represents the power demand of the load as a function of its terminal voltage as follows:

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$$P_{Li} = P_{LiN}(p_{1i}(\frac{V_i}{V_{iN}})^2 + p_{2i}(\frac{V_i}{V_{iN}}) + p_{3i}) \quad (2)$$

$$Q_{Li} = Q_{LiN}(q_{1i}(\frac{V_i}{V_{iN}})^2 + q_{2i}(\frac{V_i}{V_{iN}}) + q_{3i}) \quad (3)$$

Where P_{LiN}, Q_{LiN} is the real reactive power demand of bus i respectively, $Q_{LiN} = P_{LiN} tg\varphi_{iN}$; V_{iN} is the rating voltage of bus i ; $p_{1i}, p_{2i}, p_{3i}, q_{1i}, q_{2i}, q_{3i}$ is the coefficients of ZIP load model by load modeling Measurement-based and Statistic-based, $p_{1i} + p_{2i} + p_{3i} = 1, q_{1i} + q_{2i} + q_{3i} = 1$.

In fact, there are difference for load increase in load bus , that is, each bus has different the directions of load increase and the probability of load increase , therefore, in this paper, we define u is the vector of directions of load increase, λ is the range parameters of load increase, ρ is the probability vector of load increases , thus, the expectation of load increase as follows:

$$\sum_{i=1}^{N} (u_i \times P_{Li} \times \lambda) \times \rho_i \quad (4)$$

2.3 Voltage collapse critical model based on OPF

Objective function: Maximization of expectation of load increase:

$$\min F = \min \quad -\sum_{i=1}^{N} (u_i \times P_{Li} \times \lambda) \times \rho_i \quad (5)$$

Constrains :Generation Real Power limits:

$$P_{gi\min} \le P_{gi} \le P_{gi\max} \quad (6)$$

Where $P_{gi\min}, P_{gi\max}$ is the limits of generating unit i .

Voltage Control and Reactive Support*:*

$$Q_{gi\min} \le Q_{gi} \le Q_{gi\max} \quad (7)$$

$$V_{i\min} \le V_i \le V_{i\max} \quad (8)$$

$$T_{i\min} \le T_i \le T_{i\max} \quad (9)$$

Where $Q_{gi}, Q_{gi\min}, Q_{gi\max}$ are stand for reactive output, maximal and minimal reactive limit of generating unit i respectively. $V_i, V_{i\min}, V_{i\max}$ are stand for node voltage, minimal and maximal limits of voltage respectively, $T_{i\min}, T_i, T_{i\max}$ are stand for the minimal limits of tap situation , tap situation, maximal limits of tap situation .

Real power balance:

$$P_{Gi} - P_{LiN}(1+u_i\lambda)(p_{1i}(\frac{V_i}{V_{iN}})^2 + p_{2i}(\frac{V_i}{V_{iN}}) + p_{3i}) - V_i \sum_{j=1}^{j=n} V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}) = 0 \quad (10)$$

Reactive power balance:

$$Q_{Gi} - Q_{LiN}(1+u_i\lambda)(q_{1i}(\frac{V_i}{V_{iN}})^2 + q_{2i}(\frac{V_i}{V_{iN}}) + q_{3i}) - V_i \sum_{j=1}^{j=n} V_j (G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}) = 0 \quad (11)$$

If bus i is installed SVC, then Q_{SVC} in include in (11).

Transmission constraints:

$$P_{l\min} \le P_{li} \le P_{l\max} \quad (12)$$

Where $P_{li} = V_i^2 G_{ij} - V_i V_j (G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}), P_{l\min}, P_{l\max}$ are stand for the real power of transmission line l , limits of transfer capacity of transmission lines l

$$\alpha_{iSVC\min} \le \alpha_{iSVC} \le \alpha_{iSVC\max} \quad (13)$$

Where α_{iSVC} is ith SVC fire angle, $\alpha_{iSVC\min}, \alpha_{iSVC\max}$ are stand for the control limits of SVC , respectively

3 Algorithms for Votage Collapse Critical Piont Based OPF Considering SVC and Load Increase Uncertainties

3.1Particle swarm optimization

Particle Swarm Optimization is a novel optimization method developed by Kennedy and Eberhart [12]. It is based on the behavior of individuals (i.e., particles or agents) of a swarm. Its roots are in zoologist's modeling of the movement of individuals (e.g., fishes, birds, or insects) within a group. It has been noticed that members within a group seem to share information among them, a fact that lead to increased efficiency of the group. The PSO algorithm searches in parallel using a group of individuals similar to other AI-based heuristic optimization techniques. An individual in a swarm approaches to the optimum or a quasi optimum through its present velocity, previous experience, and the experience of its neighbors.

Let *x* and *v* denote a particle coordinates (position) and its corresponding flight speed (velocity) in a search space, respectively. The best previous position of particle is recorded and represented as *pbest*. The index of the best particle among all the particle in the group is presented as *gBest*. At last, the modified velocity and position of each particle can be calculated as shown in the following formulas:

$$v_{i+1} = K \times [w \times v_i + \varphi_1 \times rand() \times (pBest - x_i) + \varphi_2 \times rand() \times (gBest - x_i)] \quad (14)$$

$$x_{i+1} = x_i + v_{i+1} \quad (15)$$

where i is pointer of iterations, x_i is the current position of particle at iteration i, v_i is the velocity of particle at iteration i, w is the inertia weight factor, φ_1,φ_2 is the acceleration constant, $rand()$ is the uniform value in the range[0,1], K is the constriction factor , is a function of φ_1,φ_2 as reflected in (11)

$$K = \frac{2}{\left|2-(\varphi_1+\varphi_2)-\sqrt{(\varphi_1+\varphi_2)^2-4(\varphi_1+\varphi_2)}\right|} \quad (16)$$

The inertia weight is set according to the following equation

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{iter_{\max}} \times iter \quad (17)$$

Where $iter_{\max}, iter$ is the maximum number of iterations, and the current number of iterations, respectively.

To ensure uniform velocity through all dimensions, the maximum velocity is as

$$v^{\max} = (x^{\max} - x^{\min})/N \quad (18)$$

Where N is a chosen number of iterations.

3.2 PSO for voltage collapse critical point considering SVC control and load increase uncertainties

Step 1: Input parameters of system, and specify the lower and upper boundaries of each variable.

Step 2: Initialize randomly the particles of the population. These initial particles must be feasible candidate solutions that satisfy the practical operation constraints.

Step 3: To each particles of the population, employ the Newton-Raphson method to calculate power flow and the transmission loss.

Step 4: Calculate the evaluation value of each particle by using the evaluation the first objective function and the non-stationary multi-stage assignment penalty function in the population.

Step 5: Compare each particle's evaluation with its *pBest*. The best evaluated value among the *pBest* is *gBest*.

Step 6: Update the time counter $t=t+1$.

Step 7: Update the inertia weight w given by (17).

Step 8: Modify the velocity v of each particle according to (14).

Step 9: Modify the position of each particle according to (15). If a particle violates its position limits in any dimension, set its position at the proper limits.

Step 10: Each particle is evaluated according to its updated position. The *pBest* is the best position history. Only when a new solution dominates the current *pBest*, is the *pBest* is updated.

Step 11: If one of the stopping criteria is satisfied then go to Step 12. Otherwise, go to Step 6

Step 12: The particle that generates the latest *gBest* is the optimal value.

4 Examples and Analysis

In this paper, a 5-bus 2-generator 3-load test system is used to simulation. The single-line diagram of power system and parameters are given in [11], the parameters of SVC are given in Tab 1. The parameters of load demand , ZIP load model coefficients and load increase probability are given in Table 2. This paper adopts the per unit system to simulate.

Table 1 Pameters of SVC

X_C	X_L	X_{SL}	$\alpha_{\min}$	$\alpha_{\max}$	V_{REF}
0.96	0.45	2	1.5708	3.054	1.0

Table 1 Load demand,, Coefficients of ZIP load model and load increase probability

	Bus 3	Bus 4	Bus 5
P_{LiN}	0.5	0.5	0.4
Q_{LiN}	0.7	0.6	0.4
P_{1i}	0.74	0.83	0.20
P_{2i}	0.15	0.11	0.50
P_{3i}	0.11	0.06	0.30
Q_{1i}	0.37	0.41	0.30
Q_{2i}	0.20	0.30	0.23
Q_{3i}	0.43	0.29	0.47
ρ	0.9	0.8	0.7

In the simulation results, Table 3 shows the comparison of objective function values, maximal loadability and fire angle of SVC with or without SVC; Table 4 is the comparison of generator output with or without SVC.

Table 3 Comparsion of objectives values, maximal loadability and fire angle with/without SVC

	Without SVC	Bus 3 with SVC	Bus 4 with SVC	Bus 5 with SVC
λ	0.1093	0.8849	1.0349	0.8668
F	0.3136	2.5397	2.9703	2.4877
α	------	1.6072	1.6090	1.7055

From Table 3, before SVC is installed in the system, maximal voltage collapse critical point, that is, maximal loadability is 0.1093 to satisfy all the system security limits, the maximal expectation is 0.3136, after SVC is installed, the maximal loadabiity and the maximal expectation are increased, however, we can see that when SVC is installed at different locations, the effect is also different. That is, the degree of increase is difference for situation of

SVC. Because the SVC provide the reactive power, system reactive level is improved. At same time, because of difference load increase and network situation, there are different increased level for different SVC site. Then, we will face the problem of where should we put the TCSC, The optimal location of SVC is determined by many factors such as the topology of the system, the load pattern of the system, the type of contingencies etc. This is an ongoing research of our research team.

Table 4 Comparsion of generator with/without SVC

	Without SVC	Bus 3 with SVC	Bus 4 with SVC	Bus 5 with SVC
P_1	0.5358	1.5472	1.6341	0.8788
P_2	1.0297	0.8994	0.9985	1.6873
Q_1	1.1	1.1	1.1	0.6438
Q_2	0.9	0.2658	0.1474	0.9

From Table 4, several points can be observed. First, when the SVC and load increase uncertainties constraints are considered in the OPF, the generator output is changed, the reactive power output of generator is lower than the normal OPF without these constraints. It can be explained the same as scenario 1 that more constraint considered in the OPF problem will reduce the OPF solution space. Second, the power flow control aims can be reached by the use of FACTS device.

5 CONCLUSIONS

This paper presents a approach for solving voltage collapse critical point based on Particle Swarm Optimization (PSO). The proposed method is formulated as AC Optimal Power Flow (OPF) for maximizing expectation of the distance to voltage collapse, which also takes the generator capacity, transmission lines capability, tap position of On-load tap changer (OLTC), node voltage security constraints, steady control characteristic of Static Var Compensator (SVC), load static voltage characteristic and load increase uncertainties into account. Then, the mixed-integer non-linear optimisation problem is solved by PSO. The proposed optimal power flow (OPF) formulation was implemented to a program in Matlab environment and tested on 5-bus 2-generator 3-load test system. Numerical results demonstrate the good performance of the OPF approach in handling the power flow control problem, voltage stability enhancement and congestion relief with SVC device. The test results also show that the proposed approach are rationality and feasibility.

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