A preventive control model for static voltage stability considering the active power transfer capabilities of weak branches

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Abstract: - The voltage instability of power system often occurs when the active power on one or more weak branches exceeds its transfer capability. This paper presents a preventive control model for voltage stability using the active power transfer capabilities of weak branches as static voltage stability margin constraints. A local line-based voltage stability index is used to determine the critical contingencies, weak branches and transfer capability of each weak branch. A static security analysis method, which is based on DC power flow equations, is used to establish the non-linear active power flow expressions on weak branches following each critical contingency. The static voltage stability margin constraints can be obtained from the active power flow expressions and transfer capabilities of weak branches. A quadratic optimal model for preventive control including the proposed static voltage stability margin constraints is presented. The simulation results for the IEEEE14-bus system and IEEE118-bus system demonstrate the correctness and effectiveness of the proposed preventive control model for static voltage stability.

Key-Words: - Electric power system; Voltage control; Preventive control; Static voltage stability; Weak branches; Quadratic optimal model

1 Introduction

In recent years, voltage instability occurred in many power systems all over the world and resulted in power failure [1, 2]. Thus, in order to relieve or at least minimize the system from the voltage instability problem, many electric utilities have made a great deal of effort in system studies related to voltage stability. Voltage stability mainly includes dynamic/transient voltage stability and static voltage stability. There are many research achievements on the assessment method for static voltage stability [2-6]. However, it is extremely important to use effective preventive control to improve the pre-contingency operating state of power system to guarantee the static voltage stability in various contingency conditions and stressed load condition.

The preventive control for the static voltage stability can mainly be formulated by the optimal power flow (OPF) models considering the static voltage stability margin constraint [7-14]. And there are two basic and complementary concepts for these models: linearization optimization models and nonlinear optimal models. References [7-12] proposed the linearization optimization models where the static voltage stability margin constraints were expressed by the linearization sensitivity of static voltage stability index with respect to control variables. Unfortunately, the power system is a nonlinear system and the nonlinear characteristic is predominant when it is unstable or close to collapse point. Therefore, a linearization model has limitations [15]. References [13, 14] presented the nonlinear model in which the static voltage stability margin constraints were expressed by power flow equations with load parameter in normal operating condition, stressed load condition and multi-contingency conditions. This control model can reflect the nonlinear characteristic of power system. However, when a power system is very big or a large number of critical contingencies must be considered, the number of static voltage stability margin constraints is extremely large and the preventive control model becomes very complicated. This results in difficulties in solving the model and even no feasible solution for the preventive control [16].

Actually, the static voltage instability generally originates from one or several weak branches whose active powers exceed their transfer capabilities. If the static voltage stability margin constraints can be expressed by the active power constraints of weak branches, the preventive control model will be greatly simplified. In order to achieve the goal, determining weak branches causing the static voltage stability problem is a crucial step. There are several localized line-based voltage stability indices which can identify weak branches [17-19]. Particularly, the voltage stability indices presented in References [18] and [19] can be used to estimate the maximum transfer capabilities of weak branches. If the active powers on weak branches exceed their maximum transfer capabilities, the static voltage stability problem occurs.

Based on the concept above, this paper presents a preventive control optimization model using the active power constraints of weak branches as static voltage stability margin constraints. A localized line-based voltage stability index is used to determine critical contingencies as well as corresponding weak branches and their transfer capabilities. A static security analysis based on DC power flow equations is used to obtain the quadratic expressions for active powers on weak branches in each critical contingency, which leads to a quadratic preventive control model. It has been proved that a quadratic optimization model is very efficient in computations when the predictor corrector primal dual interior point method (PCPDIPM) is used [20].

The rest of the paper is organized as follows. The formulation of the quadratic optimization model for preventive control is presented in Section 2. The solution of the proposed preventive control is presented in Section 3. The simulation results are provided in Section 4, followed by conclusions in Section 5.

2 Formulation of the proposed preventive control model

In this section, the static voltage stability margin constraints are established and the quadratic optimization model for preventive control is built. In the proposed preventive control, N-1 contingencies of branch outages are considered. Note that the normal operating state is treated as a special case of contingency condition in the mathematical expression.

2.1 The static voltage stability margin constraints for the proposed preventive control

In order to establish the static voltage stability margin constraints expressed by the active power constraints of weak branches, it must be used a localized line-based voltage stability index to identify the weak braches and their corresponding transfer capabilities firstly. Reference [19] presented a localized line-based voltage stability index for real time application, which is called the Extended Line Stability Index (ELSI). The ELSI has considered the impact of external system beyond a line and can quickly recognize weak branches and their maximum transfer capabilities corresponding to the voltage collapse point. And Reference [19] proposed the derivation and computation of the ELSI. This paper will explain how to use the ELSI to determine the weak branches and their transfer capabilities. After that, the active powers on weak braches in critical contingencies, which are expressed by the preventive control optimal variables, will be introduced.

2.1.1 Determination of critical contingencies as well as corresponding weak branches and their transfer capabilities

Reference [19] proved that the ELSI of each branch must be larger than 1.0 or equal to 1.0 for guaranteeing the static voltage stability of a power system. The larger the ELSI is, the farther the power system is from its voltage collapse point. In operation practice of utilities, operators do not allow their system to be operated very near the voltage collapse point and a secure margin must be applied. This corresponds to a threshold value of ELSI which is little bit larger than 1.0. The threshold for ELSI can be specified depending on the security requirement at the control center of a utility. The threshold is denoted by α in the proposed preventive control. The difference between α and 1.0 reflects the desired margin of static voltage stability, which can be determined by individual power companies.

When the ELSI is used to determine critical contingencies and corresponding weak branches, the power flow in each contingency condition must be calculated. For an unsolvable case which possibly results from voltage instability or numeric calculation problem, a minimizing load shedding model similar to that given in Reference [21] is used to restore solvability of power flow. For a solvable case, the power flow can be directly obtained. Based on the power flow solution, the ELSI and actual active power on each operating branch are calculated. For the contingency state of branch kl in outage, if the ELSI of any branch ij is smaller than α, the contingency of branch kl in outage is determined to be a critical contingency, and branch ij is determined to be a weak branch whose permissible maximum transfer capability $P_{ij\_weak\max}$ can be expressed using the ELSI by Equation (1).

$$P_{ij\_weak\max} = \mathrm{ELSI}_{ij\_weak} \times P_{ij\_weak} \tag{1}$$

where, $P_{ij\max}$, P_{ij} and ELSI_{ij} respectively represent the maximum transfer capability, actual active power and ELSI of branch ij in the contingency state of branch kl in outage.

It should be pointed out that the ELSI is not a unique index to represent such a permissible transfer capability. Conceptually, as long as a method can provide this transfer capability on individual branches, Equation (1) can be used in the proposed model. The advantage of using the ELSI is that it can be quickly and easily calculated for individual branches from a regular power flow (solvable case) or a simple optimal power flow (unsolvable case) following a contingency. Also, the ELSI has incorporated the impacts of external system beyond a line.

2.1.2 Quadratic expressions for active powers on weak branches in critical contingencies

In the critical contingency of branch kl in outage, the active power on weak branch ij can be calculated by Equation (2) using the static security analysis based on DC power flow equations [22].

$$P_{ij1}(e,f) = P_{ij0}(e,f) + \rho_{ij}^{kl} P_{kl0}(e,f)\frac{X_{kl}}{X_{ij}} \tag{2}$$

where, X_{ij} and X_{kl} respectively represent the reactance of branch ij and branch kl; e , f respectively represent the real parts and imaginary parts of the bus voltage vectors in normal operating state; $P_{ij0}(e\ ,f)$ and $P_{kl0}(e\ ,\ f)$, which are the quadratic function of e and f under rectangular coordinate system, respectively represent the active power on branch ij and branch kl in normal operating state; $P_{ij1}(e, f)$ represents the active power of branch ij in the critical contingency on branch kl in outage; ρ_{ij}^{kl} represents the transfer coefficient of branch kl with respect to branch ij. And in normal operating condition, the expression of $P_{ij1}(e, f)$ is same to $P_{ij0}(e, f)$ because the value of ρ_{ij}^{kl} is zero. In the critical contingency condition, ρ_{ij}^{kl} can be computed by Equation (3) [22].

$$\rho_{ij}^{kl} = (S^{ij})^{\mathrm{T}}[B^{'}(0)]^{-1}S^{kl} / (X_{kl} - (S^{kl})^{\mathrm{T}}[B^{'}(0)]^{-1}S^{kl}) \tag{3}$$

where , S represents the node-branch incident matrix; when bus i is the root node of bth branch, the ith row and bth column element of matrix S is one; when bus j is the end node of bth branch, the jth row and bth column element of matrix S is negative one; when bus k isn't linked with bth branch, the kth row and bth column element of matrix S is zero; S^{kl} and S^{ij} respectively represent the column of matrix S with respect to branch kl and branch ij. $B^{'}(0)$ represents the susceptance matrix of DC power flow in normal operating state.

2.1.3 Static voltage stability margin constraints of the proposed preventive control model

Based on Equation (1) and Equation (2), the active power constraints of weak branches in critical contingencies can be established by Equation (4).

$$P_{ij0}(e,f) + \rho_{ij}^{kl} P_{kl0}(e,f)\frac{X_{kl}}{X_{ij}} \le P_{ij\_weak\max} \tag{4}$$

As long as there is one branch whose active power exceeds its transfer capability in a contingency, the static voltage stability violation will occur. Therefore, Equations (4), which are the active power constraints of weak branches, can be used as the static voltage stability margin constraints of the proposed preventive control model. Actually, there are only a few weak branches resulting in static voltage instability in a power system. In other words, the number of the static voltage stability margin constraints expressed by Equations (4) is small. In this way, the proposed preventive control model for static voltage stability becomes a small scale optimization problem. Because Equations (4) are the quadratic function of the optimal variables, the quadratic optimization model for preventive control can be established in Section 2.2 and solved efficiently using the PCPDIPM which is appropriate for a quadratic form [20].

It must be noted that Equation (2) remains the nonlinear characteristic of power system because it is the quadratic function of bus voltage vector. And the minor error resulting from Equation (2) is included in the transfer capability margin which is set according to conservatism. In other words, the minor error is the small part of the transfer capability margin which is represented by the threshold α.

2.2 Proposed quadratic optimization model for preventive control

After obtaining the static voltage stability constraint in critical contingencies, the proposed preventive control model can be established by Equations (5)-(17). In the proposed preventive control model, the objective is to minimize the load-shedding and the network active power loss. The unknown controllable variables to be optimized include the active power outputs P_G of generators, reactive power outputs Q_G of generators, reactive power injections Q_C of shunt capacitors, reactive power injections Q_R of shunt reactors, LTC (loading tap changers) turn ratios k and active load curtailments C. The unknown state variables to be optimized include the real parts e and imaginary parts f of bus voltages.

$$\min \quad \sum_{i\in N_\mathrm{B}} P_{\mathrm{G}i} - \sum_{i\in N_\mathrm{B}} (P_{\mathrm{D}i} - C_i) + \sum_{i\in N_\mathrm{B}} w_i C_i \tag{5}$$

s.t.

$$\begin{aligned} &P_{\mathrm{G}i} - (P_{\mathrm{D}i} - C_i) - \sum_{ij\in S_{\mathrm{L}i}} P_{\mathrm{L}ij}(e,f) - \\ &\sum_{ij\in S_{\mathrm{T}i}} P_{\mathrm{T}ij}(e,f) = 0 \qquad i = 1,\cdots,N_\mathrm{B} \end{aligned} \tag{6}$$

$$\begin{aligned} &Q_{\mathrm{G}i} + Q_{\mathrm{C}i} + Q_{\mathrm{R}i} - (Q_{\mathrm{D}i} - C_i Q_{\mathrm{D}i}/P_{\mathrm{D}i}) - \sum_{ij\in S_{\mathrm{L}i}}^{N_\mathrm{B}} Q_{\mathrm{L}ij}(e,f) - \\ &\sum_{ij\in S_{\mathrm{T}i}} Q_{\mathrm{T}ij}(e,f) = 0 \qquad i = 1,\cdots,N_\mathrm{B} \end{aligned} \tag{7}$$

$$e_i f_m - e_m f_i = 0 \qquad t = 1,\cdots,N_\mathrm{T} \tag{8}$$

$$e_i - k_t e_m = 0 \qquad t = 1,\cdots,N_\mathrm{T} \tag{9}$$

$$V_{i\min}^2 \le V_i^2 = e_i^2 + f_i^2 \le V_{i\max}^2 \qquad i = 1,\cdots,N_\mathrm{B} \tag{10}$$

$$k_{t\min} \le k_t \le k_{t\max} \qquad t = 1,\cdots,N_\mathrm{T} \tag{11}$$

$$P_{\mathrm{G}i\min} \le P_{\mathrm{G}i} \le P_{\mathrm{G}i\max} \qquad i = 1,\cdots,N_\mathrm{G} \tag{12}$$

$$Q_{\mathrm{G}i\min} \le Q_{\mathrm{G}i} \le Q_{\mathrm{G}i\max} \qquad i = 1,\cdots,N_\mathrm{G} \tag{13}$$

$$Q_{\mathrm{C}i\min} \le Q_{\mathrm{C}i} \le Q_{\mathrm{C}i\max} \qquad i = 1,\cdots,N_\mathrm{C} \tag{14}$$

$$Q_{\mathrm{R}i\min} \le Q_{\mathrm{R}i} \le Q_{\mathrm{R}i\max} \qquad i = 1,\cdots,N_\mathrm{R} \tag{15}$$

$$0 \le C_i \le P_{\mathrm{D}i} \qquad i = 1,\cdots,N_\mathrm{B} \tag{16}$$

$$P_{ij0}(e,f) + \rho_{ij}^{kl} P_{kl0}(e,f)\frac{X_{kl}}{X_{ij}} \le P_{ij\_weak\max} \qquad ij \in S_{\mathrm{L}\_weak} \tag{17}$$

where N_B, N_G, N_C, N_R and N_T respectively represent the number of system buses, number of generator buses, number of shunt capacitor buses, number of shunt reactors buses and number of LTC branches; $S_{\mathrm{L}i}$ and $S_{\mathrm{T}i}$ respectively represent the set of line branches and LTC branches connected to bus i; S_{L_weak} represents the weak branches set. $P_{\mathrm{D}i}$ and $Q_{\mathrm{D}i}$ respectively represent the active and reactive power loads at bus i. C_i represents the active power load curtailment at bus i. The reactive power load curtailment at bus i is assumed to be proportional to C_i with a constant power factor, which is shown in Equation (7). w_i represents the weighting factor reflecting the importance of load at bus i; the magnitudes of the weighting factors only need to be selected in a relative sense. (Note that every weighting factor is set to be 100 in the given examples in Section 4, which indicates equal importance for loads at each bus.)

Equations (6) and (7) respectively represent the equality constraints for the active and reactive power flows. In these equations, $P_{\mathrm{L}ij}(e, f)$,$Q_{\mathrm{L}ij}(e, f)$, $P_{\mathrm{T}ij}(e, f)$ and $Q_{\mathrm{T}ij}(e, f)$, which are quadratic functions of optimal variables e and f, respectively represent the active and reactive powers on line branch ij and LTC branch ij. And their expressions can be referenced to Reference [20]. Equations (8) and (9) respectively represent the voltage conversion relation of LTC branches, which are denoted in Reference [20].

Equations (10)-(16) respectively represent the constraints of the lower limits and upper limits for the voltage magnitudes at each bus, turn ratios of LTC, active power and reactive power outputs of generators, reactive power injections of shunt capacitor and shunt reactors, and active power load curtailments at each bus. Equation (17) is the static voltage stability margin constraints, which have been derived earlier in Equation (4).

The proposed preventive control optimization model has the following three features:

- The model reflects the nonlinear characteristics of power system since it includes not only the nonlinear equality constraints for power flow but also the quadratic constraints for the static voltage stability margin. Therefore, it can overcome the limitations in linear optimization models.
- The number of weak branches of causing static voltage instability is always small in an actual power system. Using the active power constraints of weak branches to represent the static voltage stability margin constraints in the model has greatly reduced the size of the problem to be solved.
- The model is in a purely quadratic form as shown in Equations (5)-(17) which are either linear or quadratic functions of optimal variables. When the interior point method in Reference [20] is used to solve the model, the Hessian matrix is calculated only once in the entire optimization process. This feature, together with the characteristic of the small number of the static voltage stability margin

constraints, makes the model computationally efficient in resolution.

3 Solution of the proposed preventive control

Based on the above preventive control model, the solution steps of the proposed preventive control are as follows:

Step1: initialization of the data

Initially, the iterative times of the proposed preventive control is denoted by K_p and set to be one; the threshold of ELSI is set to be α; the initial state of the power system is assumed to be the normal operating state before the proposed preventive control. According to the initial state, the contingency set includes all N-1 contingencies of branch outages and the normal operating state.

Step2: determination of critical contingencies as well as corresponding weak branches and their transfer capabilities

- The power flow is calculated to obtain the power flow solution for each contingency in the contingency set. For an unsolvable case which possibly results from voltage instability or numeric calculation problem, a minimizing load shedding model similar to that given in Reference [21] is used to restore solvability of power flow. For a solvable case, the power flow can be directly obtained.
- Based on the power flow solution, the ELSI and actual active power of each operating branch are calculated. For some contingency state, if the ELSI of any branch is smaller than α, the contingency is determined to be a critical contingency, and the corresponding branch whose ELSI is smaller than α is determined to be a weak branch.
- According to the ELSI and the actual active power on weak branch in the corresponding critical contingency, the transfer capability of weak branch can be calculated by Equation (1).

Step3: stopping criterion of the proposed preventive control

If there is no weak branch whose ELSI is smaller than α in all contingencies, then stop and output the result of the preventive control. Conversely, turn to Step 4.

Step 4: solution of the proposed preventive control

- According Equation (4), the active power constraints of weak branches in the corresponding critical contingencies are established. And the preventive control optimazation model can be built by Equations (5)-(17). The PCPDIPM is used to solve the optimal model.
- According to the solution of PCPDIPM, change the initial control variables of the power system and the iterative times of the proposed preventive control plus one. Return to Step 2.

4 Simulations

4.1 The basic data of the test systems

The correctness and effectiveness of the proposed preventive control is demonstrated using the simulations for the IEEE 14-bus system and IEEE 118-bus system. The following assumptions are made to ensure that the IEEE 14-bus system case and the IEEE 118-bus system case become possibly to loss static voltage stability in some contingency conditions.

- In the IEEE 14-bus system, the active load at bus 14 is increased to be 53.8MW, and the reactive load is increased with an assumption of a constant power factor. This case is denoted by IEEE14-1.
- In the IEEE 14-bus system, the active load at bus 14 is increased to be 60MW, and the reactive load is increased with an assumption of a constant power factor. This case is denoted by IEEE14-2.
- In the IEEE 118-bus system, the active loads at buses 43, 44 and 45 are respectively increased to be 6MW, 62MW, 140.45MW; and the reactive loads are increased with an assumption of a constant power factor.
- In the normal operating condition and any contingency condition, the threshold α of ELSI is set to be 1.1.

4.2 Results and analysis of simulation

Before the preventive control, the power flow is calculated and the static voltage stability is analyzed in normal operating state and each contingency state of the three test systems. The information of critical contingencies and the corresponding weak branches is shown in Table 1. The maximum transfer capacities of weak branches, which are shown in the fifth column, are determined according to Equation (1). The calculated results indicate the start points for the three test systems are in the insecure operation state since the active powers on weak branches in critical contingencies exceed their maximum transfer capabilities and the ELSI of each weak branch is smaller than 1.1.

Table1. Information of critical contingencies and weak branches before the proposed preventive control

Test system	Critical contingency /weak branch	Active power on weak branch(p.u.)	ELSI of weak branch	The maximum transfer capability of weak branch(p.u.)
IEEE14-1	branch1-2 in outage/branch 1-5	3.2754	1.0535	3.1369
	branch 9-14 in outage / branch 13-14	0.6460	1.0967	0.6441
IEEE14-2	branch 1-2 in outage / branch 1-5	3.4067	1.0363	3.2094
	branch 9-14 in outage / branch 13-14	0.8288	1.0011	0.7543
IEEE118-bus system	branch 34-43 in outage / branch 43-44	0.3793	1.0607	0.3657
	branch 44-45 in outage / branch 43-44	0.6782	1.0499	0.6473
	branch 45-46 in outage / branch 45-49	2.0191	1.0552	1.9369

As mentioned in Introduction, in some nonlinear preventive control models, the power flow equality constraints with load parameter are respectively used as the static voltage stability margin constraints, which has limitation when the preventive control considers multi-contingency conditions. Here, the number of static voltage stability margin constraints in the proposed preventive control model is compared with the static voltage stability margin constraints mentioned above. The result is shown in Table 2. It can be seen that the number of constraints in the proposed model is far smaller than that of power flow equality constraints with load parameter, which can greatly reduce the size of the preventive control problem. This advantage will become more significant for a larger power system.

Table2. Comparison for number of static voltage stability constraints in two preventive control models

Test system	The number of critical contingencies	The number of static voltage stability margin constraints	
		The active power constraints of weak branches	The number of power flow equality constraints with load parameter
IEEE14-1	2	2	56
IEEE14-2	2	2	56
IEEE118-bus system	3	3	708

After the first iteration of the proposed preventive control, the values of control variables are adjusted by the optimization model and the second contingency screening is performed. After the second contingency screening, the information of the critical contingencies and weak branches illustrated in Table 1 is shown in Table 3. It can be seen from Table 3 that the ELSI values of the weak branches become larger than 1.1 and the active powers on the weak branches become lower than their maximum transfer capabilities shown in Table 1. And after the second contingency screening, there is no critical contingency and weak branch for each of the three systems. This suggests that the system becomes secure from an insecure state through the proposed preventive control model since there is no violation from voltage stability.

Table3. Information of critical contingencies and weak branches illustrated in Tab.1 after the first iteration of the proposed preventive control

Test system	Critical contingency /weak branch	Active power on weak branch(p.u.)	ELSI of weak branch
IEEE14-1	branch 1-2 in outage / branch 1-5	3.1335	1.1091
	branch 9-14 in outage / branch 13-14	0.6409	1.1018
IEEE14-2	branch 1-2 in outage / branch 1-5	3.1751	1.1088
	branch 9-14 in outage / branch 13-14	0.6527	1.1001
IEEE118-bus system	branch 34-43 in outage / branch 43-44	0.3624	1.1400
	branch 44-45 in outage / branch 43-44	0.6471	1.3585
	branch 45-46 in outage / branch 45-49	1.8999	1.1979

For the three test systems, the entire preventive control process ends after the first iteration of the proposed preventive control. A few more iterations may be required for other systems. The other results of the entire preventive control for the three test systems are summarized in Table 4. The iteration numbers in the PCPDIPM, active network power loss and load curtailment are also given in Table 4. It can be seen that the load curtailment is not required to ensure the static voltage stability margin in all contingency conditions for both the IEEE 14-1 and IEEE 118-bus system after the proposed preventive control. Whereas it requires 0.0611 MW load curtailment for IEEE14-2 to satisfy the static voltage stability margin in all contingency conditions. This demonstrates the effectiveness and correctness of the proposed preventive control model.

Table4. Result of the entire preventive control process

Test system	Iteration number of PCPDIPM	Network active power loss (p.u.)	Load curtailment (p.u.)
IEEE14-1	15	0.5079	0.0000
IEEE14-2	15	0.5087	0.0611
IEEE118-bus system	12	1.3384	0.0000

4.3 Validating the static voltage stability after the proposed preventive control

A further simulation analysis using the continuation power flow (CPF) method is carried out to validate the correctness and effectiveness of the proposed preventive control. Due to limitation of space, only one contingency case for the IEEE 118-bus system, which is the outage of branch 34-43, is illustrated.

The *P*-*V* curves at bus 43 after the outage of branch 34-43 for the two cases without and with the proposed preventive control are plotted in Fig.1. In the CPF method, the load parameter λ, which represents the distance from the current operating point to the voltage collapse point, is defined as voltage stability margin [7, 13]. The system is assumed to be voltage secure if this margin is greater than a specifically required value which generally is 0.1 in a contingency condition [7, 13]. In this example, "λ=0" denotes the operating point right after the outage of branch 34-43. Point A and point B respectively denote the operating points following the contingency without and with the proposed preventive control. Without the proposed preventive control, the critical value of load parameter λ is 0.0767 following the outage of branch 34-43, which cannot satisfy the desired margin whose value is 0.1 in the contingency condition. Also, the voltage magnitude of bus 43 at the point A is lower than 0.85p.u. and is not allowed in real power system operation. On the other hand, with the proposed preventive control, the critical value of load parameter λ is increased to be 0.1659 which meets the requirement of the desired static voltage stability margin in the contingency condition, and the voltage magnitude of bus 43 at the point B becomes higher than 0.9p.u. and is acceptable in actual real power system. The results in Fig.1 verified that the proposed preventive control model could correctly and effectively bring the system state from an insecure state to a secure state.

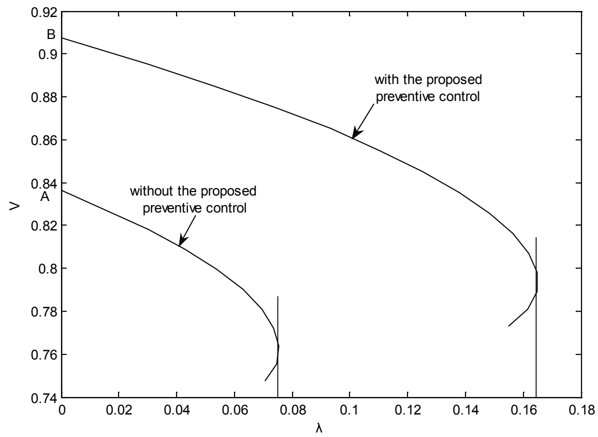

Fig.1. *P*-*V* curves at bus 43 after the outage of branch 34-43

5 Conclusion

Majority of preventive control models for static voltage stability that have been presented so far are based on the linearization assumption. A possible reason is the consideration in computing burdens. This paper proposed a new preventive control optimization model for static voltage stability with three features. Firstly, the proposed model can reflect the nonlinear characteristics of power system and overcome the limitations of linearization models. Secondly, the static voltage stability margin constraints are represented using the active power constraints only on weak branches which can be easily identified by a local voltage stability index. This greatly reduced the number of preventive control constraints since the number of weak branches causing voltage instability is always small in a real power system. Thirdly, the proposed model is expressed in a purely quadratic form which can be efficiently solved using the predictor-corrector primal dual interior method. The second and third features together can significantly reduce computing efforts.

The IEEE 14-bus system and IEEE 118-bus system are used as examples. The correctness and effectiveness of the proposed preventive control model are demonstrated by the simulation results of the test systems and verified by the results obtained from the continuation power flow method.

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