POWER SYSTEM TRANSIENT STABILITY PREVENTIVE CONTROL BASED ON OPTIMAL POWER FLOW

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Abstract – In this paper, a power system transient stability preventive control method is proposed. This method makes full use of the merit of optimal power flow that it harmoniously combine and coordinate security and economy, and this method may reduce the total fuel cost to the lowest point while rescheduling generation to achieve transient stability of the system at the same time. It is established in this paper the structural block diagram of this transient stability preventive control method, along with the core of this method: the mathematical model and solution procedure of transient stability-constrained optimal power flow (TSCOPF). Finally, the validity of the proposed method has been examined by analyzing the preventive control results of a 10-generator model system and a 30-generator model system.

Keywords: power system, preventive control, optimal power flow (OPF), interior point method (IPM), transient stability

1 INTRODUCTION

During recent years, with the ever-increasing demand of electric power, the power system has been growing more and more complicated. Particularly with the deepening of the power system marketing reform, transmission network is required to be open to power stations and consumers, which adds to the difficulty in operating a power system. Under such new circumstances, a power system could no longer be operated in a conservative way, so the significance of power system transient stability preventive control is projecting.

Generation rescheduling is one of the most effective methods for transient stability preventive control. And thanks to the continuous effort of colleagues worldwide, great progress has been made in this field, both theoretically and practically. Generation rescheduling methods already proposed are mainly as follows: method of analytic sensitivity of transient energy[1], method based on technology of artificial intelligence[2], heuristic method[3] and numerical integration method[4]. Noteworthy, analytic sensitivity method based on "extended equal area criterion"[5] has been already applied to the practical projects of control decision, while the validity of the method of "the discretization of the differential-algebraic equations"[6] has been examined in practical power systems.

Reference [1] to [5] all focus on how to achieve stable operating condition of power system by means of preventive control, while do not pay enough attention to the economy viewpoint. Theoretically, both security and economy should be considered altogether in the process of shifting the initial operating point to the new operating point within the stable region. Thus, the final operating point achieved may be the most economically favorable operating point within the stable region. This method also reflects the shift from the safety-come-first principle in the conventional circumstances of monopoly management to the requirement of harmoniously combining and coordinating security and economy in the new circumstances of power system marketing mechanism. Reference [6] sets minimizing the total fuel cost after active generation rescheduling as its optimal target, and realizes economical operating of power system while ensuring security and reliability of operating at the same time. However, that method falls short in that it only takes one single contingency into account. Actually, measures taken to improve power system's stability under a certain kind of contingency may have dramatic impact on stability of the same system under other kinds of contingencies. Therefore, to apprehend the most favorable operating point concerning both economy and security, all the possible contingencies should be taken into consideration.

The above analysis demonstrates that in order to ensure power network security under the circumstances of power marketing mechanism, a higher requirement to the transient stability preventive control is raised: to perform an overall optimum concerning both economy and security, with all the possible contingencies taken into consideration at the same time. To achieve such a goal, transient stability-constrained optimal power flow (TSCOPF) serves as an ideal tool. Reference [7] originates the idea of TSCOPF, and establishes a mathematical model of it, and also offers a successive nonlinear programming method to solve TSCOPF. Reference [8] further develops TSCOPF by establishing a mathematical model which considers multiple contingencies, and it also brings forward the interior point nonlinear programming method to solve TSCOPF.

On the basis of the former research on TSCOPF which is illustrated in reference [8], this paper brings forward a new method based on transient stability-constrained optimal power flow in performing power system transient stability preventive control. The detailed procedure of this method is elaborated on in this paper, while the validity of this method is also examined by solving a 10-generator model system and a 30-generator model system.

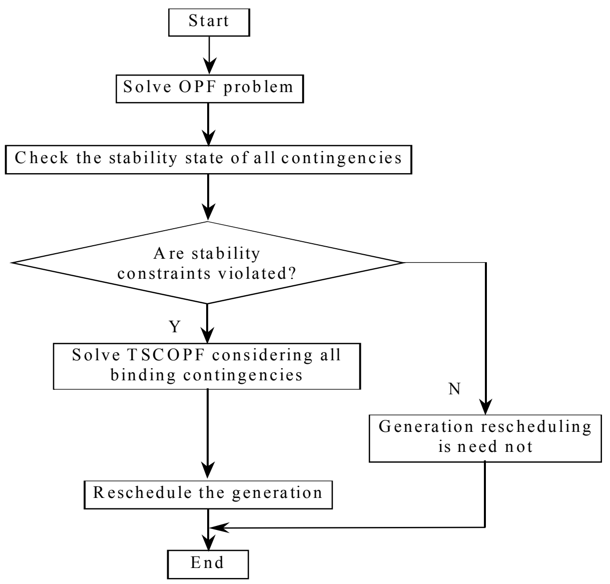

Figure 1: Overall procedure of transient stability preventive control based on OPF.

2 PROCEDURE OF TRANSIENT STABILITY PREVENTIVE CONTROL

First let us distinguish two different definitions: OPF and TSCOPF. OPF is related to optimal power flow without considering transient stability constraints, while TSCOPF refers to optimal power flow with transient stability constraints taken into consideration.

It is illustrated in Figure 1 the process of transient stability preventive control based on OPF. Given the economy of operating power system, it is assumed in this paper that the initial operating point of the system before generation rescheduling is based on the optimal result of OPF. Therefore, the solution procedure of our method may be described concisely by the following steps:

Step 1: Solving a standard OPF problem. Various methods may be adopted to complete this step, and in this paper, we have chosen the interior point nonlinear programming method to solve OPF problem, the same as we choose in solving a TSCOPF problem.

Step 2: Check to see if the solution of the OPF respects stability constraints for all contingencies. These contingencies may be determined in the contingency screening segment, while the stability state can be examined through method of numerical integration.

Step 3: If the system remain stable under all contingencies, it would be obvious that the operating point of the system is already within the stable region, and it is the most economically favorable operating point within the stable region. In that case, generation rescheduling is not necessary at all. In other cases, move on and carry out Step 4 to Step 5.

Step 4: Solving a TSCOPF problem which considers all of the binding contingencies. This step is the key part in the whole procedure of transient stability preventive control.

Step 5: Rescheduling generation in accordance with the optimal solution of TSCOPF. The adjustments of active generation need to be decreased (-) / increased (+) for every machine are given by:

$$\Delta P_i = P_{iTSCOPF} - P_{iOPF} \quad (i \in S_{\mathrm{G}}) \tag{1}$$

where S_{G} is set of generators.

3 MATHEMATICAL MODEL AND SOLUTION ALGORITHM OF TRANSIENT STABILITY PREVENTIVE CONTROL

As is depicted in Figure 1, to perform transient stability preventive control based on optimal power flow, an OPF problem and a TSCOPF problem are to be solved. What need to be pointed out is that the mathematical model of TSCOPF is based on the model of OPF, with equality constraints and inequality constraints added in.

3.1 Mathematical Model of OPF

An OPF problem is a constrained nonlinear programming problem. And a standard OPF problem may be formulated as follows:

$$\begin{cases} \min \quad F \\ \text{s.t.} \quad \boldsymbol{H}_{\mathrm{pf}} = \boldsymbol{0} \\ \qquad \underline{\boldsymbol{G}}_{\mathrm{opf}} \le \boldsymbol{G}_{\mathrm{opf}} \le \overline{\boldsymbol{G}}_{\mathrm{opf}} \end{cases} \tag{2}$$

where F is a objective function, which in this paper refers to total fuel cost; H_{pf} are power flow equations; G_{opf} refers to inequality constraints, with $\overline{G}_{\mathrm{opf}}$ and $\underline{G}_{\mathrm{opf}}$ being its upper and lower limits respectively.

3.2 Mathematical Model of TSCOPF

A multi-contingency TSCOPF problem may be formulated as follows:

$$\begin{cases} \min \quad F \\ \text{s. t.} \quad \boldsymbol{H}_{\mathrm{pf}} = \boldsymbol{0}\ ,\ \boldsymbol{H}_{\mathrm{iv}} = \boldsymbol{0}\ ,\ \boldsymbol{H}_{\mathrm{s}}(k) = \boldsymbol{0} \\ \qquad \underline{\boldsymbol{G}}_{\mathrm{opf}} \le \boldsymbol{G}_{\mathrm{opf}} \le \overline{\boldsymbol{G}}_{\mathrm{opf}} \\ \qquad \underline{\boldsymbol{G}}_{\mathrm{s}} \le \boldsymbol{G}_{\mathrm{s}}(k) \le \overline{\boldsymbol{G}}_{\mathrm{s}} \\ \qquad k \in S_{\mathrm{K}} \end{cases} \tag{3}$$

where H_{iv} are initial-value equations; H_{s} are swing equations undergone discretization treatment; G_{s} refers to transient stability constraints; S_{K} is set of contingencies.

Transient stability for various contingency conditions is ensured by introducing a suitable criterion. For TSCOPF study, it is convenient to apply the criterion using rotor angles with respect to center of inertia (COI): *For a system to be stable, rotor angles with respect to COI should not be greater than a threshold (like 100 degrees) during the transient duration.* Transient stability constraints G_s may be formulated as follows:

$$\begin{cases} \underline{\delta} \le \delta_i - \delta_{\mathrm{COI}} \le \overline{\delta} \quad (i \in S_{\mathrm{G}}) \\ \delta_{\mathrm{COI}} = \sum_{i \in S_{\mathrm{G}}} (M_i \delta_i) \Big/ \sum_{i \in S_{\mathrm{G}}} M_i \end{cases} \tag{4}$$

where δ_i is the rotor angle of i-*th* generator, with $\overline{\delta}$ and $\underline{\delta}$ being its upper and lower limits respectively; M_i refers to moment of inertia of i-*th* generator; δ_{COI} is the angle of the center of inertia (COI) in the system.

3.3 Solution Algorithm

An OPF problem is a large-scale nonlinear programming problem, while a TSCOPF problem has an even larger scale. Solutions to those problems not only depend on quick and effective optimization algorithm, but also have to fulfill rigid requirement in realizing the algorithm, thus the workload of programming is huge.

In this paper, interior point nonlinear programming method is adopted to solve OPF problems and TSCOPF problems. The major merit of this method lies on its light calculation workload and its favorable convergence property. Details of the method can be reached by referring reference [9].

To enhance calculating rate, sequencing of the correction equations should be properly arranged in realizing the method, while a suitable data structure should be carefully chosen. Both reference [10] and [8] have adopted the interior point nonlinear programming method, the former analyses the problem related to data structure when solving a OPF problem, while the latter discusses the problem about proper arrangement of the correction equations when solving a TSCOPF problem. Results of both references are applied to the transient stability preventive control method brought forward in this paper.

Noteworthy, although methods adopted to solve an OPF problem and a TSCOPF problem are identical, distinct difference exists between them regarding to modeling methods, due to the fact that an OPF problem involves only algebraic equations while a TSCOPF problem involves algebraic-differential equations. Moreover, it is much more difficult to solve a TSCOPF problems, compared with an OPF problem.

4 VERIFICATION OF TSCOPF PROGRAM

The TSCOPF problem is a large-scale nonlinear programming problem and the question about how to verify the validity of the solution is of great significance. Based upon a well-tested OPF program, writing in FORTRAN by the Power System Laboratory of Hiroshima University (http://www.psl.sys.hiroshima-u.ac.jp), we implemented a TSCOPF program. To test the validity of the mathematical model, the algorithm and the program, we have designed a verification procedure as follows: From the TSCOPF solution of our proposed method, besides achieving the optimal operating point, as a byproduct we also can obtain the swing curves of all machines, and we call them dynamic responses (A). Assigning the achieved optimal operating point as the initial operating point, we perform a transient stability analysis by adopting a CRIEPI's (Central Research Institute of Electric Power Industry, Japan) program to the same chosen model systems, under the same circumstances. The results of this program are the swing curves of all machines, and we call them dynamic responses (B). Then compare the dynamic responses (A) with the dynamic responses (B) to check their coincidence. If the result shows that they are the same, it would be convincing to confirm that the TSCOPF solution is right. Otherwise, the TSCOPF solution may not hold water. Factually, the result of our test demonstrates the coincidence of the two dynamic responses, so that the validity of our proposed method is successfully verified. Figure 2 illustrates this process.

Furthermore, it should be noted that, as all the contingencies are considered at the same time, the sequence of contingency constraints does not affect the solution result. This algorithm will converge to the optimal solution no matter what the sequence of contingency constraints is.

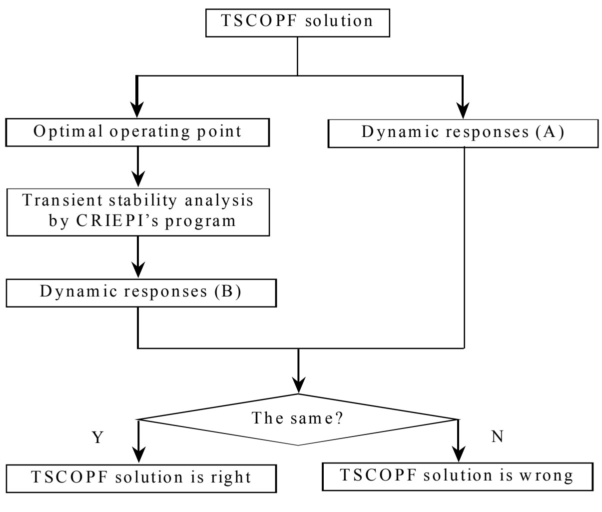

Figure 2: Verification of TSCOPF program.

5 ANALYSIS OF EXAMPLES

This section demonstrates the validity of transient stability preventive control method brought forward in this paper, by analyzing the optimal preventive control results of two test systems. Meanwhile, in order to make it easy to crosscheck the solution with solutions achieved through other different methods by other colleagues, we have adopted two standard model systems from IEEJ for our examples: the IEEJ-WEST10 system and the IEEJ-WEST30 system. The system diagrams and all parameters of both model systems are open to public which can be reached from the website of IEEJ: http: // www.iee.or.jp/pes/model/.

Before concretely analyzing the solution, an instruction to the composition of the adopted model systems is given firstly as follows:

(1) Structured by IEEJ, the 10-generator model system and the 30-generator model system adopted in this paper are two standard systems specific to 60Hz power network of Japan. The 10-generator model system is made up of 10 generators, 27 buses and 42 transmission lines; while the 30-generator model system is made up of 30 generators, 115 buses and 129 transmission lines. Connecting diagrams and related variables can be reached by referring the documentation [11].

(2) According to the operating experience in practical systems, IEEJ has defined fault positions specific to the two model systems respectively which should be considered when performing stability analysis. And those fault positions are marked out in the system diagram[11]. In the following examples, set of contingencies is made up of those fault positions defined by IEEJ, rather than determined through the contingency screening segment. 8 contingencies are considered in the 10-generator model system (A to H), while 6 are considered in the 30-generator model system (A to F).

(3) Contingencies are permanent three-phase-to-ground fault occurred at one of the two-circuit lines, which last for 70 ms.

(4) $\overline{\delta}$ and $\underline{\delta}$ in formula (4) are assigned +100º and -100º respectively.

5.1 Solution Analysis of Preventive Control of the 10-generator Model System

For the convenience to illustrate the proposed method, in the following we will explain the test results step-by-step in the same solution sequence as is expressed in section 2:

(1) A standard OPF problem is solved. The initial operating point before generation rescheduling is determined by the optimal result of OPF. Table 1 gives the total fuel cost and Table 2 shows active generations for respective generators before rescheduling.

(2) At the initial operating point before generation rescheduling, the stability level of the system is low, and there are 5 binding contingencies: A, B, C, D and H, as can be seen in Table 1. Power system stability analyzing program from CRIEPI is adopted to judge stability state in this paper.

(3) As there exists unstable contingencies, transient stability preventive control must be carried out to introduce the operating point into the stable region.

(4) A TSCOPF problem with binding contingencies A, B, C, D and H is solved, and the new operating point after generation rescheduling is determined by the optimal result of TSCOPF. Table 1 and Table 2 show the total fuel cost and active generation for generators after rescheduling generation.

(5) Reschedule generation, and the operating point of the system is shifted from the initial operating point to the new one. The adjustments of generation needed for every generator is given by formula (1).

Sequence of contingencies	Stability state of contingencies	
	Before rescheduling	After rescheduling
A	unstable	stable
B	unstable	stable
C	unstable	stable
D	unstable	stable
E	stable	stable
F	stable	stable
G	stable	stable
H	unstable	stable
Total fuel cost / thousand yens	222775	226515
Δ total fuel cost / thousand yens	+3740	

Table 1: Stability state of contingencies before and after generation rescheduling and the total fuel cost in the 10-generator model system.

Generators	Active generation before rescheduling (pu)	Active generation after rescheduling (pu)	Adjustments of active generation (pu)
G1	10.470	8.505	-1.965
G2	7.169	7.575	+0.406
G3	9.000	7.943	-1.057
G4	2.069	1.920	-0.149
G5	5.561	7.597	+2.036
G6	6.842	8.171	+1.329
G7	7.292	6.598	-0.694
G8	4.500	4.500	0.000
G9	9.000	8.797	-0.203
G10	13.869	14.101	+0.232

Table 2: Active generation of generators respectively before and after generation rescheduling in the 10-generator model system.

To test the stability state after generation rescheduling, this paper has adopted the stability analyzing program from CRIEPI. The test result is shown in Table 1, demonstrating that after generation rescheduling, the system maintain its stability under all contingencies. It is obvious that generation rescheduling with this method has dramatically improved the stability of the system, and may receive satisfying preventive control result.

As is stated before, the best merit of the transient stability preventive control method based on OPF is that the new operating point after generation rescheduling is the most economically favorable operating point within the stable region. However, compared to the total fuel cost before rescheduling, the cost becomes higher, as can be seen in Table 1. And this result also reflects the fact that economy and security is a pair of contradiction, while improving stability level is always at the cost of sacrificing economy.

5.2 *Solution Analysis of Preventive Control of the 30-generator Model System*

In order to test the validity of the transient stability preventive control method proposed in this paper on systems of larger scales, we adopt a 30-generator model system to solve and analyze. The test result is shown in Table 3 and Table 4.

Set of contingencies of the 30-generator model system is composed of 6 contingencies. At the initial operating point before generation rescheduling, there exists 4 binding contingencies: A, B, C and D. Through solving the TSCOPF problem with above 4 binding contingencies, we may achieve a new operating point after generation rescheduling. It is shown by the stability analysis test that: after generation rescheduling, stability level of the system is dramatically improved, the system remains stable after all the contingencies at the new operating point. Likewise, improvement of the system's stability level is also achieved at the cost of economy. Therefore, after generation rescheduling, the production cost of the system is increased.

Sequence of contingencies	Stability state of contingencies	
	Before rescheduling	After rescheduling
A	unstable	stable
B	unstable	stable
C	unstable	stable
D	unstable	stable
E	stable	stable
F	stable	stable
Total fuel cost / thousand yens	178636	179742
Δ total fuel cost / thousand yens	+1106	

Table 3: Stability state of contingencies before and after generation rescheduling and the total fuel cost in the 30-generator model system.

6 CONCLUSIONS AND FUTURE WORK

In this paper, a new power system transient stability preventive control method based on OPF is proposed. Transient stability constrained optimal power flow (TSCOPF) being its tools, this method is to achieve the most economically point within the stable region, so as to realize the harmonious coordination and combination of economy and security when operating power system. This paper illustrates the detailed procedure of the proposed transient stability preventive control method, and it also offers the related mathematical model and solution procedure. In the final part of this paper, we analyze respectively the preventive control results of a 10-generator model system and a 30-generator model system, both of which adopt the proposed preventive control method. And the test results have justified the validity of this proposed method.

For future work, larger test systems with more stability constraints will be tested to show how this methodology can work in practical large size networks.

Generators	Active generation before rescheduling (pu)	Active generation after rescheduling (pu)	Adjustments of active generation (pu)
G1	8.500	8.398	-0.102
G2	4.700	4.700	0.000
G3	0.577	0.480	-0.097
G4	1.442	0.585	-0.857
G5	0.452	0.452	0.000
G6	0.858	0.944	+0.086
G7	0.630	0.669	+0.039
G8	2.300	2.300	0.000
G9	2.782	3.083	+0.301
G10	4.569	4.471	-0.098
G11	1.140	1.140	0.000
G12	2.651	3.580	+0.929
G13	4.320	5.153	+0.833
G14	2.300	2.300	0.000
G15	3.817	3.209	-0.608
G16	3.500	3.500	0.000
G17	0.880	1.578	+0.698
G18	3.400	2.569	-0.831
G19	1.410	1.234	-0.176
G20	3.684	3.822	+0.138
G21	1.272	0.875	-0.397
G22	1.042	1.597	+0.555
G23	2.467	2.245	-0.222
G24	0.750	0.750	0.000
G25	0.450	0.450	0.000
G26	0.585	0.585	0.000
G27	0.720	0.653	-0.067
G28	1.805	1.692	-0.113
G29	1.154	1.063	-0.091
G30	2.800	2.800	0.000

Table 4: Active generation of generators respectively before and after generation rescheduling in the 30-generator model system.

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BIOGRAPHIES

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