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Optimization of Transient Stability Control Part-II: For Cases with Different Unstable Modes

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Abstract: Part-I of this two-part paper develops an optimal algorithm for transient stability control to coordinate the preventive actions and emergency actions for a subset of contingencies with an identical unstable mode. In this portion, several subsets of contingencies having dissimilar unstable modes are dealt with. Preventive actions benefiting a subset of contingencies may go against the stability of others, thus coordination among the optimal schemes for individual subsets is necessary. The coordination can be achieved by replacing some preventive actions with contingency-specified emergency actions. It is formulated as a classical model of economic dispatch with stability constraints and stability control costs. Such an optimal algorithm is proposed based on the algorithm in Part-I of the paper and is verified by simulations on a Chinese power system.

Keywords: Extended equal area criterion (EEAC), nonlinear mixed programming, optimization, power systems, transient stability control.

1. INTRODUCTION

In comparing the coordination between preventive control (PC) and corrective control for static securities [1,2], the coordination between PC and emergency control (EC) for transient stability control (TSC) is a relatively new area of research [3,4]. The unstable mode (UM) is a very important concept used to characterize the system separation. If a TSC action enhances the stability of a UM, it may further the instability of other UMs. UM identification is the key for (1) decoupling all the contingencies into subsets, each of which is characterized by a unique UM; (2) selecting the search direction; and (3) coordinating the conflicts among the PC actions.

Many efforts have been engaged in developing sensitivity analysis for estimating stability limits and designing TSC [5-7] with some success. The extended equal area criterion (EEAC) is a rigorous quantitative method, which can quickly assess stability limits via sensitivity analysis and identify the UM [8]. This provides a solid foundation for optimal TSC. If the original operating point $\mathbf{X}_0$ is unstable for some contingencies, PC may be activated prior to any contingency occurrence in order to move the system to a target point $\mathbf{X}_T$. If $\mathbf{X}_T$ is still insecure, the relevant EC should be activated immediately just after detecting an unstable contingency.

Xue [3] proposed a general optimization framework for coordinating PC and EC, where the task is formulated as a nonlinear hybrid-programming problem with both integer and continuous variables and with numerous stability constraints. The objective function is the sum of the daily cost for PC and the possibility-weighted cost for EC. Related ideas have been presented by Hill et al. for network control of voltage profile and stability [4]. Based on the formulation in [3], Xue, Li and Hill [9] developed an optimal PC+EC algorithm for a subset of contingencies with an identical UM. It firstly identifies the credible harmful contingencies and divides them into subsets according to their UMs. The contingencies in such a subset are relative to an identical set of critical machines, therefore, a certain action has the same tendency to influence these contingencies, and PC and EC actions can be optimized for the subset.

However, subsets with different UMs may have opposite responses to the identical control action. Therefore, additional coordination among the optimal schemes for the individual subsets is required. This paper presents an optimal TSC algorithm for

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accomplishing this task and shows its effectiveness with simulations on a Chinese power system.

2. LOCALLY OPTIMAL TSC VS GLOBALLY OPTIMAL TSC

An unstable system always separates into a cluster of critical machines (cluster-S) and that of non-critical machines (cluster-A).

According to EEAC theory, a control action on the cluster-A affects the stability in a way opposite to the way when this action is put on the cluster-S. If a generator belongs to cluster-S of one subset of contingencies, and at the same time belongs to cluster-A of another subset, any action applied to this generator would place contrary effects on the two subsets.

An EC action, such as fast-valving, generator tripping, load shedding and dynamic braking, is contingency specified. It is activated only if the relevant contingency has been detected. The harmful effects of an activated EC action don't appear if no relevant contingency occurs during the same time period. Since EC actions for different contingencies are activated at different occasions, their conflicts don't occur in practice.

In contrast, no matter whether and what contingency occurs, a PC action should be activated in advance. Its cost is contingency independent and has to be paid all along. Generation rescheduling is a typical PC action, which shifts some generation power from the critical machines to the non-critical ones according to the objective UM. It is helpful for stabilizing a subset to reduce the generation related to its UM, however, it may impair the stability of other UMs.

The proposed TSC optimization procedure includes two steps: the first step is the local coordination for each subset respectively; the second one is the global coordination among the locally optimal TSC schemes.

For locally optimal TSC, the concerned contingencies react to a PC action in the same qualitative way, with differences only in their extents. There is no conflict caused in the generation rescheduling, but rather some adjustment between PCs and ECs.

For globally optimal TSC, however, the actual generation rescheduling pattern is identical for all subsets, and it may introduce negative effects to some subsets while improving others. This will cause insufficient control for some contingencies and require additional EC actions to account for it.

3. THE MODEL OF OPTIMAL TSC FOR CONTINGENCIES WITH VARIOUS UMS

The locally optimal PC+EC model proposed in [9] is modified to consider m different subsets as follows.

$$\min c(\mathbf{x}_\mathrm{T}) = \min \sum_{k=1}^{\mathrm{m}} (c_{\mathrm{PC}.k}(\mathbf{x}_\mathrm{T}) + c_{\mathrm{EC.k}}(\mathbf{x}_\mathrm{T}, \mathbf{e}_k)) \qquad (1)$$

$$= \min \sum_{k=1}^{\mathrm{m}} (c_{\mathrm{PC}.k}(\mathbf{x}_\mathrm{T}) + \sum_{i=1}^{\mathrm{n_k}} \alpha_i c_{\mathrm{EC}i}(\mathbf{x}_\mathrm{T}, \mathbf{e}_i)),$$

$$s.t. \quad \mathbf{g}(\mathbf{x}_\mathrm{T}) = \mathbf{0}, \qquad (2)$$

$$\mathbf{h}(\mathbf{x}_\mathrm{T}, \mathbf{e}) \geq \mathbf{0}, \qquad (3)$$

where m is the number of the contingency subsets, each of which has a unique UM; n_K is the total amount of contingencies in the k-th subset; C (or C_{PC}) is the total TSC (or PC) cost for an interested time interval; C_{EC} (or $C_{\mathrm{EC}i}$) is the total cost for EC actions $\mathbf{e}$ (or the cost of $\mathbf{e}_i$ for contingency-i); α_i is the expected number of times of the contingency-i during the assessing time interval; $\mathbf{X}_\mathrm{T}$ is a target point resulting from PC actions.

(2) represents load flow constraints etc. Inequality (3) represents various security constraints including transient stability. $C_{ECi}(\mathbf{X_T})$ is the solution of the following sub-problem:

$$\min_e c_{\mathrm{EC}i}(\mathbf{e}_i(\mathbf{x}_\mathrm{T})), \qquad (4)$$

$$s.t. \quad \mathbf{f}(\mathbf{e}) \geq \mathbf{0}, \qquad (5)$$

$$\lambda_i(\mathbf{x}_\mathrm{T}, \mathbf{e}_i) \geq \mathbf{0}. \qquad (6)$$

Inequality (5) represents capacity constraints of the emergency actions: the accumulative quantity of every sort action cannot exceed its maximum value; the total value of exclusive actions cannot exceed the relevant maximum value. Inequality (6) ensures that the system security has a positive margin for every pre-assigned contingency.

4. GLOBALLY OPTIMAL TSC

4.1. Mechanism for resolving PC conflicts

A two-cluster system is described by:

$$M_s\ddot{\delta}_s = P_{ms}(t) - P_{es}(\delta, t),$$

$$M_a\ddot{\delta}_a = P_{ma}(t) - P_{ea}(\delta, t),$$

where $\delta = \delta_s - \delta_a$. The dynamic equation of δ is

$$\ddot{\delta} = (P_{ms}/M_s - P_{ma}/M_a) - (P_{es}/M_s - P_{ea}/M_a)$$

$$= P_m - P_e.$$

With a control, it becomes:

$$\ddot{\delta}' = (P'_{ms}/M'_s - P'_{ma}/M'_a) - (P'_{es}/M'_s - P'_{ea}/M'_a)$$

$$= P'_m - P'_e.$$

The stability margin changes from

$$\eta = \int_{\delta_o}^{\delta_{DSP}} (P_e - P_m) d\delta \quad \text{to}$$

$$\eta' = \int_{\delta_o}^{\delta'_{DSP}} (P'_e - P'_m) d\delta.$$

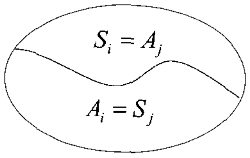

Fig. 1. A case with two complementary Ums.

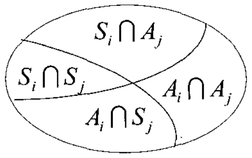

Fig. 2. A general case.

This means that a control action putting on cluster-S has an effect on stability opposite to the same item acting on cluster-A. Moreover, any over-control is not only uneconomical, but also harmful for other UMs.

Fig. 1 is an extreme case, where the cluster-S of UM-i is just the cluster-A of UM-j. In such a case, conflicts in TSC are unavoidable. Fig. 2 provides a more general case.

If rescheduling generation from S_i to A_i is used as a PC action to improve the stability of UM-i, four cases are possible: (1) Shifting from $S_i \cap S_j$ to $A_i \cap A_j$; it improves both UM-i and UM-j; (2) Shifting from $S_i \cap S_j$ to $A_i \cap S_j$ or (3) Shifting from $S_i \cap A_j$ to $A_i \cap A_j$; it improves UM-i but almost has no influence on UM-j; (4) Shifting from $S_i \cap A_j$ to $A_i \cap S_j$; it improves UM-i, but harms UM-j.

For a case where both UM-i and UM-j need PC actions, if the available capacity of $A_i \cap A_j$ or the reducible capacity of $S_i \cap S_j$ is large enough, conflicts can be avoided; otherwise, additional EC actions must be properly introduced to solve the conflicts.

4.2. Pictorial explanation

Sterling et al. discovered the conflicts between PC actions required by different contingencies. They suggested that knowledge concerning the likelihood and severity of these contingencies could be used to solve the conflicts, however no details were given [5].

In the objective function of the optimal TSC model, namely equation (1), α_i represents the likelihood of contingency i, while $C_{EC.i}$ is the indication of its severity. The product of $\alpha_i C_{EC.i}$ well reflects the risk of contingency i. The global TSC optimization can be considered as a task of economic dispatch.

The costs mainly consist of two parts: (1) the generation costs related to the rescheduling; and (2) the cost of EC actions.

The TSC cost curve of each subset of contingencies described in [9] can be regarded as the generation cost curve in economic dispatch.

Figs. 3 and 4 present such an example of two contingencies with $S_i \cap S_j = \Phi$, where Φ is an empty set. P_i denotes the change in generation from cluster-S of UM-i into its cluster-A. A negative P_i means a generation shifting from cluster-A of UM-i into its cluster-S.

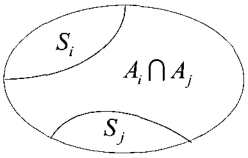

Fig. 3. A case with $S_i \cap S_j = \Phi$.

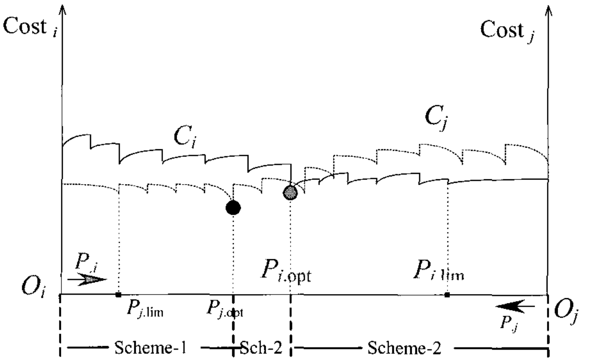

Fig. 4. Pictorial explanation of the global coordination for two contingencies of different Ums.

For the convenience of explanation, the original economic operating point is labeled as O_i (or O_j) for i (or j). $P_{i.lim}$ (or $P_{j.lim}$) represents the minimum generation shifting to stabilize contingency i (or j). The amount of generation capacity between O_i and O_j is the maximum increasable generation of $A_i \cap A_j$, labeled as $P_{ij.\max} = \overline{O_i O_j}$. If $P_{i.lim}+P_{j.lim}<P_{ij.max}$, the system can be stabilized with pure PC actions; otherwise, additional EC actions are necessary.

The two sawtooth curves represent the TSC cost for contingency i and j respectively. $P_{i.opt}$ (or $P_{j.opt}$) is the generation shifting of the locally optimal TSC scheme for contingency i (or j).

If $P_{i.\text{opt}} + P_{j.\text{opt}} \le P_{ij.\max}$, there is no conflict between the two locally optimal schemes, otherwise additional EC actions have to be applied to compensate the insufficient stability.

4.3. Solution model for the example

The above framework is quite general; although the real world problems are usually very complicated.

(1) Objective function

The objective function is the total TSC cost for contingencies i and j,

$$\min\ (C_i + C_j), \tag{7}$$

where C_i, (or C_j) denotes the TSC cost for i (or j).

(2) Constraints

Constraint-1: Bound of the total generation shifting

$$-P_{ij.o} \le P_i + P_j \le P_{ij.\max}, \tag{8}$$

where $P_{ij.o}$ is the original economic generation in $A_i \cap A_j$, while $P_{ij.\max}$ represents the maximum amount of increasable generation in $A_i \cap A_j$.

Constraint-2: Bounds of the generation of i and j

$$\max(-P_{\mathrm{A}i.\mathrm{o}}, -P_{\mathrm{S}i.\max}) \le P_i \le \min(P_{\mathrm{S}i.\mathrm{o}}, P_{\mathrm{A}i.\max}), \quad (9)$$

$$\max(-P_{\mathrm{A}j.\mathrm{o}}, -P_{\mathrm{S}j.\max}) \le P_j \le \min(P_{\mathrm{S}j.\mathrm{o}}, P_{\mathrm{A}j.\max}), \quad (10)$$

where $P_{Sj.\max}$ (or $P_{Sj.\max}$) is the maximum increasable generation in cluster-S of i (or j); $P_{Ai.\max}$ (or $P_{Ai.\max}$) is that in cluster-A; $P_{Si.\mathrm{o}}$ (or $P_{Sj.\mathrm{o}}$) is the actual generation in cluster-S of i (or j); $P_{Ai.\mathrm{o}}$ (or $P_{Aj.\mathrm{o}}$) is that of cluster-A.

For contingency i, the generation shifting, P_i, from its cluster-S to cluster-A should be smaller than the maximum increasable generation in cluster-A as well as the actual generation of cluster-S. Simultaneously, the generation shifting from cluster-A to cluster-S ($-P_i > 0$), should be larger than the maximum increasable generation in cluster-S as well as the actual generation of cluster-A.

For the extreme case in Fig. 1, the coordination model is just a special case with $P_i + P_j = 0$.

4.4. Recursion

The case in Fig. 3 is taken to demonstrate the global coordination algorithm. The range of P_{ij} is divided into three sections by $P_{i.\mathrm{opt}}$ and $P_{j.\mathrm{opt}}$ as shown in Fig. 4. Accordingly, three TSC schemes can be arranged as the candidates of the globally optimal solution. Each of them is characterized by the shifting generation of cluster-S_i, that of cluster-S_j, EC actions for i and EC actions for j.

Located in the left section, scheme-1 is characterized by the locally optimal scheme $P_{j.\mathrm{opt}}$ for contingency j and the lowest cost solution within the section for contingency i.

Scheme-2 is inside the right section and consists of the locally optimal scheme $P_{i.\mathrm{opt}}$ for contingency i and the lowest cost solution within the section for contingency j.

Scheme-3 ranges within the middle section ($P_{j.\mathrm{opt}}$, $P_{i.\mathrm{opt}}$). It consists of the lowest cost solution within (P_{ij}-$P_{j.\mathrm{opt}}$, Pi.opt) for contingency i and the lowest cost solution within (P_{ij}-$P_{i.\mathrm{opt}}$, $P_{j.\mathrm{opt}}$) for contingency j.

The globally optimal scheme is the one with the minimum cost among the three. Both schemes 1 and 2 can be obtained with the optimization in [9].

The task of solving scheme 3 is similar to the original task, with the searching range changing from (O_i, O_j) to ($P_{j.opt}$, $P_{i.opt}$). This is a recursive procedure until there is no TSC conflict, or the searching range is small enough.

4.5. General procedure

An effective optimization algorithm is needed to realize the global TSC coordination.

(1) Contingency filtering and decomposition. Screening the contingencies to identify unstable ones and their UMs, then classifying them into subsets according to their UMs.

(2) Local TSC coordination. Performing locally optimal TSC for each subset of contingencies respectively as proposed in [9].

(3) Conflicts identification. Analyzing the relationships between these schemes and justifying whether conflicts exist or not. If not, directly taking the locally optimal TSC schemes as the globally optimal TSC scheme, otherwise proceeding to the next step.

(4) Global TSC coordination.

5. SIMULATIONS

The test system is derived from an actual Chinese power grid, which is modeled with 75 generators, 730 buses and 2 external DC equivalent buses.

Without losing generality, two harmful contingencies i and j, as shown in Fig. 2 are considered. The available backup generation capacity of the common non-critical machines of the two contingencies is 227 MW.

Focusing on the optimization algorithm itself, the cost for each action is set as constant hereafter. By changing these constants, 8 test cases are arranged just based on a unique $\mathbf{X}_0$ in order to evaluate the proposed searching algorithm. While the cost constant of every EC action changes with individual cases, those of PC actions are identical for the 8 cases.

Table 1 presents the simulation results of the PC+EC scheme, pure EC (optical) scheme and pure PC (optical) scheme. ΔP is the solution of rescheduling generation, which is 0 for pure EC schemes. For all pure PC schemes, 273MW generation has to be shifted from its critical machines to non-critical ones for contingency i and 220MW for contingency j. Since their total value of 493 exceeds 227, causing pure PC schemes to be infeasible, EC actions are necessary.

The proposed optimal PC + EC scheme in case-1 is

Table 1. Comparison of various TSC schemes.

Case	PC+ EC		Pure EC	Pure PC
	ΔP(MW)	Cost	Cost	ΔP
1	206	426	550	Infeasible
2	222	422	525	
3	127	402	475	
4	206	411	525	
5	118	293	375	
6	23	273	325	
7	102	282	375	
8	222	412	525	

illustrated hereafter in detail. The shifting power for contingency i (or j) is 104MW (or 185MW). The sum of 104 and 185 is larger than 227, so PC actions for the two contingencies conflict, and coordination with EC actions is unavoidable. The first iteration gives three schemes as follows.

S-1 consists of: (a) the optimal scheme of contingency i, whose schedulable power ranges in the interval of (0, 227) and whose {real shifting power, cost} is {104, 229}; and (b) the optimal scheme of contingency j, whose schedulable power ranges in the interval of (0, 123) and whose {real shifting power, cost} is {97, 202}. Thus, S-1 is {201, 431}.

S-2 consists of {21, 236} for i, and {185, 190} for j, i.e. S-2 is {206, 426}.

S-3 consists of {49, 239} for i, and {176, 196} for j, i.e. S-3 is {225, 435}.

Obviously, S-2 has the minimum cost among the three schemes, therefore {206, 426} is the globally optimal TSC scheme for the system. All three schemes are more economical than the pure EC scheme with a cost of 550.

In all 8 cases, the cost saving of the proposed PC+EC scheme with respect to the pure EC schemes ranges from 18% to 33%, which fully validates the feasibility and effectiveness of the proposed algorithm.

6. CONCLUSIONS

The globally optimal TSC algorithm has two layers: (1) the lower layer, which coordinates the PC and EC actions for each subset of contingencies with an identical UM respectively; and (2) the upper layer, which coordinates the resultant locally optimal schemes selected by the lower layer.

If there is insufficient shift-able generation capacity for PC actions required by the locally optimal schemes, PC conflicts may occur in the upper layer. Thus, additional EC actions must be optimally arranged for some contingencies to compensate for the insufficient control resulting from the PC conflicts. This is formulated in this paper as an economic dispatch model with additional EC costs due to stability constraints. Heuristic knowledge or hypothesis is employed at the local coordination procedure, but not at the global one.

The proposed framework lays a foundation for coordinating the unique preventive action in a continuous space and the contingency specified emergency actions in a discrete space. However, this paper is still preliminary; more efforts should be devoted to improving our understanding of the optimal TSC problem before practical applications can be expected.

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Yusheng Xue for photograph and biography, see p. 340 of the June issue (vol. 3, no. 2) of this journal.

Wei Li for photograph and biography, see p. 340 of the June issue (vol. 3, no. 2) of this journal.

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