Minimal Reduction of Unscheduled Flows for Security Restoration: Application to Phase Shifter Control

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***Abstract*—More and more transmission system operators, noticeably in Europe, equip their systems with phase shifting transformers to counteract transit flows that take place in a large meshed interconnection. This paper proposes algorithms for the coordinated control of several phase shifters by one operator with the objective of reducing the unscheduled flow through its system. Minimum reduction of unscheduled flow and minimum deviation with respect to present operating point are sought in order to minimize the trouble caused, while ensuring secure operation. Attention is paid to combining pre- and post-contingency controls. The resulting algorithms, simple and compatible with real-time applications, are illustrated on a realistic test system.**

***Index Terms*—Corrective control, correctively secure operation, optimal power flow, phase shifting transformer, preventive control, transit flow, unscheduled flow.**

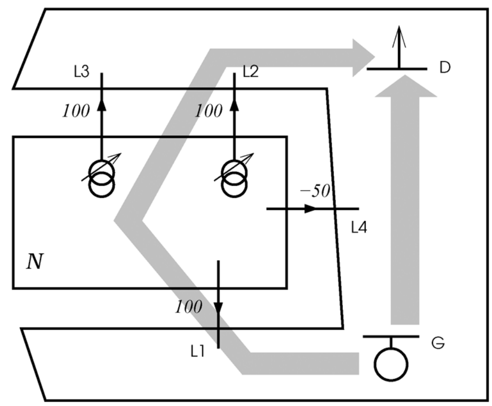

Fig. 1. Transit flow due to external transaction.

I. Introduction

A. Transit Flows: Causes and Consequences

LOOP flows, parallel path flows, inadvertent flows, and circulating flows are synonymous terms that basically refer to the fact that power can flow through several paths in a meshed network [1]. The term transit flow is used by European transmission system operators (ETSO) [2] and is adopted throughout the paper.

This share of flow between parallel paths has been observed in large interconnections since the early 1960s. In the USA, parallel flows have been reported in the PJM interconnection as well as in the WECC system [1]. Transit flows are also common in Europe, where the borders of some countries are crossed, at least partially, by power exchanges involving other countries [3], [4]. This situation is symbolically depicted in Fig. 1 where a fraction of the power due to external transaction passes through the network $\mathcal{N}$ not involved in the transaction. In recent times, transit flows have played an important role in the 2003 North American blackout [5] and in cross-border trading in European markets [6], thus necessitating proper management.

In large interconnections, consisting of several areas operated by different transmission system operators (TSO), the common practice is to plan inter-area transactions in advance, in forward, day-ahead, or even intra-day markets. For the sake of coordination, available transfer capacities (ATC) are computed between the different areas, taking into account security criteria. The final transactions settlements should respect these ATCs.

In real-time operation, however, actual power flows may differ significantly from what has been scheduled in ahead. This may originate from:

- unknown or uncoordinated transactions involving other partners in the interconnection, for instance if transactions are scheduled according to the contract path logic without making use of a flow-based model of the whole interconnection;
- changes in external generation pattern, e.g., due to wind generation variability;
- outage of external equipments.

The unscheduled flow (UF), i.e., the discrepancy between actual and expected flows, becomes a concern when it adds to the loading of inner and interconnection transmission lines and endangers security, moving the system to insecure state (when some credible contingencies could not be stood) or even emergency state (when thermal limits are overstepped even in the current operating conditions) [4], [7].

Manuscript received January 13, 2009; revised May 04, 2009. First published October 30, 2009; current version published January 20, 2010. The work of M. Glavic was supported by an FNRS grant. This work was supported by the DMA Department of RTE, the French transmission system operator. Paper no. TPWRS-01007-2008.

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Digital Object Identifier 10.1109/TPWRS.2009.2030423

B. Accommodating versus Controlling Unscheduled Flows

Several procedures are in place to deal with UFs [8]–[11]. As long as it does not endanger security, a certain level of UF can be accommodated and priced. On the other hand, curtailment of transactions, such as in the transmission loading relief procedure used in the USA, or re-dispatch of generation may be required in severe situations.

Additionally, power flows can be controlled by phase shifting transformers (PSTs) or possibly the faster, but more expensive FACTS devices [1], [4], [11]–[13]. PSTs are among the few controls, together with topology changes, that fully remain in the hands of TSOs. With reference to Fig. 1, the two PSTs can be controlled in a coordinated way to reduce the fraction of power flow passing through $\mathcal{N}$ as a result of the transaction from G to D. More PSTs are likely to be installed for increased control of transit flows, as testified by the situation in Belgium, where three PSTs are going to be put in operation on the Northern border of the country [14], [15].

In the European interconnection, an *ex post* inter-TSO payment has been put into practice since 2002. Countries receive a compensation for the use made by external agents of their networks. At the same time, they are charged for their use of the other partners' networks. The net outcome of the compensation and charges for one country must be used to modify the annual regulated transmission cost from which the transmission tariffs are computed. This results in a system of entry/exit tariffs whereby an agent who pays the modified local access tariff gains access to the entire European grid. Losses are compensated, while for infrastructure, the compensation is based on the cost of hosting cross-border flows [16], [17]. However, no real-time inter-TSO coordination procedure exists in Europe yet to mitigate UFs.

C. Objective of This Work

This paper deals with the real-time restoration of security when the appearance of some UF causes the system to operate in insecure or even emergency mode (i.e., the system would be in normal and secure state without the UF). Ahead scheduling through an ATC-type procedure is assumed to be in operation, as well as a real-time or *ex post* UF accommodation and compensation scheme.

A real-time control tool is proposed enabling a TSO to quickly restore security in its system through actions on its own controls. At the same time, this control is aimed at being as unintrusive as possible for the rest of the interconnection [18]. The first motivation for not acting more than needed (and not acting at all when not required) is to facilitate overall system operation and not to create congestions elsewhere. A second motivation may come from the above-mentioned *ex post* financial scheme which compensates the TSO for accommodating the UF.

In this context, the possibility is considered to let the system operate without satisfying the strict $\mathrm{N}-1$ security criterion, but take advantage of post-disturbance corrective actions. Since equipment outages are relatively rare events, it is cost-effective to operate the system at the economic (or market) optimum that corresponds to its present (intact) configuration, and wait for the disturbance occurrence to take corrective action. However, post-contingency adjustments may be limited, given the time left by thermal overloads, because the operator is unavailable or not trained to react or because of constraints related to the functioning of the available controls (generator ramps, change of PST settings, etc.). This suggests that a compromise should be found between preventive and corrective control actions.

This fits the general problem of operating the system in the optimal, correctively secure manner [19]–[21]. The general approach to this problem is the corrective security constrained optimal power flow (CSCOPF).

However, as UFs are to be handled in real time, resorting to a standard CSCOPF may prove inappropriate, owing to the complexity of this approach. Instead, through the introduction of an inequality constraint on the UF and the use of a specific decomposition procedure, the proposed algorithm avoids the above complexity and yields a procedure more compatible with real-time application.

The paper is organized as follows. In Section II, the above simplification of the CSCOPF problem is exposed. The mathematical expression of the UF used to this purpose is presented in Section III. After this general presentation, the approach is applied specifically to the coordinated PST control in Section IV, considering a simplified optimization. An illustrative example is detailed in Section V, while various additional aspects are discussed in Section VI. The Conclusion in Section VII summarizes the main features of the approach.

II. Outline of the Proposed Procedure

A. Security Constrained Optimal Power Flow

Security constrained optimal power flow is the framework that has been advocated for a long time to support security control activities in power systems. This problem itself has been formulated under two modes: preventive (PSCOPF) and corrective (CSCOPF). In the former, the adjustment of control variables in post-contingency states is not allowed, except if stemming from automatic response to contingencies. The underlying assumption of CSCOPF is that operational limits violation can be generally tolerated for some time without equipment damages, thereby allowing post-contingency corrective actions to be implemented.

The CSCOPF approach of interest in this work can be compactly formulated as follows:

$$\min_{\mathbf{x},\mathbf{x}_1,\ldots,\mathbf{x}_c,\mathbf{u},\mathbf{u}_1,\ldots,\mathbf{u}_c} f(\mathbf{x},\mathbf{u}) \tag{1}$$

$$\text{s.t.} \quad \mathbf{g}(\mathbf{x},\mathbf{u}) = \mathbf{0} \tag{2}$$

$$\mathbf{h}(\mathbf{x},\mathbf{u}) \leq \mathbf{0} \tag{3}$$

$$\mathbf{g}_k(\mathbf{x}_k,\mathbf{u}_k) = \mathbf{0} \quad k = 1,\ldots,c \tag{4}$$

$$\mathbf{h}_k(\mathbf{x}_k,\mathbf{u}_k) \leq \mathbf{0} \quad k = 1,\ldots,c \tag{5}$$

$$|\mathbf{u}_k - \mathbf{u}| \leq \Delta\mathbf{u}_k^{max} \quad k = 1,\ldots,c. \tag{6}$$

The objective f may be either economical (e.g., maximize social welfare) or technical (e.g., minimize deviations with respect to a reference stemming from market). $\mathbf{x}$ (respectively, $\mathbf{u}$) denotes the vector of state (respectively, control) variables in the pre-contingency configuration, (2) are the pre-contingency power flow equations and (3) the corresponding operating constraints, c is the number of contingencies, $\mathbf{x}_k$ and $\mathbf{u}_k$ are the state and control variables in the kth post-contingency configuration, with the corresponding power flow equations (4) and operating constraints (5). Finally, $\Delta\mathbf{u}_k^{max}$ is the vector of bounds on the variation of control variables between the base case and the kth post-contingency state.

For some problems, the above general formulation may not be the most appropriate. The obvious issue is the high dimensionality of the problem, resulting in prohibitive computing times and complexity of computations. To mitigate these drawbacks, the usual approach is to consider a subset of potentially active contingencies, identified by means of (steady-state) security analysis and contingency filtering techniques [20]. Benders decomposition has been also proposed [19], [22], as will be discussed in Section VI-C. Even with these mitigating approaches, designing a CSCOPF compatible with real-time requirements remains a challenge for large systems and/or when many contingencies are considered. For the specific situation of UFs threatening security, the simplification explained hereafter makes the problem much more compatible with real-time requirements.

B. Simplifying the Optimization Problem

We consider the impact of contingencies such as branch or generator outages. We assume that the system has entered an insecure (or even emergency) state with respect to some contingencies owing to an excessive transit flow.[1] Exploiting this correlation between excessive transit flow and severity of contingencies, the idea is to force the transit flow to decrease up to the point where the system is correctively secure.

To this purpose, consider the simpler OPF problem including pre-contingency constraints only:

$$\min_{\mathbf{x},\mathbf{u}} f(\mathbf{x},\mathbf{u}) \tag{7}$$

$$\text{s.t.} \quad \mathbf{g}(\mathbf{x},\mathbf{u}) = \mathbf{0} \tag{8}$$

$$\mathbf{h}(\mathbf{x},\mathbf{u}) \leq \mathbf{0} \tag{9}$$

$$t(\mathbf{x},\mathbf{u}) \leq t^{max} \tag{10}$$

where t represents the transit flow and t^{max} a bound on the latter. The $t(.)$ function is defined more precisely in the next section. Let $f^\star$ be the value of the objective at the optimum.

A variation of $f^\star$ with t^{max} is sketched in Fig. 2. Consider a progressive decrease of t^{max}, starting from a large value for which the constraint (10) is not binding. At point A, this constraint becomes active and starts impacting the value $f^\star$. From there on, the smaller t^{max}, the larger $f^\star$. At the same time, smaller and smaller values of the transit flow t are forced and, hence, the impact of contingencies becomes less severe. Therefore, we assume that there exists a point O, where the system becomes correctively secure and remains so for even smaller values of t^{max}. The curve stops at point B, where (7)–(10) becomes infeasible if t^{max} is further decreased.

Point O is the sought operating point in the proposed method. Operating at this point is interesting because security is restored

[1]In fact, the unscheduled part of the transit flow is expected to be responsible for insecurity. For the scheduled part, the system should have been already checked and made secure.

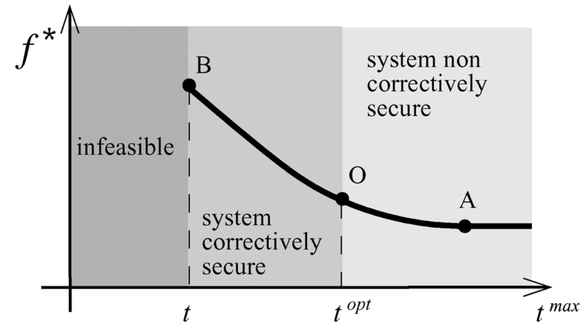

Fig. 2. Variation of objective function with t^{max}.

but the transit flow is decreased to the least extent, thereby disturbing the external system as little as possible.

Point O can be determined by searching iteratively for t^{opt}, the largest value of t^{max} such that the system is correctively secure. This single-dimensional search is simple. For a given t^{max}, the corresponding OPF (7)–(10) is solved to obtain the pre-contingency operating state $\mathbf{x}^\star$ and controls $\mathbf{u}^\star$. The next step is to determine if this operating state is correctively secure.

For the kth contingency ($k = 1,\dots,c$), we check whether there exists (at least) one $\mathbf{u}_k$ with $|\mathbf{u}_k - \mathbf{u}^\star| \leq \Delta\mathbf{u}_k^{max}$, such that the post-contingency state given by (4) satisfies the operating constraints (5). This could be done by solving the following optimization problem:

$$\min_{\mathbf{x}_k,\mathbf{u}_k,\mathbf{e}_k} \mathbf{1}^T\mathbf{e}_k \tag{11}$$

$$\text{s.t.} \quad \mathbf{g}_k(\mathbf{x}_k,\mathbf{u}_k) = \mathbf{0} \tag{12}$$

$$\mathbf{h}_k(\mathbf{x}_k,\mathbf{u}_k) \leq \mathbf{0} \tag{13}$$

$$|\mathbf{u}_k - \mathbf{u}^\star| \leq \mathbf{\Delta u}_k^{max} + \mathbf{e}_k \tag{14}$$

$$\mathbf{e}_k \geq \mathbf{0} \tag{15}$$

where $\mathbf{1}$ denotes a column vector with all components equal to 1. If the solution of this problem is such that $\mathbf{e}_k = \mathbf{0}$, then the post-contingency operating point is correctively secure.

An alternative way to check for the existence of $\mathbf{u}_k$, chosen in this paper, consists in solving the following post-contingency OPF problem:

$$\min_{\mathbf{x}_k,\mathbf{u}_k} F(\mathbf{x}_k,\mathbf{u}_k) \tag{16}$$

$$\text{s.t.} \quad \mathbf{g}_k(\mathbf{x}_k,\mathbf{u}_k) = \mathbf{0} \tag{17}$$

$$\mathbf{h}_k(\mathbf{x}_k,\mathbf{u}_k) \leq \mathbf{0} \tag{18}$$

$$|\mathbf{u}_k - \mathbf{u}^\star| \leq \mathbf{\Delta u}_k^{max}. \tag{19}$$

If this turns out to be infeasible, it can be concluded that the post-contingency operating point is not correctively secure. The advantage of this approach is that, if the optimization is feasible, its solution provides the operator with a set of post-contingency control actions that can be stored and implemented directly if the contingency ever actually occurs. Typically, the objective F deals with control adjustments; alternatively, the objective f of the pre-contingency OPF problem could be reused.

The operating point is not correctively secure if there is at least one contingency making (16)–(19) infeasible.

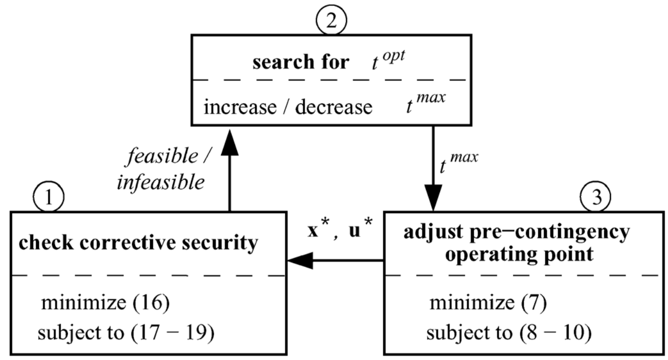

Fig. 3. Proposed decomposed CSCOPF approach.

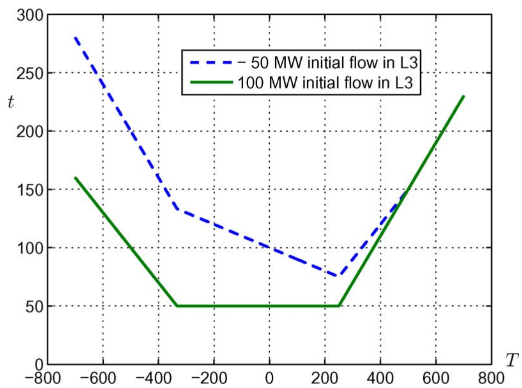

Fig. 4. Transit flow as a function of external transaction.

C. *Proposed Decomposed CSCOPF Approach*

Fig. 3 shows the various steps of the proposed approach. First, contingencies are simulated. If none of them creates a limit violation, the procedure stops; otherwise, the possibility to correct the violations in post-contingency conditions is checked by solving the OPF problem (16)–(19) for each contingency (block 1). If all problems are feasible, the system is correctively secure and the procedure terminates. Otherwise, insecurity being attributed to an excessive transit flow, t^{max} (initialized to the observed transit flow) is set to a lower value (block 2), and the corresponding pre-contingency states $\mathbf{x}^\star$ and controls $\mathbf{u}^\star$ are obtained by solving the OPF problem (7)–(10) (block 3). Based on the latter, corrective security is checked again by block 1. If some contingencies still cannot be corrected, the value of t^{max} is further decreased by block 2, while if all contingencies can be corrected, a higher value of t^{max} is tried. The procedure continues refining the value of t^{max} until t^{opt} is known up to some tolerance.

The above description clearly shows that by introducing (10) and iterating on t^{max}, the original large problem (1)–(6) has been decomposed into $c + 1$ much simpler subproblems: the problem (7)–(10) relative to pre-contingency conditions and the c problems (16)–(19) relative to post-contingency.

Of course, adding the constraint (10) yields a suboptimal solution, but this may be quite acceptable in a real-time environment. Further discussion of this aspect is provided in the results.

III. Formulation of the Transit Flow

There is no unique definition of a transit flow, and there is some degree of arbitrariness in its definition. We introduce hereafter the notion used throughout this work, with the objective of using it in the inequality constraint (10).

Consider a system exchanging power with the remaining of the interconnection through l tie-lines, in which the active power flows p_i are counted positively when exiting the system. Intuitively, there is a transit flow if some lines are bringing power in and some others are taking it out. This means that not all p_i's have the same sign. We thus define the transit flow as

$$t = \frac{1}{2}\left(\sum_{i=1}^{l}|p_i| - |\sum_{i=1}^{l}p_i|\right). \tag{20}$$

In this expression, $\sum_i p_i$ is the net power interchange (typically controlled by AGC if the system coincides with a control area), a positive value indicating a net power export. Clearly, if all p_i's have the same sign, then $\sum_{i=1}^{l}|p_i| = |\sum_{i=1}^{l}p_i|$ and $t = 0$. If not all flows have the same sign, $t > 0$ whatever the net power interchange.[2]

The effect of an external transaction is easily shown in the following example. Consider Fig. 1, with the base case power flows shown next to the tie-lines. The transit flow computed from (20) is 50 MW. Assume now that a transaction T takes place from G to D, with 40% of the additional power passing through $\mathcal{N}$. Assume furthermore the following flow distribution (the variation of losses being neglected): $-0.4T$ in line L1, $0.3T$ in L2, $0.1T$ in L3, and nothing in L4. Thus, the power flow is $100 - 0.4T$ in line L1, $100 + 0.3T$ in L2, $100 + 0.1T$ in L3, and -50 in L4. The variation of t with T is shown with solid line in Fig. 4. The transit flow does not change as long as T remains below 250 MW. Indeed, no line flow changes sign; instead, a mere redistribution of flows is taking place. For T larger than 250 MW, the flow in L1 reverses and the transit flow starts increasing as expected. A similar observation is made for a reverse transactions ($T < 0$). The dotted line in Fig. 4 refers to a base case with an initial flow of -50 MW in L3. In this case, the transaction creates a counterflow in both L1 and L3 and makes the transit flow decrease until T exceeds 250 MW.

Note that (20) includes both scheduled and unscheduled parts of the transit flow. As indicated earlier, it is likely that system security has been checked for the scheduled part and insecurity stems from the unscheduled part.

IV. Application to Phase Shifter Control

A. *Modeling Simplifications*

In the remaining of this paper, the decomposition method presented in the previous section is applied to security restoration through PST control. Since the emphasis is on coordinated control of PSTs instead of OPF algorithms, the following simplifying assumptions are made:

1) a linear model is considered, for simplicity and computational efficiency. Although it might be obtained right away

[2] Compared to the definition given in [23], the above formula gives the same transit flow values but allows an analytical treatment.

from the well-known dc approximation, a linearization of the ac power flow equations has been considered in this work. This assumption is justified by the almost linear variation of active power flows with PST angles;
2) control variables are assumed to be the PST angles only. We seek here for dedicated algorithms that can quickly help operators in the specific task of adjusting PSTs, or in some future even adjust the PSTs automatically;
3) the objective function f is of technical (instead of economical) nature. A minimum change of PST angles is considered. The motivation may be to minimize the increase in power losses that generally accompanies such changes, or to deviate as few as possible from the operating point set by the market, especially when PSTs are used to increase transactions [24].

Under assumption 1, the branch active power flows $\mathbf{p}$ vary with PST angles $\boldsymbol{\phi}$ according to

$$\mathbf{p} - \mathbf{p}^0 = \mathbf{S}(\boldsymbol{\phi} - \boldsymbol{\phi}^0) \tag{21}$$

where $\mathbf{p}^0$ and $\boldsymbol{\phi}^0$ are the base case values of the power flows and phase angles, respectively, and $\mathbf{S}$ is a $b \times n$ sensitivity matrix, where b is the number of branches and n the number of PSTs.

The PSTs have no influence on the net power interchange, under the approximation that the power losses remain unchanged. Thus, the expression

$$\left| \sum_{i=1}^{l} p_i \right| = d \tag{22}$$

does not vary with the PST angles. Using (20) and (22), the transit flow constraint can be rewritten as

$$\frac{\sum_{i=1}^{l} |p_i| - |\sum_{i=1}^{l} p_i|}{2} \leq t^{max} \Leftrightarrow \sum_{i=1}^{l} |p_i| \leq d + 2t^{max}. \tag{23}$$

B. Controllability of Transit Flow by PSTs

We assume that the available PSTs are able to control the transit flow t up to a certain point. To this purpose, there must be an adequate number of PSTs, they must be properly located so that the terms of the $\mathbf{S}$ matrix relating tie-line power flows to phase angles are large enough, and the range of PST angles should be wide enough. These important aspects, to be decided at the planning stage, are out of scope of this paper [3], [26].

In practice, the number, location, and range of PSTs may not make it possible to decrease the transit flow below some value. The smallest transit flow $\underline{t}$ that can be enforced with the available PSTs can be computed as

$$\begin{aligned} \underline{t} = \min_{\mathbf{p},\boldsymbol{\phi}} \quad & \frac{1}{2}\sum_{i=1}^{l} |p_i| - \frac{d}{2} \\ \text{subject to} \quad & \mathbf{p} - \mathbf{p}^0 - \mathbf{S}(\boldsymbol{\phi} - \boldsymbol{\phi}^0) = \mathbf{0} \\ & -\mathbf{p}^{max} \leq \mathbf{p} \leq \mathbf{p}^{max} \\ & \boldsymbol{\phi}^{min} \leq \boldsymbol{\phi} \leq \boldsymbol{\phi}^{max}. \end{aligned}$$

$\underline{t}$ is also the smallest value of t^{max} such that the optimization problem (24)–(28) is feasible. It corresponds to point B in Fig. 2.

C. Pre-Contingency OPF

With a minimum deviation objective, the linear model (21) and the transit flow constraint (23), the pre-contingency OPF (7)–(10) may take on the form

$$\min_{\mathbf{p},\boldsymbol{\phi}} \sum_{i=1}^{n} \left(\phi_i - \phi_i^0\right)^2 \tag{24}$$

$$\text{subject to} \quad \mathbf{p} - \mathbf{p}^0 - \mathbf{S}(\boldsymbol{\phi} - \boldsymbol{\phi}^0) = \mathbf{0} \tag{25}$$

$$-\mathbf{p}^{max} \leq \mathbf{p} \leq \mathbf{p}^{max} \tag{26}$$

$$\boldsymbol{\phi}^{min} \leq \boldsymbol{\phi} \leq \boldsymbol{\phi}^{max} \tag{27}$$

$$\sum_{i=1}^{l} |p_i| \leq d + 2t^{max} \tag{28}$$

where (26) accounts for the thermal limits of the branches, and (27) for the available range of PST angles. For a low enough t^{max}, the constraint (28) will be active at the optimum, unless an active constraint (26) forces a lower transit flow.

An L_1-norm objective $\sum_{i=1}^{n} |\phi_i - \phi_i^0|$ can be also considered but has been found to cause undesirable distortion of power flows, as it tends to make full use of controls with higher sensitivities. The L_2 norm (24) distributes the control effort more evenly over the PSTs.

Since the PSTs are discrete devices, each ϕ has to be rounded to the value corresponding to the nearest tap position.

To deal with the absolute value in (28), it is convenient to define two new variables, respectively, p_i^+ and p_i^-, such that $p_i = p_i^+ - p_i^-$ with $p_i^+, p_i^- \geq 0$. The constraint (28) is then rewritten as

$$\sum_{i=1}^{l} \left(p_i^+ + p_i^-\right) \leq d + 2t^{max}, \qquad \text{with} \quad p_i^+, p_i^- \geq 0.$$

D. Post-Contingency OPF

Let $\boldsymbol{\phi}^\star$ be the solution of the pre-contingency OPF (24)–(28).

The post-contingency OPF problem (16)–(19), aimed at checking if the system is correctively secure with respect to the kth contingency ($k = 1, \ldots, c$), takes on the form

$$\min_{\mathbf{p},\boldsymbol{\phi}} \sum_{i=1}^{n} |\phi_i - \phi_i^\star| \tag{29}$$

$$\text{subject to} \quad \mathbf{p} = \mathbf{p}^{(k)} + \mathbf{S}^{(k)}(\boldsymbol{\phi} - \boldsymbol{\phi}^\star) \tag{30}$$

$$-\mathbf{p}^{max} \leq \mathbf{p} \leq \mathbf{p}^{max} \tag{31}$$

$$\boldsymbol{\phi}^{min} \leq \boldsymbol{\phi} \leq \boldsymbol{\phi}^{max} \tag{32}$$

$$-\Delta\boldsymbol{\phi}^{max} \leq \boldsymbol{\phi} - \boldsymbol{\phi}^\star \leq \Delta\boldsymbol{\phi}^{max} \tag{33}$$

where $\mathbf{S}^{(k)}$ is the post-contingency sensitivity matrix and $\mathbf{p}^{(k)}$ the vector of post-contingency branch flows, provided by a preliminary contingency analysis. The constraint (33) expresses that in post-contingency conditions, PST angles cannot be changed from the pre-contingency values $\boldsymbol{\phi}^\star$ by more than $\Delta\boldsymbol{\phi}^{max}$, which is supposed to reflect the limited rate of change of PSTs and/or the initial response delay of operators. The choice of the objective has been discussed in Section II-B.

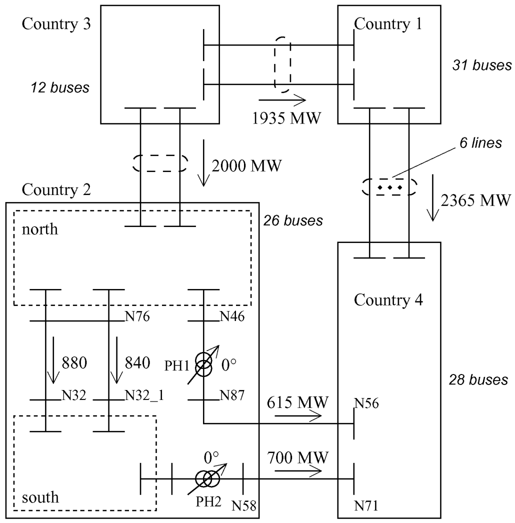

Fig. 5. Test system structure and base case operating point.

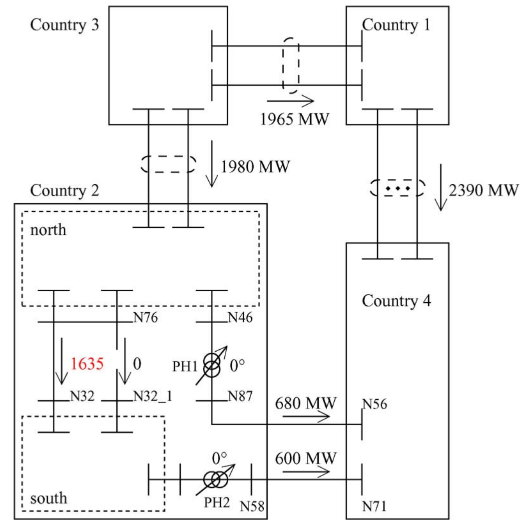

Fig. 6. Power flows after tripping of line N76-N32_1.

The following items are noteworthy:

1) the above optimization has to be performed for each contingency endangering the system. Obviously, the correction $\boldsymbol{\phi} - \boldsymbol{\phi}^\star$ is expected to vary with the contingency;
2) in the above procedure, it is implicitly assumed that the available PSTs have controllability over the overload problem. Thus, the contingencies of concern here are those that can be corrected by the PSTs. To check this, the above optimization can be performed with the constraints (33) removed. If the problem remains infeasible, the PSTs cannot help, and the corresponding contingencies should be treated by other means;
3) $\Delta\boldsymbol{\phi}^{max}$ may change with the contingency severity: a higher overload must be corrected in a smaller time and hence a smaller $\Delta\boldsymbol{\phi}^{max}$ should be imposed.

V. Illustrative Example

A. Test System

The results have been obtained on a test system, loosely inspired of a small portion of the UCTE system. Its overall structure is shown in Fig. 5. It is made up of four subsystems, corresponding to different countries and different TSOs. The figure provides the number of buses in each subsystem. The subsystem of Country 2 is equipped with two PSTs, identified by PH1 and PH2.

The active power flows that exist in the base case situation, with both PST angles equal to zero are shown in Fig. 5. The transit flow through Country 2 is $t = (3315 - 685)/2 = 1315$ MW.

A deeper look at the diagram reveals the presence of a "major" and a "minor" loop. The major loop includes the tie-lines connecting the four systems. Inside this loop, Countries 1 and 3 are exporting power while Countries 2 and 4 are importing. The two PSTs of Country 2 are placed cutting the loop, in parallel to each other. Moving their angles in the same direction, the TSO of Country 2 can redirect some power flow from path 3-2-4 towards path 3-1-4. The minor loop includes two paths from north to south of Country 2, one through the internal lines N76-N32 and N76-N32_1 and the other through the tie-lines N87-N56 and N58-N71. The two PSTs are placed in series with each other inside this minor loop, and moving their angles in opposite directions redistributes the power between the two above-mentioned paths.

B. Security Analysis

We consider security analysis in Country 2. Out of all $\mathrm{N}-1$ contingencies, two of them end up in line overloads: the loss of lines N76-N32 and N76-N32_1. Fig. 6 shows the distribution of power flows after the tripping of N76-N32_1: line N76-N32 is significantly loaded above its capacity of 1215 MW (taken as 90% of its MVA capacity to account for reactive power and leave a security margin).

As for the security analysis of any system nested inside an interconnection, a correct representation of the external system (Countries 1, 3, and 4 in this case) is essential to assess the effect of both contingencies and PST adjustments. The tests have been performed assuming that the whole system model is available to the TSO of Country 2, but an equivalent, or a combination of unreduced and equivalent models, could be also used to account for the system external to Country 2.

C. Linearization

The model is obtained by linearizing the ac power flow equations as follows.

We start from a base case situation with PST angles $\boldsymbol{\phi}^0$ and power flows $\mathbf{p}^0$. The sparse power flow Jacobian is computed at this operating point and LU-decomposed. Using a well-known sensitivity formula [25], each column of the $\mathbf{S}$ matrix is obtained by solving one sparse linear system involving the available factors of the transposed Jacobian. $\boldsymbol{\phi}^0$, $\mathbf{p}^0$, and $\mathbf{S}$ are reused each time the pre-contingency problem (24)–(28) is solved (block 3 in Fig. 3) to obtain an updated $\boldsymbol{\phi}^\star$.

Before solving the post-contingency problem (29)–(33) (block 1 in Fig. 3), and given the PST angles $\boldsymbol{\phi}^\star$, a full ac power flow is solved to obtain the flows $\mathbf{p}^{(k)}$ that result from both the kth contingency and the pre-contingency PST adjustments.

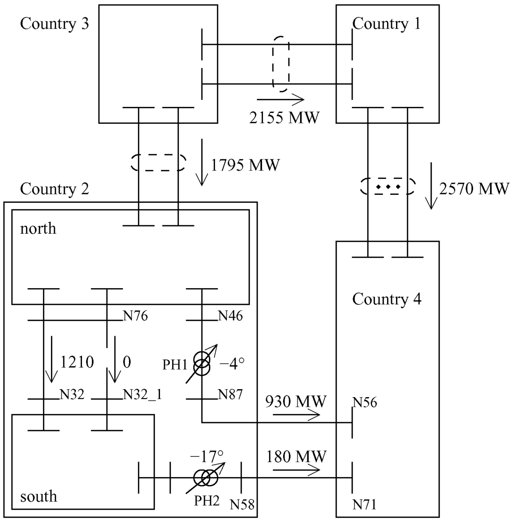

Fig. 7. Power flows after tripping of line N76-N32_1 and corrective control by PSTs.

The corresponding Jacobian is LU-decomposed and used to determine the $\mathbf{S}^{(k)}$ matrix, using the above-mentioned formula.

The power flow model used to compute the $\mathbf{S}$ and $\mathbf{S}^{(k)}$ matrices involves the external system, unreduced and/or equivalenced, according to what is available to the TSO of concern. The former option has been considered in this work.

Thanks to the very close to linear relationship between branch power flows and PST angles, as well as the sensitivity matrix updates, the linearized model was found to be extremely accurate. A comparison of power flows obtained from, respectively, the linearized and the full ac power flow models, revealed discrepancies no larger than 0.2 MW on the branch flows.

D. Corrective Control of Line Overloads by PSTs

Before the application of the algorithm, we demonstrate the effectiveness of the PSTs in alleviating the overload caused by the tripping of line N76-N32_1, which is the contingency requiring the largest control effort.

We first consider the PST angles that correctively clear the overload without any limit of the type (33). We thus solve the optimization problem (29)–(32) with $\boldsymbol{\phi}^{\star}$ equal to the base case values $\boldsymbol{\phi}^0 = (0°, 0°)$. The angles and the resulting power flows are shown in Fig. 7. The line flow is reduced below its limit thanks to: 1) a common decrease of PST angles that redistributes the flows in the major loop, decreasing the transit flow though Country 2 from 1280 to 1175 MW; and 2) a more pronounced action of PH2 that redistributes the flows inside the minor loop.

If the post-contingency change of ϕ_2 from 0° to $-17°$ (see Fig. 7) is deemed too large and limited to a lower value, ϕ_1 cannot compensate and the optimization problem (29)–(32) becomes infeasible, indicating that the system is not correctively secure.

E. Preventive Restoration of Corrective Security

We now illustrate the method presented in Section II (see also Fig. 3) to make the system secure with respect to both contingencies previously mentioned.

TABLE I
ITERATIONS TO RESTORE CORRECTIVE SECURITY

iter. No	t^{max} (in MW)	block 3 ϕ_1^*	block 3 ϕ_2^*	block 1 outcome
0	1315	0^o	0^o	not correctively secure
1	658	infeasible		
2	986	-19^o	-20^o	correctively secure
3	1151	-10^o	-11^o	correctively secure
4	1233	-5^o	-6^o	not correctively secure
5	1192	-7^o	-8^o	correctively secure
6	1213	-6^o	-7^o	correctively secure

TABLE II
PREVENTIVE AND CORRECTIVE PST SETTINGS FOR VARIOUS $\Delta\phi^{max}$

$\Delta\phi^{max}$	ϕ_1^*	ϕ_2^*	t (in MW)	ϕ_1^{post}	ϕ_2^{post}
5^o	-14^o	-16^o	1065	-10^o	-21^o
10^o	-6^o	-7^o	1213	-5^o	-17^o
15^o	-2^o	-2^o	1280	-4^o	-17^o
20^o	0^o	0^o	1315	-4^o	-17^o

We assume a maximum post-contingency angle change $\Delta\phi^{max}$ of 10°. Hence, for the initial operating point shown in Fig. 5, the system is not correctively secure (as shown in Section V-D for the loss of line N76-N32_1) and the PST angles have to be adjusted in the pre-contingency configuration.

A binary search (also known as dichotomic search, or bisection method) is used in block 2 of Fig. 3 to determine the highest value of t^{max} such that the system is correctively secure. This consists in building a smaller and smaller interval $[t_l\ t_u]$ such that for $t^{max} = t_l$, the system is correctively secure while for $t^{max} = t_u$, it is not. At each step, the value $t^{max} = (t_u + t_l)/2$ is tested and taken as the new t_l (respectively, t_u) if the system is found correctively secure (respetively, insecure). The procedure is repeated until $|t_u - t_l|$ becomes smaller than a tolerance ϵ. The best initial value for t_l is $\underline{t}$ (discussed in Section IV-B) but a 0 MW value has been taken in the tests, saving the computation of $\underline{t}$ at the expense of an additional iteration of the binary search. t_u has been initialized at the base transit flow (1315 MW).

The main results are listed in Table I. At the first iteration, with t^{max} set to $(1315 + 0)/2 = 658$ MW, the optimization of block 3 is infeasible, meaning that the PSTs cannot force such a low transit flow. Obviously, block 1 cannot be executed. Thus, after setting t_l to 658 MW, we proceed with the second iteration, corresponding to $t^{max} = (1315 + 658)/2 = 986$ MW.

The third and fourth columns of Table I give the pre-contingency settings determined by block 3, while the last column indicates whether this new operating point is found correctively secure by block 1. The tolerance ϵ being set to 25 MW, the procedure stops after six iterations.

The settings to be finally actually implemented, in a preventive mode, are $\phi_1^{\star} = -6°$ and $\phi_2^{\star} = -7°$, which decrease the transit flow to 1213 MW.

Table II presents the results obtained by repeating the procedure for various values of $\Delta\phi_1^{max} = \Delta\phi_2^{max} = \Delta\phi^{max}$. The second and third columns give the pre-contingency PST angles, leading to the transit flow value shown in the fourth column. The last two columns provide the final values that should be given to PST angles, in the post-contingency configuration, to clear the line overload caused by the tripping of N76-N32_1. As expected, the more one resorts to corrective control actions (i.e., the larger $\Delta\phi^{max}$), the less the pre-contingency operating point is changed (and, hence, the less intrusive the change in transit flow).

The variations observed in the table can be explained as follows. First, the post-contingency angles are the closest to the pre-contingency ones ($\boldsymbol{\phi}^{\star}$) that alleviate the post-contingency overloads. Second, for some pre-contingency PST angle settings, $\Delta\boldsymbol{\phi}^{max}$ may be not large enough to allow for post-contingency correction. In this case, the pre-contingency angles are modified in the direction that reduces the transit flow, resulting into new values of $\boldsymbol{\phi}^{\star}$. As a result, when seeking for post-contingency corrections, starting from the new $\boldsymbol{\phi}^{\star}$, different post-contingency settings will be found (still closest to this new $\boldsymbol{\phi}^{\star}$). This is why the post-contingency settings vary so much with $\Delta\boldsymbol{\phi}^{max}$.

VI. Discussions

A. Requirements of the Method

The following conditions have to be fulfilled for the proposed procedure to be successful. First, the available PSTs must have controllability over the transit flow. Second, the contingency should be secured by decreasing the transit flow. A typical situation is when a corridor is loaded by the transit flow and the outage of a line in this corridor causes overload of parallel lines. If the transit flow reduction cannot help, the contingency will remain harmful at the minimum flow $\underline{t}$.

If these conditions are not met, another objective and/or additional (probably more expensive) controls should be considered to address the security problem.

B. Optimality of the Method

Fig. 8 shows a characterization of the pre-contingency operating points corresponding to various values of (ϕ_1, ϕ_2). This diagram was obtained by repeatedly solving the optimization problem (29)–(33) with $(\phi_1^{\star}, \phi_2^{\star})$ set to each pair of integer values in the shown range. The maximum post-contingency correction $\Delta\phi^{max}$ was set to $10°$, as in Table I. At the points shown with crosses, the optimization problem was infeasible; hence, the system is not correctively secure. At the points shown with circles, the problem had a solution, indicating that the system is correctively secure. Finally, at the points shown with disks, the contingencies were harmless and the system secure; there was thus no need for PST adjustments.

Assume that the system is operating initially at $(\phi_1^{\circ} = 0°, \phi_2^{\circ} = 0°)$. The arrow that starts from this point in Fig. 8 is the path of (pre-contingency) PST angles obtained by solving (24)–(28) for decreasing values of t^{max} in (28), i.e., smaller and smaller transit flow. The points generated by block 3 of the proposed procedure (see Fig. 3) lie on this path. The binary search converges to the point $(\phi_1 = -6°, \phi_2 = -7°)$, where the arrow enters the correctively secure region.

The variations of the post-contingency angle settings shown in Table II can be further explained in the light of Fig. 8. For smaller $\Delta\phi^{max}$, the correctively secure region shrinks closer to the secure area. Hence, when moving along the arrow in Fig. 8 (which decreases the transit flow), the operating point enters the correctively secure region for different angle settings. In particular, with $\Delta\phi^{max} = 5°$, this happens for $\boldsymbol{\phi}^{\star} = (-14°, -16°)$, from which the closest secure angle settings are $(-10°, -21°)$.

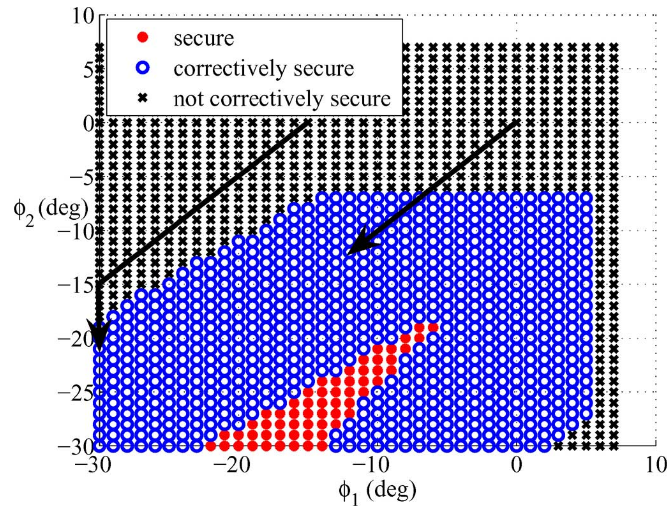

Fig. 8. Characterization of pre-contingency operating points.

In fact, there are many ways to enter the correctively secure region. For instance, minimizing the Euclidian distance to the initial point $(\phi_1^{\circ} = 0, \phi_2^{\circ} = 0)$ would lead to the solution $(\phi_1 = 0°, \phi_2 = -7°)$. This operating point is closer to the initial point but at this point the operation of system 2 is more disturbed due to a significant redistribution of power flows inside the minor loop. The proposed algorithm does not yield this solution because the pre-contingency changes are constrained to obey (28). In fact, having attributed the security problem to a certain cause (an excessive transit flow), the algorithm tries to find the closest correctively secure operating point towards the direction that mitigates this cause.

Assume now that the initial operating point is $(\phi_1^{\circ} = -14°, \phi_2^{\circ} = 0°)$. The search direction is parallel to the previously discussed path, until ϕ_1 hits its minimum of $-30°$, causing the path to change direction. In this case, the binary search will converge to $(\phi_1 = -30°, \phi_2 = -19°)$.

The fact that the search is limited towards the direction that mitigates t may lead to not finding a solution. This happens when $\Delta\phi^{max}$ is small, shrinking the correctively secure region and causing the path to pass around it. In addition, if the requirements listed in Section VI-A are not met, the correctively secure region will not be reached by applying the method, since either the search direction will not be towards this region, or the PSTs will not be able to affect the transit flow and hence move the operating point towards the sought direction.

C. Analogy With Benders Decomposition

The proposed problem decomposition offers some similarities with the Benders decomposition method [19], [21], [22], [27], [28] from which it differs, however, as discussed hereafter.

In the context of PSCOPF and CSCOPF, the most appealing application of Benders decomposition consists of splitting the original problem into:

- one master problem, in which a solution is found to the pre-contingency subproblem (1)–(3); and
- several smaller slave problems, each dealing with one contingency and checking if there exists a control $\mathbf{u}_k$ satisfying (4)–(6).

Each infeasible slave subproblem generates the so-called feasibility cut constraint to be added at the next iteration to the master problem. Iterations between the master and the slave subproblems continue, with the cuts updated at each iteration, until the original problem (1)–(6) is solved to some tolerance.

In the proposed approach the problem is also split into a master problem dealing with the pre-contingency situation (block 3 in Fig. 3) and slave problems, each relative to a post-contingency situation (block 1 in the same figure). The information passed from slave to master problems is used to adjust the pre-contingency operating point.

However, the main differences with respect to Benders method lie in both the nature and the handling of the information returned to the master problem. The latter consists of a synthetic two-valued variable per contingency. The values stemming from the various contingencies are easily combined into a single infeasible/feasible information. Instead of adding mathematical constraints to the master optimization, the engineering knowledge of the problem (insecurity attributed to transit flow) drives the pre-contingency adjustments. While being less general (the situation of Fig. 2 must apply) and suboptimal (to the extent discussed in the previous section), the proposed scheme guarantees fast convergence to the solution, as a binary search is used to find point O in Fig. 2. This may not be the case with Benders decomposition, as quoted in some papers reporting on the non-monotonic decrease of the objective function [21] or the slow final convergence (known as "tailing-off effect") [28]. Finally, with Benders decomposition, the size and the structure of the master problem vary from one iteration to the other, depending on the cut constraints added. This is not the case in the proposed method.

D. Computational Efficiency

Several features contribute to making the overall procedure suitable for real-time applications.

First, the decomposition presented in Section II (and applicable to nonlinear CSCOPF) succeeds replacing the highly-dimensional problem (1)–(6) with smaller subproblems. The binary search leads to a low, predictable number of iterations, which could even be decreased by extrapolating/interpolating the next value of the transit flow from past iterations.

As regards the particular application to PST control considered in Section IV:

- the linearized formulation allows resorting to proven, efficient optimization solvers;
- by focusing on the PSTs, the optimization involves a reduced number of control variables;
- the computation of a sensitivity matrix $\mathbf{S}$ involves factorizing the sparse power flow Jacobian and substituting one sparse vector per column of the matrix, i.e., per PST. Efficient sparsity programming solvers are available to this purpose. Furthermore, the optimal ordering step can be performed once for all in the pre-contingency topology.

E. Control of PSTs by Multiple TSOs

This paper focuses on the control of PSTs owned by a single TSO. Note, however, that the control of PSTs by multiple TSOs within an interconnection raises coordination issues. For instance, several TSOs having PSTs and using them to reduce a transit flow could end up in a situation where the effect of the PSTs cancel each other out. Reference [29] illustrated other interactions that may result from conflicting TSO policies.

By keeping PST control transparent and as few intrusive as possible, the approach of this paper contributes to avoiding the above-mentioned conflicts. The issue, however, deserves further consideration. A possible framework was proposed in [30]. The proposed solution is the Nash equilibrium of a sequence of optimizations performed by the various TSOs, each of them taking into account the other TSO's settings as well as operating constraints relative to the whole system. The key for the success of the procedure is that all TSOs should be willing to provide the other TSOs with information about the system for which they are responsible.

VII. Conclusion

The coordinated control of multiple PSTs to decrease unscheduled flow experienced by a TSO inside an interconnection has been considered.

First, a definition of the transit flow has been proposed, linked to tie-line power flows in opposite directions.

Next, a simplification to the general corrective security-constrained optimal power flow problem has been proposed, which allows decomposing this large-scale problem into simpler subproblems. Based on the assumption that the security problem can be attributed to an excessive transit flow, the algorithm investigates a sequence of pre-contingency operating points towards the direction that decreases this flow. It converges to the correctively secure operating point with the transit flow reduced to the lowest extent possible. By so doing, the control is aimed at being as few intrusive as possible for other TSOs in the interconnection.

Finally, this approach has been applied to the reduction of an excessive transit flow by PSTs in order to deal with insecure situations. The algorithm determines the best possible combination of pre- and post-contingency PST adjustments, with limits specified on the post-contingency angle changes.

The features and limitations of this procedure have been illustrated on a test system.

The embedded optimization problems are simple and suitable to real-time operation. The method could assist the operator in quickly checking if transit flow control by PSTs can restore security or if more expensive actions are needed. The algorithm could be at the heart of a controller coordinating the PSTs, and allowing faster post-contingency adjustments.

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