Steady-State Security Control Using a Sensitivity-Based Approach

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ABSTRACT

Real time security assessment is gaining more and more attention with the increasing complexity of electrical power systems. Steady-state security control is made to keep the system in a state without violating any constraints. In this paper, an algorithm based on the first-order sensitivities is presented both for real power and for reactive power security control. Relations between uncompensated sensitivity factors used for corrective control and compensated sensitivity factors used for preventive control have been derived theoretically. It is found that the combined effects of a line outage and a line switching cannot be summed directly, because of inherent nonlinearity. The effectiveness of the proposed method is investigated by studying the Taiwan power system.

1. INTRODUCTION

With the growing size of power systems and the complexity of operating conditions, power system security, which deals with the system's ability to withstand outage events, is of greater concern to the system operator as well as to the system planner than it was in the past. In order to assess the security of a power system, a proper classification of security levels is necessary. A security regime can be divided into normal, alert, emergency and restorative states [1, 2]. For the purpose of steady-state security, the alert state indicates that the system is operating within limits, but a contingency analysis program predicts there will be an MW overload or a voltage violation

problem when a certain outage occurs. Preventive control should be taken to improve security, that is, to return the system to the normal state. In an emergency state, the system is in danger of overloads or voltage violations unless corrective control is taken to restore it at least to the alert state.

Steady-state security control strategies are categorized according to whether they primarily affect real power or reactive power problems. Actions that can be taken to relieve power flow overloads include the control of phase shifter flows, area interchanges, generation rescheduling, load shifting and line switching, etc. In the event of voltage problems, actions that can be taken are transformer tap adjustments, generator voltage adjustments and capacitor/reactor switching, etc. In the literature, numerous approaches have been devised to realize the above control actions. Some of these utilized the optimization techniques such as the optimal power flow (OPF) [3 - 5]. There are no new requirements for use of OPF for security control, except for additional constraints imposed on the limits of the circuit loadings, bus voltages, and control actions, etc. For the security-constrained OPF using the linear programming approach, it is necessary to calculate the sensitivities of each constraint with respect to the controlling parameters in order to get the linearized operating constraints.

There are some different opinions about the optimal solution of the security problem. When abnormalities occur in a system due to a contingency, optimal dispatch is not, in general, of greatest concern to the operator, but rather system security.

Hence, some other methods stressing the ability to make recommended decisions to the dispatcher to enhance the security are proposed, with no attempt to find the optimal solution. A typical approach is the network

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sensitivity method [6]. There are two types of sensitivities: generation shift factors with respect to generation rescheduling, and line outage distribution factors with respect to line switching. Extending generation shift factors to include load shift factors is straightforward if loads are allowed to be adjusted. These factors are not required to be precomputed but can be obtained efficiently by using the sparse matrix inverse technique [7, 8]. The control actions determined by the network sensitivity method or optimal power flow must be identified through an AC load flow test [8].

The concept of sensitivity factors has been used extensively in various power system problems. The network sensitivity method, based on the DC load flow, is not suitable for voltage correction. Although use of the linearized reactive power model alone may not work well for the purpose of reactive power contingency selection, it is still worthwhile to see whether this approach is suitable for voltage correction. Based on the linearized reactive power flow equations, the sensitivity factors relating the voltage changes to the changes of voltage correction actions can be defined as in the real power case. The results shown in this paper reveal that this approach is rather promising. It is useful to know that not all of the sensitivity factors of the system are required; only the terms related to the overloaded branches or voltage violated buses are calculated [8]. These terms are calculated using relevant elements of the sparse impedance and branch reactances.

By combining the effects of contingency outages and the changes of control actions simultaneously, the modified (or compensated) sensitivity factors can be used to achieve the preventive control. In other words, should a certain outage cause a violation problem, the same corrections can be made using compensated factors as were run with the uncompensated factors. In general, the combined effects can be obtained using superposition. However, it is shown in this paper that, unless certain conditions are satisfied, the combined effects of a line outage and a line switching cannot be added directly because of their nonlinear relationships.

The main features of this paper are summarized as follows: (1) the method based on the linearized AC power flow is proposed for eliminating system overloads and voltage viola-

tions; (2) relations between the sensitivity factors, compensated sensitivity factors, corrective controls and preventive controls are carefully examined; (3) steady-state security control of a real power system (Taiwan power system) is analyzed using the proposed method.

2. METHODOLOGY OF REAL POWER CONTROL

2.1. Linearized AC power flow

The linearized AC power flow can be obtained simply from the fast decoupled load flow model [9] by setting the V terms of the forcing function to 1.0 per unit:

$$\mathbf{B}' \Delta \theta = \Delta \mathbf{P} \quad (1)$$

$$\mathbf{B}'' \Delta \mathbf{V} = \Delta \mathbf{Q} \quad (2)$$

where $\Delta \mathbf{P}$ and $\Delta \mathbf{Q}$ are vectors of real and reactive power changes, $\Delta \theta$ and $\Delta \mathbf{V}$ vectors of changes in voltage angles and magnitudes,

$$B'_{ij} = -1/x_{ij}, \quad B'_{ii} = \sum (1/x_{ij})$$

$$B''_{ij} = b_{ij}, \quad B''_{ii} = -\sum b_{ij} - \text{SH}_i$$

x_{ij} and b_{ij} are the reactance and susceptance of branch $i-j$, and SH_i is the total shunt admittance at bus i .

Both matrices $\mathbf{B}'$ and $\mathbf{B}''$ are real, symmetrical and sparse but in different dimensions since the swing bus is excluded from $\mathbf{B}'$ and PV buses are excluded from $\mathbf{B}''$. Using the technique mentioned in ref. 10, both matrices can be triangularized using the same ordering, regardless of bus types. Equations (1) and (2) can be rewritten as

$$\Delta \theta = \mathbf{X}' \Delta \mathbf{P} \quad (3)$$

$$\Delta \mathbf{V} = \mathbf{X}'' \Delta \mathbf{Q} \quad (4)$$

where $\mathbf{X}'$ and $\mathbf{X}''$ are the sparse inverses of $\mathbf{B}'$ and $\mathbf{B}''$, respectively.

Since Taiwan power system is the only power system in Taiwan and there are no phase shifters, the actions being considered to alleviate overloads are generation adjustments, load shifts and line switching.

The methods for reducing overloads are discussed in this section, while the voltage problem is left to the next section.

2.2. Generation adjustment and load shift

2.2.1. Corrective control

Assume that overloaded branch l is to be relieved. The effect of adjusting generations

or loads on the flow of branch l can be evaluated with generation/load shift factors:

$$A(l, i) = \frac{1}{x_l} (X'_{ni} - X'_{mi}) \quad (5)$$

where X'_{ni} and X'_{mi} are elements of $\mathbf{X}'$, x_l is the reactance of line l , n and m are terminal buses of line l , and i is an adjustable generator or load bus.

Total effects of simultaneous changes on several buses can be calculated using superposition. Thus, the reduction of flow on branch l requires

$$\Delta P_l = P_l - \bar{P}_l \leq \sum_{i \in \Omega_G} |A(l, i) \Delta P_i| + \sum_{j \in \Omega_L} |A(l, j) \Delta P_j| \quad (6)$$

where $\bar{P}_l$ is the power limit of line l , P_l the base-case flow in line l directed from n to m , Ω_G the set of adjustable generator buses, Ω_L the set of adjustable load buses, ΔP_i the change in injected power at generator bus i , and ΔP_j the change in injected power at load bus j .

The direction of the adjustments can be decided according to the sign of the shift factor, namely,

- increasing generation at bus i if $A(l, i) < 0$
- decreasing generation at bus i if $A(l, i) > 0$
- increasing load at bus j if $A(l, j) > 0$
- decreasing load at bus j if $A(l, j) < 0$

The amount of adjustment at generator bus i is the minimum (ΔP_i^c) of values between the generation limit at bus i , the generation limit at the reference bus and $|\Delta P_i / A(l, i)|$. The amount at load bus j is the minimum of values between the load change limit and $|\Delta P_j / A(l, j)|$.

The next step is to determine which buses should be included in sets Ω_G and Ω_L . Clearly, Ω_L will be an empty set if load shifts are avoided, and generation rescheduling is executed prior to load shifting. A bus in sets Ω_G or Ω_L must satisfy the following requirements: (1) the bus with a higher value of $|A(l, i) \Delta P_i^c|$ is put into the sets prior to the bus with a lower one, and (2) it must not cause overload of any other branch. Following the requirements, buses are entered into the sets Ω_G or Ω_L until eqn. (6) is satisfied.

The flow diagram of generation rescheduling including load shifting is shown in Fig. 1.

2.2.2. Preventive control

Should a line outage at line k occur, the generation/load shift factor between overloaded branch l and bus i is

$$\hat{A}(l, i) = \frac{1}{x_l} (\hat{X}'_{ni} - \hat{X}'_{mi}) \quad (7)$$

where the symbol $\hat{}$ represents the outaged condition.

Elements $\hat{X}'_{ni}$ and $\hat{X}'_{mi}$ can be replaced by the elements X'_{ni} and X'_{mi} of the base case using the matrix inversion lemma:

$$\hat{X}'_{ni} = X'_{ni} + \frac{(X'_{pn} - X'_{qn})(X'_{pi} - X'_{qi})}{x_k - (X'_{pp} + X'_{qq} - 2X'_{pq})} \quad (8)$$

$$\hat{X}'_{mi} = X'_{mi} + \frac{(X'_{pm} - X'_{qm})(X'_{pi} - X'_{qi})}{x_k - (X'_{pp} + X'_{qq} - 2X'_{pq})} \quad (9)$$

where x_k is the reactance of line k , and p and q are the terminal buses of line k .

So,

$$\begin{aligned} \hat{A}(l, i) &= \frac{1}{x_l} (X'_{ni} - X'_{mi}) \\ &\quad + \frac{x_k}{x_l} \frac{(X'_{pn} - X'_{qn}) - (X'_{pm} - X'_{qm})}{x_k - (X'_{pp} + X'_{qq} - 2X'_{pq})} \\ &\quad \times \frac{1}{x_k} (X'_{pi} - X'_{qi}) \\ &= A(l, i) + D(l, k) A(k, i) \end{aligned} \quad (10) \quad (11a)$$

where $D(l, k)$ is the line outage distribution factor between lines l and k in a base case. The right-hand side of eqn. (10) is the so-called compensated generation/load shift factor. Since compensated factors are calculated using the X' matrix of the base case, they can be used for preventive control to alleviate violations due to a contingency.

Equation (11a) reveals that the combined effects of a line outage and generation/load shifting control can be obtained using superposition. That is to say,

$$\Delta P_l = [A(l, i) + D(l, k) A(k, i)] \Delta P_i \quad (11b)$$

$$= A(l, i) \Delta P_i + D(l, k) A(k, i) \Delta P_i \quad (11c)$$

$$= A(l, i) \Delta P_i + D(l, k) \Delta P_k \quad (11d)$$

Fig. 1. Generation/load shifting algorithm.

2.3. Line switching

2.3.1. Corrective control

The line outage distribution factor between overloaded branch l and dropping branch t is

$$D(l, t) = \frac{x_t X'_{rn} - X'_{sn}) - (X'_{rm} - X'_{sm})}{x_l x_t - (X'_{rr} + X'_{ss} - 2X'_{rs})} \quad (12)$$

where x_t is the reactance of line t , and r and s are the terminal buses of line t .

Only the lines corresponding to negative distribution factors can be selected for switching. The algorithm for switching is shown in Fig. 2.

Fig. 2. Line switching algorithm.

2.3.2. Preventive control

Should a line outage at line k occur, the distribution factor between overloaded branch l and switching line t ($k \neq t$) is

$$\hat{D}(l, t) = \frac{x_t (\hat{X}'_{rn} - \hat{X}'_{sn}) - (\hat{X}'_{rm} - \hat{X}'_{sm})}{x_l \quad x_t - (\hat{X}'_{rr} + \hat{X}'_{ss} - 2\hat{X}'_{rs})} \quad (13)$$

Substitution of the 'capped' values with 'uncapped' values gives

$$\begin{aligned} \hat{D}(l, t) = & \frac{x_t}{x_l} \{ [x_k - (X'_{pp} + X'_{qq} - 2X'_{pq})] \\ & \times [(X'_{rn} - X'_{sn}) - (X'_{rm} - X'_{sm})] \\ & + [(X'_{pn} - X'_{qn}) - (X'_{pm} - X'_{qm})] \\ & \times [(X'_{pr} - X'_{qr}) - (X'_{ps} - X'_{qs})] \} \\ & \times \{ [x_k - (X'_{pp} + X'_{qq} - 2X'_{pq})] \\ & \times [x_t - (X'_{rr} + X'_{ss} - 2X'_{rs})] \\ & - [(X'_{pr} - X'_{qr}) - (X'_{ps} - X'_{qs})]^2 \}^{-1} \quad (14) \end{aligned}$$

If

$$\begin{aligned} [x_k - (X'_{pp} + X'_{qq} - 2X'_{pq})] \\ \times [x_t - X'_{rr} - (X'_{rr} - X'_{ss} - 2X'_{rs})] \\ \gg [(X'_{pr} - X'_{qr}) - (X'_{ps} - X'_{qs})]^2 \end{aligned} \quad (15)$$

then $\hat{D}(l, t)$ can be rewritten as

$$\begin{aligned} \hat{D}(l, t) = & \frac{x_t (X'_{rn} - X'_{sn}) - (X'_{rm} - X'_{sm})}{x_l \quad x_t - (X'_{rr} + X'_{ss} - 2X'_{rs})} \\ & + \frac{x_k (X'_{pn} - X'_{qn}) - (X'_{pm} - X'_{qm})}{x_l \quad x_k - (X'_{pp} + X'_{qq} - 2X'_{pq})} \\ & \times \frac{x_t (X'_{rp} - X'_{sp}) - (X'_{rq} - X'_{sq})}{x_k \quad x_t - (X'_{rr} + X'_{ss} - 2X'_{rs})} \quad (16) \end{aligned}$$

$$= D(l, t) + D(l, k) D(k, t) \quad (17a)$$

Only under the condition of eqn. (15) can the combined effects of a line outage and a line switching be added directly, or

$$\Delta P_l = D(l, t) \Delta P_t + D(l, k) \Delta P_k \quad (17b)$$

However, the condition of eqn. (15) may not be satisfied for all possible switching lines. This is equivalent to saying that, in general, the effect on the power flow of tripping a line with another circuit out of service (as in the corrective case) and that of tripping two lines subsequently in the normal case (as in the preventive case) are not equal.

3. METHODOLOGY OF REACTIVE POWER CONTROL

In this section, the method of voltage control based on the linearized reactive power equations is considered. Control actions under consideration include generator voltage adjustment, transformer tap adjustment and capacitor/reactor switching. Although the tap and capacitor/reactor are discrete in nature, the analysis will be performed using the continuous approach. Thus, the closest integer to the computed value is used for discrete setting. In the rest of this section, the voltage at bus j is assumed to be relieved.

3.1. Generator remote voltage adjustment

3.1.1. Corrective control

The voltage change at PV bus i creates incremental reactive power injections, $b_{ui} \Delta V_i$, at each bus u connected to bus i . Using eqn. (4), the sensitivity factor between bus voltage V_j and bus voltage V_i is

$$S_{VV}(j, i) = \frac{\Delta V_j}{\Delta V_i} = \sum_u X''_{ju} b_{ui} \quad (18)$$

The direction of adjustment is easily decided according to the sign of the factor S_{VV} , and the control effort is the minimum of values between the voltage limit and $|\Delta V_j / S_{VV}(j, i)|$, where ΔV_j is the desired amount of correction. The voltage limit at PV bus i can be obtained either from experience or by comparing its Q limit and the reactive generation change, where

$$\Delta Q_i = V_i \sum b_{iu} \Delta V_u + V_i \Delta V_i b_{ii} \quad (19)$$

The flow diagram of generator voltage adjustment is shown in Fig. 3.

3.2.1. Preventive control

In order to derive the compensated factors S_{VV} for preventive control, two types of sensitivity factor are defined first. Sensitivity factor $S_{jV}(k, i)$ refers to the change in reactive flow in line k with a change in bus voltage V_i , and sensitivity factor $S_{Vj}(j, k)$ refers to the change in bus voltage V_j with the base-case reactive flow in line k (J_k). It is shown in the Appendix that

$$S_{jV}(k, i) = \sum_u (X''_{pu} - X''_{qu}) b_{iu} \quad (20)$$

Fig. 3. The algorithm for generator voltage adjustment.

and

$$S_{VJ}(j, k) = \frac{X_{jp}'' - X_{jq}''}{1 - b_{pq}(X_{pp}'' + X_{qq}'' - 2X_{pq}'')} \quad (21)$$

Following these relations, the compensated factor $\hat{S}_{VV}(j, i)$ for the contingency of a line k outage can be expressed as

$$\hat{S}_{VV}(j, i) = S_{VV}(j, i) + S_{VJ}(j, k) S_{JV}(k, i) \quad (22)$$

Equation (22) reveals that the combined effect of this type of sensitivity factor can be calculated using superposition.

Figure 3 can be used directly for preventive control by replacing factor S_{VV} with factor $\hat{S}_{VV}$.

3.2. Transformer tap adjustment

3.2.1. Corrective control

Let the tap of a transformer in line l , having terminal buses n and m , be used for correcting the voltage at bus j . The tap increment, Δt_l , creates incremental reactive

power injections $-\Delta t_l b_{nm}$ and $\Delta t_l b_{nm}$ at the n and m buses, respectively. Then, by eqn. (4), the sensitivity factor relating a change in bus voltage ΔV_j to a change in the tap of a transformer in line l , Δt_l , can be calculated as

$$S_{VT}(j, l) = \frac{\Delta V_j}{\Delta t_l} = (X_{jn}'' - X_{jm}'') b_{nm} \quad (23)$$

The algorithm in Fig. 3 can also be used for tap adjustment with slight modifications.

3.2.2. Preventive control

It is easy to show that

$$\hat{S}_{VT}(j, l) = S_{VT}(j, l) + S_{VJ}(j, k) S_{JT}(k, l) \quad (24)$$

where line k is the outaged line, and the sensitivity factor $S_{JT}(k, l)$ refers to the change of reactive flow in line k with a change of transformer tap at branch l .

3.3. Capacitor/reactor (shunt device) switching

3.3.1. Corrective control

From eqn. (4), the sensitivity factor relating the change in bus voltage V_j to a change of shunt admittance at bus i is

$$S_{VS}(j, i) = \frac{\Delta V_j}{\Delta b_j} = X_{ji}'' \quad (25)$$

Figure 3 can still be applied for shunt device switching with slight modifications.

3.3.2. Preventive control

It is easy to show that

$$\hat{S}_{VS}(j, i) = S_{VS}(j, i) + S_{VJ}(j, k) S_{JS}(k, i) \quad (26)$$

where line k represents the line outage contingency and the sensitivity factor $S_{JS}(k, i)$ refers to the change of reactive flow in line k with a change of shunt admittance at bus i (see Appendix).

4. EXAMPLES AND RESULTS

4.1. Description of the study system

The system under study is the Taiwan power (Taipower) system which consists of 23 generators, 195 buses and 251 branches. Of the 251 branches, 97 were transformers with in-phase taps. There are no phase shifters in the system. Most of the generators are geographically located in the northern and southern areas of Taiwan. The heavy lines in the one-line diagram depicted in Fig. 4 indicate the

Fig. 4. One-line diagram of Taiwan power system.

345 kV trunk lines, and the remaining lines are the 161 kV lines. The load level of the base case with all constraints satisfied is 7920.7 MW. In the following discussions, steady-state security control will be performed for the contingencies which cause either system overloads or voltage violations. The contingencies which were selected using the contingency selection algorithm are shown in Table 1.

4.2. Real power security control

There are two contingencies to be considered, one with a branch which is 102% loaded and the other with two branches which are 108.7% and 120.5% loaded, respectively. Various control actions determined by the sensitivity-based approach are tried to alleviate the

TABLE 1

Study cases

(a) Contingencies having overload problems

Outaged branch	Violations (MW%)
1009 - 1069	416 - 419 (102%)
115 - 1001	511 - 514 (120.5%)
	1009 - 1069 (108.7%)

(b) Contingencies having voltage problems

Outaged branch	Violations (V_{pu})
28 - 629	630 (0.9389), 629 (0.9399) 623 (0.9492)
346 - 416	803 (0.9353), 819 (0.9355) 412 (0.9357), 809 (0.9391) 827 (0.9395), 407 (0.9396) 805 (0.9400), 801 (0.9421) 416 (0.9428), 807 (0.9436) 1065 (0.9482), 810 (0.9498)

TABLE 2

Generation/load shift factors

(a) Outaged branch: 1009 - 1069

Generation shift factors

Bus No.	Value	Bus No.	Value
112	-0.5950	10	-0.0365
199	-0.5950	33	-0.0364
30	-0.0702	34	-0.0364
29	-0.0702	35	-0.0364
26	-0.0426	3	-0.0354
9	-0.0365	4	-0.0354

Load shift factors

Bus No.	Value	Bus No.	Value
814	-0.5950	410	-0.5575
808	-0.5652	806	-0.5524
820	-0.5575	828	-0.4405
810	-0.5575	848	-0.4063
415	-0.5575	804	-0.3880

(b) Outaged branch: 115 - 1001

Generation shift factors

Bus No.	Value	Bus No.	Value
223	-0.1605	221	-0.1496
220	-0.1496	222	-0.1496

Load shift factors

Bus No.	Value	Bus No.	Value
1002	-0.7089	1040	-0.2063
1004	-0.7089	1069	-0.2063
1006	-0.7089	1070	-0.2063
1008	-0.7089	525	-0.1605
1012	-0.7089	1020	-0.1605
1026	-0.7089	1022	-0.1605
1028	-0.7089	1036	-0.1605
1066	-0.7089	1010	-0.1586
1094	-0.7089	1044	-0.1586
1024	-0.2376	1018	-0.1496

TABLE 3

Comparison between exact and approximate distribution factors

(a) Outaged branch: 1009 - 1069

Dropping branch	Exact value	Approximate value
115 - 1001	-0.8042	-0.8015
107 - 625	-0.5832	-0.5832
347 - 349	-0.4619	-0.4619
346 - 416	-0.2906	-0.2906
417 - 807	-0.1993	-0.1993

(b) Outaged branch: 115 - 1001

Dropping branch	Exact value	Approximate value
512 - 1023	-1.0000	-0.9494
522 - 524	-0.3649	-0.3601
527 - 529	-0.2020	-0.2013
1023 - 1069	-0.1725	-0.1718
522 - 1019	-0.0019	-0.0020

overloads. The sensitivity factors corresponding to the generation shift, load shift and line switching controls are listed in Tables 2 and 3. From Table 2, it can be seen that, with generation rescheduling only, the case having slight overloading can be corrected completely but the severe case fails, unless load shifting is permitted. The validity of the corrections can be proved by testing an AC power flow, the results of which are shown in Table 7. From Table 3, it seems that it is possible to use line switching for alleviating overloads. But in fact it cannot be accepted even for the less severe case, because line switching is always accompanied by voltage violations, as can be seen in Table 7.

It has been mentioned in §2.3.2 that the compensated distribution factors defined in eqn. (10) are not equal to the exact distribution factors used for preventive control. However, the results shown in Table 3 reveal that there is no significant difference for those switching lines having higher values of the distribution factors.

4.3. Reactive power security control

Two contingencies, one with voltage violations at three buses and the other with voltage violations at twelve buses, are considered. Sensitivity factors corresponding to the generator remote voltage control, transformer tap adjustment and capacitor/reactor switching are shown in Tables 4, 5 and 6, respectively.

TABLE 4

Generator voltage sensitivity factors

(a) Outaged branch: 28 - 629

PV bus No.	Value	PV bus No.	Value
9	0.1291	35	0.0677
10	0.1291	112	0.0450
3	0.1026	237	0.0445
4	0.1026	238	0.0443
33	0.0677	30	0.0293
34	0.0677	223	0.0287

(b) Outaged branch: 346 - 416

PV bus No.	Value	PV bus No.	Value
9	0.09057	238	0.06899
10	0.09057	30	0.06129
112	0.07850	29	0.05051
3	0.07046	199	0.04918
4	0.07046	33	0.04743
237	0.06928	34	0.04743

TABLE 5

Transformer tap sensitivity factors

(a) Outaged branch: 28 - 629

Transformer circuit	Value	Transformer circuit	Value
629 - 630	1.0000	311 - 314	-0.0329
346 - 349	0.8193	813 - 814	-0.0282
416 - 417	0.0571	521 - 524	-0.0224
326 - 329	-0.0446	521 - 529	-0.0207

(b) Outaged branch: 346 - 416

Transformer circuit	Value	Transformer circuit	Value
346 - 349	0.3818	521 - 524	-0.0312
416 - 417	0.2720	521 - 529	-0.0298
813 - 814	-0.0478	326 - 329	-0.0091
511 - 512	0.0461	311 - 314	-0.0001

TABLE 6

Capacitor/reactor sensitivity factors

(a) Outaged branch: 28 - 629

Bus No.	Value	Bus No.	Value
630	0.0582	802	0.0094
624	0.0231	804	0.0079
626	0.0104	808	0.0076

(b) Outaged branch: 346 - 416

Bus No.	Value	Bus No.	Value
804	0.0278	810	0.0121
848	0.0230	415	0.0121
802	0.0164	410	0.0121
806	0.0130	820	0.0121

TABLE 7

Validity of control actions

(a) Overload problems

Outaged branch	Generation rescheduling	Gen./load shift	Line switching
1009 - 1069	O.K.	Not necessary	Divergent
115 - 1001	O.K.	O.K.	Divergent

(b) Voltage problems

Outaged branch	Gen. voltage control	Transformer tap control	Capacitor/reactor switching
28 - 629	O.K.	O.K.	O.K.
346 - 416	O.K.	O.K.	O.K.

As can be seen in Table 7, these control actions are all valid for alleviating violations of two contingencies. Hence, the approach based on the linearized reactive power flow equations is suitable for voltage correction.

5. CONCLUSIONS

A fast algorithm for steady-state security control is presented in this paper. The algorithm, based on sensitivity analysis, has the ability to handle both overload and voltage problems. The control actions under consideration include generation rescheduling, load shifting, line switching, generator voltage adjustment, transformer tap adjustment and capacitor/reactor switching. It can be concluded from the study of Taiwan power system that the corrections made by the proposed method are successful for eliminating system abnormalities.

Compensated sensitivity factors, used for preventive control, with respect to various control actions are carefully examined in this study. It is found that the combined effects of a line outage contingency and a line switching correction cannot simply be added by superposition.

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APPENDIX

Derivation of $S_{JV}(k, i)$

By definition

$$S_{JV}(k, i) \triangleq \frac{\Delta J_k}{\Delta V_i} \quad (\text{A-1})$$

where J_k is the reactive flow in line k and V_i is the voltage at bus i . Based on the linearized model and assuming the tap ratios in a base are 1.0 per unit, the incremental reactive flow ΔJ_k can be calculated as

$$\Delta J_k = (\Delta V_p - \Delta V_q) b_{pq} \quad (\text{A-2})$$

where p and q are the terminal buses of line k , and b_{pq} is the susceptance of line k .

Also, eqn. (17) gives

$$\Delta V_p = \sum_u X''_{pu} b_{iu} \Delta V_i \quad (\text{A-3})$$

$$\Delta V_q = \sum_u X''_{qu} b_{iu} \Delta V_i \quad (\text{A-4})$$

where u is the bus connected to bus i .

Substitution of eqns. (A-2) and (A-3) into (A-1) gives

$$S_{JV}(k, i) = \sum_u (X''_{pu} - X''_{qu}) b_{iu} b_{pq} \quad (\text{A-5})$$

Derivation of $S_{VJ}(j, k)$

By definition

$$S_{VJ}(j, k) \triangleq \frac{\Delta V_j}{J_k} \quad (\text{A-6})$$

where V_j is the voltage at bus i and J_k is the base-case reactive flow in line k . The outage at line k can be simulated with injections ΔQ_p and ΔQ_q at buses p and q , respectively. The outage modeling criterion requires

$$\Delta Q_p = -\Delta Q_q = \hat{J}_k \quad (\text{A-7})$$

where the symbol $\hat{}$ refers to the condition where the outaged line is still left in the system and the injections are imposed.

The voltage changes can be calculated using eqns. (4) and (A-7):

$$\begin{aligned} \Delta V_p &= X''_{pp} \Delta Q_p + X''_{pq} \Delta Q_q \\ &= (X''_{pp} - X''_{pq}) \Delta Q_p \end{aligned} \quad (\text{A-8})$$

$$\begin{aligned} \Delta V_q &= X''_{pq} \Delta Q_p + X''_{qq} \Delta Q_q \\ &= (X''_{pq} - X''_{qq}) \Delta Q_p \end{aligned} \quad (\text{A-9})$$

$$\begin{aligned} \Delta V_j &= X''_{jp} \Delta Q_p + X''_{jq} \Delta Q_q \\ &= (X''_{jp} - X''_{jq}) \Delta Q_p \end{aligned} \quad (\text{A-10})$$

But

$$\hat{J}_k = b_{pq}(\hat{V}_p - \hat{V}_q) \quad (\text{A-11})$$

$$= b_{pq}(V_p - V_q) + b_{pq}(\Delta V_p - \Delta V_q) \quad (\text{A-12})$$

$$= J_k + b_{pq}(\Delta V_p - \Delta V_q) \quad (\text{A-13})$$

Substitution of eqns. (A-7), (A-8) and (A-9) into (A-12) gives

$$\Delta Q_p = \frac{1}{1 - b_{pq}(X''_{pp} + X''_{qq} - 2X''_{pq})} J_k \quad (\text{A-14})$$

After combining eqns. (A-10) and (A-14),

$$\begin{aligned} S_{VJ}(j, k) &= \frac{\Delta V_j}{J_k} \\ &= \frac{X''_{jp} - X''_{jq}}{1 - b_{pq}(X''_{pp} + X''_{qq} - 2X''_{pq})} \end{aligned} \quad (\text{A-15})$$

Derivation of $S_{JS}(k, i)$

By definition

$$S_{JS}(k, i) \triangleq \frac{\Delta J_k}{\Delta b_i} \quad (\text{A-16})$$

where b_i is the shunt admittance at bus i .

Since

$$\Delta b_i = V_i^2 \Delta Q_i \cong \Delta Q_i \quad (\text{A-17})$$

from eqn. (4),

$$\Delta V_p = X''_{pi} \Delta Q_i \quad (\text{A-18})$$

$$\Delta V_q = X''_{qi} \Delta Q_i \quad (\text{A-19})$$

Substitution of eqns. (A-18) and (A-19) into (A-2) gives

$$S_{JS}(k, i) = (X''_{pi} - X''_{qi}) b_{pq} \quad (\text{A-20})$$

Derivation of $S_{JT}(k, l)$

By definition

$$S_{JT}(k, l) \triangleq \frac{\Delta J_k}{\Delta t_l} \quad (\text{A-21})$$

where t_l is the tap of the transformer at branch l .

Combining eqns. (A-2) and (23),

$$S_{JT}(k, l) = [(X''_{pn} - X''_{pm}) - (X''_{qn} - X''_{qm})] b_{pq} b_{nm} \quad (\text{A-22})$$