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
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 violations; (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:

\[
\begin{align*}
B' \Delta \theta &= \Delta P \\
B' \Delta V &= \Delta Q \quad (1)
\end{align*}
\]

where \( \Delta P \) and \( \Delta Q \) are vectors of real and reactive power changes, \( \Delta \theta \) and \( \Delta V \) vectors of changes in voltage angles and magnitudes,

\[
\begin{align*}
B'_{ij} &= \frac{1}{x_{ij}}, & B'_{ii} &= \sum (1/x_{ij}) \\
B''_{ij} &= b_{ij}, & B''_{ii} &= -\sum b_{ij} - SH_i
\end{align*}
\]

\( x_{ij} \) 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 \( B' \) and \( B'' \) are real, symmetric and sparse but in different dimensions since the swing bus is excluded from \( B' \) and PV buses are excluded from \( B'' \). 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

\[
\begin{align*}
\Delta \theta &= X' \Delta P \\
\Delta V &= X'' \Delta Q \quad (3)
\end{align*}
\]

where \( X' \) and \( X'' \) are the sparse inverses of \( B' \) and \( B'' \), 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:

\[
A(l, i) = \frac{1}{x_l} (X'_{ni} - X_{mi})
\]

(5)

where \( X'_{ni} \) and \( X_{mi} \) are elements of \( X' \), \( x_l \) 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

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

(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 \( m \), \( \Omega_G \) the set of adjustable generator buses, \( \Omega_L \) the set of adjustable load buses, \( \Delta P_i \) the change in injected power at generator bus \( i \), and \( \Delta P_j \) 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 (\( \Delta P_i^\text{c} \)) 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 \( \Omega_G \) and \( \Omega_L \). Clearly, \( \Omega_L \) will be an empty set if load shifts are avoided, and generation rescheduling is executed prior to load shifting. A bus in sets \( \Omega_G \) or \( \Omega_L \) must satisfy the following requirements: (1) the bus with a higher value of \( |A(l, i)\Delta P_i^\text{c}| \) 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 \( \Omega_G \) or \( \Omega_L \) 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 over-loaded branch \( l \) and bus \( i \) is

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

(7)

where the symbol \( \hat{\cdot} \) 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:

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

(8)

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

(9)

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

So,

\[
\hat{A}(l, i) = \frac{1}{x_k} (X'_{ni} - X_{mi})
\]

\[
+ \frac{x_k (X'_{pn} - X'_{qn}) - (X'_{pm} - X'_{qm})}{x_k - (X'_{pp} + X'_{qq} - 2X'_{pq})} 
\]

\[
\times \frac{1}{x_k} (X'_{pi} - X'_{qi})
\]

(10)

\[
= A(l, i) + D(l, k) A(k, i)
\]

(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,

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

(11b)

\[
= A(l, i) \Delta P_i + D(l, k) A(k, i) \Delta P_i
\]

(11c)

\[
= A(l, i) \Delta P_i + D(l, k) \Delta P_k
\]

(11d)
2.3. Line switching

2.3.1. Corrective control

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

$$D(i, t) = \frac{x_t (X'_{rn} - X'_{sn}) - (X_{rm} - X_{sm})}{x_t - (X'_{rn} + X'_{sn} - 2X'_{rs})}$$  \hspace{1cm} (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. 1. Generation/load shifting algorithm.

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

\[
\hat{D}(l, t) = \frac{x_t}{x_l} \left[ (X_{rn} - X_{sn}) - (X_{rm} - X_{sm}) \right] \\
+ \left[ (X_{pn} - X_{qs}) - (X_{pm} - X_{qm}) \right] \\
- \left[ (X_{pr} - X_{qr}) - (X_{ps} - X_{qs}) \right]^2 \quad (13)
\]

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

\[
\hat{D}(l, t) = \frac{x_t}{x_l} \left[ (X_k - (X_{pp} + X_{qq} - 2X_{pq})] \\
\times \left[ (X_{rn} - X_{sn}) - (X_{rm} - X_{sm}) \right] \\
+ \left[ (X_{pn} - X_{qs}) - (X_{pm} - X_{qm}) \right] \\
\times \left[ (X_{pr} - X_{qr}) - (X_{ps} - X_{qs}) \right] \\
\times \left[ x_t - (X_{rr} + X_{rs} - 2X_{rs}) \right] \\
- \left[ (X_{pr} - X_{qr}) - (X_{ps} - X_{qs}) \right]^2 \quad (14)
\]

If

\[
[x_k - (X_{pp} + X_{qq} - 2X_{pq})] \\
\times [x_t - X_{rr} - (X_{rr} - X_{rs} - 2X_{rs})] \\
\geq \left[ (X_{pr} - X_{qr}) - (X_{ps} - X_{qs}) \right]^2 \quad (15)
\]

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

\[
\hat{D}(l, t) = \frac{x_t}{x_l} \left[ (X_{rn} - X_{sn}) - (X_{rm} - X_{sm}) \right] \\
+ \left[ (X_{pn} - X_{qs}) - (X_{pm} - X_{qm}) \right] \\
\times \left[ x_t - (X_{rr} + X_{rs} - 2X_{rs}) \right] \\
= D(l, t) + D(l, k) D(k, t) \quad (17a)
\]

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

\[
\Delta P_t = \hat{D}(l, t) \Delta P_l + D(l, k) \Delta P_k \quad (17b)
\]

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

\[
S_{VV}(j, i) = \frac{\Delta V_j}{\Delta V_i} = \sum_u X_{pu} b_{ui} \quad (18)
\]

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 \( |\Delta V_i|/S_{VV}(j, i)| \), where \( \Delta V_i \) 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

\[
\Delta Q_i = V_i \sum_i b_{ui} \Delta V_u + V_i \Delta V_i b_{ii} \quad (19)
\]

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 \( S_{VV}(j, k) \) 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

\[
S_{JV}(k, i) = \sum_u (X_{pu} - X_{qu}) b_{iu} \quad (20)
\]
Designate worst voltage violated bus as j

Specify the desired correction $\Delta V_j$

Calculate $S_{VV}(j, i)$, i.e. PV bus

Calculate $\Delta V_i$ and determine its direction

Order candidate list by $|S_{VV}(j, i)| \Delta V_i$ (i): ordered i

(i) = (i) + 1

Any other bus voltage violation?

Yes

Insufficient correction

No

$\sum S_{VV}(j, i) | \Delta V_i | = | \Delta V_j |

Last PV bus?

Yes

Gen. voltage adjustment list

No

Fig. 3. The algorithm for generator voltage adjustment.

and

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

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

$$\hat{S}_{VV}(j, i) = S_{VV}(j, i) + S_{VJ}(j, k) S_{JT}(k, l) \tag{22}$$

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, $\Delta t_l$, 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 $\Delta V_j$ to a change in the tap of a transformer in line l, $\Delta t_l$, can be calculated as

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

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

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

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

$$S_{VS}(j, i) = \frac{\Delta V_j}{\Delta b_j} = X''_{ji} \tag{25}$$

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

3.3.2. Preventive control

It is easy to show that

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

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
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

<table>
<thead>
<tr>
<th>Study cases</th>
<th>Violations (MW%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Contingencies having overload problems</td>
<td></td>
</tr>
<tr>
<td>Outaged branch</td>
<td>416 - 419 (102%)</td>
</tr>
<tr>
<td>1009 - 1069</td>
<td></td>
</tr>
<tr>
<td>115 - 1001</td>
<td></td>
</tr>
<tr>
<td>1009 - 1069 (108.7%)</td>
<td></td>
</tr>
<tr>
<td>(b) Contingencies having voltage problems</td>
<td></td>
</tr>
<tr>
<td>Outaged branch</td>
<td>Violations (Vpu)</td>
</tr>
<tr>
<td>28 - 629</td>
<td>630 (0.9389), 629 (0.9399)</td>
</tr>
<tr>
<td>346 - 416</td>
<td>803 (0.9353), 819 (0.9355)</td>
</tr>
<tr>
<td></td>
<td>412 (0.9357), 809 (0.9391)</td>
</tr>
<tr>
<td></td>
<td>827 (0.9395), 407 (0.9396)</td>
</tr>
<tr>
<td></td>
<td>805 (0.9400), 801 (0.9421)</td>
</tr>
<tr>
<td></td>
<td>416 (0.9428), 807 (0.9436)</td>
</tr>
<tr>
<td></td>
<td>1065 (0.9482), 810 (0.9498)</td>
</tr>
</tbody>
</table>

### 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 | -0.0364 |
| 9 | -0.0965 | 4 | -0.0364 |

| 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 |

<table>
<thead>
<tr>
<th>(b) Outaged branch: 115 - 1001</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Generation shift factors</td>
<td></td>
</tr>
<tr>
<td>Bus No.</td>
<td>Value</td>
</tr>
<tr>
<td>223</td>
<td>-0.1496</td>
</tr>
<tr>
<td>220</td>
<td>-0.1496</td>
</tr>
</tbody>
</table>

| 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 | 555 | -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

<table>
<thead>
<tr>
<th>Dropping branch</th>
<th>Exact value</th>
<th>Approximate value</th>
</tr>
</thead>
<tbody>
<tr>
<td>115 - 1001</td>
<td>-0.8042</td>
<td>-0.8015</td>
</tr>
<tr>
<td>107 - 625</td>
<td>-0.5832</td>
<td>-0.5832</td>
</tr>
<tr>
<td>347 - 349</td>
<td>-0.4619</td>
<td>-0.4619</td>
</tr>
<tr>
<td>346 - 416</td>
<td>-0.2906</td>
<td>-0.2906</td>
</tr>
<tr>
<td>417 - 807</td>
<td>-0.1993</td>
<td>-0.1993</td>
</tr>
</tbody>
</table>

(b) Outaged branch: 115 - 1001

<table>
<thead>
<tr>
<th>Dropping branch</th>
<th>Exact value</th>
<th>Approximate value</th>
</tr>
</thead>
<tbody>
<tr>
<td>512 - 1023</td>
<td>-1.0000</td>
<td>-0.9494</td>
</tr>
<tr>
<td>522 - 524</td>
<td>-0.3649</td>
<td>-0.3601</td>
</tr>
<tr>
<td>527 - 529</td>
<td>-0.2020</td>
<td>-0.2013</td>
</tr>
<tr>
<td>1023 - 1069</td>
<td>-0.1725</td>
<td>-0.1718</td>
</tr>
<tr>
<td>522 - 1019</td>
<td>-0.0019</td>
<td>-0.0020</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>PV bus No.</th>
<th>Value</th>
<th>PV bus No.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0.1291</td>
<td>35</td>
<td>0.0677</td>
</tr>
<tr>
<td>10</td>
<td>0.1291</td>
<td>112</td>
<td>0.0450</td>
</tr>
<tr>
<td>3</td>
<td>0.1026</td>
<td>237</td>
<td>0.0445</td>
</tr>
<tr>
<td>4</td>
<td>0.1026</td>
<td>238</td>
<td>0.0443</td>
</tr>
<tr>
<td>33</td>
<td>0.0677</td>
<td>30</td>
<td>0.0293</td>
</tr>
<tr>
<td>34</td>
<td>0.0677</td>
<td>223</td>
<td>0.0287</td>
</tr>
</tbody>
</table>

(b) Outaged branch: 346 - 416

<table>
<thead>
<tr>
<th>PV bus No.</th>
<th>Value</th>
<th>PV bus No.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>0.09057</td>
<td>238</td>
<td>0.06899</td>
</tr>
<tr>
<td>10</td>
<td>0.09057</td>
<td>30</td>
<td>0.06129</td>
</tr>
<tr>
<td>112</td>
<td>0.07850</td>
<td>29</td>
<td>0.05051</td>
</tr>
<tr>
<td>3</td>
<td>0.07046</td>
<td>199</td>
<td>0.04918</td>
</tr>
<tr>
<td>4</td>
<td>0.07046</td>
<td>33</td>
<td>0.04743</td>
</tr>
<tr>
<td>237</td>
<td>0.06928</td>
<td>34</td>
<td>0.04743</td>
</tr>
</tbody>
</table>

TABLE 5
Transformer tap sensitivity factors
(a) Outaged branch: 28 - 629

<table>
<thead>
<tr>
<th>Transformer circuit</th>
<th>Value</th>
<th>Transformer circuit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>629 - 630</td>
<td>1.0000</td>
<td>311 - 314</td>
<td>-0.0329</td>
</tr>
<tr>
<td>346 - 349</td>
<td>0.8193</td>
<td>813 - 814</td>
<td>-0.0282</td>
</tr>
<tr>
<td>416 - 417</td>
<td>0.0677</td>
<td>521 - 524</td>
<td>-0.0224</td>
</tr>
<tr>
<td>326 - 329</td>
<td>-0.0446</td>
<td>521 - 529</td>
<td>-0.0207</td>
</tr>
</tbody>
</table>

(b) Outaged branch: 346 - 416

<table>
<thead>
<tr>
<th>Transformer circuit</th>
<th>Value</th>
<th>Transformer circuit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>346 - 349</td>
<td>0.3818</td>
<td>521 - 524</td>
<td>-0.0312</td>
</tr>
<tr>
<td>416 - 417</td>
<td>0.2720</td>
<td>521 - 529</td>
<td>-0.0298</td>
</tr>
<tr>
<td>813 - 814</td>
<td>-0.0478</td>
<td>326 - 329</td>
<td>-0.0091</td>
</tr>
<tr>
<td>511 - 512</td>
<td>0.0481</td>
<td>311 - 314</td>
<td>-0.0001</td>
</tr>
</tbody>
</table>

TABLE 6
Capacitor/reactor sensitivity factors
(a) Outaged branch: 28 - 629

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Value</th>
<th>Bus No.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>630</td>
<td>0.0562</td>
<td>802</td>
<td>0.0094</td>
</tr>
<tr>
<td>624</td>
<td>0.0231</td>
<td>804</td>
<td>0.0079</td>
</tr>
<tr>
<td>626</td>
<td>0.0104</td>
<td>808</td>
<td>0.0076</td>
</tr>
</tbody>
</table>

(b) Outaged branch: 346 - 416

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Value</th>
<th>Bus No.</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>804</td>
<td>0.0278</td>
<td>810</td>
<td>0.0121</td>
</tr>
<tr>
<td>848</td>
<td>0.0230</td>
<td>415</td>
<td>0.0121</td>
</tr>
<tr>
<td>802</td>
<td>0.0164</td>
<td>410</td>
<td>0.0121</td>
</tr>
<tr>
<td>806</td>
<td>0.0130</td>
<td>820</td>
<td>0.0121</td>
</tr>
</tbody>
</table>
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.

REFERENCES


APPENDIX

Derivation of $S_{J,V}(k, i)$

By definition

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

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 $\Delta J_k$ can be calculated as

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

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

Also, eqn. (17) gives

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

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

where $u$ is the bus connected to bus $i$.

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

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

Derivation of $S_{V,J}(j, k)$

By definition

$$S_{V,J}(j, k) \triangleq \frac{\Delta V_j}{J_k} \quad (A-6)$$
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 $\Delta Q_p$ and $\Delta Q_q$ at buses $p$ and $q$, respectively. The outage modeling criterion requires

$$\Delta Q_p = -\Delta Q_k = \hat{J}_k$$  \hspace{1cm} (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):

$$\Delta V_p = X''_{pp} \Delta Q_p + X''_{pq} \Delta Q_q$$  \hspace{1cm} (A-8)

$$\Delta V_q = X''_{qp} \Delta Q_p + X''_{qq} \Delta Q_q$$  \hspace{1cm} (A-9)

$$\Delta V_j = X''_{jp} \Delta Q_p + X''_{jq} \Delta Q_q$$  \hspace{1cm} (A-10)

But

$$\hat{J}_k = b_{pq}(\hat{V}_p - \hat{V}_q)$$  \hspace{1cm} (A-11)

$$= b_{pq}(V_p - V_q) + b_{pq}(\Delta V_p - \Delta V_q)$$  \hspace{1cm} (A-12)

$$= J_k + b_{pq}(\Delta V_p - \Delta V_q)$$  \hspace{1cm} (A-13)

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

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

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

$$S_{\nu,j}(j, k) = \frac{\Delta V_j}{J_k}$$

$$= \frac{X''_{jp} - X''_{jq}}{1 - b_{pq}(X''_{pp} + X''_{qq} - 2X''_{pq})}$$  \hspace{1cm} (A-15)

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

By definition

$$S_{JS}(k, i) \triangleq \frac{\Delta J_k}{\Delta b_i}$$  \hspace{1cm} (A-16)

where $b_i$ is the shunt admittance at bus $i$.

Since

$$\Delta b_i = V_i^2 \Delta Q_i \cong \Delta Q_i$$  \hspace{1cm} (A-17)

from eqn. (4),

$$\Delta V_p = X''_{pi} \Delta Q_i$$  \hspace{1cm} (A-18)

$$\Delta V_q = X''_{qi} \Delta Q_i$$  \hspace{1cm} (A-19)

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

$$S_{JS}(k, i) = (X''_{pi} - X''_{qi}) b_{pq}$$  \hspace{1cm} (A-20)

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

By definition

$$S_{JT}(k, l) \triangleq \frac{\Delta J_k}{\Delta t_l}$$  \hspace{1cm} (A-21)

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

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

$$S_{JT}(k, l) = [(X''_{pn} - X''_{pm}) - (X''_{qn} - X''_{qm})] b_{pq} b_{nm}$$  \hspace{1cm} (A-22)