Abstract- In this paper, an efficient voltage stability contingency ranking method without screening including unstable contingencies is proposed. The concept of the advanced power flow compensation is introduced for the fast N-1 contingency computation. The rapid derivation of the estimated necessary load shedding amount is also used for the voltage stability contingency ranking including unstable contingencies. The proposed ranking method can arrange contingency cases in descending order based on the severity of voltage stability index and the necessary load shedding amount for stabilizing unstable contingencies. The performance of the proposed ranking method is validated via the test calculations on a 6-bus model system and a 30-bus model system.

Index Terms-- Power flow, load shedding, N-1, contingency, ranking, voltage stability index.

I. INTRODUCTION

Although there have been much researches of voltage stability, less attention has been paid to voltage stability contingency ranking methods. It should be noted that N-1 contingency in this paper is given by opening a faulted line on a double circuit lines without a ground fault. The proposed ranking method makes it possible to arrange contingency cases in descending order according to the severity of voltage stability index and the amount of load shedding, although unstable load buses are included in contingency cases. The proposed ranking method has three characteristics. The first one is to improve the efficiency for the N-1 contingency computation. The second one is to estimate the necessary load shedding amount for voltage collapse contingency cases. The final one is to propose the index for the voltage stability contingency ranking. The conventional researches have been conducted for the above characteristics individually. As for the rapidness of the contingency computation, voltage flow sensitivity coefficient is widely applied [1-3]. However, the estimated accuracy of the solutions for voltage stability limit case would be low. As for the load shedding approach, various techniques such as AI techniques are applied [4-9]. However, pre-processing for the designated power system is required for any conventional approach, which has less applicability for the real power system. As for the N-1 ranking method, the voltage stability margin obtained from P-V curve is widely used for the index of voltage stability contingency ranking. However, several number of power flow calculations are necessary to obtain the P-V curve for the conventional approach, which are hardly applied to the N-1 contingency analysis in bulk power system. The proposed ranking method considers these three characteristics simultaneously and enhances the efficiency of deriving the voltage stability contingency ranking using a concept of advanced power flow compensation and some other small innovations. The remaining portion of this paper is organized as follows. The flow of the proposed contingency method is described in Section II. The derivation of bus voltages for N-1 contingencies based on a concept of power flow compensation is presented in Section III. The proposed N-1 ranking method including voltage collapse contingency cases is introduced in Section IV. The validity of the proposed ranking method using test model systems is examined in Section V. The future work is discussed in Section VI.

II. FLOW OF THE PROPOSED CONTINGENCY METHOD

In order to propose a new voltage stability contingency ranking method, the following assumptions are introduced in this paper.

i) Only long-term voltage stability is considered. In other words, transient voltage stability is outside of our scope. The basic calculation consists of power flow calculation using Newton-Raphson (N-R) method.

ii) Severity of the voltage stability is evaluated by the minimum voltage stability margin from the margins at all the load buses for each N-1 contingency case.

iii) Magnitude of the estimated load shedding amount which is denoted by \( \Delta P_{\text{cut}} \) required for stabilizing unstable load buses is closely related to the severity of voltage stability.

Fig. 1 shows the general diagram of the proposed contingency method which consists of the following 4 steps.

Step 1: In order to obtain post-contingency voltage solutions for N-1 contingencies efficiently, the estimated post-contingency voltages are calculated applying the power flow sensitivity coefficient \( \alpha \) to the pre-contingency Jacobian matrix.
Step 2: With the above post-contingency voltage solutions, the voltage stability indices for each contingency case are calculated, and evaluated whether the contingency case is stable or collapse.

Step 3: In case of the stable contingency case, the \( V_{P_{\text{idx}}} \) of the load bus which gives the least voltage stability margin is treated as the severity of the contingency case.

Step 4: If the contingencies case is voltage collapse, the necessary load shedding amount for stabilizing unstable contingencies is estimated.

III. DERIVATION OF BUS VOLTAGES FOR N-1 CONTINGENCY BASED ON THE INTRODUCTION OF THE CONCEPT OF THE ADVANCED POWER FLOW COMPENSATION

The compensation sensitivity coefficient \( \alpha \) for N-1 contingency can be calculated using DC method approximately as shown in Equation (1), which is described in detail in reference [11].

\[
\alpha = \frac{yE}{P} = \frac{1}{1 - y(Z_{se} + Z_{re} - 2Z_{se})} \tag{1}
\]

where
- \( y \): the admittance between two buses
- \( E \): the equivalent voltage source
- \( P \): the power transfer from one bus to another bus
- \( Z_{se} \): the driving-point impedance matrix for a sending end
- \( Z_{re} \): the driving-point impedance matrix for a receiving end
- \( X_{se} \): the transfer impedance matrix between a sending end and a receiving end

When the compensation sensitivity coefficient is applied to the Jacobian, the increase in Q loss which denotes reactive power loss in post-contingency has to be considered. The DC method is basically known as a calculation considering the change of active power \( \Delta P \) in post-fault contingency. Because the increment of the active power transmission loss caused by \( \Delta P \) is quite small, say 1 through 2%, most of the pre-fault power flow is just rerouted due to a contingency, and the concept of the power flow compensation can be applied.

On the other hand, the Q loss increases significantly due to opening a faulted line. Therefore, the concept of the power flow compensation which is applied for the active power loss cannot be applied for the Q loss. It is necessary to subtract the amount of the deviation of the Q loss additionally. The Q loss for the whole branches which consist of \( n \) lines is expressed in Equation (2). The deviation of the Q loss which is denoted by \( \Delta Q_{\text{los}} \) is derived from Equation (3).

\[
\Delta Q_{\text{los}} = n(P^2x) \tag{2}
\]

where
- \( x \): a single line reactance for the designated branch

\[
\Delta Q_{\text{los}} = (n - 1)(\alpha P^2)x \tag{3}
\]

When the power system configuration is treated as a radial system, the coefficient of the \( \Delta Q_{\text{los}} \) is 1/(\( n \) - 1) by assigning \( \alpha = n / (n - 1) \) to Eq.(3). If \( n \) is 2, \( \Delta Q_{\text{los}} \) is 1.0, which means that the same amount of the pre-contingency Q loss is removed from the system due to a N-1 contingency. This Q loss is automatically reflected as the normal N-R method is executed. However the \( \Delta Q_{\text{los}} \) cannot be ignored because the Jacobian is used for a measure of the power flow compensation. Fig. 2 shows the mismatch between pre-contingency power flow solutions and post-contingency power flow solutions with the compensation coefficient. In this figure, \( P_{sr} \) and \( Q_{sr} \) are the pre-contingency power flows on the faulted line. The accuracy of the bus voltages for the N-1 contingencies depends on the linearity of the Jacobian. Thus, the concept of the power flow compensation is advanced considering the reactive power loss for Jacobian matrix for N-1 contingency cases.

IV. N-1 VOLTAGE STABILITY CONTINGENCY RANKING METHOD INCLUDING VOLTAGE COLLAPSE CASES

In order to determine whether the designated load bus is voltage stable or voltage collapse for each N-1 contingency case, the following two conditions are introduced in this
paper. When either of the two conditions as mentioned above is satisfied for a N-1 contingency case, the N-1 contingency case is judged as being voltage collapse.

i) \( V_{P_{\text{ini}}} = 90 \) and \( \frac{V_{P_{\text{ini}}} - V_{P_{\text{ini}}} \cdot 0.5}{100 - V_{P_{\text{ini}}} - 0.5} \)

ii) \( V_{P_{\text{ini}}} < V_{P_{\text{ini}}} \cdot 0.5 \)

where

\( V_{P_{\text{ini}}} \): the pre-contingency voltage stability index

\( V_{P_{\text{ini}}} \): the post-contingency voltage stability index

The load shedding amount \( \Delta P_{\text{cut}} \) required for the voltage stabilization is calculated for the unstable load bus(es) on each N-1 contingency case judged as voltage collapse. The voltage collapse contingency cases are arranged in descending order for the voltage collapse contingency ranking according to the necessary load shedding amount.

Because the unstable load buses have already been specified in the previous section, the derivation of the necessary load shedding amount for stabilizing voltage collapse contingency cases, i.e. for the convergence of a power flow program is the main issue. In general, the static voltage collapse is defined when no intersection of the system and load characteristics exists for the designated load \( PL_0 \).

Consequently, the necessary load shedding amount should be larger than the difference between the P-V curve nose for a N-1 contingency and the load \( PL_0 \).

In order to estimate the necessary load shedding amount, the Jacobian of the N-R method is formulated using the load voltage characteristic in Eq. (4) on condition that the load bus voltage undergoes voltage collapse. The N-1 power flow condition is obviously reflected to the Jacobian.

\[
P + jQ = \left( \frac{V}{V_0} \right)^m (P_0 + jQ_0)
\]

where

\( m \): the voltage characteristic index

\( P_0 \): initial active power load;

\( Q_0 \): initial reactive power load;

\( V_0 \): initial load bus voltage

In case of \( m = 1 \), the load characteristic is the constant current characteristic shown as a straight line in Fig. 3. An intersection of the system and load characteristics is expected near the P-V curve nose for N-1 contingency cases. \( P_c \) in Fig. 3 is the active power load which has the above intersection.

The bus voltages are calculated when the N-R method with the derived Jacobian is executed by one iteration. If the \( P \) and \( Q \) are obtained by substituting the bus voltages to Eq. (4), the solution of \( P \) would be close to \( P_c \). Thus, the estimated (or approximate) necessary load shedding amount \( \Delta P_{\text{cut}} \) can be derived from the calculation of \((PL_0 - P)\).

V. VERIFICATION OF THE PROPOSED RANKING METHOD USING MODEL SYSTEMS

In this section, two model systems are used for verifying the proposed ranking method. The first model system which has 6 nodes (See Fig. 4) is used mainly for verifying the accuracy of the concept of the advanced power flow compensation. The second model system which has 30 nodes, i.e. a modified IEEE model system is used mainly for the accuracy of the proposed ranking method. It is noted that all of the transmission lines consists of a double circuit line and the N-1 contingency in this paper is given by opening a faulted line on a double circuit lines without a ground fault.

A. Verification of the Proposed Contingency Method on a 6-bus Model System

The power flow compensation sensitivity coefficients \( \alpha \) for each branch are listed in Table 1. As shown in Table 1, the calculated \( \alpha \) for the branch of a radial power system configuration is 2.0, while the rest of the calculated \( \alpha \) is \( 1.0 < \alpha < 2.0 \). Therefore, the appropriateness of eq. (1) is clarified through Table 1.

<table>
<thead>
<tr>
<th>Line No.</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
<th>L5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity ( \alpha )</td>
<td>1.5294</td>
<td>1.4440</td>
<td>1.5294</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The estimated magnitude and angle of load bus voltages for N-1 contingencies are shown in Fig.5. In this figure, the solutions obtained by the normal N-R method are also shown.
as the exact solutions for purpose of comparison. It should be noted that L1 contingency case causes voltage collapse in which the power flow program fails convergence. Fig. 5(a) also indicates the solutions one iteration after the N-R method is executed for the same N-1 contingencies. The one-iteration-solutions obtained by the N-R method do not appear identical to the exact values. On the other hand, the solutions obtained by the proposed contingency method appear identical to the exact values.

The voltage stability indices for N-1 contingencies which are denoted by $VP_{\text{idx1}}$ and are derived from the above voltage solutions are shown in Fig. 5(b). L2, L3, and L4 contingency cases are a voltage stable case. These voltage stability indices $VP_{\text{idx1}}$ obtained by the proposed contingency method appear identical to the exact value. On the other hand, L1 contingency case is a voltage collapse case. Fig. 5(b) shows that $VP_{\text{idx0}}$ and $VP_{\text{idx1}}$ for load bus N4 are 75.0 and 96.6 respectively. In this case, the conditions for determining voltage instability described in section 4 are shown in below:

\[ VP_{\text{idx1}} \geq 90, \quad VP_{\text{idx0}} - VP_{\text{idx1}} \geq 96.6 - 75.0 \geq 0.5 \]

The above conditions conclude that the L1 contingency case is a voltage collapse case and load bus N4 is selected as the load bus to which the load to be shed is connected.

Therefore, the load characteristics of the load at bus N4 are changed using Eq. (4), and the computation based on the N-R method is executed by one iteration. The obtained $V_4$ is 0.9329 and $\Delta P_{\text{cut}}$ derived from Eq. (4) is 0.047.

Estimated necessary load shedding amount $\Delta P_{\text{cut}}$ for L1 contingency case is shown in Fig. 6. In order to verify the accuracy of the estimated $\Delta P_{\text{cut}}$, the exact post-contingency P-V curve is also drawn in Fig. 6. It is clarified that the L1 contingency case is an apparently voltage collapse case, and the estimated load shedding amount $\Delta P_{\text{cut}}$ for load bus N4 is 0.047, which can be treated as an acceptable estimated load shedding amount for the voltage stability contingency ranking.

**B. Verification of the Proposed Ranking Method on a Modified 30-bus Model System**

A modified IEEE30 model system shown in Fig. 7 is used for validating the accuracy of the proposed ranking method. The modified model contains 32 branches, which means the number of N-1 contingency cases is 32. Some generators are shifted from the centre to the edge of the power system in order to create voltage collapse cases using the model system.

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Fig. 6. Estimated load shedding amount for L1 contingency case with P-V curve for load bus N4

Fig. 7. Modified IEEE 30-bus system
Fig. 8 shows the voltage stability contingency ranking based on the proposed voltage stability indices $VP_{idx}$ and the necessary load shedding amount. As shown in Fig. 8, the severity of the voltage stability can be evaluated in descending order, although the unstable buses are included for the line L1, L20, L5 and L17 tripping contingency cases.

![Fig. 8. N-1 voltage stability contingency ranking for 150% peak load level on the modified IEEE 30-bus system](image)

Fig. 9 shows the estimated necessary load shedding amount for the line L5 and L17 contingency cases when the line L5 or L17 is disconnected respectively. In order to validate the proposed ranking method, the P-V curves at load bus N5 shown in dotted lines, are calculated for the line L5 and L17 contingency cases.

It can be clarified that the proposed ranking method obtains enough accuracy of the necessary amount of load shedding for arranging contingency case including unstable load buses in descending order.

![Fig. 9. Estimated load shedding amount for L5 and L17 contingency cases](image)

VI. CONCLUSION

An efficient voltage stability contingency ranking method was developed, and the performance of the proposed method was validated using the 6-bus model system and the modified IEEE 30-bus model system. The contributions of the developed method are reduction of the computational cost for the ranking, and incorporation of voltage collapse contingency cases into the voltage stability contingency ranking. It was clarified that the voltage collapse can be avoided due to the load shedding at the unstable load buses through validation cases. The developed method is expected to make it possible to identify not only the voltage collapse contingency cases but also the unstable load buses for the future peak load profiles effectively.

REFERENCES