On Pitfalls of Current Security Assessment Practice in Multi-Area Power Systems

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Abstract—After the recent blackouts and incidents in Europe and USA, e.g. in 2003 and 2006, an increasing interest in security issues of multi-area power systems has arisen. The challenge is coordination of transmission systems operators that are responsible for their own control area but not for the whole system. Coordination is needed because often the transmission system operators have limited information on the neighboring control areas. Therefore, contingencies occurring inside one control area may not be noticed in other areas without appropriate coordination among transmission system operators even though they may have severe consequences. In this paper, we show that lack of coordination among transmission system operators may lead to insecure operation of the multi-area power system even though transmission system operators find their own control areas secure and show that security of single control areas may not imply security of the whole multi-area system. The results indicate that in order to ensure a secure operation of a multi-area power system, coordination and data exchange among transmission system operators should be improved in the future compared with the situation at the moment.

I. INTRODUCTION

Today, a high level of reliability and security is expected from power systems. In order to achieve this target, power systems have to be robust against contingencies taking place in the systems. Recent developments, where systems have been more inter-connected with each other, cause challenges for the security assessment practices. In these interconnected systems, several transmission system operators (TSOs) operate their own area, but do not necessary coordinate actions among others. These power systems are often called multi-area power systems where the name refers to multiple control areas operated by TSOs. This development towards larger power systems operated by many TSOs has recently shown to exhibit certain problems. In 2003, a vast blackout took place in Italy [1], [2] and another incident in Europe took place in 2006 [2]. These severe events initiated an interest to study security related problems in multi-area power systems. Also among TSOs, cooperation initiatives CORESO [3], TSC [4] and SSC [5] have been launched aiming at improving security practices within Continental Europe.

One example of a multi-area power system is the system in Continental Europe. European network of transmission system operators for electricity (ENTSO-E) has published the Operation Handbook (OH) [6] that guides practices of the security assessment. In Policy 3 of OH, ENTSO-E introduces the standards for the security assessment. In Policy 4 of OH, data exchanges between TSOs are presented in order to coordinate the security assessment at day-ahead.

Coordination means exchange of data of systems among TSOs. According to Policy 4, the TSOs provide a detailed network model for other TSOs at least for six reference times. For other time points, no detailed network model is necessary provided by TSOs. However, the modeling of neighboring control areas in multi-area power systems is an important task of TSOs in the security assessment process. For the most of the time, TSOs have limited access to information regarding the neighboring control areas and this could lead to problems as will be shown in this paper. Currently, the so called x-node modeling is used to model the tie-line connections to other systems and it is introduced in OH of ENTSO-E.

TSOs use the so called N-1 security criterion to ensure a secure operation of the system [6]. This criterion means that the system has to operate within security limits after a contingency. In this paper, we have shown that the x-node modeling may lead to a situation where both TSOs get a result that their system is N-1 secure. However, the whole system is not N-1 secure. We have found that the reason is the assumption of constant tie-line flows after contingencies of the x-node modeling. We have also compared results of the x-node method with a full information case. This comparison reveals the effects of lack of coordination and data exchange in multi-area systems on results.

The rest of the paper has the following structure: Section 2 presents methods used and Section 3 presents the results obtained. Finally, in Section 4 we draw conclusions.

II. METHODS

A. Simulation Methods

We have used a DC power flow model [7] in our simulations. The DC power flow model assumes the following simplifications [7]:

- Magnitudes of node voltages are 1 p.u.
- Resistances of transmission lines are neglected
- Differences of voltage angles are small

Taking these simplifications for granted, we may use the following formulation to compute the angles of voltages at buses [7]:

\[ \theta = B^{-1}P_{\text{net}}, \]
where $P_{net}$ is the net power injection vector at the nodes, $B$ is the nodal admittance matrix and the vector $\theta$ contains the angles of voltages.

From the angles of voltages $\theta$, the power flows can be solved utilizing the following formula:

$$F = \hat{X}^{-1} T \theta,$$

where $\hat{X}$ is a matrix containing reactances of lines at the diagonal and $T$ is the adjacency matrix.

B. Modeling of Tie-Lines

Because TSOs perform the security assessment independently in multi-area systems and they have direct information just about their own grid, the modeling of neighboring control areas is an important issue. According to OH of ENTSO-E [6] and Policy 4, the surrounding control areas of a TSO are modeled using the x-node modeling method. This method represents the tie-line connections to the neighboring control areas by busbars with a load or generation unit, Fig. 1.

In our simulations, to find the tie-line flows, we have solved a DC power flow problem. Then we take values from this solution for the equivalent units of x-nodes. Formally, this can be presented as follows:

$$P_{x\text{-node}}^j = F_i$$

where $P_{x\text{-node}}^j$ is the equivalent unit at the x-node $j$ and $F_i$ is the power flow (export/import) of the corresponding tie-line $i$. Here, the sign of the equivalent unit is determined depending on whether the control area exports or imports electricity. The export is considered as a load and therefore $P_{x\text{-node}}^j$ gets a negative value. An import of electricity imposes a positive sign for $P_{x\text{-node}}^j$.

A problem may arise to determine how to split the exported/imported power among tie-lines, if there exist two or more tie-lines between control areas. Often, TSOs have methods to estimate these tie-line flows [6]. From this on, we have assumed that we have a method to estimate the tie-line flow perfectly in the operation planning phase. In real-time operation, the value for the equivalent unit at the x-node is obtained by the TSO from measurements and, thus, the results presented later within this paper apply also for security assessment done in real-time operation, in this respect.

III. RESULTS

A. Test System

We have used a 6-bus test system that has two control areas, Fig. 2. The detailed parameters of the system are given in Appendix. In the system, we have a situation where the control area A exports 1 p.u. of electricity into the control area B. We also assume that both areas have a TSO that is responsible for the security assessment of the corresponding system. We have considered only line faults in our simulations.

B. Power Flow Solutions

First, we have performed the power flow computation using x-node models. There is no difference between the solutions when using the x-node method or the whole system, Table I. This assumes that TSOs know how the exported or imported power flows distribute among these two lines while doing the security assessment in the operational planning phase. Possible errors in the estimates cause errors in the power flow solution.

In real-time, TSOs get real-time information from the SCADA system. The power flows of tie-lines are measured and this data is then acquired by the TSO. Thus, the model built describes the situation very well and gives a power flow solution with no errors in power flows computed.

C. Changes of Tie-Line Flows After Line Faults

After a line fault, the power flows within the system redistribute. The redistribution occurs according to the physical laws and does not obey human-made structures like borders of control areas or countries. Therefore, the assumption behind the x-node method may not be valid anymore. The x-node method assumes that tie-line flows are constant because the export or import of electricity is modeled using a constant generation or load unit.

We have studied the validity of the x-node method using our test system. The changes of tie-line flows after contingencies are presented in Fig. 3. The figure states that in case of a trip of the second line the tie-line flows change much compared to the situation where all components were in operation. The reason is the second line that has a high loading. In the base case, the power flow of this line is 4.73 p.u. Therefore, when this power flow redistributes in the system after the line trip, it...
has to find a new path. The results indicate that much of this power flow go to the second control area and come back using the second tie-line. This can be explained by the fact that the power finds a new path with the shortest electrical distance. If we use the x-node method, we can not see this difference in tie-line flows after the contingency and consider increasing loading levels of lines in the second area.

D. Power Flows in N-1 Situation With Whole Model

From the security assessment point of view, results of the previous section are very interesting. In the N-1 security assessment, the situation after a contingency is studied and post-contingency power flows are scanned and checked whether or not overloaded lines exist in the system. However, if the changes of tie-line flows are not considered properly, the results may be erroneous. In order to make a comparison regarding the N-1 results using full information meaning the whole system and the x-node method, we have performed the power flow computation in the N-1 situation for the whole system first. The results are presented in Table II. In Table II, the columns indicate the power flows after a trip of this line. The diagonal elements are zero because when the line is not in operation, there is no power flow through the line.

These results indicate the same thing as the previous results regarding changes of tie-line power flows. After the trip of the second line, the third line has an increased loading. The loading increases from -1.19 p.u. to -4.9 p.u. Moreover, the power flow of the fifth line increases from 0.19 p.u. to 3.97 p.u. These results indicate that a high loop flow occurs in the system after the trip. Increased line loading of lines 1 and 4 are also detected inside the first control area. The second control area has increased loading of lines 6 and 8. The loading of the line 7 decreases from 0.75 p.u. to 0.48 p.u. but changes its direction. These results are changes of power flows from the N to N-1 situation.

E. Power Flows in N-1 Situation With X-Node Model

In order to compare the results obtained using the whole model with the x-node method, we computed power flows in the N-1 situation for Systems A and B separately using the x-node method. The equivalent units were taken from the power flow solution.

From Table III we see that power flows of tie-lines are constant. The line 3 has a power flow of -1.19 p.u. after every contingency and the second tie-line has a constant flow of 0.19 p.u. Thus, there is a large conflict compared to the results obtained using the whole model.

For System B, the results of the computation using the x-node method are presented in Table IV. We see again the constant tie-line flows of lines 3 and 5. Moreover, we see the highest loading of a line within System B is 2.19 p.u. If we compare this value with the power flow that we obtained using the whole model, we see that lines 6 and 8 are much more...
highly loaded in the real case than based on the computations done by the TSO of System B.

F. Security Assessment Results

Until this point, we have not considered line ratings that limit maximum power flows allowed of lines. The results we obtained show that it is possible to make such a configuration where both areas perform the security assessment and get a result that they are N-1 secure when using the x-node method, but the whole system is not secure.

Our results show that a fault within one control area may not overload any lines within their own area, but a line within the second control area might be overloaded. This situation can be obtained if we introduce the following maximum line ratings \( F_{\text{max}} \) for lines:

\[
F_{\text{max}} = \begin{bmatrix} 11 & 6 & 5 & 6 & 5 & 3 & 3 & 4 \end{bmatrix}^T.
\]

If these line ratings are considered, we see that the line rating of the line 1 is higher than any power flow of this line within System A when using the whole model or the x-node model. The same statement holds also for the second line. The third line is a tie-line as well as the fifth line. The highest loading of the fourth line is 2.03 p.u. but the x-node model gives a result of 5.81 p.u. If the line rating is 6, none of the lines is overloaded. Thus, the TSO of System A draws a conclusion that his system is N-1 secure because all power flows after contingencies are below the maximum power flow limit given.

TABLE I

<table>
<thead>
<tr>
<th>Line</th>
<th>Whole Model</th>
<th>System A</th>
<th>System B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.08 (11)</td>
<td>1.08 (11)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4.73 (6)</td>
<td>4.73 (6)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-1.19 (5)</td>
<td>-1.19 (5)</td>
<td>-1.19 (5)</td>
</tr>
<tr>
<td>4</td>
<td>-1.10 (5)</td>
<td>-1.10 (5)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.19 (5)</td>
<td>0.19 (5)</td>
<td>0.19 (5)</td>
</tr>
<tr>
<td>6</td>
<td>0.94 (3)</td>
<td></td>
<td>0.94 (3)</td>
</tr>
<tr>
<td>7</td>
<td>-0.75 (3)</td>
<td></td>
<td>-0.75 (3)</td>
</tr>
<tr>
<td>8</td>
<td>1.25 (4)</td>
<td></td>
<td>1.25 (4)</td>
</tr>
</tbody>
</table>

TABLE II

<table>
<thead>
<tr>
<th>Line</th>
<th>Trip of a line</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00 (11) 2.32 0.31 2.25 0.20 0.23 0.16 0.22</td>
</tr>
<tr>
<td>2</td>
<td>4.79 0.00 4.86 5.63 4.91 5.11 4.24 5.04</td>
</tr>
<tr>
<td>3</td>
<td>-1.21 -4.97 0.00 -1.37 1.00 -0.79 -1.39 -0.86</td>
</tr>
<tr>
<td>4</td>
<td>1.00 -2.03 -1.14 0.00 -1.90 -1.10 -1.10 -1.10</td>
</tr>
<tr>
<td>5</td>
<td>0.24 3.59 1.40 0.17 0.00 0.24 0.19 0.14</td>
</tr>
<tr>
<td>6</td>
<td>0.95 3.49 0.14 1.06 0.81 0.00 0.39 1.86</td>
</tr>
<tr>
<td>7</td>
<td>-0.74 0.48 -1.14 0.94 0.81 -0.21 0.00 -2.00</td>
</tr>
<tr>
<td>8</td>
<td>1.26 2.48 0.86 1.31 1.19 1.79 2.00 0.00</td>
</tr>
</tbody>
</table>

TABLE III

<table>
<thead>
<tr>
<th>Line trip</th>
<th>Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1.00 (11) 10.82 (11) 0.00 (11) -2.25 (11) 0.00 (11)</td>
<td></td>
</tr>
<tr>
<td>2 4.81 (6) 0.00 (6) 0.00 (6) 5.81 (6) 0.00 (6)</td>
<td></td>
</tr>
<tr>
<td>3 -1.19 (5) -1.19 (5) 0.00 (5) -1.19 (5) 0.00 (5)</td>
<td></td>
</tr>
<tr>
<td>4 -1.83 (6) -3.81 (6) 0.00 (6) 0.00 (6) 0.00 (6)</td>
<td></td>
</tr>
<tr>
<td>5 0.19 (5) 0.19 (5) 0.00 (5) 0.19 (5) 0.00 (5)</td>
<td></td>
</tr>
<tr>
<td>6 - - - - -</td>
<td></td>
</tr>
<tr>
<td>7 - - - - -</td>
<td></td>
</tr>
<tr>
<td>8 - - - - -</td>
<td></td>
</tr>
</tbody>
</table>
The net power injection vector describes the net injections at nodes. The values of the vector are

\[ P_{\text{net}} = \begin{bmatrix} 6 \\ 1 \\ -6 \\ -1 \\ -2 \\ 2 \end{bmatrix}. \]
The reactance matrix is used to compute the power flows of branches from the voltage angle differences. The matrix is

\[
\hat{X} = \begin{bmatrix}
\frac{8}{9} & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \frac{1}{9} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \frac{1}{4} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{3} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{5} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{5} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{6} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{4}
\end{bmatrix}.
\]

The matrix \(T\) is the adjacency matrix. The matrix has the following structure:

\[
T = \begin{bmatrix}
1 & -1 & 0 & 0 & 0 & 0 \\
1 & 0 & -1 & 0 & 0 & 0 \\
-1 & 0 & 0 & 1 & 0 & 0 \\
0 & -1 & 1 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 & -1 & 0 \\
0 & 0 & 0 & 1 & 0 & -1 \\
0 & 0 & 0 & 0 & -1 & 1
\end{bmatrix}.
\]

This reactance matrix \(X\) is used to construct the nodal admittance matrix \(B\) for the power flow computation. The matrix is

\[
X = \begin{bmatrix}
0 & \frac{8}{9} & \frac{1}{9} & \frac{1}{4} & 0 & 0 \\
\frac{8}{9} & 0 & \frac{1}{3} & 0 & 0 & 0 \\
\frac{1}{9} & \frac{1}{3} & 0 & 0 & \frac{1}{5} & 0 \\
\frac{1}{4} & 0 & 0 & 0 & \frac{1}{5} & \frac{1}{6} \\
0 & 0 & \frac{1}{5} & \frac{1}{5} & 0 & \frac{1}{4} \\
0 & 0 & 0 & \frac{1}{6} & \frac{1}{4} & 0
\end{bmatrix}.
\]