

THE EFFECTS OF EXTERNAL MODELING ERRORS ON  
ON-LINE SECURITY ANALYSIS

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ABSTRACT

The on-line security analysis function in a control center today processes the steady-state results of several hundred contingencies to periodically determine the security of the power system. For accurate results the analysis must be done on a representation of the total interconnected network. This requires the modeling of the external systems from which the control center does not receive real time data. In the absence of data links between control centers, the real time status and analog data for the external systems must be assumed or estimated. In this paper, the effects of errors in this assumed data on the security analysis results are presented. Using these effects as the criteria, the two most common external modeling methods are compared for their robustness by testing on two different power systems. The results show that status errors affect the security analysis results more than analog errors, that errors electrically closer to the internal system have larger effects than those further away, and that the reduced external models produce less accurate results than the more extensive models.

INTRODUCTION

On-line steady state contingency analysis are commonly used today to continually monitor the security of a power system. The base case for this analysis is the model of the real time interconnected network. The real time model for the portion of the network that is observable is obtained by the state estimator. However, most of the interconnected neighboring systems are usually unobservable because the real time data from these external systems are not available to the control center computers. The modeling of these unobservable systems in the absence of real time data is a difficult problem that has been approached by different approximate methods. The state of the art in external modeling has recently been reviewed in two papers [1,2].

In general, there are two main approaches to the problem. In the External Equivalent methods, the external network is reduced to the boundaries of the internal system off line and this equivalent is then

matched in real time at the boundaries. The different variations of this approach use different reduction techniques (Ward, REI or variations) and different boundary matching procedures [3-8]. In the External Solution methods, a large portion of the external network is modeled explicitly by extrapolating the loading levels in real time and then solving the network. The variations of this approach use different network solution methods like power flow and state estimation [9-11].

Although the calculation procedures to obtain the real time external model are different for these different methods, one aspect is common to all. The real time data is not available and have to be extrapolated, either explicitly or implicitly, in the procedure. The effects of errors in assuming this real time data is a matter of obvious concern. Actually, the external model is not of primary interest to the operator and errors in the external model caused by wrong real time data assumptions are not detrimental per se. However, the accuracy of the external model can affect the accuracy of the contingency analysis results for the internal system and this is, of course, very important. Thus, the effects of wrong real time data assumptions for the external system, on the contingency analysis results for the internal system, are of considerable interest. It has been pointed out [12,13] that errors in analog data assumptions have little effect on the contingency analysis results because of the incremental nature of contingency analysis calculation.

Many of these different methods for external modeling have been implemented at control centers, but comparisons of their performance have seldom been conducted. Thorough comparisons of equivalencing methods are available [12,13] but equivalencing is only a subset of external modeling. Moreover, these comparisons do not address the effects of wrong status data assumptions. More recently, comparison between power flow solutions and state estimator solutions for the external model [9,11] has shown some advantages for the latter. A major difficulty in conducting such comparisons is that the software development required to test each method is quite large and several methods are usually not available to the same research team.

In this paper, a comparison of the two major approaches is presented. The most commonly used method for the external equivalent approach is compared with the most common external solution method on two different systems of 118 and 500 buses. The effects of external status errors (and some analog errors) on the internal contingency analysis results are studied and compared. The methods compared are described first followed by the power systems used in the testing. The testing procedure, which is carefully designed to simulate on-line usage, is presented next. The test results and the conclusions complete the paper.

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### METHODS TESTED

The external solution method that is the most common today [1] represents explicitly a significant portion of the external networks. The real time load levels are extrapolated from the real time internal system load and the generation and load patterns are assumed according to the time of day. The status of breakers are assumed to be normal. This external model is then solved by a power flow. Matching at the boundary buses is achieved by considering them to be slack buses with their complex voltages held at the values calculated by the state estimator.

The most common external equivalent method today [1] uses the Ward equivalent of the external network obtained off-line assuming typical connectivity and loading levels. The external system is reduced to the internal system boundary. The real time update of the external model is obtained by simply changing the boundary bus injections to eliminate boundary mismatches.

These two methods were implemented and tested. A power flow program was modified to test the external solution method. This modification was needed to enable it to handle multiple slack buses as the boundary matching has to be done by treating all the boundary buses as slack.

To test the external equivalent method a network reduction program using the Ward method was developed to run in conjunction with the power flow program. This reduction capability and the multiple slack capability of the program were then used to conduct the testing.

### TEST POWER SYSTEMS

For meaningful test results it is necessary to conduct the testing on realistic systems of reasonable size. However, the larger the system the greater is the difficulty of data processing and isolating the relevant results. With this in mind, two medium size power systems were chosen as the test systems.

The first test system is the 118 bus IEEE system. This represents a portion of the midwestern United States and has been used extensively as a test system by many researchers. A diagram of the system (Figure 1) shows how the system was divided into five areas. These areas were created so that area 1 could be considered the internal network and the other four as external networks.

The second test system is a 500 bus system that represents the southwestern United States. This system is divided into six areas among which the largest one represents central Arizona and is considered the internal network. The other five areas represent the rest of the western network although portions of these areas are actually equivalenced representations.

### TESTING METHODOLOGY

The purpose of this testing is to evaluate the effectiveness of the two external modeling methods. This effectiveness is determined by the accuracy of the on-line contingency analysis results. The error in the contingency analysis results are usually introduced because of errors in the real time data assumed for the external networks. Since the effects of errors in the analog data, that is, in the load and generation at individual buses, are known to be insignificant, they were not used in this testing. Instead, the following types of errors were investigated:

- o transmission line status
- o generator unit status
- o interchange level between external areas

The testing for the effects of status errors in external network data has not been reported in any earlier work. It was generally believed that status errors for important external lines and generators would have significant impact on the contingency analysis results. This testing was designed to determine this impact in a quantitative way. Another kind of error that is introduced quite frequently is in the interchange levels between external areas. Although the interchange level between the internal area and the external areas are usually known exactly, the transactions between neighboring utilities have to be guessed at and their generation pattern adjusted accordingly. These errors, however, are analog errors but since their effects have not been specifically tested earlier, it was determined to do so in this research.

To set up the experiment a control set is first determined. This means that a series of contingency analysis cases are run on the power system with completely correct real time data available from the external networks. This set thus comprised the true contingency analysis results with which the test results can be compared.

Then an error (line status, generator status, or interchange level) is introduced in the external network. The external modeling method is used with this erroneous data to form the full network model which is then used to obtain the contingency analysis results. These results can then be compared with the true results to determine the effect of the erroneous starting data. This test is conducted for different errors and with both external modeling methods.

The following steps summarize the test procedure:

1. Start with solved power flow case for power system.
2. Run the following power flow cases:
  - 2 cases with single line outage in an external area
  - 2 cases with single generator outage in an external area
  - 2 cases with different interchange between external areas
 These six cases (called RA1 through RA6) represent six different operating conditions for the power system.
3. On each operating condition (RA1-RA6) run a set of internal contingencies. Eight single contingencies of line and generator outages were selected. The contingency analysis results then constituted the true results.
4. For each of the six (RA) operating conditions, the external model computation is done using the external solution method. It is assumed that the external outage or change in transaction is not known. That is, the power system is solved with the true internal conditions but erroneous external conditions. To achieve this using the external solution method the following steps are taken for each RA case:
  - (a) Use the boundary bus voltages from the RA case to change them into slack buses.
  - (b) Solve the power system using the base case conditions, that is, without the external outage or change in transaction of the RA case. This achieves the same effect as the correct solution of the internal network and the solution of the external networks with normal conditions (base case) although the external networks actually have one abnormality (RA case).
  - (c) The boundary bus injections from (b) are then used to turn those buses into load or generator buses. For each case RA1

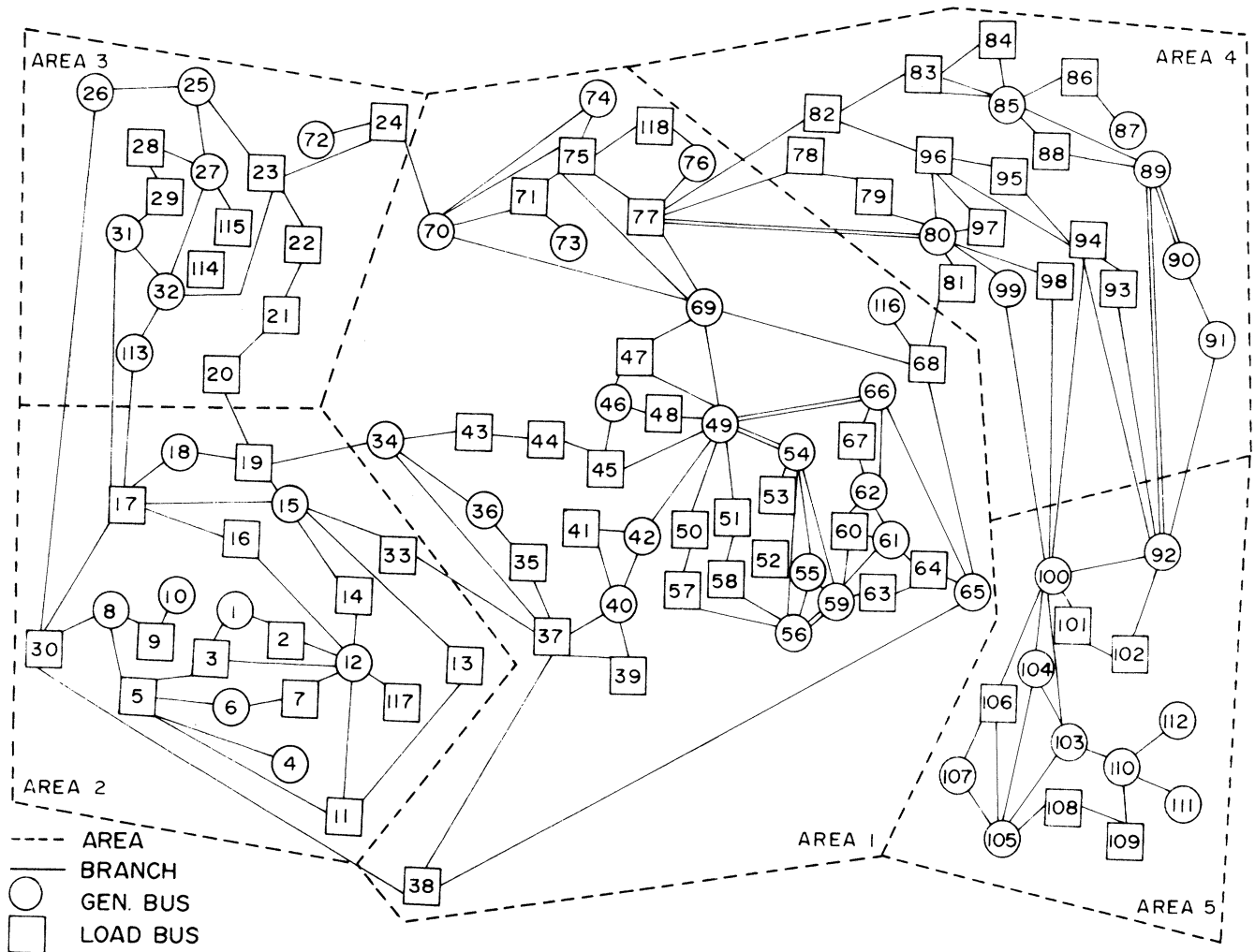


Fig. 1 IEEE 118 bus system divided into five areas

- through RA6, a corresponding case WN1 through WN6 is created.
5. On each solution WN1 through WN6 the same contingencies as in Step 3 are run. These contingency results are then those that have the effects of the erroneous assumption in the external model. These results can be compared to the true results of Step 3 to determine the resulting errors of using the external solution method.
  6. Repeat Step 4 using the external equivalent solution. The following steps to achieve this are slightly different than that of Step 4:
    - (a) Reduce base case to the boundary buses.
    - (b) Use the boundary bus voltages from each RA case to turn the boundary buses of the reduced base case into slack buses and solve. This achieves the same effect as the correct solution of the internal network and the boundary matching to accommodate the fixed reduced model.
    - (c) The boundary bus injections from (b) are then used to turn these buses into load or generator buses. For each case RA1 through RA6, a corresponding case WR1 through WR6 is created.
  7. Repeat Step 5 for each of the solutions WR1 through WR6. These contingency analysis results can be compared to the true results of Step 3 to determine the resulting errors

of using the external equivalent method.

8. The external solution method and the external equivalent method can be compared by comparing the contingency analysis errors produced in Step 5 with those in Step 7.

The six operating conditions with different external model changes were chosen to be typical examples. The number six was enough to provide a variety but small enough to be manageable. The choice of eight contingencies were similarly motivated.

To keep the comparison of the contingency results manageable, certain values were chosen for comparison. Eighteen lines in the internal network were chosen and these line flows monitored. This is similar to the violation check list used in on-line security analysis packages. In addition to the line flows, the number of overvoltages ( $\geq 1.05$  pu) and undervoltages ( $\leq 0.95$  pu) for each contingency was monitored.

#### TEST RESULTS

The output from a series of contingency analysis cases is voluminous and is difficult to analyze to draw general conclusions. Such results are also difficult to present in compact form. Table 1 provides a sample of the type of analysis done with the test results on the 118 bus system. This table shows the maximum errors in line loading for different contingency cases caused by errors in external modeling assumptions. Eight different contingencies of internal line and generator outages are listed along the left hand column. The top row lists two

TABLE 1

## MAXIMUM PERCENTAGE ERROR IN LINE LOADING FOR 118 BUS SYSTEM

EXT. ASSP. →	30 - 26		103 - 105		GEN 25		GEN 100		I.E. (2,3)		I.E. (4,5)	
INT. OUT	WN	WR	WN	WR	WN	WR	WN	WR	WN	WR	WN	WR
49 - 66	0.176	0.431	0.352	0.339	0.028	0.494	0.136	0.146	0.127	0.186	0.03	0.326
70 - 71	0.195	0.434	0.364	0.324	0.032	0.447	0.114	0.151	0.117	0.178	0.027	0.311
61 - 60	0.181	0.423	0.363	0.309	0.032	0.449	0.115	0.150	0.118	0.179	0.027	0.298
64 - 65	1.456	1.518	0.348	0.355	0.028	0.463	0.135	0.166	0.202	0.203	0.025	0.341
49 - 45	0.195	0.450	0.357	0.341	0.024	0.441	0.115	0.146	0.110	0.195	0.031	0.329
GEN. 61	0.21	0.40	0.37	0.93	0.037	0.40	0.10	0.16	0.05	0.17	0.03	0.30
GEN. 49	0.99	0.24	0.45	1.21	0.146	0.39	0.43	1.29	0.28	0.33	0.03	0.89
GEN. 65	8.33	8.47	0.58	0.84	0.039	0.35	0.09	0.19	0.102	0.17	0.03	6.58

external line status assumption errors, two external generator status assumption errors, and two 100MW interchange errors between external areas. For each external model error, WN and WR denote the non-reduced and the reduced external model, respectively.

Some of the larger errors in line loading occur when the error in the external data is electrically closer to the internal system. In Table 1 this is true for generator status errors, for interchange transaction errors and to a lesser extent, for line status errors. The generator on bus 25 is further from the internal system than the generator on bus 100 and errors in their status cause significantly different errors in the contingency analysis results. An interchange error between areas 2 and 3, both of which have connections to the internal area, causes higher errors in the results than an interchange error between areas 4 and 5 because area 5 is not connected to the internal area and is electrically far removed. The lines 30-26 and 103-105 are not at significantly different distances from the internal area and their status errors, therefore, produce similar errors in the results.

The errors produced by the interchange errors were somewhat smaller than those produced by line and generation status errors. This may reflect the fact that interchange errors are analog errors and they tend not to influence incremental results such as contingency analysis. However, the magnitude of these errors were not so much lower than those caused by status errors that they can be totally ignored.

In examining the differences between the external solution method and the external equivalent method, it can be seen that the larger external representation generally produces lower errors than the reduced equivalent model. However, certain external data errors seem to have a particularly amplified effect on the resulting errors. In the case of an error in the interchange between areas 4 and 5, the external equivalent method produces much larger errors than the external solution method. When the generator status on bus 25 is assumed wrong, the external equivalent method again produces larger errors than the external solution method. This behavior tends to suggest that certain errors in the real time data are in direct contradiction to the assumptions made in the modeling of the reduced equivalent and in those cases produce highly erroneous results.

A similar set of cases were run on the 500 bus system and Table 2 shows some of the results. Unlike Table 1, this table shows the number of line loading errors over 0.5% among the 18 monitored lines, providing another measure of accuracy for the external models. The general conclusions were the same for both the 118 bus and the 500 bus power systems. However, the quantitative measures were quite different. For example, the difference between the external solution and the external equivalent methods were less pronounced for the 500 bus system. This could be explained by the fact that the unreduced representation of the external areas for the 500 bus southwestern system was already equivalenced from a larger WSCC system. Thus, reducing it further did not significantly increase the error.

The errors in the contingency analysis voltage results were not examined for their individual accuracy. Instead, only the number of undervoltage and overvoltage buses was monitored. The external models seem to give good results although the 500 bus system produced more errors than the 118 bus system. The reduced model does not produce significantly different results than the larger external model. However, the percentage errors in the voltage calculations need to be examined before general conclusions can be drawn about the voltage sensitivity to the external models.

It can then be said that, in general, errors in the real time data for the external systems have more of an effect on the contingency analysis results when they are closer to the internal system. The errors in the transactions between external areas have a smaller effect than status errors but cannot be totally neglected. For both transaction errors and generator status errors, the significant factor is how the assumed generation pattern is different from the true generation pattern. Finally, the external solution method gives smaller errors than the external equivalent method especially under certain conditions.

It was obvious, in the course of these tests, that the results were affected by the difference in the test systems. The choice of external model errors, internal contingencies, and violation checklists also can affect the results. Although general conclusions could be drawn for a specific system, testing should be done to determine the exact behavior of a proposed external model.

TABLE 2

NUMBER OF ERRORS OVER 0.5% FOR 18 LINE LOADS FOR 500 BUS SYSTEM

EXT. ASSP. →	468 - 478		488 - 490		GEN. 475		GEN. 484		I.E. (2,4)		I.E. (3,6)	
INT. OUT.	WN	WR	WN	WR	WN	WR	WN	WR	WN	WR	WN	WR
301 - 306	0	0	9	7	0	0	4	6	0	1	0	0
207 - 278	1	1	10	10	1	0	9	8	1	1	0	1
91 - 371	1	2	8	7	0	1	9	8	1	1	0	2
53 - 310	0	0	9	10	0	0	5	4	0	2	0	0
205 - 369	0	0	5	6	0	0	10	10	0	1	0	0
GEN. 259	0	0	6	10	0	0	10	10	3	3	0	0
GEN. 93	0	0	9	8	0	0	9	7	6	3	0	0
GEN. 133	0	0	8	7	0	0	10	9	4	5	0	0

CONCLUSIONS

The effects of external modeling errors on on-line contingency analysis are studied. If the errors are electrically more remote from the internal system they produce smaller errors in the contingency analysis results. Status errors tend to produce higher effects than analog errors although not all analog errors are negligible. Errors in interchange between external areas and other errors that cause erroneous generation patterns can cause significant deviation from the correct contingency results. In the comparison of the two main external modeling methods used today, a more explicit representation of the external systems produced more correct results than a reduced representation. However, the external equivalent method produced results that were comparable to the external solution method under some conditions and much worse under others. This may be because the reduction assumptions were in direct contradictions under certain conditions, suggesting that equivalents obtained off-line should be used very carefully for on-line analysis. Finally, it should be pointed out that although two main methods were studied on two medium sized power systems, the conclusions can only be applied in a general sense. The particular interconnected nature of a single utility has a profound influence on the performance of its external system and the external model to be used should be individually determined for that utility.

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REFERENCES

1. A. Bose, "Modeling of External Networks for On-Line Security Analysis," IEEE Transactions on Power Apparatus and Systems, August, 1984.
2. F. F. Wu and A. Monticelli, "Critical Review of External Network Modeling for On-Line Security Analysis," International Journal on Electrical Power and Energy Systems, October, 1988.
3. J. F. Dopazo, M. H. Dwarakanath, J. J. Li and A. M. Sasson, "An External Equivalent Model Using Real-Time Measurements for System Security

Evaluation," IEEE Transactions on Power Apparatus and Systems, March, 1977.

4. T. E. DyLiacco, S. C. Savulescu and K. A. Ramarao, "An On-Line Topological Equivalent of Power System," IEEE Transactions on Power Apparatus and Systems, Sept./Oct., 1978.
5. A. Monticelli, S. Deckmann, A. Garcia and B. Stott, "Real-Time External Equivalents for Static Security Analysis," IEEE Transactions on Power Apparatus and Systems, March/April, 1979.
6. J. F. Dopazo, G. Irisarri and A. M. Sasson, "Real-Time External System Equivalent for On-Line Contingency Analysis," IEEE Transactions on Power Apparatus and Systems, Nov., 1979.
7. E. Housos and G. Irisarri, "Real-Time Results with On-Line Network Equivalents for Control Center Applications," IEEE Transactions on Power Apparatus and Systems, Dec., 1981.
8. R. A. M. van Amerongen and H. P. van Meeteren, "A Generalized Ward Equivalent for Security Analysis," IEEE Transactions on Power Apparatus and Systems, June, 1982.
9. K. I. Geisler and A. Bose, "State Estimation Based External Network Solution for On-Line Security Analysis," IEEE Transactions on Power Apparatus and Systems, August, 1983.
10. A. Monticelli and F. F. Wu, "A Method that Combines Internal State Estimation and External Network Modeling," IEEE/PES Winter Meeting, Dallas, TX, Feb., 1984.
11. K. I. Geisler and N. K. Tripathi, "State Estimation Based External Network Solutions: Field Testing," submitted to the IEEE/PES Winter Meeting, New York, NY, Feb., 1985.
12. S. Deckmann, A. Pizzolante, A. Monticelli, B. Stott and O. Alsac, "Studies on Power System Load Flow Equivalenting," IEEE Transactions on Power Apparatus and Systems, Nov./Dec., 1980.
13. S. Deckmann, A. Pizzolante, A. Monticelli, B. Stott and O. Alsac, "Numerical Testing of Power System Load Flow Equivalents," IEEE Transactions on Power Apparatus and Systems, Nov./Dec., 1980.