Power System Planning Studies on a Real Utility System

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Abstract—**In a power system, a contingency refers to an outage of power system components such as transformers, generators, lines, etc. due to faults or failure. A contingency could lead to voltage and power flow problems. This paper describes practical contingency studies based on a real power system provided by a utility. The aim of this study is to find out contingencies that cause undervoltage, overvoltage or overloading problems. Once the trouble-causing contingencies are identified, a violation mitigation process is carried out to eliminate the voltage and flow violations. The critical load level, defined as the load level below which the violations disappear, is determined. Contingency studies involving spare transformers are also performed to verify whether spare transformers will meet the design specifications if they replace the transformers in service. A study called MW-Mile calculation for the system is also performed for reliability evaluation purposes.**

Index Terms—**Critical Load Level, Double Contingency, Power System Planning.**

I. Introduction

An outage of a power system element such as a line or a generator due to faults or component failure may cause voltage deviations at buses, overloading on lines, power angle instability, or even severe blackouts. In order to ensure the power system reliability, contingency analyses are usually performed as part of power system operation and planning [1-3]. Contingency analysis can help utilities to identify potential problems, design corrective actions in advance, make better decisions for maintenance, and take better control actions in real time.

In this paper, contingency analysis is carried out on a power system by using software PSS/E (Power Simulator for Engineering) [4-6]. Violations caused by given contingencies are obtained and violation alleviation process is implemented. Contingency results evinced that most low voltage and flow violations can be relieved by reducing the load. Spare transformer study offers utility information on potential problems due to replacing an existing transformer.

In the rest of the paper, Section II describes the power system we studied. The AC contingency analysis of the utility system is presented in Section III. In Section IV, methods for reducing load and performing AC contingency for reduced load cases are demonstrated in two subsections. Some of the contingency study results are displayed in Section V. In Section VI, a special contingency study involving spare transformers is discussed. MW-Mile calculation is then performed for a system, followed by the conclusion.

II. Description of The Study

The power system studied in this paper is a real power system consisting of 60553 buses in 137 different areas. Our study focuses on one utility area. According to the utility's request, they want to make sure no undervoltage, overvoltage or overloading problem will happen in this area if the system suffers from certain contingencies. As a result, we perform contingency analysis for 300000 special double contingencies, and then find out the critical load level for each problem component (a bus or a branch). The given contingencies may contain 1 or 2 of the following elements: 1. Outage of a single transmission line; 2. Outage of a generator; 3. Outage of a transformer. For each double contingency, PSS/E 32.0.5 has been employed for AC contingency calculation. After that, a violation report is generated, listing all voltage and overloading issues. By cutting down the load, violations are relieved and finally eliminated. Then, the critical load levels are determined. It should be mentioned that the study only cares about problems occurred in the studied area, and also only the system load in this area is adjusted.

III. Contingency Analysis

As mentioned in section II, contingency analysis is performed by using software PSS/E, a powerful power system simulator. Based on required input files and specified solver parameters, PSS/E is able to output contingency calculation results under various operating conditions.

Several important files are needed as the input files for PSS/E. In this study, these files are provided by the utility.

doi:10.4304/jcp.8.1.79-84

1) Saved case file (*.sav): A power flow case containing all the information about buses, generators, loads, branches, etc. It is the system to be studied.

2) Subsystem description data file (*.sub): This file defines a newly created subsystem. It indicates all the buses and subsystems that are to be included in this new subsystem.

3) Monitored element data file (*.mon): Network elements (buses, branches, etc.) to be monitored and recorded are specified in this file. In this study, all buses in the area studied with voltages less than 0.9 p.u. or higher than 1.05 p.u. will be monitored and recorded; all branches in the area studied with flow larger than 100% of Rate B (the emergency rating for a branch) will be monitored and recorded.

4) Contingency description data file (*.con): This file lists all the contingencies to be tested during AC contingency analysis.

When the above files are ready, one can perform AC contingency calculation using PSS/E according to the following steps.

Step 1: Load the original saved case file (*.sav).

Step 2: Open **Power Flow → Linear Network → DFAX**. Specify desired input and output files' names. In this step, a distribution factor data file (*.dfx) is generated with the help of the prepared three input files (*.sub, *.con and *.mon). Contingency descriptions and subsystem specifications are stored in the *.dfx file.

Step 3: Open **Power Flow → Solution → ACCC.** Contingency solution engine will help to solve the contingency calculation and output the results into a contingency solution output file (*.acc). In this study, full Newton-Raphson is chosen as the solution engine. Please note this step may take several hours if a lot of contingencies are to be tested on a very large system.

Step 4: Open **Power Flow → Reports → AC Contingency reports**. A reporting file (*.txt) containing all the voltage and flow violations is built in this step.

The violation reporting file usually consists of 4 parts: general information, branch flow violation items, voltage violation items and contingency legend. The first part displays the criteria for voltage and flow violations, the input and output files' names, and the parameter setting used in contingency analysis. The following 2 parts presents all the violated branches and buses with detailed information respectively. Part 4 lists all the contingencies causing voltage or flow violations, and detailed events for each contingency.

By extracting useful information from the violation reporting file, we found 55 concerned contingencies, among which 35 contingencies are causing overloading problems while 20 contingencies are leading to low voltage issues. No overvoltage issues are identified.

IV. Violation Mitigation Process

The violation mitigation process for concerned contingencies is explained in this section. In order to alleviate the adverse effects caused by the concerned contingencies, the total load of the studied area is reduced successively at step rate of 1% of the total load until all under-voltage and flow violations are eliminated. At the same time, the power generation by generators is cut down by the same amount to balance the load.

In this section, subsection *A* demonstrates an approach to reduce the load and generation. Later, AC contingency analysis for reduced load cases is presented in subsection *B*. We start load and generation reduction from 1% of the total load, and then check the violation results. If there are still some concerned violations left, redo subsection *A* and *B* with another 1% load reduction of the original load. The steps are iterated until all concerned violations disappear.

A. Load and Gerneration Reduction

When the system is under normal operation, the total real power produced in the studied area is 5354.4 MW. However, total real power generation can only drop to 2842.0 MW due to the limits of generators' minimum capacity. Consequently, the largest amount of real power can be reduced is: 5354.4 - 2842.0 = 2511.6 MW. In order to further decrease the real power generation after the deduction of load exceeds its maximum value, we modify the power interchange between the studied area and a chosen neighboring area.

The following steps illustrate how to perform load and generation reduction based on the original saved case file.

Step 1: Load the original saved case file (*.sav).

Step 2: Open **Power Flow → Changing → Scale generation, load, shunt**. A window named 'Scale Powerflow Data' will pop up in this step. Enter the 'Selected bus subsystem' interface, and then select the studied area's name. Now, only generation and load from this area can be modified.

Step 3: In window 'Scale Powerflow Data', click 'Go' to enter the load reduction interface. If the desired deduction of load is no more than 2511.6 MW, do step 4 and then step 6. Otherwise, do step 5 and then step 6.

Step 4: Decrease both the load and the power generation by the desired amount. Check 'Enforce machine power limits' so that no machine will exceed power limits or be turned off.

Step 5: Adjust area interchange accordingly. For example, let us assume that we want to drop the load and power generation by 3000 MW. First, lower the load by 3000 MW. Second, reduce the real power generation by its maximum value, 2511.6 MW. Remember to check

‘Enforce machine power limits’ in the load reduction process. Then, modify the power interchange between the studied area and a selected neighboring area to the expected values. Go to the area tab in the network window, you can see the interchange value (in MW) for all the areas. The original interchange for the studied area is 33 MW, and the original interchange for the chosen neighboring area is 72 MW. So the new interchange for the studied area should be: 33 + (3000 – 2511.6) = 521.4 MW, and the new interchange for its neighboring area should be: 72 - (3000 – 2511.6) = -416.4 MW. The total power interchange of all areas should be kept zero.

Step 6: Solve power flow for the modified case and save it as a new case (**.sav). Here, full Newton-Ralphson method is adopted to solve the power flow.

B. AC Contingency Calculation for Modified Cases

The purpose of this section is to check whether all under voltage and overloading problems are removed. If not, continue load reduction process and then check the results again until no unexpected issues exist.

With the modified cases acquired from the previous subsection, we can perform AC contingency analysis to see to what level the violations have been mitigated.

AC contingency calculation procedure for reduced load cases is presented as follows:

Step 1: Create a new contingency description data file (**.con) containing only double contingencies which cause low voltage and/or overloading issues. This is because we are only interested in under voltage and overloading problems. These special contingencies can be distinguished in the violation reporting file obtained in Section III.

Step 2: Load the modified saved case file (**.sav).

Step 3: Open **Power Flow → Linear Network → DFAX** to build the distribution factor data file (*.dfx) with the help of the prepared three input files (*.sub, **.con and *.mon).

Step 4: Open **I/O Control → Direct Progress output**. Specify progress output destination type as file and progress output destination file name. The progress output destination file will store the progressing details for each contingency in later steps.

Step 5: Open **Power Flow → Solution → ACCC** to output the contingency calculation results in *.acc file. Full Newton-Raphson is chosen as the solution engine here.

Step 6: Open **I/O Control → Direct Report output**. Specify report output destination type as file and report output destination file name. The report output destination file will be used in the next step.

Step 7: Open **Power Flow → Reports → AC Contingency reports**. A reporting file (*.txt) containing all voltage and flow violations is constructed in this step.

V. CONTINGENCY STUDY RESULTS

Identified violations during contingencies may be eliminated by reducing the system load. In this section, some of the results obtained from the study are presented. Fig. 1(a), 1(b) and 1(c) display how the branch flow changes with the reduced load under 3 different double contingencies. In Fig. 1(a), ‘Branch 342-781’ represents the power line between bus 342 and bus 781.

According to Fig. 1, the horizontal axis represents the loading level of the studied area in percentage. Vertical axis shows the branch flow level for violated branches as a percentage of Rating B. As can be seen, the power flows for violated branches are above 100% of Rating B in full loading condition. However, with the load being reduced gradually, branch flow drops steadily. In the end, the flow violations are eliminated.

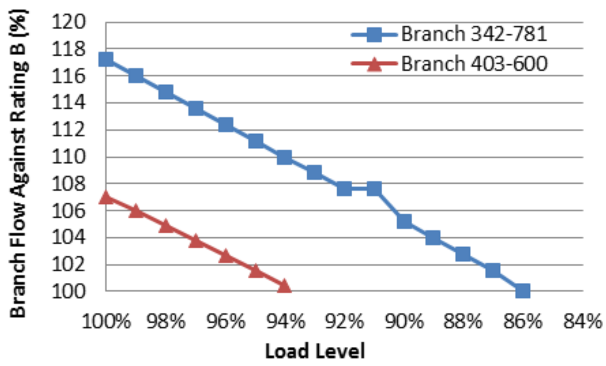

Figure 1(a). Branch flow mitigation under contingency 1-49425

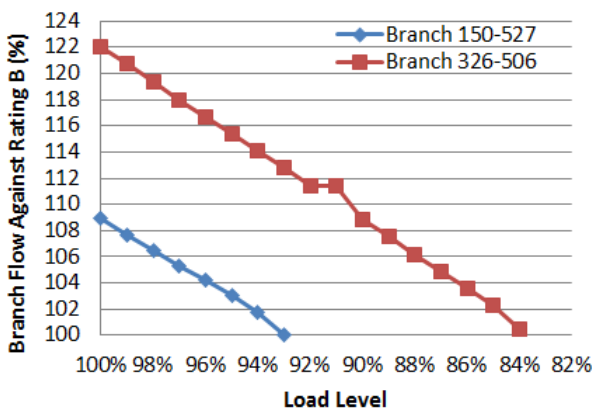

Figure 1(b). Branch flow mitigation under contingency 1-53295

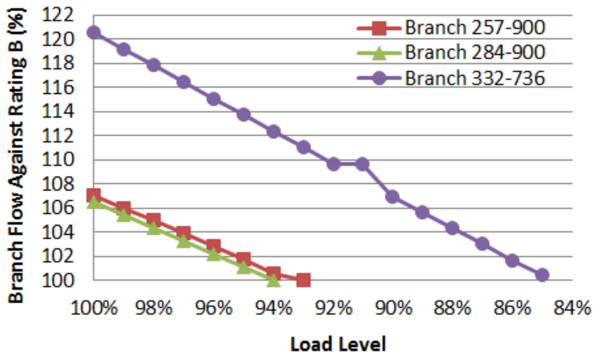

Figure 1(c). Branch flow mitigation under contingency 3-9900

Mitigation process for undervoltage issues caused by 3 different double contingencies are depicted in Fig. 2(a), 2(b) and 2(c). Per unit voltage values for buses in Fig. 2 go up with decreased total load. After all bus voltages go above 0.9 per unit, low voltage problems are solved.

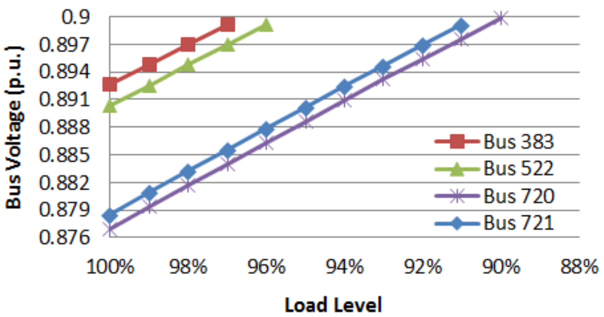

Figure 2(a). Low voltage mitigation under contingency 1-7406

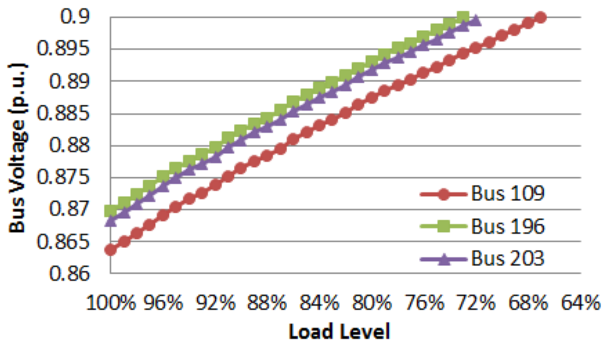

Figure 2(b). Low voltage mitigation under contingency 1-32198

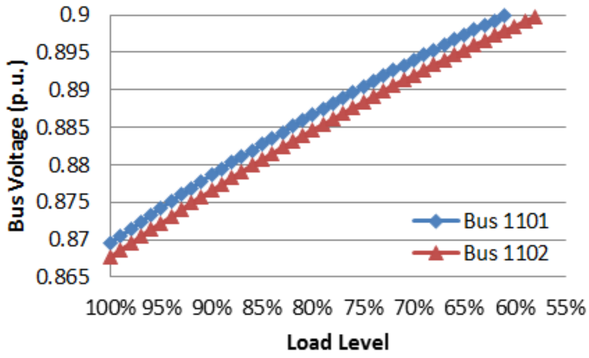

Figure 2(c). Low voltage mitigation under contingency 3-53606

Fig. 1 and Fig. 2 show some violations that have been eliminated before all generators reach their minimum capacity limits. After this stage, generation is further lowered by adjusting interchange between the studied area and the selected neighboring areas. Some of the results for such cases are presented in Fig. 3.

In Fig. 3(a), flow violation for Branch 257-332 and Branch 332-736 are eliminated at 47% and 51% of total load, respectively. Low voltage violation disappears after load level goes below 40% in Fig. 3(b).

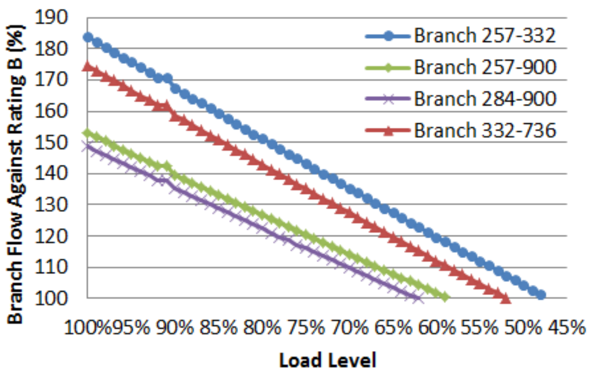

Figure 3(a). Branch flow mitigation under contingency 1-31940

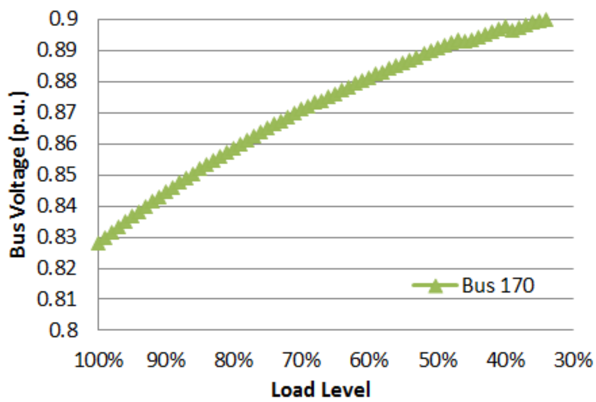

Figure 3(b). Low voltage mitigation under contingency 1-54163

After gathering all the violation mitigation process data, one can easily determine the critical load level for a specific branch under a specific contingency. According to Fig. 3(a), Table 1 lists the critical load level for all the violated branches under contingency 1-31940. With the data in the following table, utility can determine how to cut down the load when contingency 1-31940 occurs.

TABLE 1.
CRITICAL LOAD LEVELS FOR VIOLATED BRANCHES UNDER CONTINGENCY 1-31940

Monitored Bus	Contingency	Critical Load Level
Branch 257-900	1-31940	47%
Branch 257-900	1-31940	58%
Branch 284-900	1-31940	61%
Branch 332-736	1-31940	51%

Furthermore, in the contingency mitigation process, it is found that some branch flow violations cannot be eliminated by reducing the load in the studied area. Certain branch flows will remain constant or even increase with reduced load level.

One of the examples is given here. Under a specific contingency 1, the power flow for a branch (branch 1) remains almost the same when the load level in the studied area is decreased gradually. The contingency 1 involves opening two branches (branch 2 and branch 3). Analysis shows that a load (load 1) was originally supplied by branch 1, 2 and 3, and the load does not belong to the studied area. After branches 2 and 3 are opened, the load will be supplied by branch 1 only. However, only the load in the studied area is reduced, and the load 1 is kept unchanged. As a result, the branch flow on branch 1 does not change, or only change insignificantly when the load in the studied area is reduced. In this case, the studied utility has to work together with its neighboring utilities to solve the potential problem.

VI. SPECIAL CONTINGENCY STUDIES INVOVING SPARE TRANSFORMERS

Transformers are essential components in a power system, and a utility has a certain number of backup transformers. A backup transformer may not necessarily have the same parameters as the backed-up transformer in service. Therefore, if the backup transformer replaces the in-service transformer in case of failure of the in-service transformer, the system may have voltage and flow problems. Thus, appropriate studies are needed to find out whether any problems would occur if a spare transformer replaces a transformer in service, and further identify proper remedial actions, if problems occur.

Fig. 4 shows the results conducted on the system, and only the concerned subsystem is depicted. The transformer between Bus 1 and Bus 2 is the one to be replaced by a backup transformer. Fig. 4 and 5 present the branch flows and voltages during normal operation using the existing transformer and the spare transformer. Fig. 6 and 7 display the branch flows and voltages with the existing transformer and the backup transformer when a neighboring branch is open.

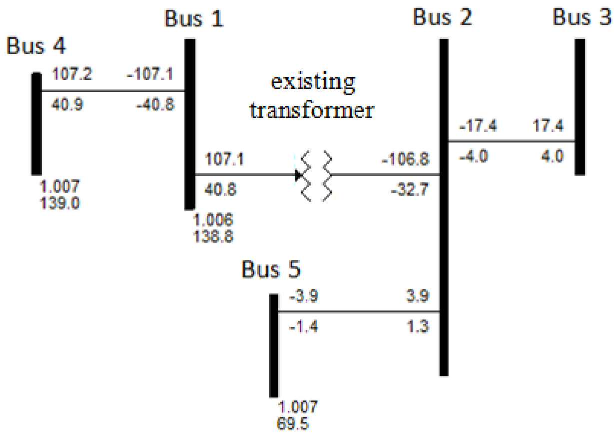

Figure 4. Branch flows and voltages using the existing transformer during normal operation

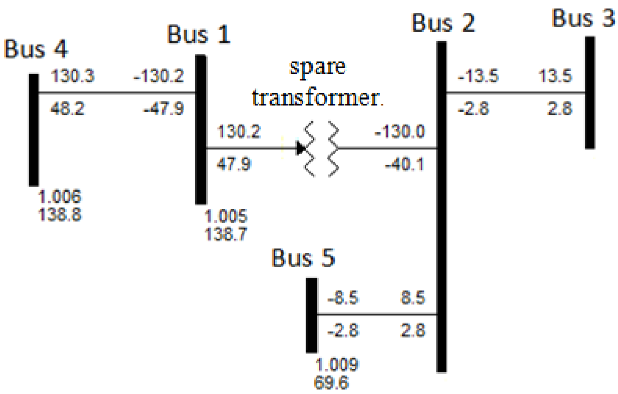

Figure 5. Branch flows and voltages using the backup transformer during normal operation

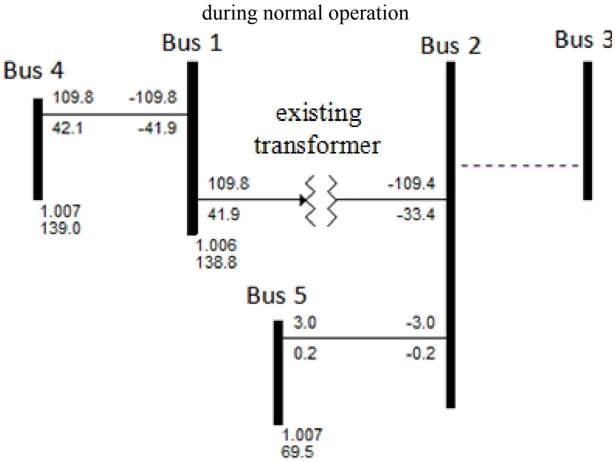

Figure 6. Branch flows and voltages using the existing transformer during the contingency

As can be seen from Fig. 4, under both operations, branch flow between Bus 1 and Bus 4 increases about 20% when the original transformer is replaced by the spare one. Based on this information, utility needs to be cautious to replace the existing transformer by the backup one, because the replacement may cause large flow increase in certain branches. The utility may need to find an alternative transformer to serve as the backup transformer for this specific in-service transformer.

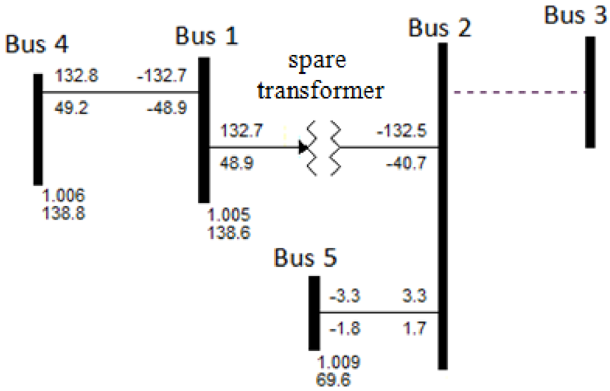

Figure 7. Branch flows and voltages using the backup transformer during the contingency

VII. MW-Mile Calculation

In planning studies, a quantity of interest is called MW- Mile, which is calculated as the product of the length of a transmission line in miles and the MW load this line supplies. We have performed MW-Mile study for a real power system. Microsoft Access database is utilized for data management and analysis. SQL statements are applied to find out the total loads supplied by a line and perform the multiplication. The load obtained through a forecast program is utilized for future years to calculate the MW-Mile values. Generally speaking, a too large MW-Mile may mean potential low reliability, since loss of this line may lead to loss of all the loads. One potential way to reduce MW-Mile is to divide the line into smaller segments, which will certainly incur costs, but will increase reliability.

Sample MW-Mile values for selected entities are reported in Table 2. In the table, column 1 indicates a line, and other columns represent the MW-Mile value for specified years based on forecasted load. It is evinced that this value normally increases each year due to load increase, with an exception for Entity 5. Certainly, future new line construction and reconfiguration will impact the results, but this result provide a general picture of the MW-Mile value assuming no major network changes.

Table 2.
MW-Mile values for some selected entities in future years

Entity	MW-Mile value for each year				
	2012	2013	2014	2015	2016
1	0.1	0.1	0.1	0.1	0.1
2	0.6	0.6	0.6	0.6	0.6
3	225.9	228.1	232.2	233.6	232.8
4	226.7	231.2	234.4	237.8	237.8
5	228.0	228.7	228.1	227.2	223.9
6	1559.6	1582.2	1596.4	1612.2	1605.8

VIII. Conclusion

In this paper, contingency analysis of a real power system is presented. In the study, 300000 specific double contingencies are tested on the system. Based on the AC contingency calculation results obtained by PSS/E, the contingencies that lead to low voltage or overflow problems are identified. In order to alleviate the concerned violations, load reduction in the studied area has been carried out. At the same time, the power generation is decreased to balance the deducted load. After all generators meet their capacity limits, the power interchange between the area studied and selected neighboring areas is adjusted to allow further reduction in power generation. Critical load level for each violation has been determined at which all violations are eliminated. Contingency study results obtained by PSS/E demonstrate the effectiveness of employing load reduction in mitigating violations. However, for some special cases involving loads from other areas, the utility has to deal with the problem together with other utilities. Contingency study on spare transformers and MW-Mile study, which are also of significance in power system planning, are also performed.

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