An Examination

of Transmission System Flexibility Metrics

by

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ABSTRACT

In recent years, with the increasing penetration of solar generation, the uncertainty and variability of the power system generation also have increased. Power systems always require a balance between generation and load. The generation of the conventional generators must be scheduled to meet the total net load of the system with the variability and uncertainty of the solar resources integrated. The ability to match generation to load requires certain flexibility of the conventional generation units as well as a flexible transmission network to deliver the power. In this work, given the generation flexibility primarily reflected in the ramping rates, as well as the minimum and maximum output of the generation units, the transmission network flexibility is assessed using the metric developed in this work.

The main topic of this thesis is the examination of the transmission system flexibility using time series power flows (TSPFs). First, a TSPFs program is developed considering the economic dispatch of all the generating stations, as well as the available ramping rate of each generating unit. The time series power flow spans a period of 24 hours with 5-minute time interval and hence includes 288 power flow snapshots. Every power flow snapshot is created based on the power system topology and the previous system state. These power flow snapshots are referred to as the base case power flow below.

Sensitivity analysis is then conducted by using the TSPFs program as a primary tool, by fixing all but one of the system changes which include: solar penetration, wires to wires interconnection, expected retirements of coal units and expected participation in the energy

imbalance market. The impact of each individual change can be evaluated by the metric developed in the following chapters.

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1. INTRODUCTION

Satisfactory power system operation requires balanced power supply and demand. With the increasing penetration of renewable resources, there is more uncertainty, and variability in the power system net demand resulting from the natural characteristic of the renewable resources. In order to manage the associated variability and uncertainty more flexibility in the supply side as well as the power delivery side which includes both transmission and distribution system is essential. Net demand which can also be referred to as net load is the total demand in the system minus the generation of all the renewable resources. The duck curve generated by the California Independent System Operator (CAISO) [1] illustrates the impact of renewable resources on the net demand of the power system. The duck curve shows four noteworthy ramp periods and two distinct peaks of the net load for one day. Each of these peaks has two significant ramps which requires a flexible generation response. One of the peaks occurs in the morning hours and the other one occurs in the late afternoon. Flexible conventional resources that have enough ramping capability and generation reserve are assumed in this work. The flexibility of the transmission network to deliver the varying power flow is evaluated based on the metric developed in the following chapters.

In this work, only the transmission network with variable solar generation and conventional generation is considered, and all the loads are directly connected to the 69kV buses in the system. Distributed solar generation is integrated with the loads at 69kV buses. The utility-scale solar generation is connected to the system individually. The simulated power system model in this work represents the entire Western Electricity Coordinating Council (WECC) system that includes about two dozen areas. Only one area is represented in greater detail with the transmission network voltage levels varying from 69kV, 115kV, 345kV to 500kV.

1.1 Problem Description

Power system flexibility is the capability of the power system to accommodate the uncertainty and the variability in both the generation and the load. Existing works on power system flexibility measurement mainly focus on the supply side and the demand side, but rarely pay attention to the transmission network that connects these two sides. With the increased penetration of renewable resources and the associated uncertainty, there is a possibility of the transmission system experiencing unexpected congestion which reduces the system flexibility. It is critical to evaluate the transmission system flexibility to cope with these changes using an appropriate metric for future transmission planning purposes. The primary objective of this work is to develop a time series power flows (TSPFs) program to examine the system flexibility. Static power flow study is always an integral part of the transmission planning process done by the electric utilities, time series power flows (TSPFs) are widely used in distribution level system studies, while peak case power flow analysis is more commonly used at the transmission level combined with associated contingency analysis. Compared to peak load power flow analysis, time series power flows (TSPFs) which are utilized in this work can provide a more comprehensive perspective of the power system behavior for the entire day.

1.2 Contributions

1.2.1 TSPFs Program

The TSPF program is developed as the primary tool to assess the system flexibility. The GE Positive Sequence Load Flow (PSLF) software is used as the power system simulation tool in this work. EPCL is a programming language that is designed to work in conjunction with GE PSLF to enable the available functions that can handle automatic data manipulation and report generation. the TSPF program is written based on Python and EPCL programming languages. The basic idea of the TSPF program is to calculate the power generation of the conventional generating units for each base case time series power flow in the Python main script from the solar and load profile data inputted into the program. Then the Python main function sends all the generation and load data to the GE PSLF by creating the EPCL script and calling the PSLF subprocess in the Python main function. The details of this program will be introduced in Chapter 3.

1.2.2 Transmission System Flexibility Metric

The static power flow analysis and associated contingency analysis are conducted through the entire work. Selected transmission line and transformer contingencies are examined for each time series base case. For the base case power flow analysis, the loadings on all the branches in the study area are examined. The loading levels are treated as overloads when they exceed 90% of the branch rating. In the contingency analysis, a certain number of selected contingencies are run for each time series base case. The result of the contingency analysis facilitates an alternate measure of the system flexibility. The numbers of contingencies that cause a certain branch to be overloaded are counted for each time interval and constitute an index that indicates how the transmission network performs under system outage. The details of the metrics will be discussed later.

1.3 Organization

This thesis is organized as follows. Chapter 1 gives a brief introduction to the work done in this thesis. Chapter 2 gives a literature review of the power system flexibility and the existing metrics for evaluating the power system flexibility. Chapter 3 gives a detailed explanation of the TSPF program developed in this work. Chapter 4 describe the flexibility metrics developed in this thesis. Chapter 5 focuses on the sensitivity analysis conducted and shows the results of the TSPF simulations conducted on the studied system. Chapter 6 concludes the thesis and discusses future work in this area.

2. LITERATURE REVIEW

The generation resource mix changes significantly with time because of environmental concerns and resource shortages worldwide. Increasing fuel prices and environmental concerns have stimulated the sustained growth of renewable generation in power systems. However, the renewable generation, such as wind and solar, is variable with the weather conditions introducing more variability and uncertainty to the generation portfolios. Historically, the power systems have been designed and operated to accommodate the variability and uncertainty, but primarily based on the load cycle, the random load variation and the unpredictable outages in the system. The extra variability and uncertainty introduced by the renewable generation result in a significant change in the characteristic of the bulk power system and require changes in the operation and planning of the system.

2.1 Power System Flexibility

Flexibility is the ability to adapt to changes. With respect to power generation, it is the ability of all the conventional generators to respond to the net load variation. The net load is defined to be the aggregate of the power system load and the variable generation of the renewable resources. The reason for the summation of the system load and the renewable generation is that they both have similar uncertain and variable characteristics. Studying the impact of the renewable generation on the bulk power system flexibility should be combined with the behavior of the load [2]. With high penetration of renewables in the power system, the uncertainty and variability in the net load are increased which may require more flexibility from the controllable conventional generators. The flexible conventional generators need to have enough ramping capability as well as enough operating reserves to follow these net load variations in the system. From the perspective of the load, demand response has been used to shift the peak load to the off-peak period using price incentives, providing some essential flexibility and planning reserves for the power system [2]. Both flexible conventional generation and demand response can be recognized as flexible resources in the power system. In addition, energy storage devices can provide flexibility by shifting the overgeneration to the peak load period.

The transmission system does not provide flexibility but provides the bridge between the flexible resources and the flexible demand, for example, the flexible conventional generation and the variable generation at some specific locations. The transmission system is a relatively static system compared to the distribution system which is dynamic due to the complex connectivity characteristic. There are very limited improvements and upgrades in the transmission grid in a short-term planning process, but with the increasing penetration of the renewable generation and the retirement of coal generating stations, the transmission system could become less flexible due to the unexpected congestion caused by the changing resource mix. It is critical for the power system to have enough flexibility to accommodate the variability and uncertainty of the supply side as well as the unforeseen contingencies that can happen during the normal operation of the power system. Moreover, there are possibly new issues for the transmission grid imposed by the emerging operational practice, for example, the participation in the Energy Imbalance Market (EIM). These challenges should be taken into consideration while studying the flexibility of the transmission system to identify necessary system asset improvements and upgrades.

2.2 Energy Imbalance Market (EIM)

Except for the flexible resources discussed in the last section, the power exchange between balancing areas (BAs) can also provide extra flexibility for the power system by reducing the ramping requirements for the conventional generating units under the premise that there is sufficient transmission capability between different balancing areas. The power exchange between different BAs is driven by the market system which tries to find the energy that has the lowest cost to serve the real-time load. Example of such market model is the CAISO Energy Imbalance Market (EIM), which is a part of CAISO real-time market. The participation in the EIM requires re-dispatch among the conventional generating stations and changes in the tie line power flow between each BA. The objective of EIM is to economically utilize all the participating generation and benefit from geographical diversity. But from the point of each BA, participating in EIM may maximize the utilization of the transmission system or increase the possibility of violating the transmission constraints when transferring power between different areas. If the violation occurs inside the BA when participating in the market, it will cause the locational electric energy prices to increase negating the benefit of joining the EIM. Even if the balancing area participates in the EIM, each participator is still responsible for the reliable operation of the power and transmission system inside the area. In conclusion, participating in the EIM may affect each balancing area in adverse ways, these possibilities must be evaluated before participating the energy imbalance market operation.

The famous duck curve generated by the California Independent System Operator (CAISO) illustrates the impact of the variable generation especially the solar generation on the net load of the system and also gives an idea of how the participation in the EIM should work. This duck curve reveals two major ramps in one day, which follows the regulation of the working hours of the society as the sun rises and sets. So, there is a naturally load shifting option between the neighboring balancing areas that are in different time zones. By shifting the load in the morning and late afternoon hours between BAs, participation in the EIM can ease the ramping stress for the conventional generators in each BA.

2.3 Flexibility Evaluation

The flexibility requirement for the power system is primarily from the continuously forced power balance constraint. When the imbalance occurs in the power system, flexible resources must have the capability to compensate for the changes, while the transmission system should also have enough margin to deliver the power generated by the flexible resources. Appropriate metrics should be developed to evaluate these capabilities. As directed by the NERC Integration of Variable Generation Task Force (IVGTF) [2], power system metrics can be developed from three starting points: the magnitude, the response, and the frequency. There are already existing metrics for measuring the flexibility of the power resources. For instance, the operating reserves which are the power system's ability to compensate for large generation loss or other high ramp-up requirements can be recognized as a magnitude metric. The insufficient ramping resource expectation (IRRE), which is proposed as a long term-planning metric that follows a similar structure to the loss of load expectation (LOLE) method in [5], can be classified as a ramping response metric based on the probability theory. The frequency metric should be combined with the minimum up and down times of the conventional generators, the base load generators are likely to have less frequency flexibility because of those constraints. Since combined-cycle units are widely used nowadays, most of which are not limited by the frequency of start up and shut down, the development of the frequency metric is not urgent.

In the previous paragraph, all three kinds of metrics are well applied to measure the flexibility of the generation resources. But the flexibility of the transmission system should also be assessed using appropriate metrics. Since the transmission system cannot respond to the system power imbalance, it only makes sense to develop the metric from the magnitude aspect. There are no such metrics to evaluate the transmission system flexibility at the moment, and a metric will be developed in this thesis in a later section.

3. TIME SERIES POWER FLOWS

Time series power flows (TSPFs) is literally a series of power flow snapshots in time. The timespan of the power flows can be a year, month or day with certain time intervals between each snapshot. In this work, the time series of one day with a time interval of 5 minutes is adopted. The time series power flow analysis has already been widely used in distribution system analysis, but in the transmission system, the peak load power flow analysis is used to do the system planning analysis. The TSPFs developed in this chapter are specialized for the transmission system with all the utility scale generation and the load integrated at the sub-transmission voltage level buses.

The TSPF program is developed as a tool to evaluate the flexibility of the transmission system. Instead of a transmission sufficiency study which can be simply conducted by running the peak load power flow cases, the transmission flexibility study requires the capture of each imbalance during the possible operation horizon as the renewable generation varies within the studied time span. The TSPF program can capture the power imbalance, which is then compensated by the conventional generators at each time interval assuming there is enough generation flexibility. Economic dispatch rules are applied when dispatching the imbalance power among the conventional generators.

The TSPF program has two optional functions that can be enabled before the entire simulation. One is contingency analysis which is integrated in each time interval of the TSPFs program. Only transmission line and transformer N-1 contingencies are considered for each base case power flow. The number of overloaded transmission lines and transformers are utilized as an index of the flexibility metric. The actual loading of each branch is recorded for the evaluation of flexibility as well. The other optional function is the Energy Imbalance Market (EIM) analysis, which is only conducted during the morning and late afternoon hours when power is imported from or exported to the neighboring area. The impact of participation in the EIM of the study area is evaluated.

3.1 Program Flow

Figure 3.1 shows the flow chart of the entire time series program. The blocks are arranged in two columns, the blocks in the left column are processed in Python while the subprocesses in the right column are mainly called by Python in GE PSLF. EPCL codes of the processes in the right column are written in Python, and the EPCL codes will be overwritten at every 5-minute interval.

The time loop in the flow chart is implemented by the for-loop in Python instead of the if-goto structure. For each time interval, the time series power flow is formulated based on the initialized base case that is saved during the initialization process. The initial generation of each generator is recorded after initialization, indicated by P_ini in the flow chart. deltP is the difference between the load variation and solar variation (deltP = deltPload – deltPsolar) in the studied system between time intervals, which indicates the amount by which the conventional generation should be adjusted to compensate the load variation in that time interval.

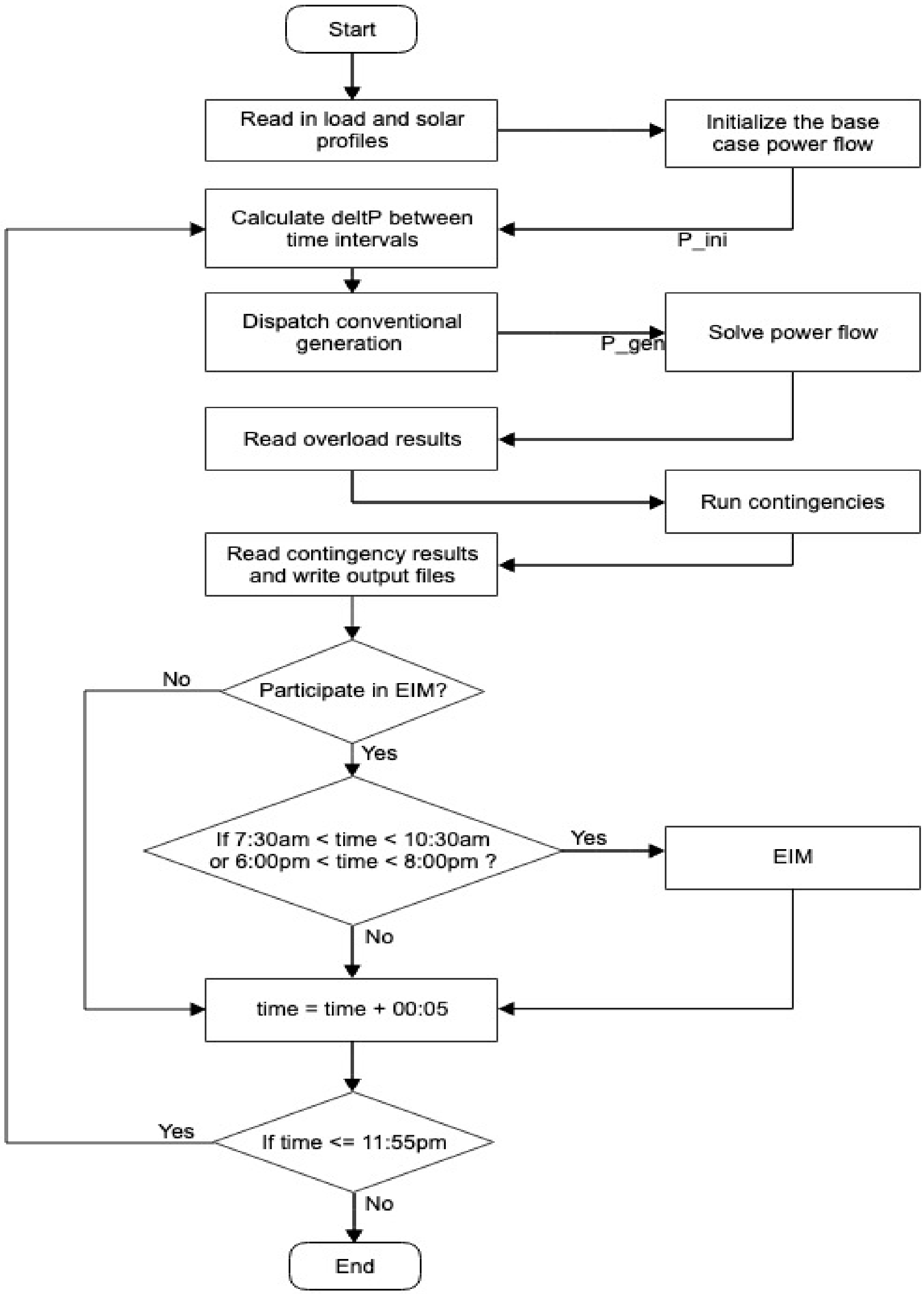

Figure 3.1 Flow Chart of Time Series Power Flows Program

3.2 Dispatch Function

The dispatch function is formulated based on the economic dispatch order provided by the local utilities. For each generating station, a pair flag indicating the pair status is specified to be equal to 0 (unpaired),1(paired), or "1&0" which indicates that a generating station has both paired and unpaired units. The generation of the paired units, which are mostly combined cycle units, must be adjusted concurrently. It is assumed that the generation of all the generators in a paired bundle is adjusted at the same time in proportion to their available generation allowance.

For each time interval, the amount of generation that needs to be dispatched is deltP. When deltP is larger than zero, the conventional generation needs to be increased, then the dispatch function will increase the generation of the units that have the lowest dispatch order position and available ramp. If deltP is negative the same procedure is extended to reduce the generation while following the reverse dispatch order.

Since some of the generators in the dispatch order hit a minimum generation limit (pmin) during the adjustment, problems will occur when the time series power flow program tries to start up a unit when deltP is less than pmin or shut down a unit when deltP is larger than pmin. To overcome this problem, the dispatch order is reversed. A unit is turned on when pmin is larger than the amount of generation needed, then the adjustment begins to reduce the generation of the unit that has the highest dispatch order and available ramp. This will occasionally result in an endless loop in the program, so the program will count the number of times that the dispatch reverses. When the number of times the dispatch reverses exceeds two, the dispatch function will stop the dispatch and record the un-dispatched deltP, and then adjust the tie line flow between the studied area and the neighboring area by the amount of the un-dispatched deltP. The load in the neighboring area is then scaled correspondingly. The minimum power generation constraints for the generators are always dealt with by solving the unit commitment problem in a short-term planning process. This is simplified by using the dispatch priority list in this work, and it is also combined with the available ramping constraint of each generator at each time interval.

3.3 Swing Bus Generation Adjustment

Swing bus generation adjustment is another function of the time series power flow program, that is not shown in the flow chart. Before the program starts, a swing bus must be specified in the system and its bus number and expected initial power generation need to be input in the input files. Since system losses change with time during the day, and the swing bus compensates for that change, the swing bus generation will change as the time series power flow changes and may lead to swing bus over generation. The swing bus generation adjustment function reads the swing bus generation after PSLF solves the power flow and checks if it is within the desired range (80% of swing generator max generation – 100% of the max generation). If not, the function will set the swing bus generation to 90% of the max generation and redispatch other conventional generators to compensate for this change.

3.4 Participation in the EIM

The TSPF program also includes a function of analyzing the effect on the transmission system when the study system is participating in the energy imbalance market (EIM). Figure 3.2 shows the flow chart for the EIM sub-program in the main time series power flow program (Figure 3.1). For each time interval, an EIM flow list is generated incrementally, the maximum value of which is calculated based on the ramp rate and generation allowance for each generator that participates in EIM. Then every possible EIM flows are applied to the power flow base case to generate the EIM base case for each time interval. The contingency analysis is only done for the maximum flow case in each time interval.

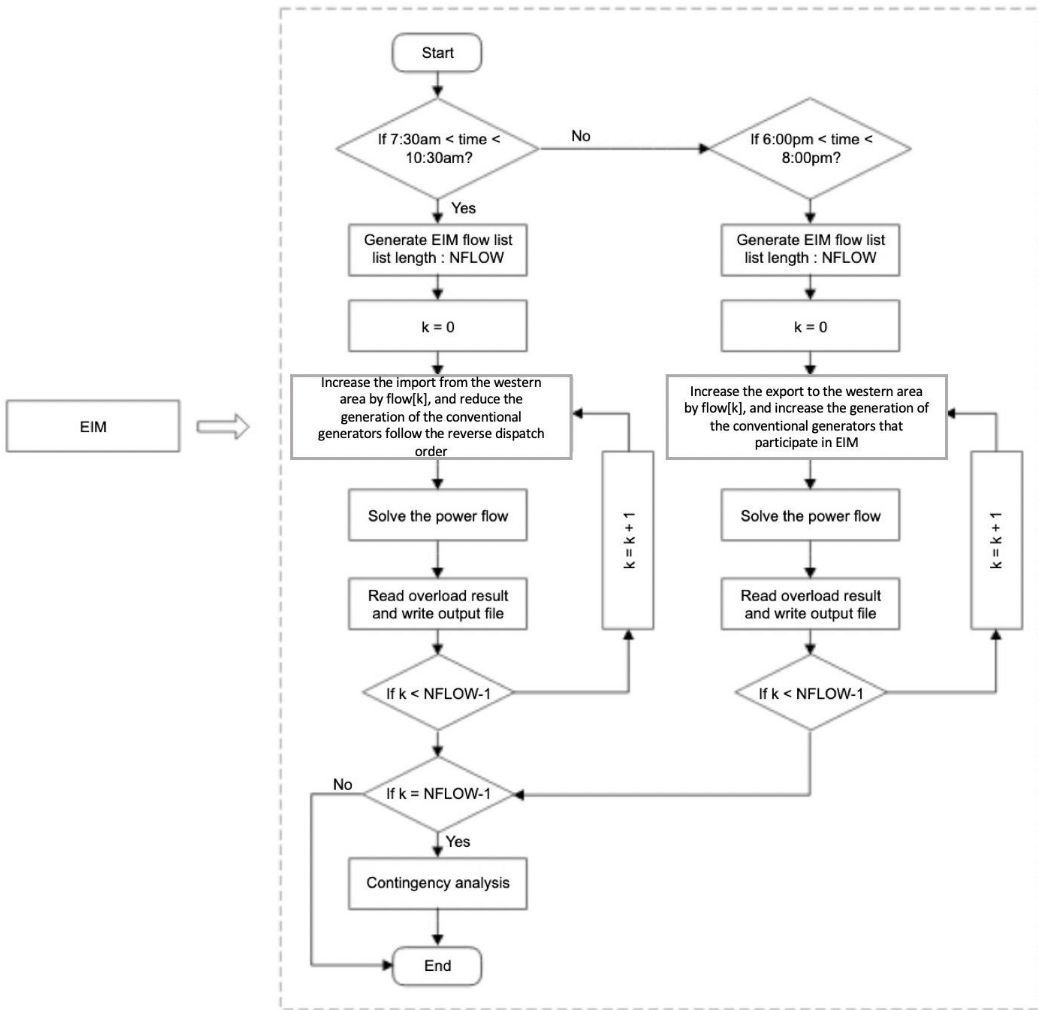

Figure 3.2 Flow Chart of Time Series Power Flows Program

3.5 Inputs and Outputs to the Program

There are several inputs to the program that need to be provided by the users. The first one is the solar generation and load profiles which should be included in one Excel file. Dispatch input files including dispatch control files and dispatch order file should also be provided by the users. In the control file, the conventional generator groups are listed as a table in the order of economic dispatch, with the number of generators in each generator group specified. The dispatch order file contains the generator dispatch order including their bus name, bus number and ramp rates (MW/min). The PSLF base case should also be input to the program. Additionally, some variables necessary for the simulation, like the base case selection information, overload percentage information and dispatch file selection flag should also be specified in the Python input file.

The solar and load profiles used in this work are plotted in Figures 3.3 and 3.4. The solar penetration examined in this work varies from 12% to 38%. It is obvious that with higher solar penetration the ramps in the net load variation become steep. Figures 3.5 and 3.6 show the net load change at each time interval which is the amount of power for the conventional generators to balance.

The output includes pre-contingency overload results, contingency overload results, and EIM participation results. These results are stored in the Python dictionary and are written into the output file. A separate plot program is created to process the results and convert the data into data frames and plot the results.

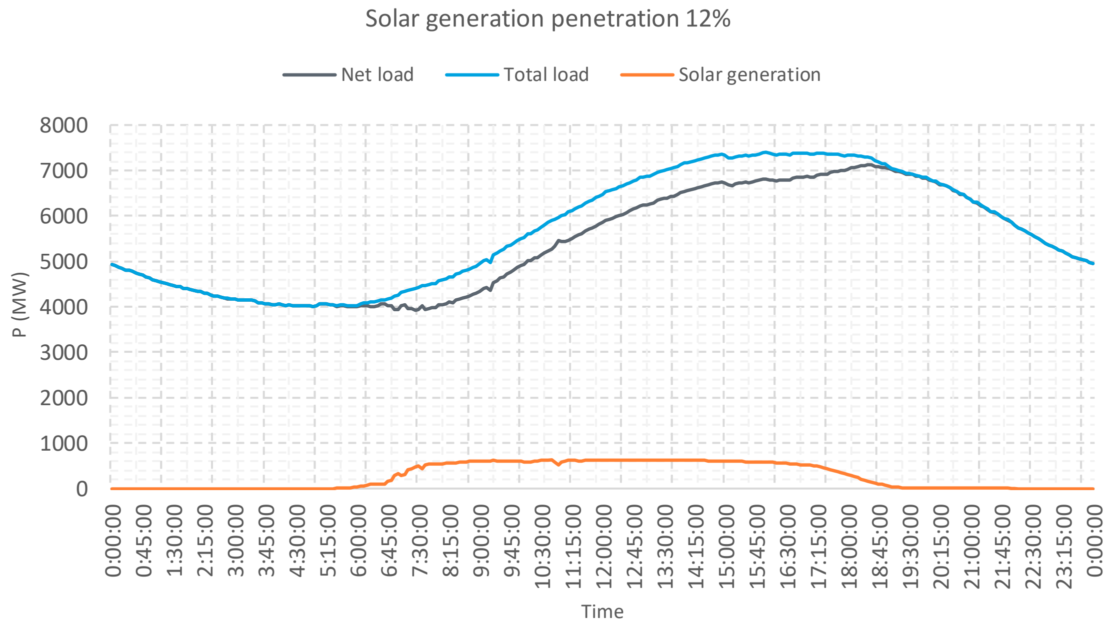

Figure 3.3 Solar and Load Profiles (12% Solar Penetration)

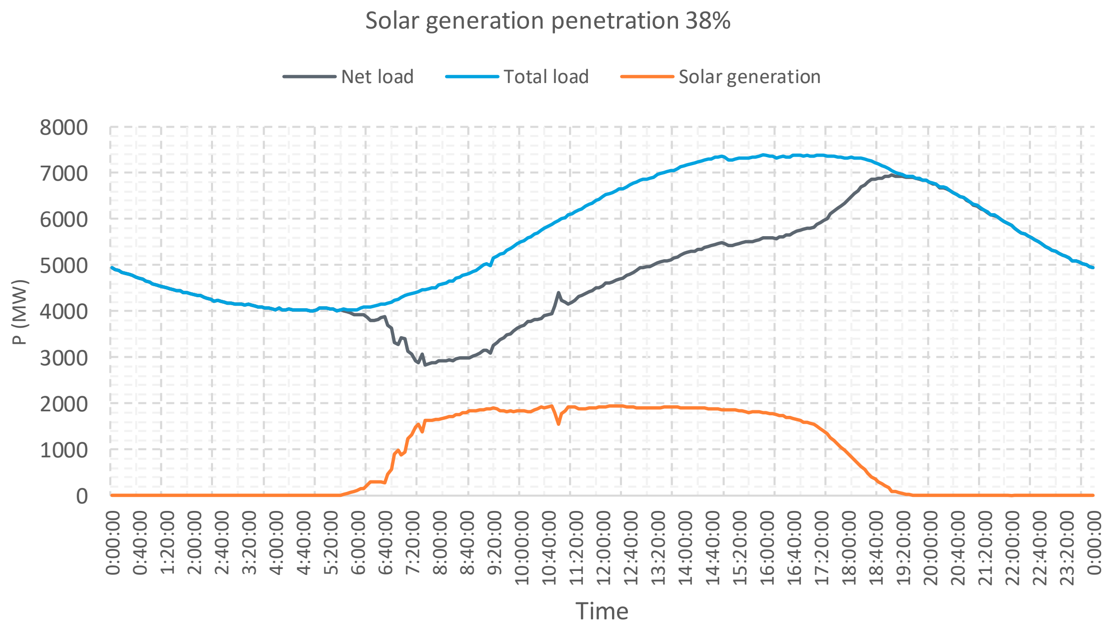

Figure 3.4 Solar and Load Profiles (38% Solar Penetration)

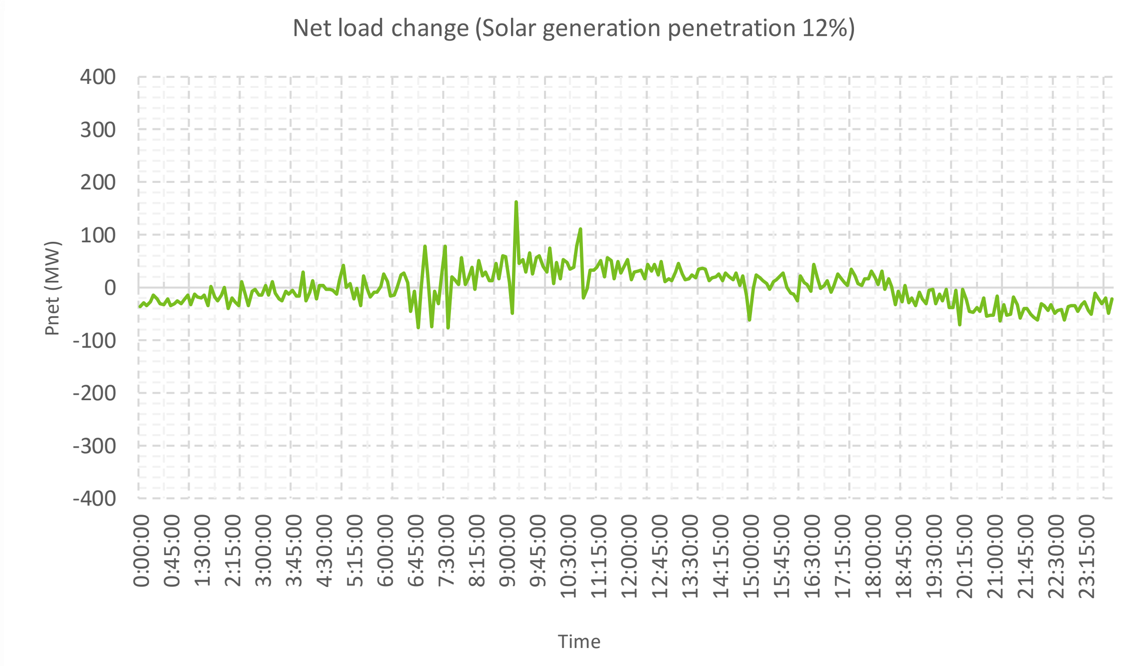

Figure 3.5 Net Load Change at Each Time Interval (12% Solar Penetration)

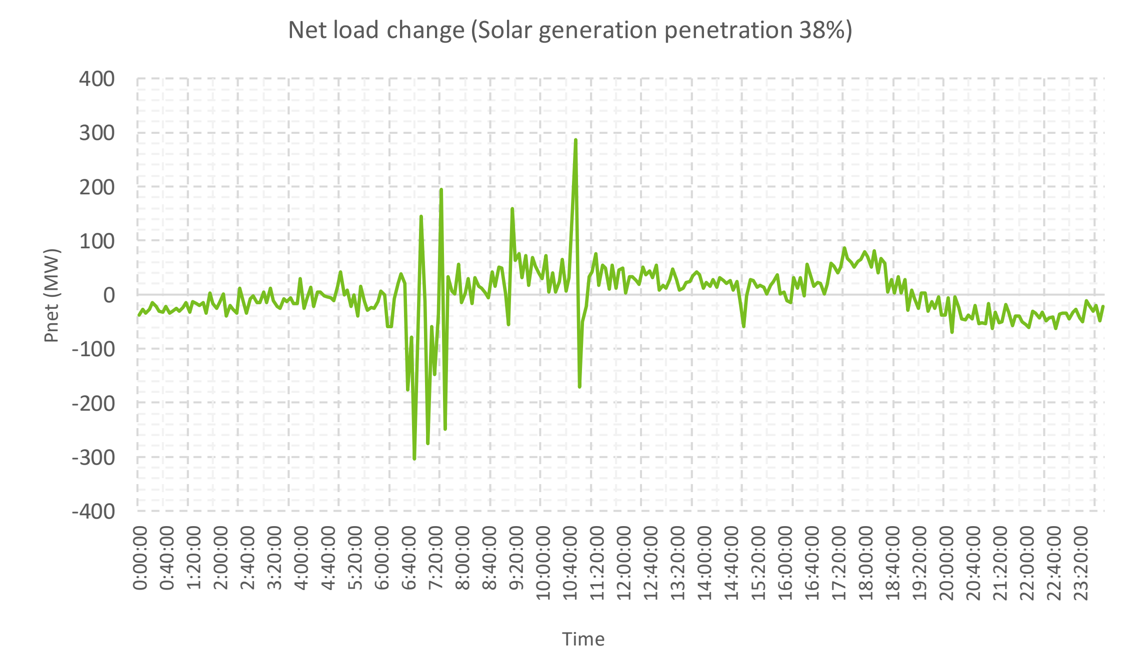

Figure 3.6 Net Load Change at Each Time Interval (38% Solar Penetration)

4. TRANSMISSION SYSTEM FLEXIBILITY METRICS

The transmission system itself does not provide any flexibility, but the flexibility of it should be evaluated as the need for flexible supply resources increases due to the generation and load variation. Flexibility of the transmission system is essential to deliver the power between the supply side and the demand side.

From the previous chapter, the TSPF program generates outputs of the overloads across the transmission system, which is the magnitude of the active flow on each branch. This loading magnitude is calculated in per unit, which is a magnitude metric described in Chapter 2 and is defined as per unit loading (PUL) in this thesis. Since time series power flows are conducted, the periods of maximum loading (PML) can also be identified by the developed program.

A major part of the TSPFs tool is the contingency analysis, relevant metrics are also defined for this specialized analysis. There are hundreds of the same set of contingencies run for each time series power flow base case and the specific EIM base case, all of which are the line and transformer N-1 contingencies from voltage level 115kV to 500kV. Overloads may occur due to the contingencies, the maximum per unit loading (MPUL) is defined as the maximum loading among all the contingency situations. The number of outages (NOTG) that causes the overloads is another metric developed in this part, which evaluates the severity of the inflexibility of the transmission system.

5. SENSITIVITY ANALYSIS

This chapter conducts the flexibility sensitivity analysis for several predicted changes in the power system: solar penetration, wire to wire connection, expected retirement of the coal generating units and participation in EIM.

The power system used in this chapter is the entire Western Electricity Coordinating Council (WECC) system, and only part of the system is studied. Other unconcerned parts of the entire system are fixed including the power generation and load in those areas as well as the exchange between areas.

For each analysis conducted, up to five figures are presented to show the system loading performance. The pre-contingency overload results show the per unit loading (PUL) of the overloaded transmission line or transformer in one figure, different colors are used to depict different branches, the abscissa shows the period considered for one day (Time), and the ordinate depicts the PUL. The post-contingency results are depicted in two separate plots: the maximum per unit loading (MPUL) plot and the number of outages (NOTG) plot. The results are then plotted twice using different criteria for post-contingency overload: over 90% of the branch rating; over 90% of the branch rating and over 102% of each time series base case branch loading. The first criterion characterizes the system performance after the contingency, the second criterion identifies overloads caused by the outages while taking into consideration that the base case could have had minimal overloads. The maximum per unit loading (MPUL) is the maximum loading for a certain branch taking into account all the contingencies at each time interval. The number of outages (NOTG) is the number of outages that cause a certain branch to overload at each time interval.

5.1 Sensitivity of Solar Penetration

This section presents the results of the sensitivity analysis when all the predicted changes are fixed but solar penetration is varied. The solar penetration is increased following the order listed in Table 5.1. The left column of Table 5.1 indicates the scenario number and the base case is numbered as scenario 0.

Table 5.1 Solar Penetration Increasing Sequence

Scenario No.	Solar
1	300MW at a 500 kV bus
2	300 MW a 230 kV bus
3	450MW at a 500 kV bus
4	200MW at a 230 kV bus
5	175MW at a 500 kV bus

5.1.1 Scenario 1-0

There are no overloads in the pre-contingency case. The results of two criteria for post-contingency are the same, hence, only one result is shown here.

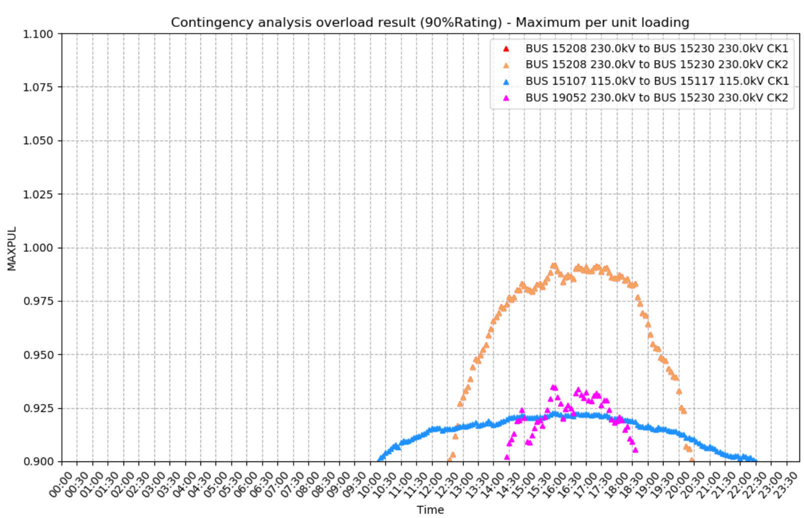

Figure 5.1 Post-Contingency Overload Result – MPUL (Scenario 1-0)

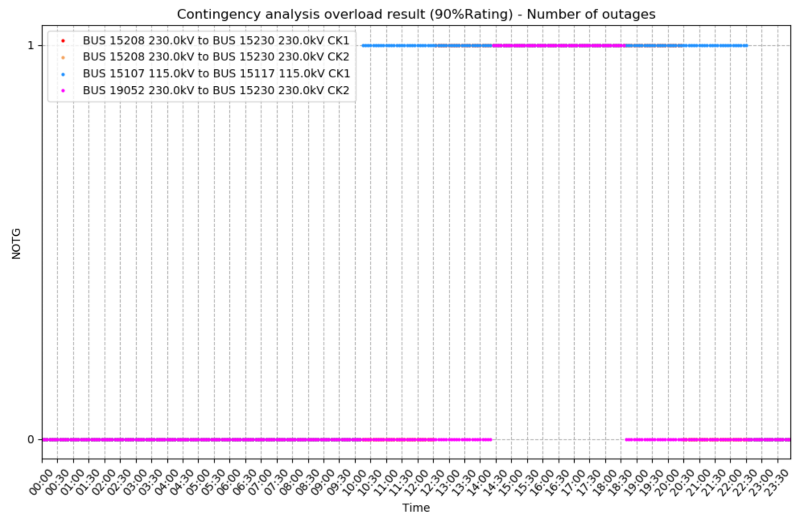

Figure 5.2 Post-Contingency Overload Result – NOTG (Scenario 1-0)

The maximum MPUL over all the time series is 0.991678 which occurs at time 15:55 at the branch "BUS 15208 230kV to BUS 15230 230kV CK2" and is caused only by one contingency.

5.1.2 Scenario 1-1

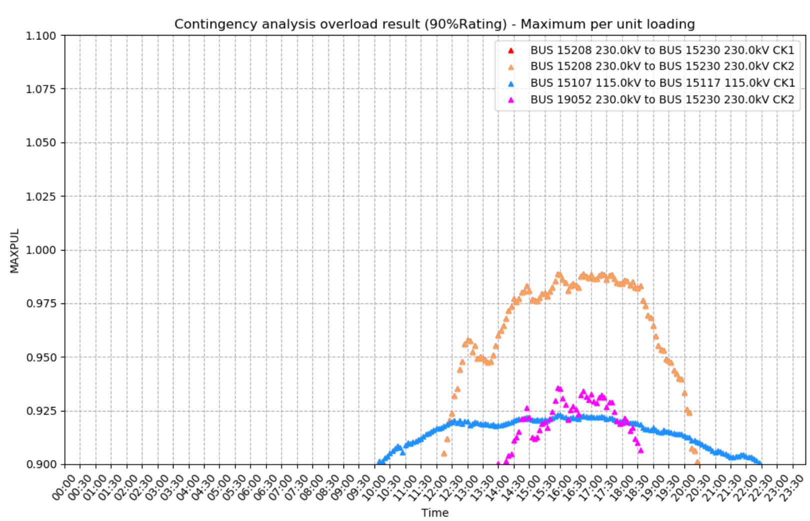

Figure 5.3 Post-Contingency Overload Result – MPUL (Scenario 1-1)

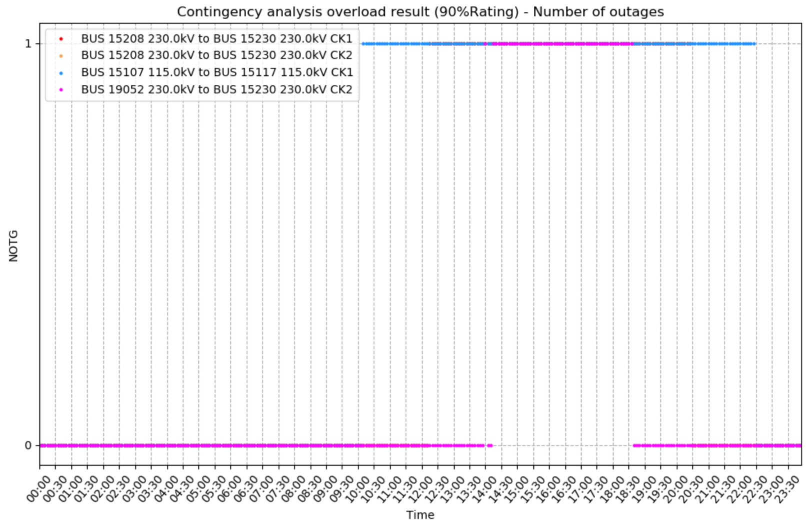

Figure 5.4 Post-Contingency Overload Result – NOTG (Scenario 1-1)

There are no overloads in the pre-contingency case. Similar results as the previous section are shown in Figures 5.3-5.4. The MPUL over all the time series is 0.988819 which occurs at time 16:45 at the branch "BUS 15208 230kV to BUS 15230 230kV CK 2" and is caused only by one contingency.

5.1.3 Scenario 1-2

After incorporating this solar generation into the system, three new overloaded branches appear in the pre-contingency case:

BUS 15606 69kV to BUS 15437 69kV CK1;

BUS 15601 69kV to BUS 15201 230kV CK3;

BUS 15571 69kV to BUS 15873 69kV CK1

as shown in Figure 5.5. The maximum PUL is 0.93328 which occurs at time 15:50 on branch "BUS 15571 69kV to BUS 15873 69kV CK 1".

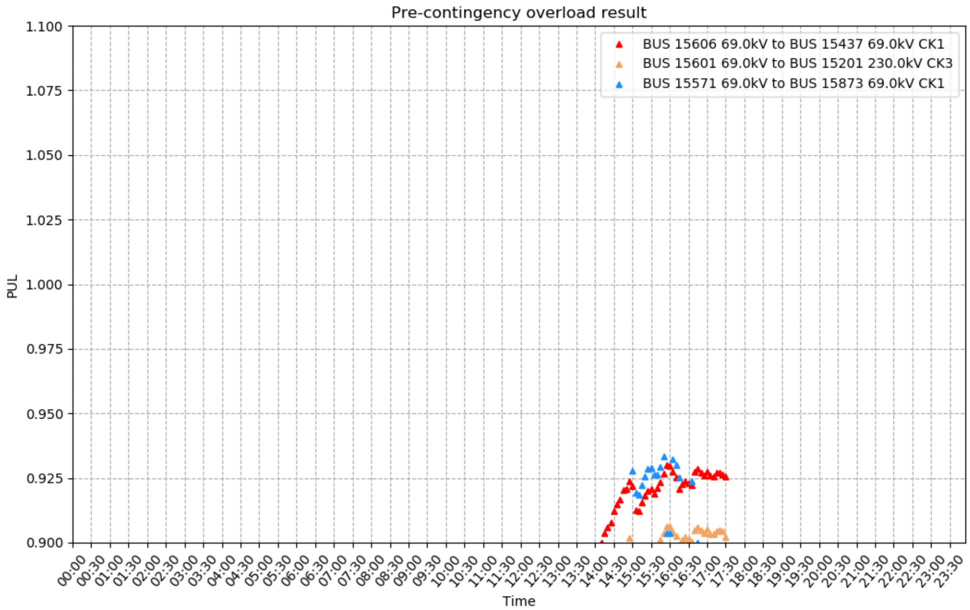

Figure 5.5 Pre-Contingency Overload Result - PUL (Scenario 1-2)

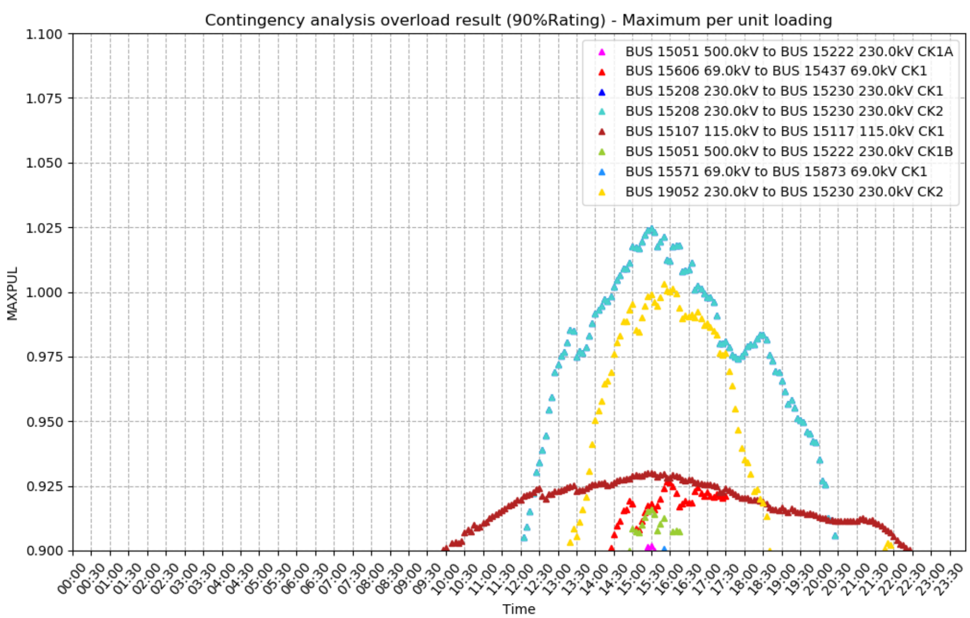

Figure 5.6 Post-Contingency Overload Result – MPUL (Scenario 1-2)

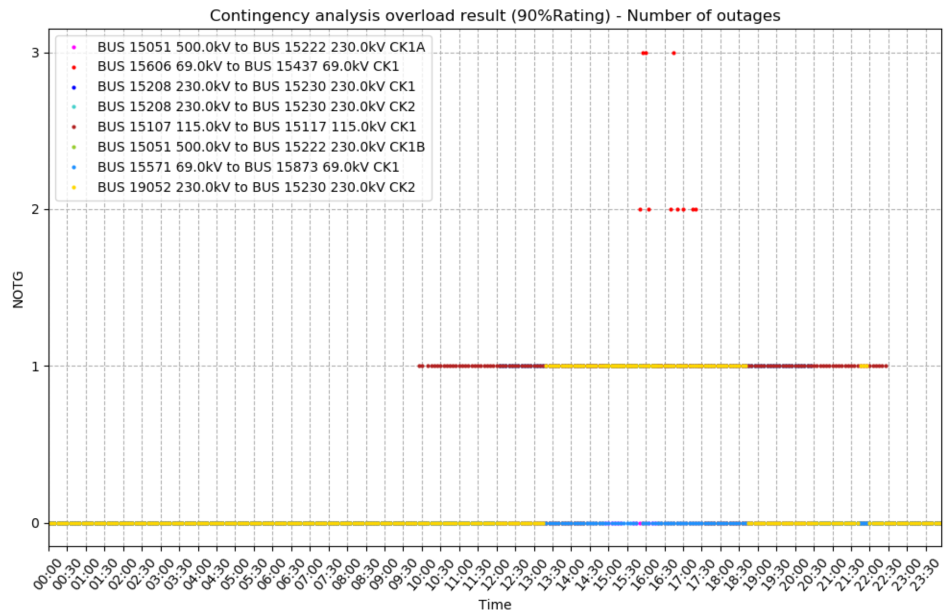

Figure 5.7 Post-Contingency Overload Result – NOTG (Scenario 1-2)

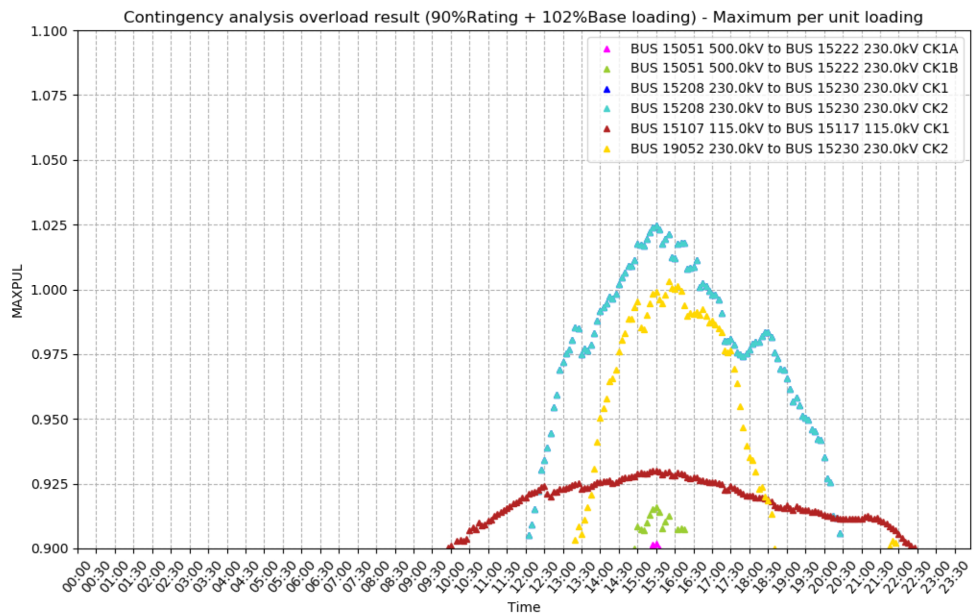

Figure 5.8 Post-Contingency Overload Result with 2nd Criteria– MPUL (Scenario 1-2)

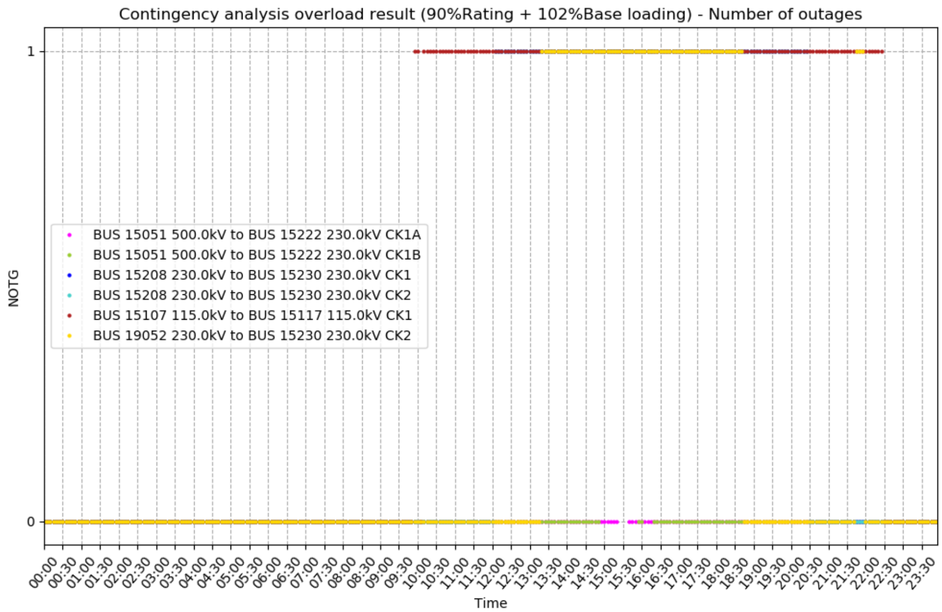

Figure 5.9 Post-Contingency Overload Result with 2nd Criteria – NOTG (Scenario 1-2)

After running the contingency analysis, two new overloaded branches are observed compared to scenario 1-1:

BUS 15051 500kV to BUS 15222 230kV CK1A

BUS 15051 500kV to BUS 15222 230kV CK1B

The most severely overloaded branches are the transmission line from BUS 15208 to BUS 15230, the maximum MPUL is 1.02453 which exceeds 100 percent with the addition of the solar generation.

5.1.4 Scenario 1-3

The maximum PUL is 0.941218 which ocurrs at time 15:55 on branch “BUS 15571 69kV to BUS 15873 69kV CK 1”. The maximum MPUL is 1.009791 which occurs at time 15:45 on branch “BUS 15208 230kV to BUS 15230 230kV CK2”.

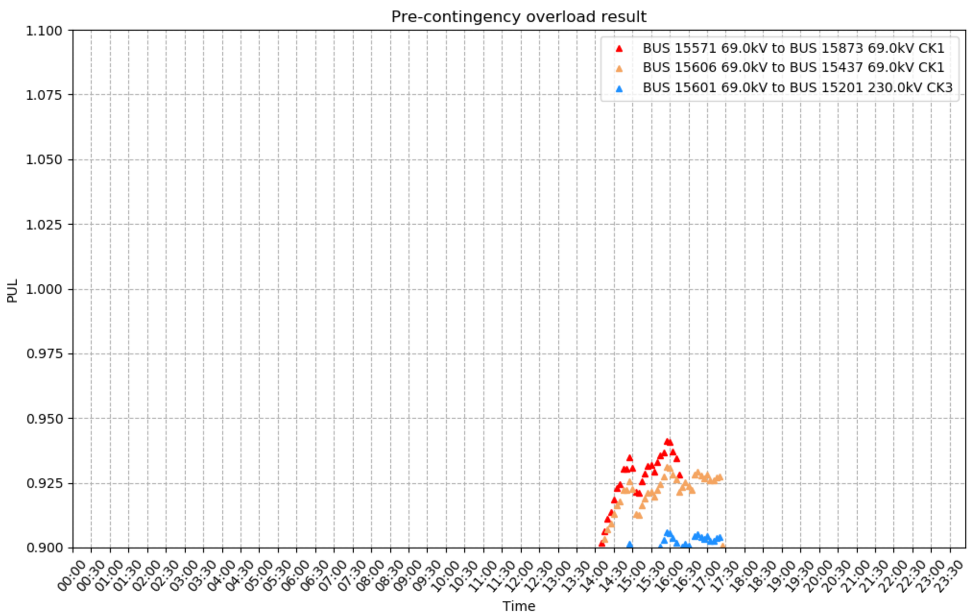

Figure 5.10 Pre-Contingency Overload Result - PUL (Scenario 1-3)

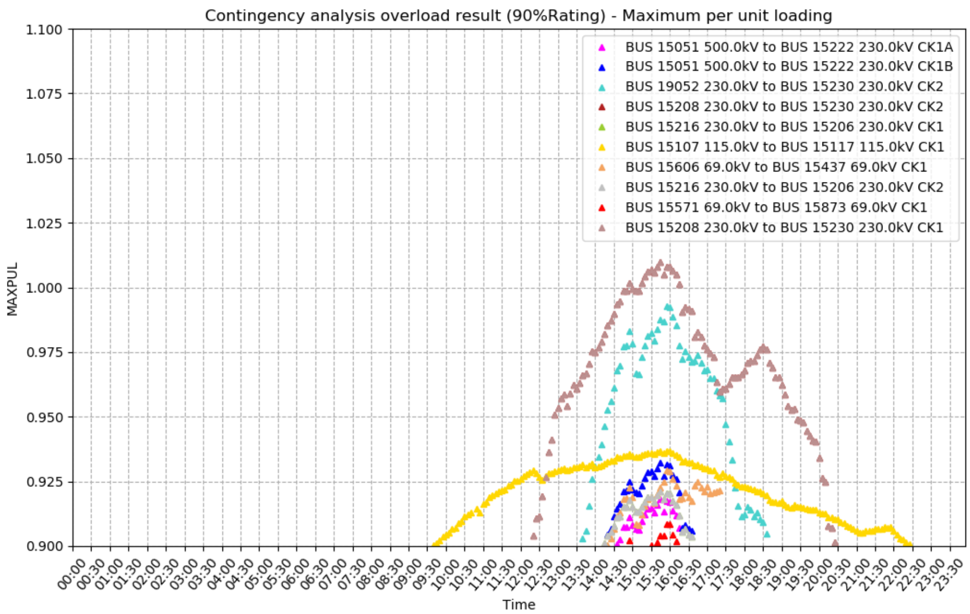

Figure 5.11 Post-Contingency Overload Result – MPUL (Scenario 1-3)

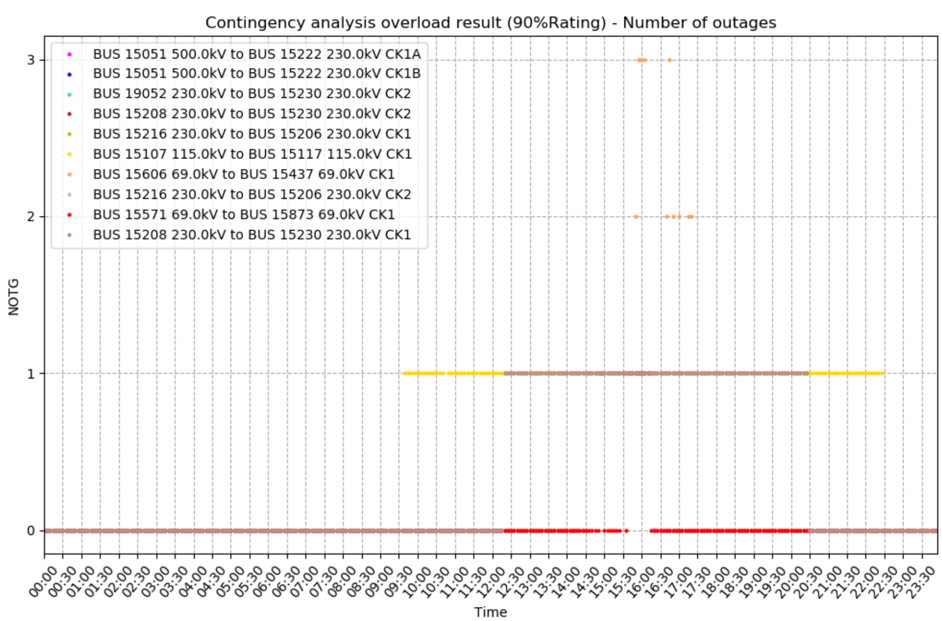

Figure 5.12 Post-Contingency Overload Result – NOTG (Scenario 1-3)

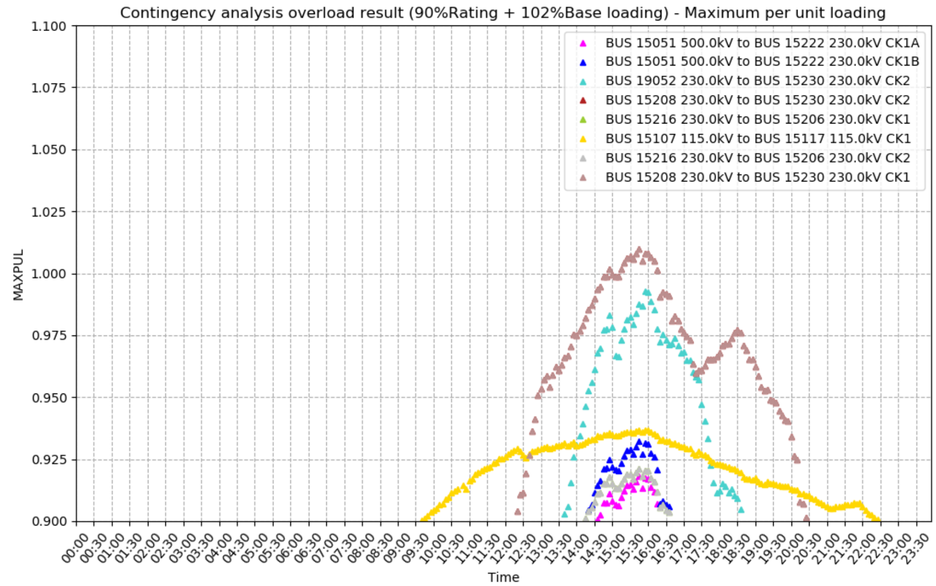

Figure 5.13 Post-Contingency Overload Result with 2nd Criteria– MPUL (Scenario 1-3)

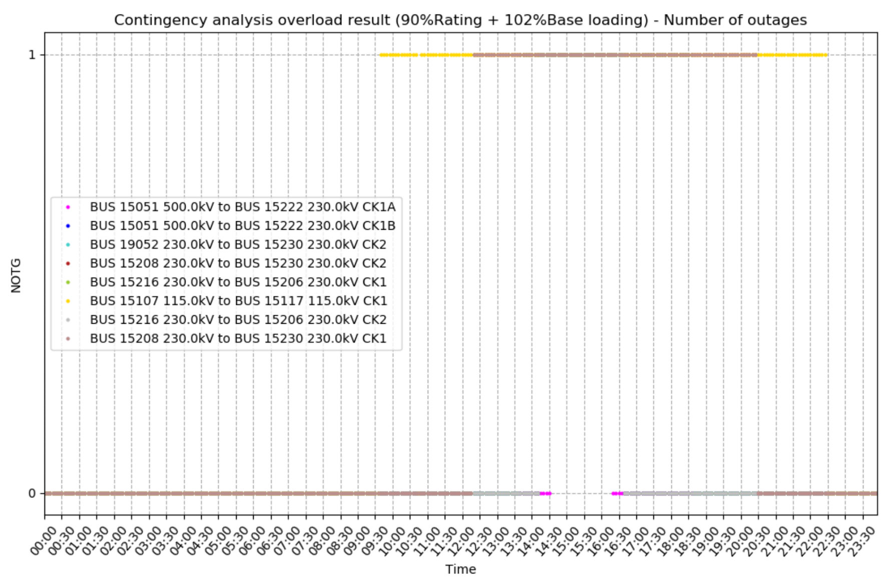

Figure 5.14 Post-Contingency Overload Result with 2nd Criteria – NOTG (Scenario 1-3)

5.1.5 Scenario 1-4

The maximum PUL is 0.95062 which occurs at time 15:00 on branch “BUS 15571 69kV to BUS 15873 69kV CK1”. The maximum MPUL is 0.986268 which occurs at time 15:15 on branch “BUS 15208 230kV to BUS 15230 230kV CK2”.

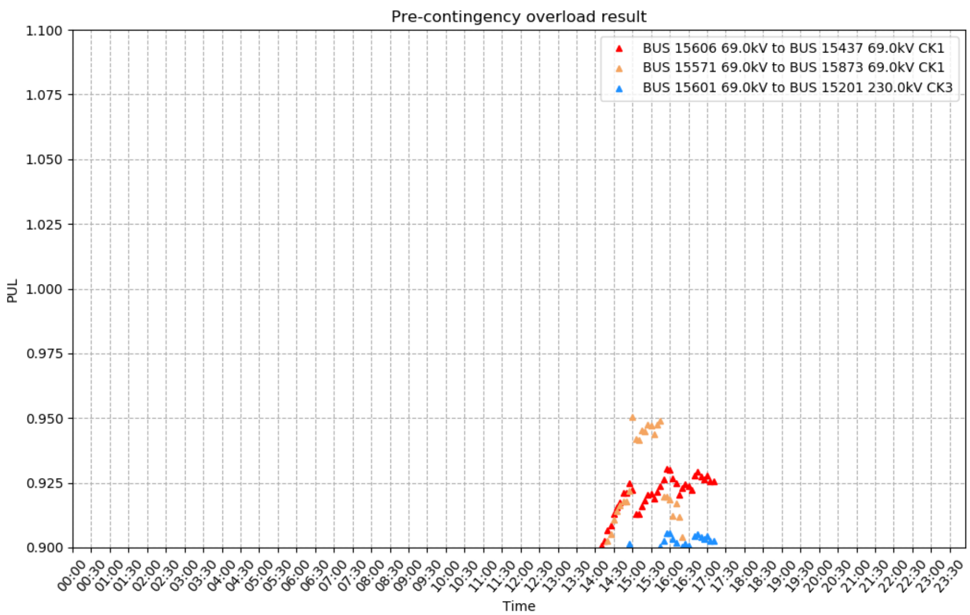

Figure 5.15 Pre-Contingency Overload Result - PUL (Scenario 1-4)

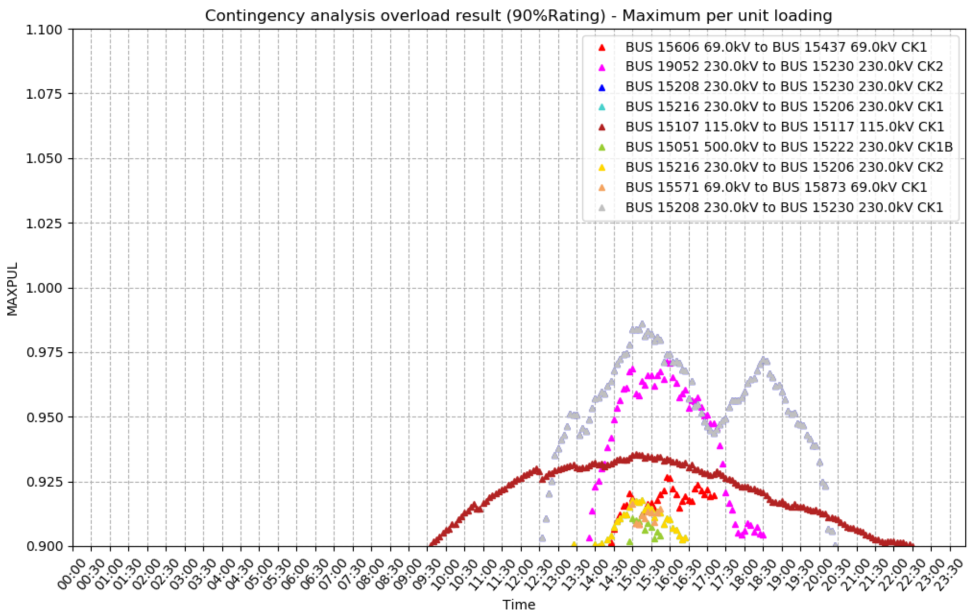

Figure 5.16 Post-Contingency Overload Result – MPUL (Scenario 1-4)

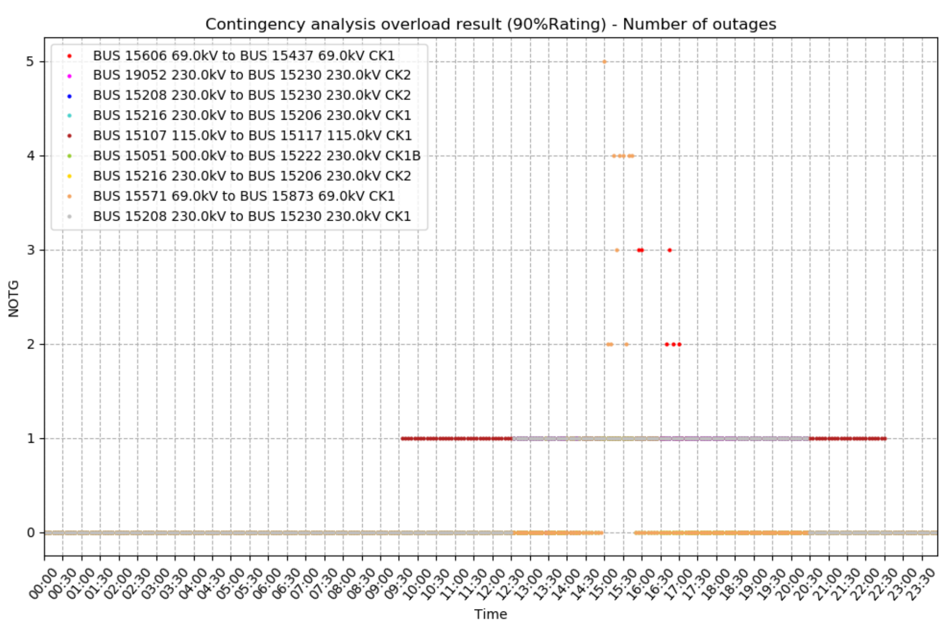

Figure 5.17 Post-Contingency Overload Result – NOTG (Scenario 1-4)

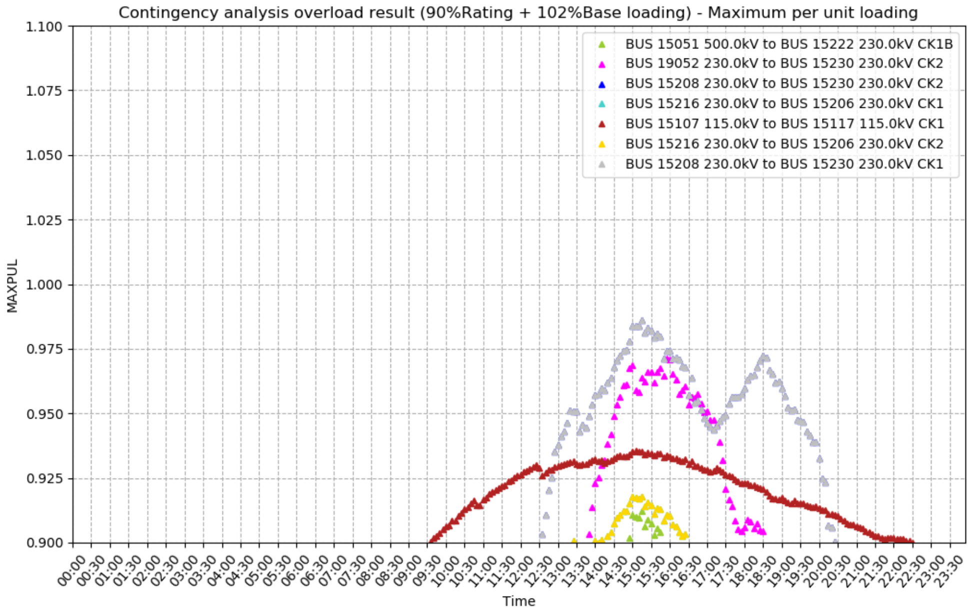

Figure 5.18 Post-Contingency Overload Result with 2nd Criteria– MPUL (Scenario 1-4)

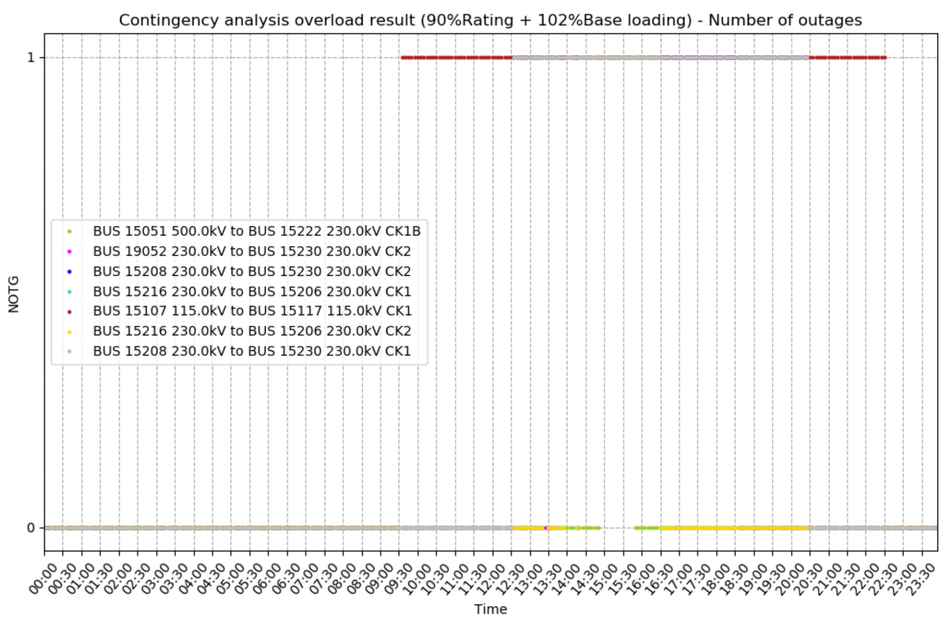

Figure 5.19 Post-Contingency Overload Result with 2nd Criteria – NOTG (Scenario 1-4)

5.1.6 Scenario 1-5

The maximum PUL is 0.951043 which occurs at time 15:00 on branch “BUS 15571 69kV to BUS 15873 69kV CK1”. The maximum MPUL is 0.985413 which occurs at time 15:15 on branch “BUS 15208 230kV to BUS 15230 230kV CK2”.

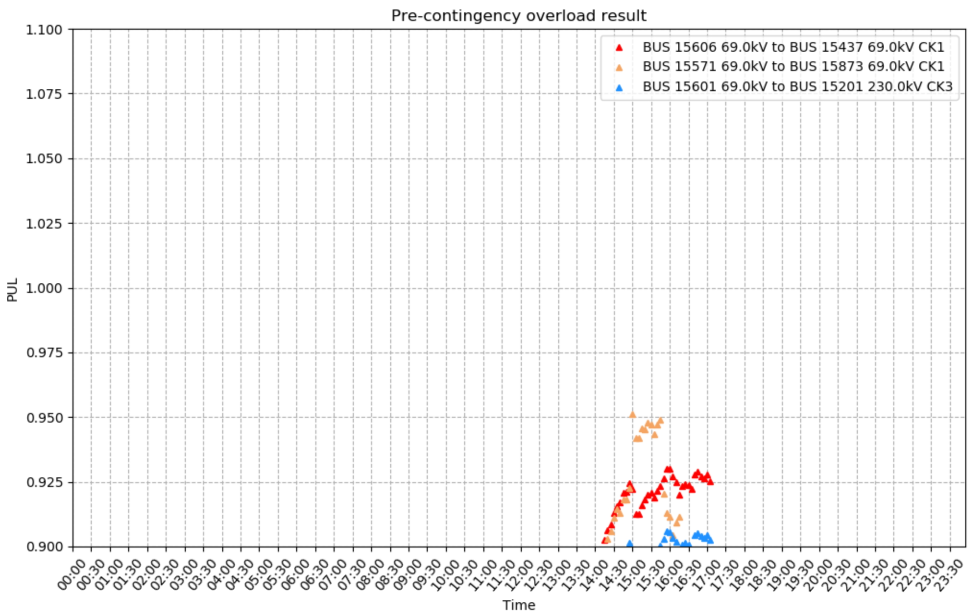

Figure 5.20 Pre-Contingency Overload Result - PUL (Scenario 1-5)

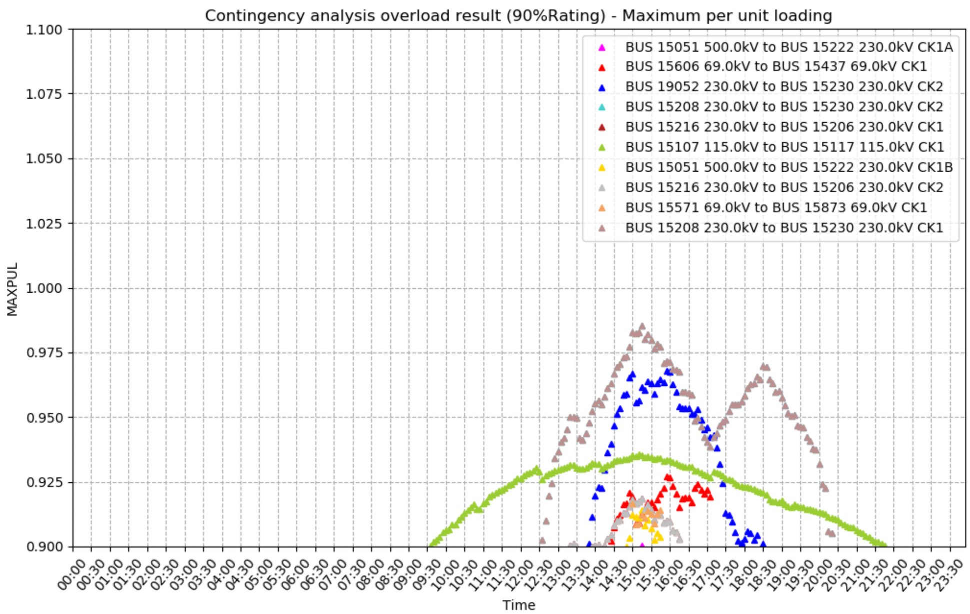

Figure 5.21 Post-Contingency Overload Result – MPUL (Scenario 1-5)

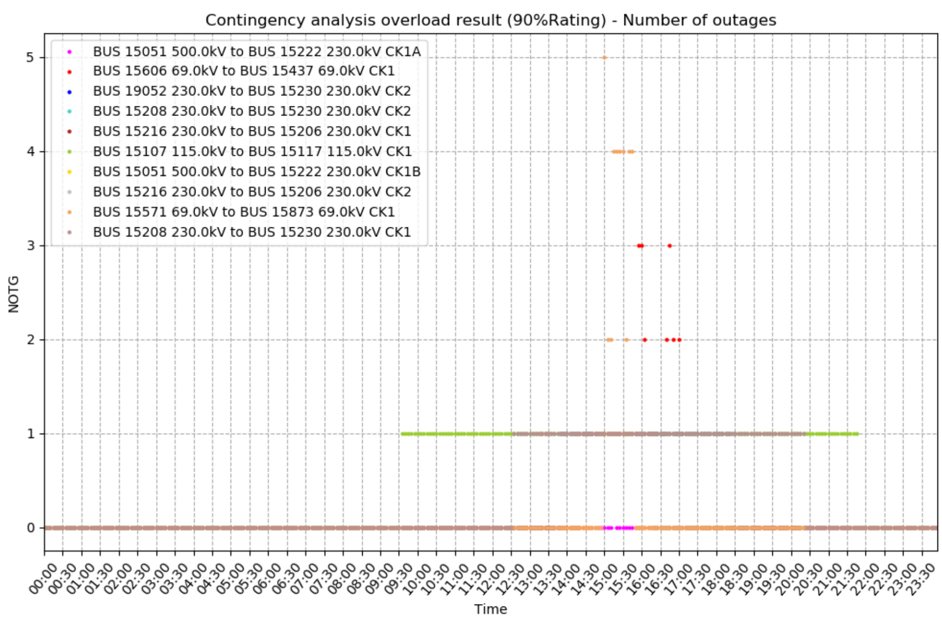

Figure 5.22 Post-Contingency Overload Result – NOTG (Scenario 1-5)

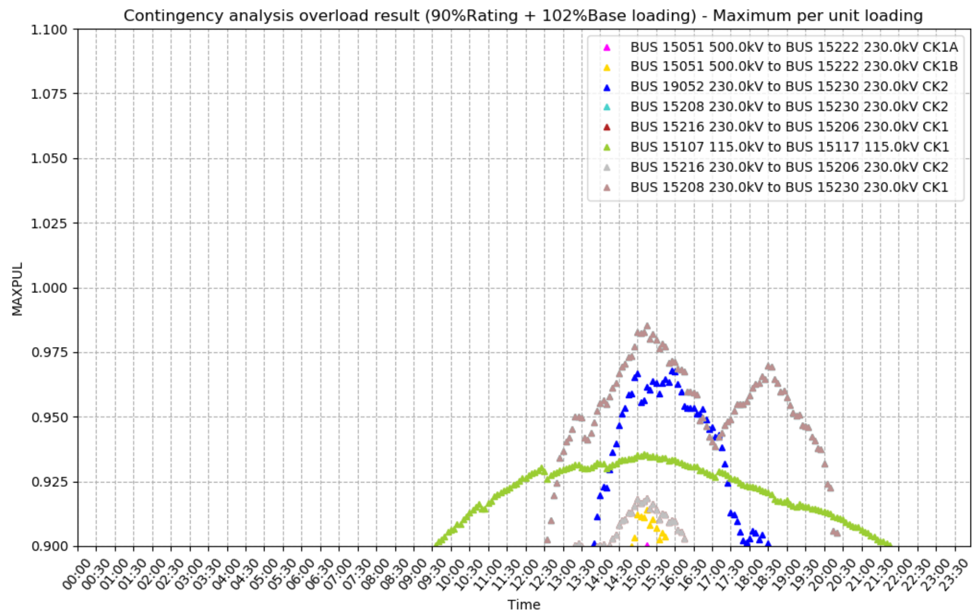

Figure 5.23 Post-Contingency Overload Result with 2nd Criteria– MPUL (Scenario 1-5)

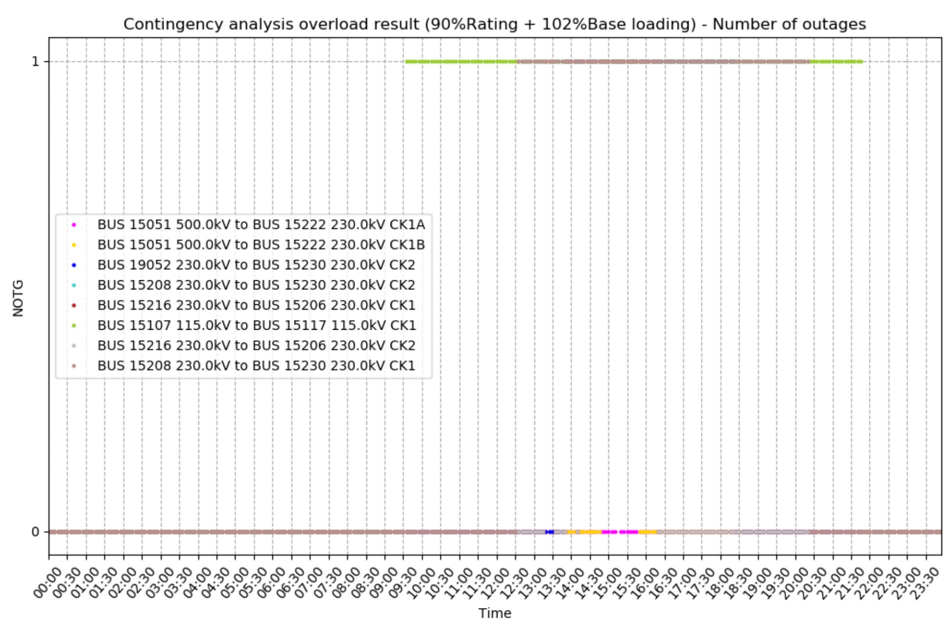

Figure 5.24 Post-Contingency Overload Result with 2nd Criteria – NOTG (Scenario 1-5)

5.2 Sensitivity of Solar Penetration with Transmission System Upgrades

Compared to section 5.1, a new power flow base case is used with some transmission reinforcements. As a result, only 3 overloaded transmission lines are observed in all cases.

5.2.1 Scenario 2-0

The maximum PUL is 1.049803 which occurs at time 18:35 on branch "BUS 15576 69kV to BUS 15872 69kV CK1". The maximum MPUL for this branch is 1.054336 which also occurs at time 18:35 and is increased by the contingency slightly. The maximum MPUL by applying the 2nd criteria is 0.909873 which occurs at time 15:55 on branch "BUS 15107 115kV to BUS 15117 115kV CK1".

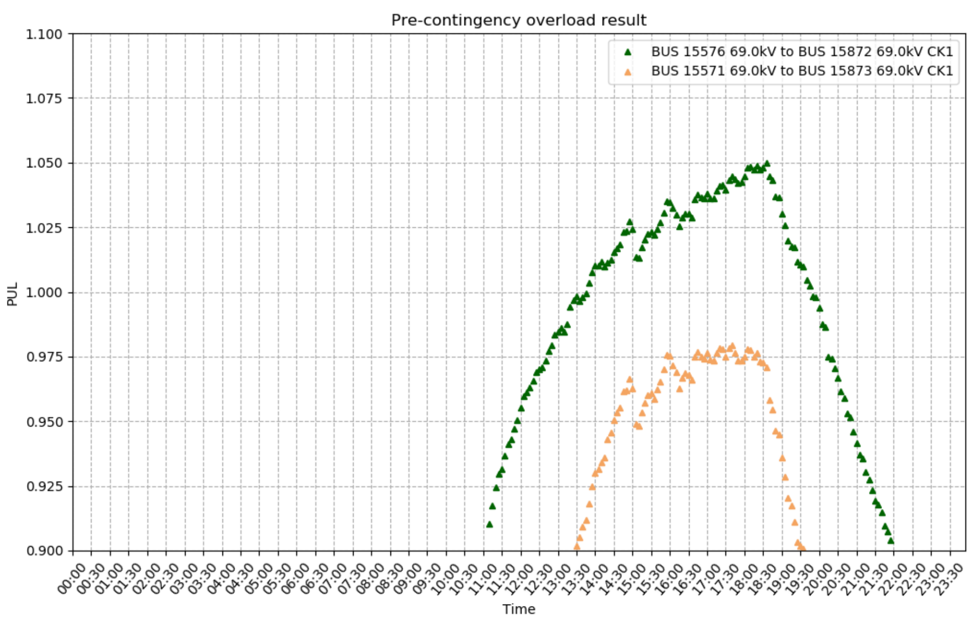

Figure 5.25 Pre-Contingency Overload Result - PUL (Scenario 2-0)

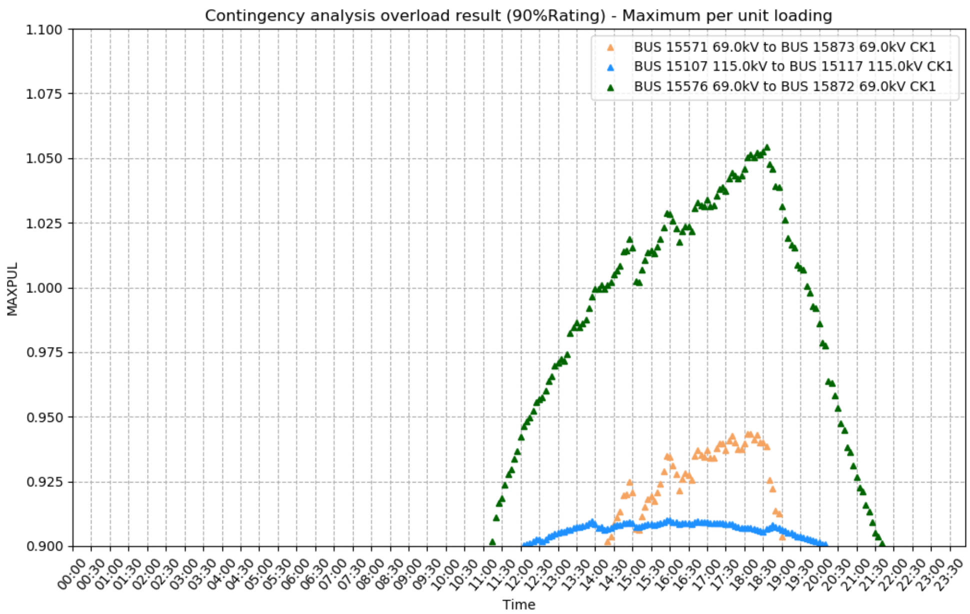

Figure 5.26 Post-Contingency Overload Result – MPUL (Scenario 2-0)

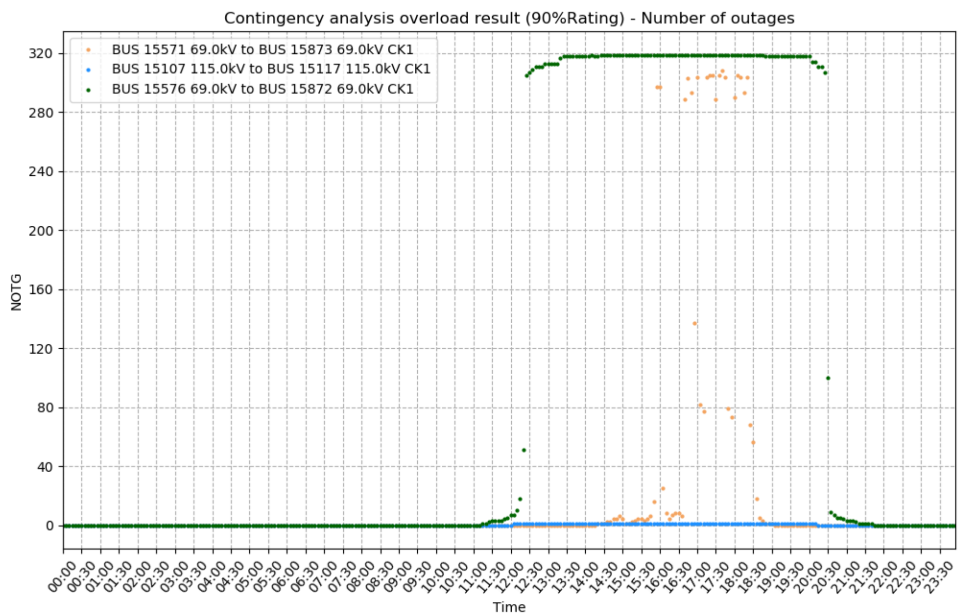

Figure 5.27 Post-Contingency Overload Result – NOTG (Scenario 2-0)

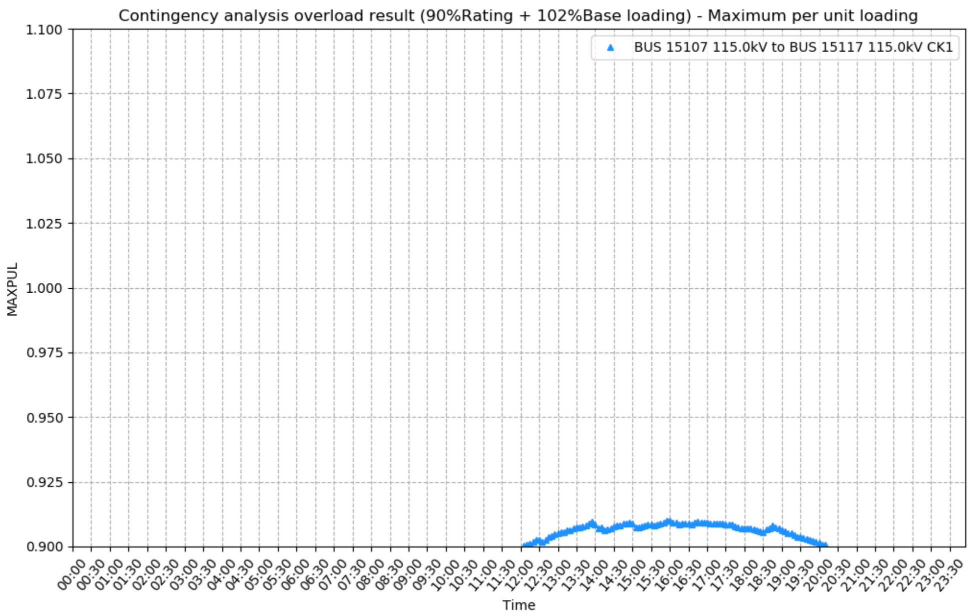

Figure 5.28 Post-Contingency Overload Result with 2nd Criteria– MPUL (Scenario 2-0)

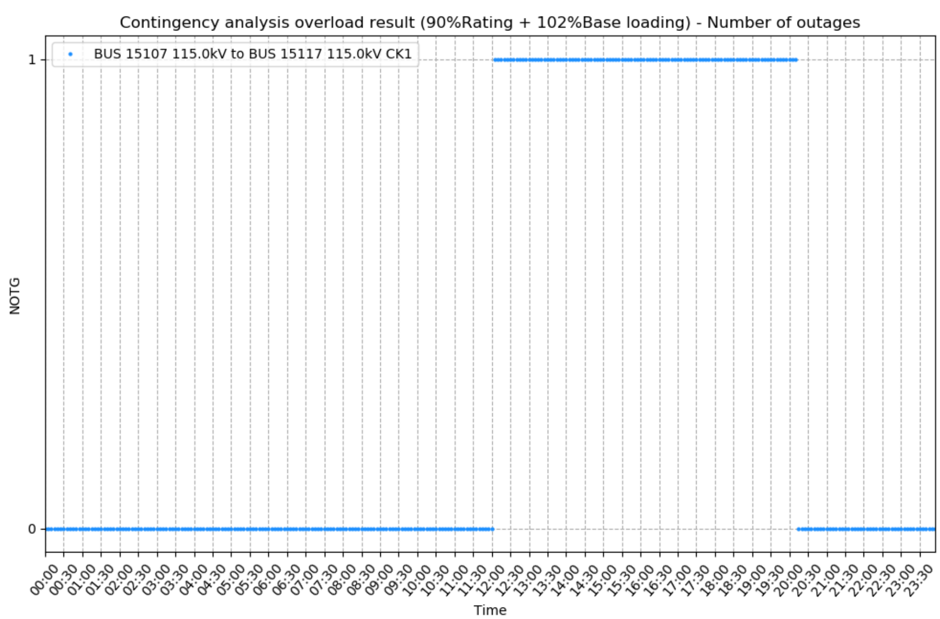

Figure 5.29 Post-Contingency Overload Result with 2nd Criteria – NOTG (Scenario 2-0)

5.2.2 Scenario 2-1

The maximum PUL is 1.044736 which occurs at time 18:35 on branch “BUS 15576 69kV to BUS 15872 69kV CK1”. The maximum MPUL for this branch is 1.046945 which also occurs at time 18:35 and is increased by the contingency slightly. The maximum MPUL by applying the 2nd criteria is 0.910589 which occurs at time 15:55 on branch “BUS 15107 115kV to BUS 15117 115kV CK1”.

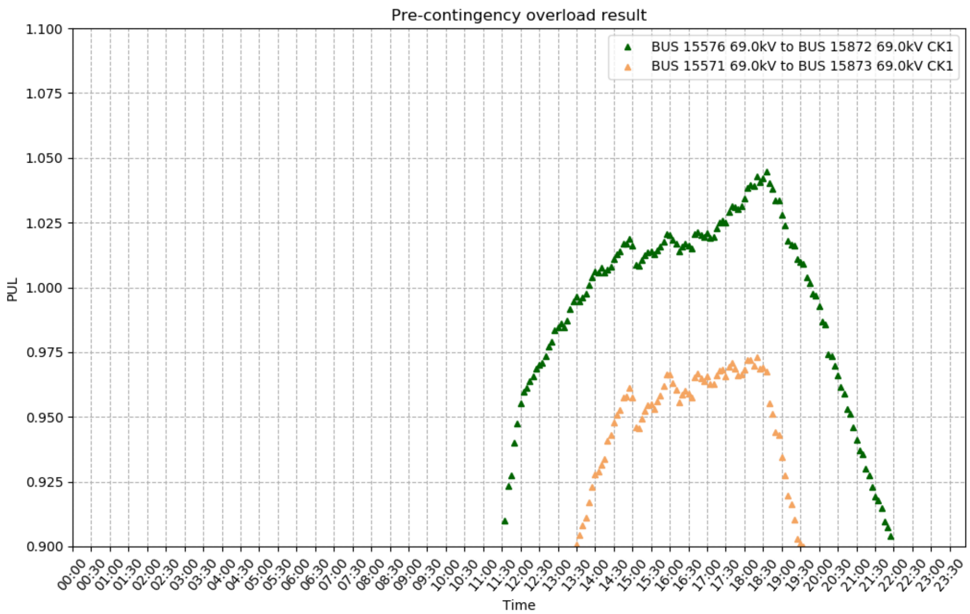

Figure 5.30 Pre-Contingency Overload Result - PUL (Scenario 2-1)

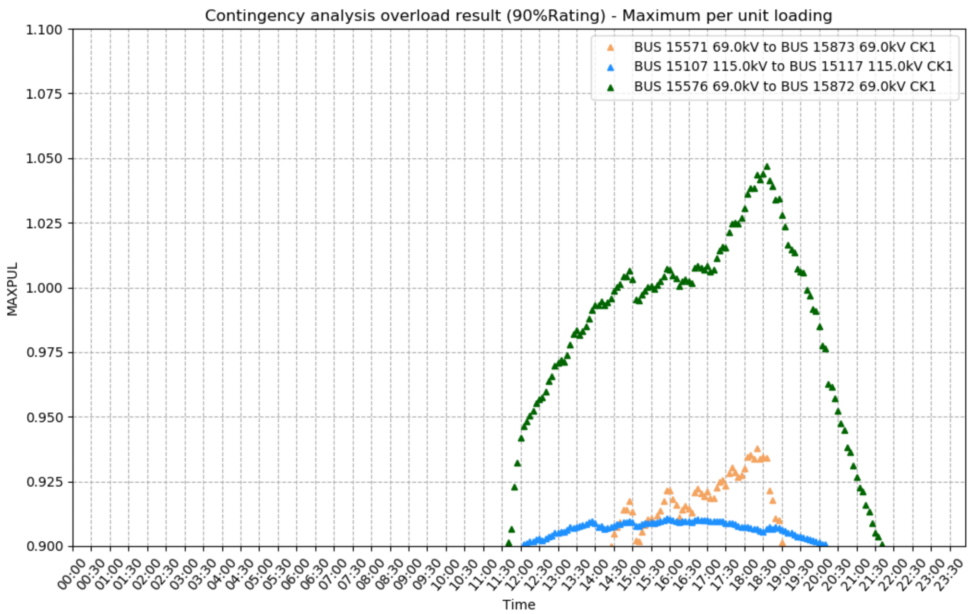

Figure 5.31 Post-Contingency Overload Result – MPUL (Scenario 2-1)

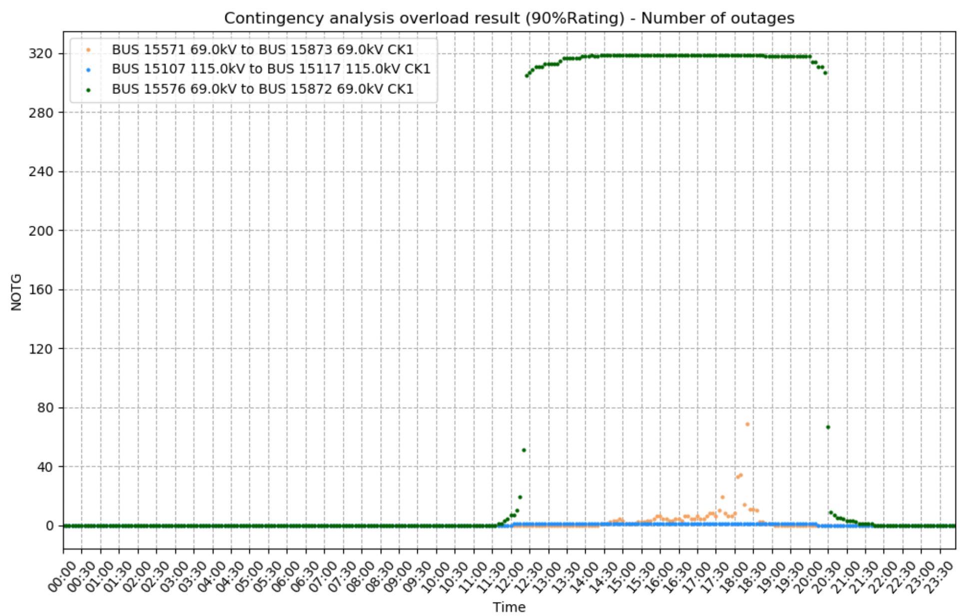

Figure 5.32 Post-Contingency Overload Result – NOTG (Scenario 2-1)

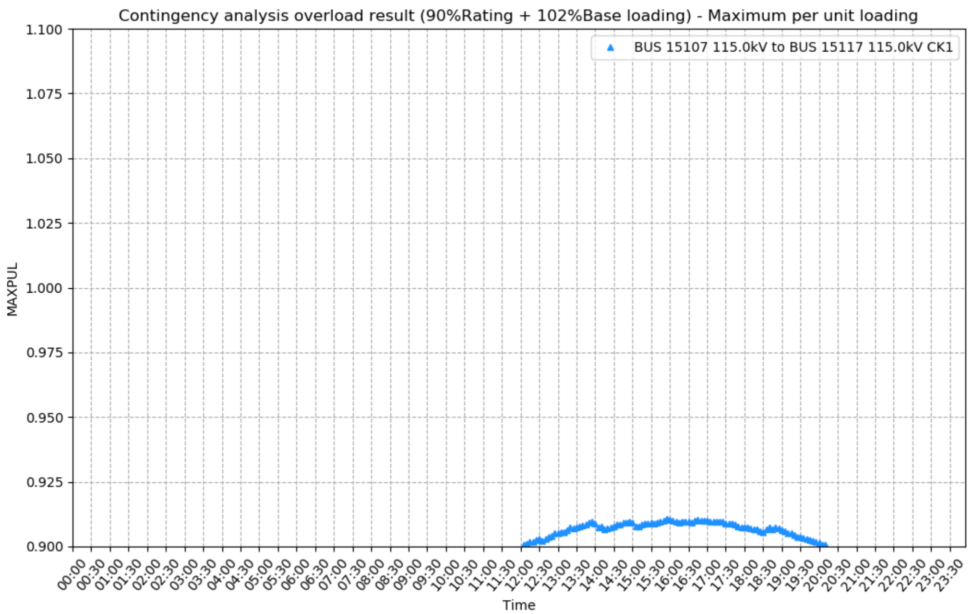

Figure 5.33 Post-Contingency Overload Result with 2nd Criteria– MPUL (Scenario 2-1)

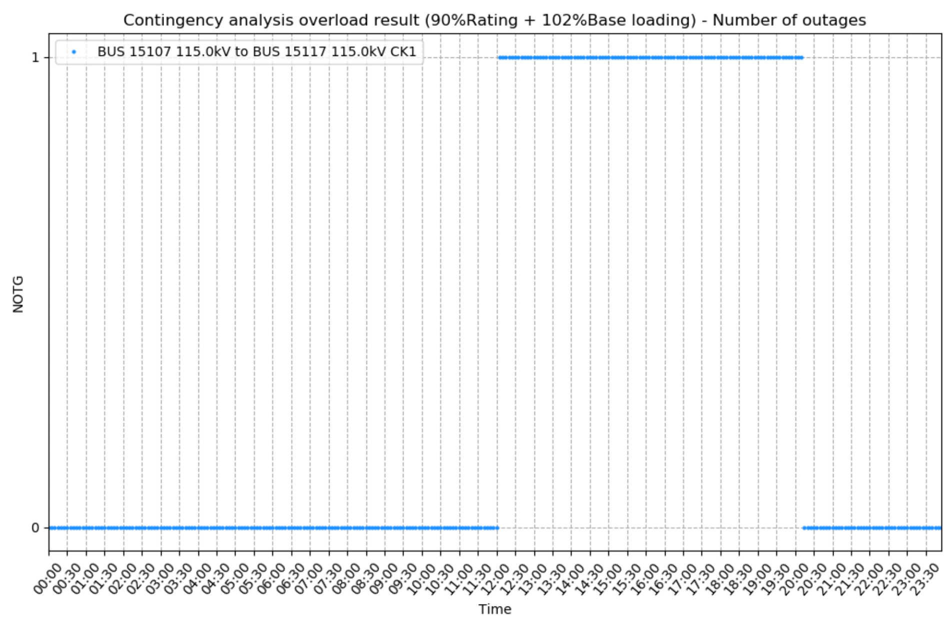

Figure 5.34 Post-Contingency Overload Result with 2nd Criteria – NOTG (Scenario 2-1)

5.2.3 Scenario 2-2

The maximum PUL is 1.043589 which occurs at time 18:35 on branch "BUS 15576 69kV to BUS 15872 69kV CK1". The maximum MPUL for this branch is 1.045236 which also occurs at time 18:35 and is increased by the contingency slightly. The maximum MPUL by applying the 2nd criteria is 0.910827 which occurs at time 14:05 on branch "BUS 15107 115kV to BUS 15117 115kV CK1".

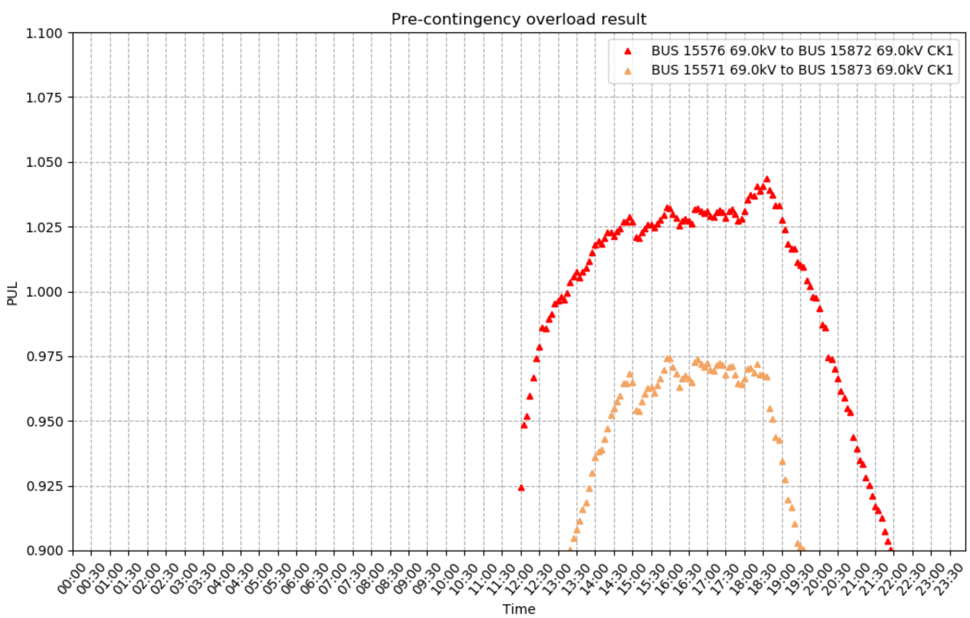

Figure 5.35 Pre-Contingency Overload Result - PUL (Scenario 2-2)

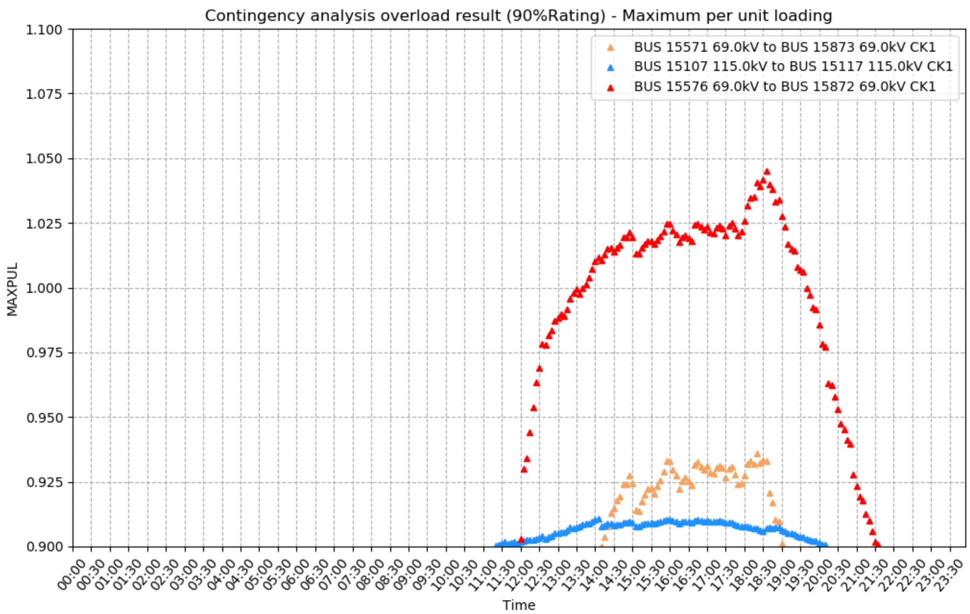

Figure 5.36 Post-Contingency Overload Result – MPUL (Scenario 2-2)

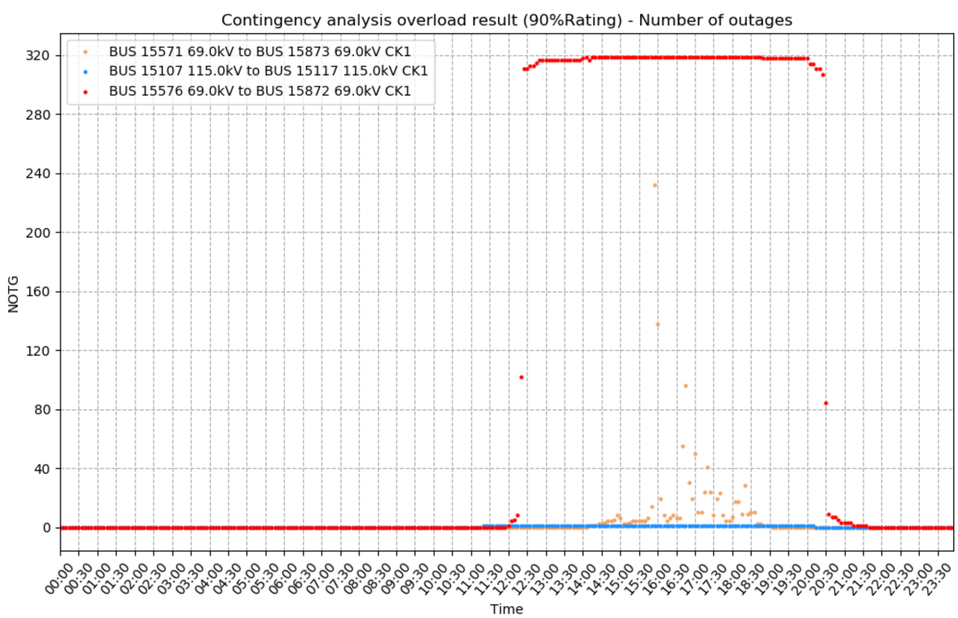

Figure 5.37 Post-Contingency Overload Result – NOTG (Scenario 2-2)

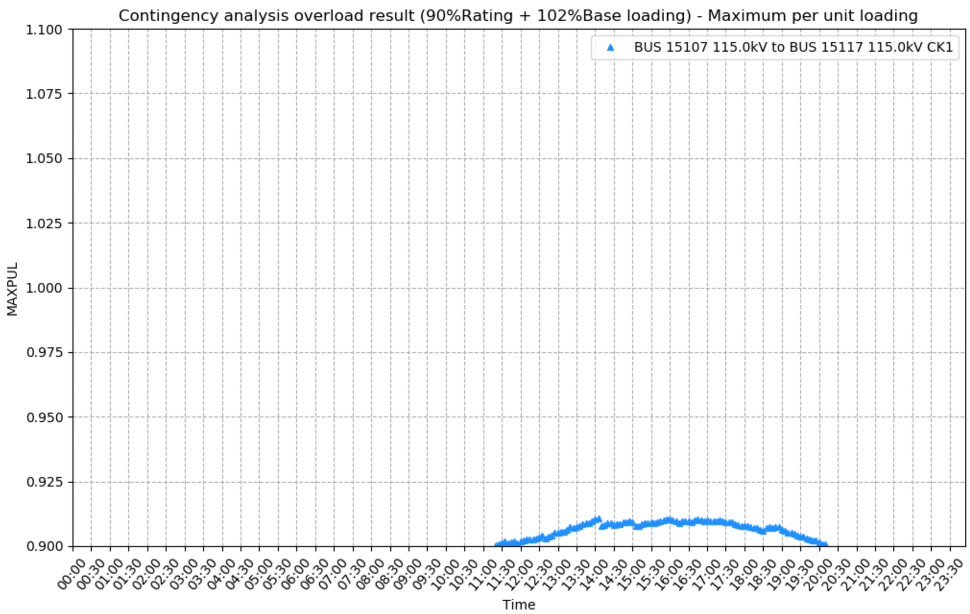

Figure 5.38 Post-Contingency Overload Result with 2nd Criteria– MPUL (Scenario 2-2)

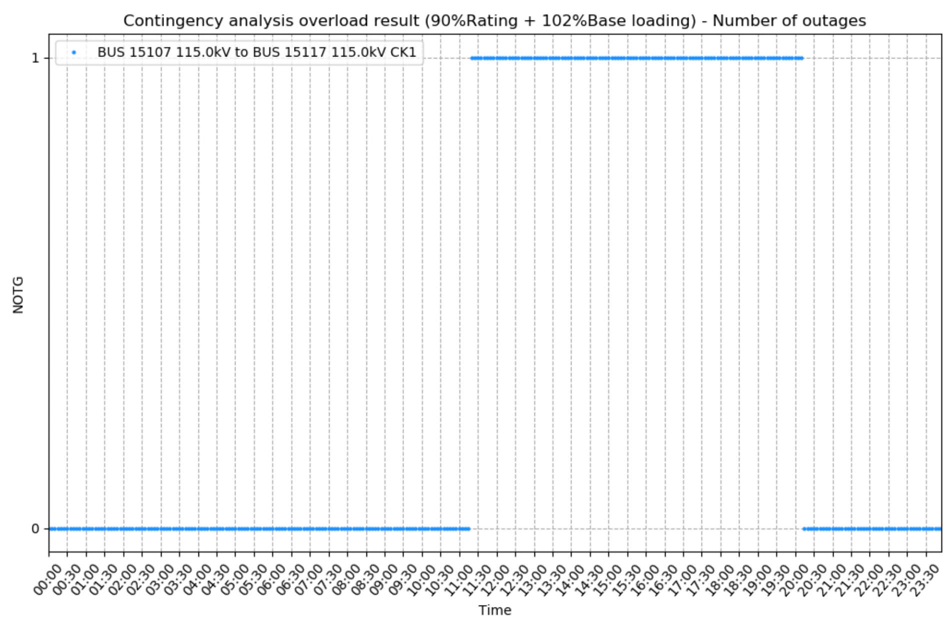

Figure 5.39 Post-Contingency Overload Result with 2nd Criteria – NOTG (Scenario 2-2)

5.2.4 Scenario 2-3

The maximum PUL is 1.037819 which occurs at time 18:35 on branch “BUS 15576 69kV to BUS 15872 69kV CK1”. The maximum MPUL for this branch is 1.036615 which also occurs at time 18:35 and is increased by the contingency slightly. The maximum MPUL by applying the 2nd criteria is 0.915804 which occurs at time 14:00 on branch “BUS 15107 115kV to BUS 15117 115kV CK1”.

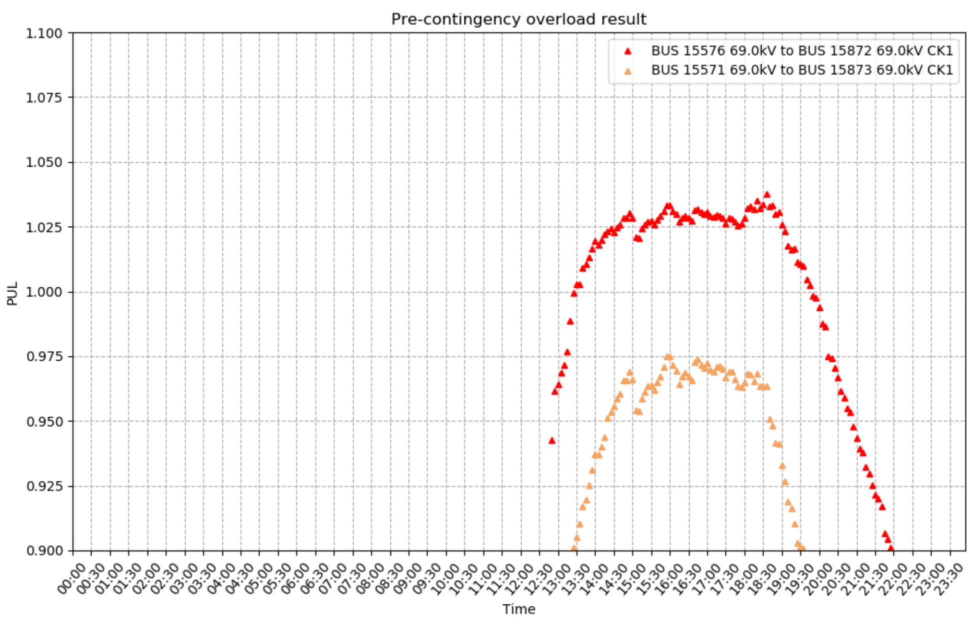

Figure 5.40 Pre-Contingency Overload Result - PUL (Scenario 2-3)

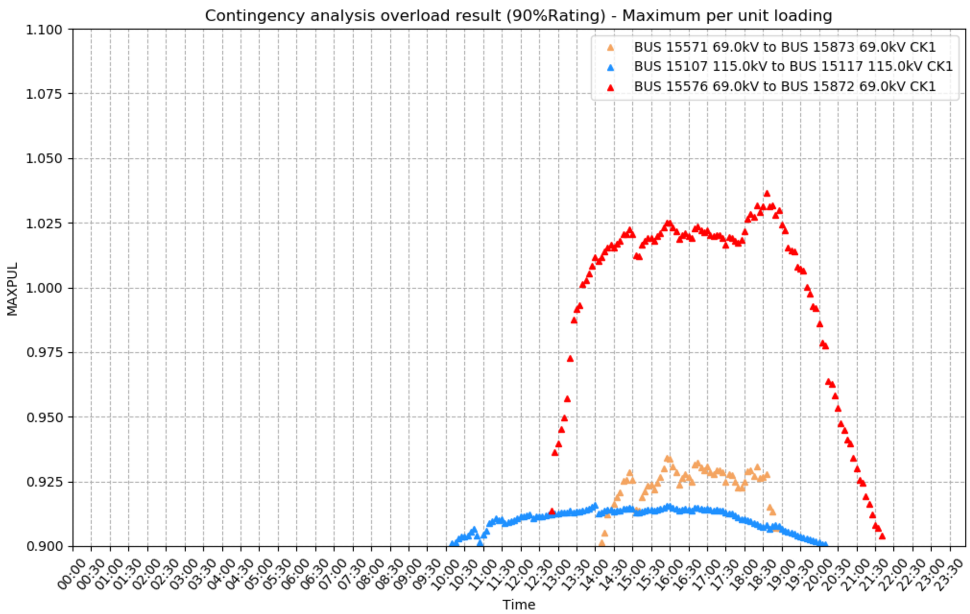

Figure 5.41 Post-Contingency Overload Result – MPUL (Scenario 2-3)

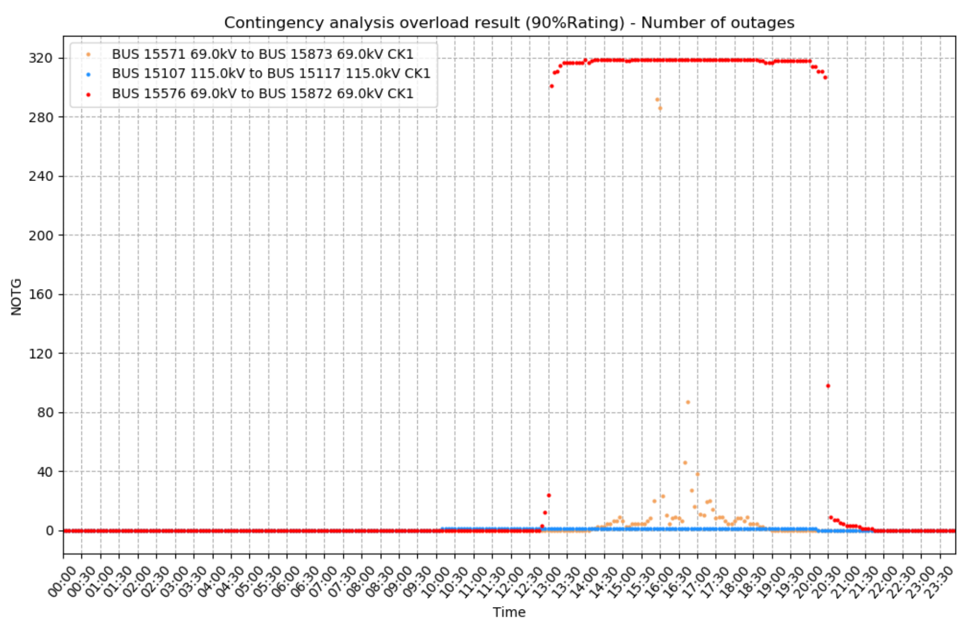

Figure 5.42 Post-Contingency Overload Result – NOTG (Scenario 2-3)

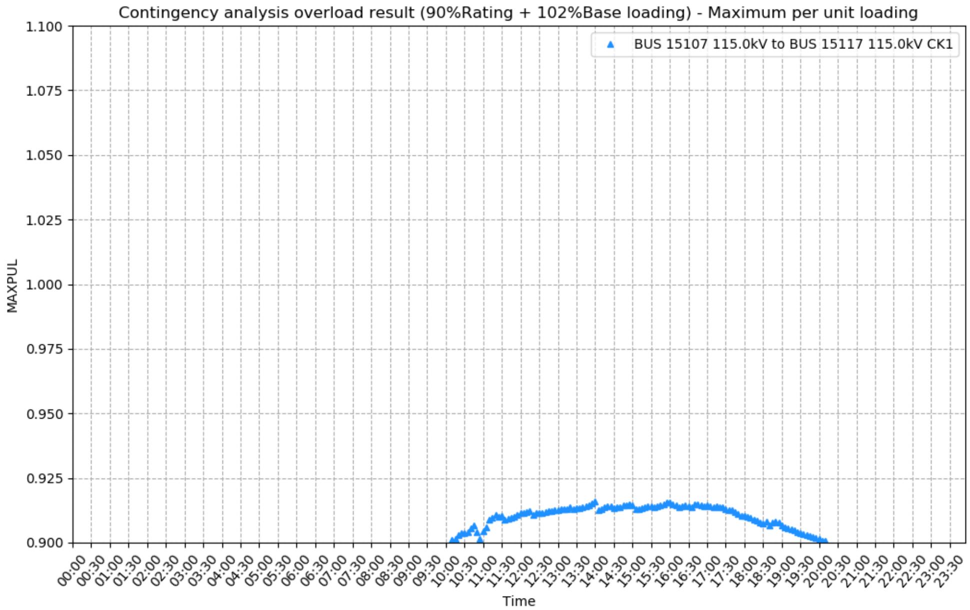

Figure 5.43 Post-Contingency Overload Result with 2nd Criteria– MPUL (Scenario 2-3)

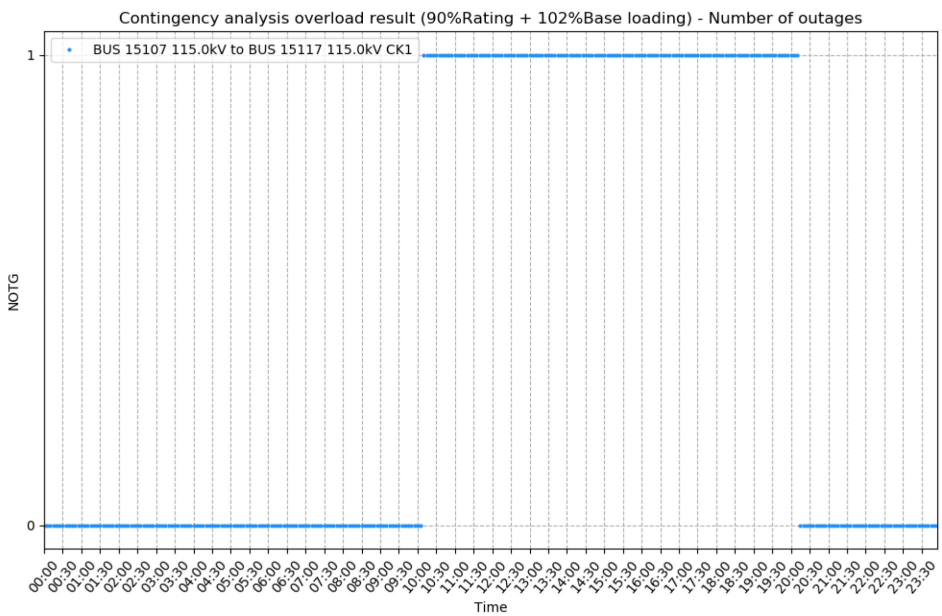

Figure 5.44 Post-Contingency Overload Result with 2nd Criteria – NOTG (Scenario 2-3)

5.2.5 Scenario 2-4

The maximum PUL is 1.045713 which occurs at time 15:55 on branch “BUS 15576 69kV to BUS 15872 69kV CK1”. The maximum MPUL for this branch is 1.043708 which also occurs at time 15:55 and is increased by the contingency slightly. The maximum MPUL by applying the 2nd criteria is 0.915976 which occurs at time 14:00 on branch “BUS 15107 115kV to BUS 15117 115kV CK1”.

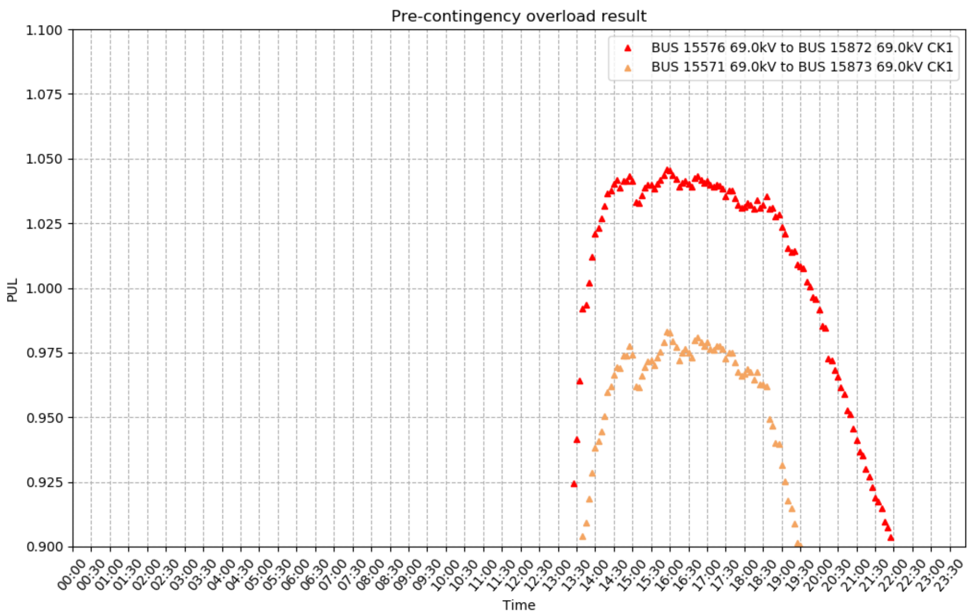

Figure 5.45 Pre-Contingency Overload Result - PUL (Scenario 2-4)

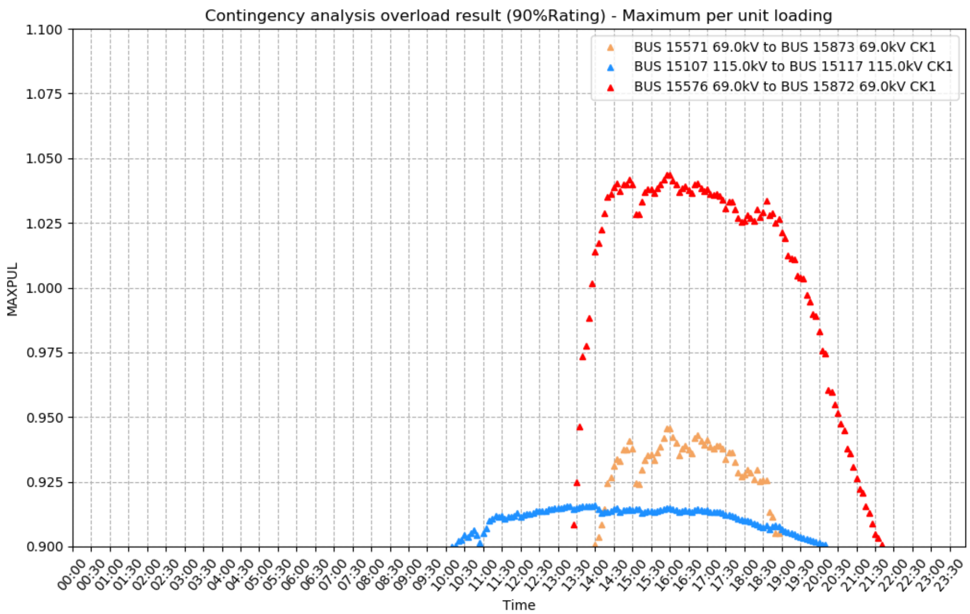

Figure 5.46 Post-Contingency Overload Result – MPUL (Scenario 2-4)

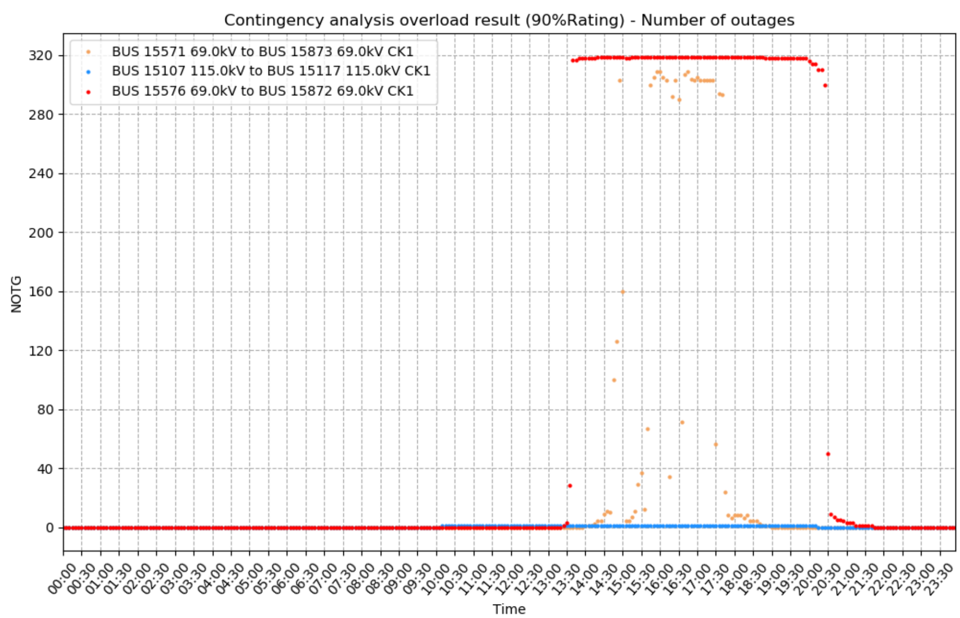

Figure 5.47 Post-Contingency Overload Result – NOTG (Scenario 2-4)

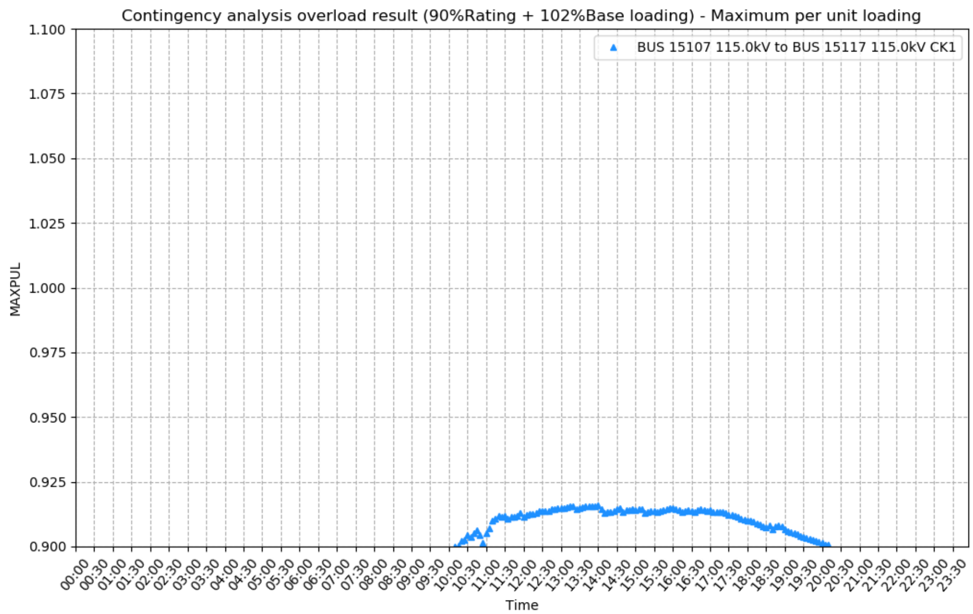

Figure 5.48 Post-Contingency Overload Result with 2nd Criteria– MPUL (Scenario 2-4)

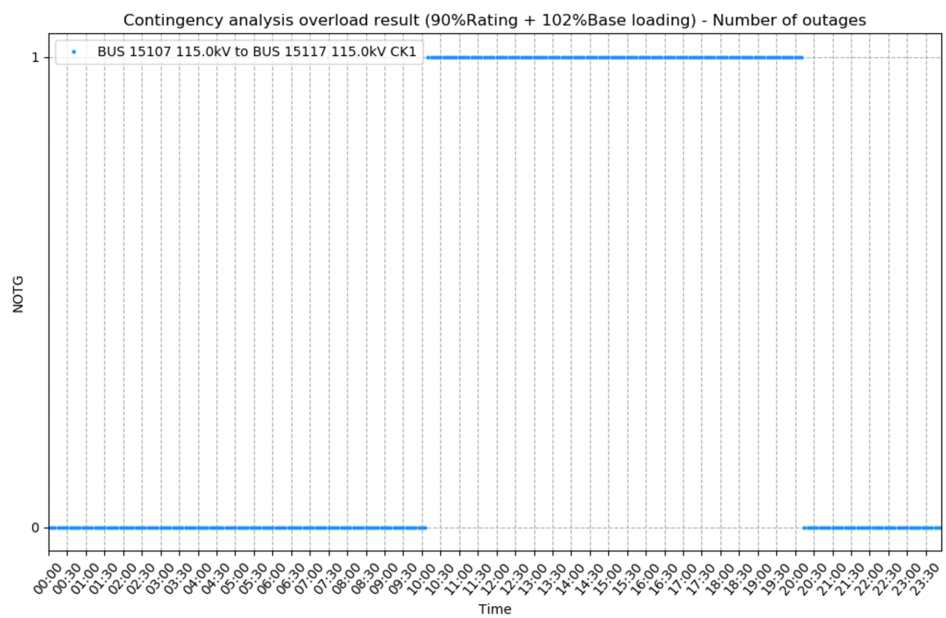

Figure 5.49 Post-Contingency Overload Result with 2nd Criteria – NOTG (Scenario 2-4)

5.2.6 Scenario 2-5

The maximum PUL is 1.045731 which occurs at time 15:55 on branch “BUS 15576 69kV to BUS 15872 69kV CK1”. The maximum MPUL for this branch is 1.043721 which also occurs at time 15:55 and is increased by the contingency slightly. The maximum MPUL by applying the 2nd criteria is 0.917223 which occurs at time 13:35 on branch “BUS 15107 115kV to BUS 15117 115kV CK1”.

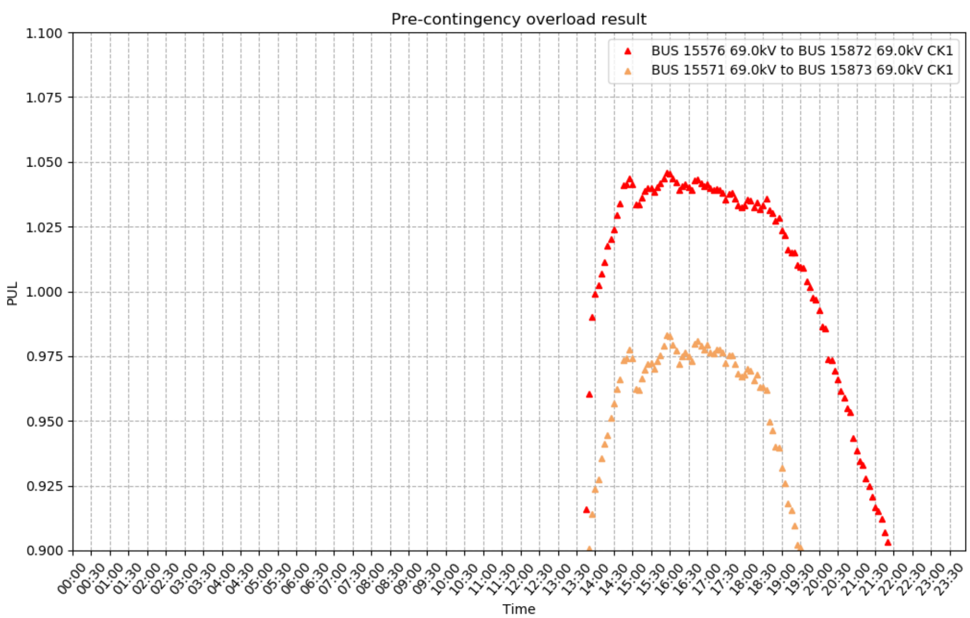

Figure 5.50 Pre-Contingency Overload Result - PUL (Scenario 2-5)

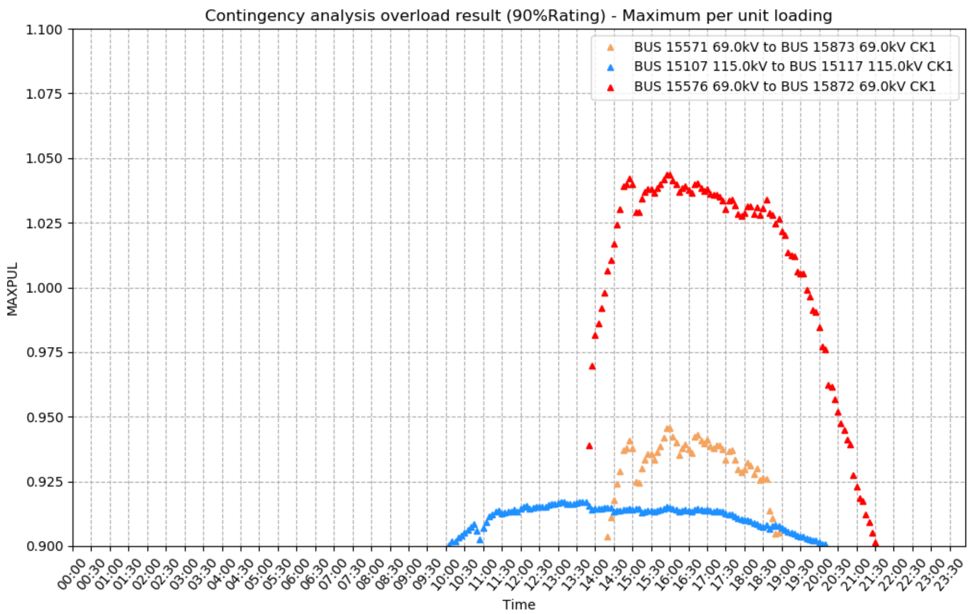

Figure 5.51 Post-Contingency Overload Result – MPUL (Scenario 2-5)

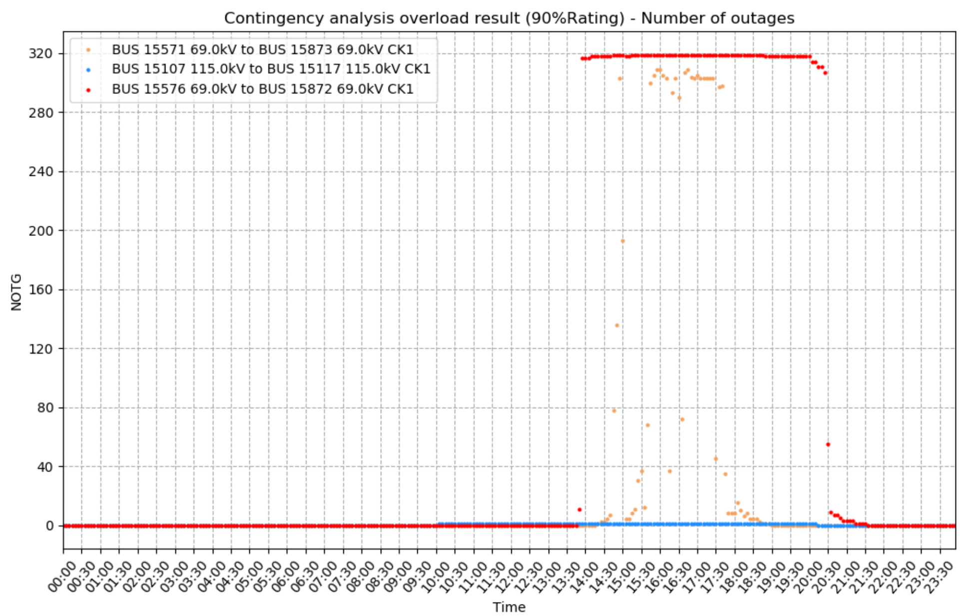

Figure 5.52 Post-Contingency Overload Result – NOTG (Scenario 2-5)

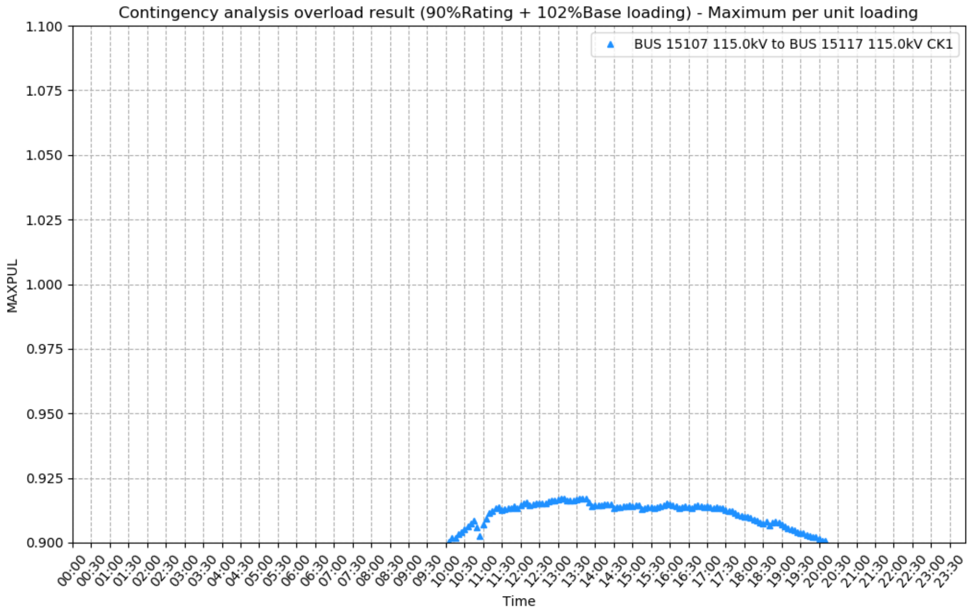

Figure 5.53 Post-Contingency Overload Result with 2nd Criteria– MPUL (Scenario 2-5)

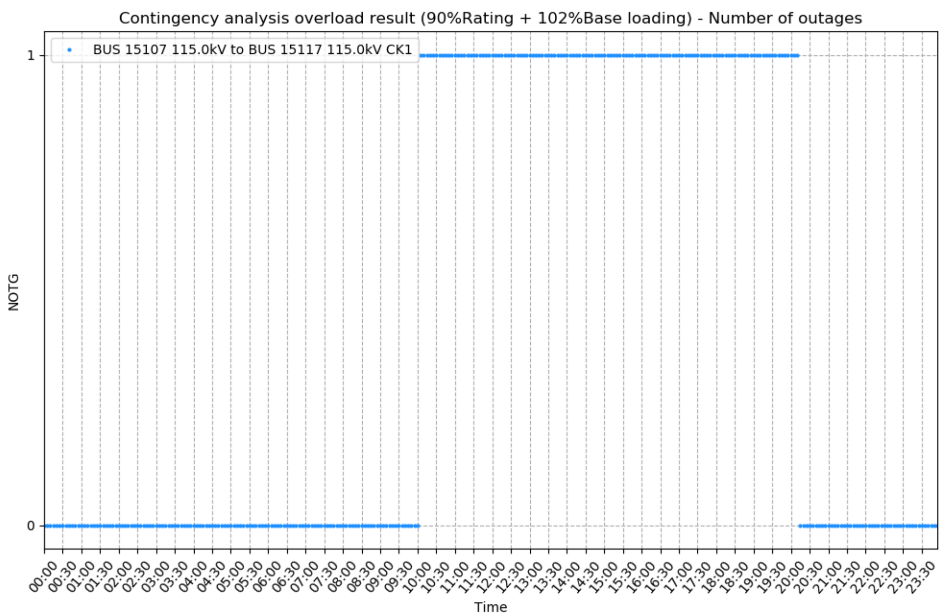

Figure 5.54 Post-Contingency Overload Result with 2nd Criteria – NOTG (Scenario 2-5)

5.3 Sensitivity of Large Unit Retirement

Compared to the initial case used in section 5.2, one coal generating station is retired in the base power flow case in this section. Only the case with the maximum solar penetration is shown in this section.

5.3.1 Scenario 3-5

The maximum PUL is 1.063257 which occurs at time 18:00 on branch "BUS 15576 69kV to BUS 15872 69kV CK1". The maximum MPUL for this branch is 1.074815 which also occurs at time 18:00 and is increased by the contingency slightly. The maximum MPUL by applying the 2nd criteria is 0.901957 which occurs at time 14:10 on branch "BUS 15107 115kV to BUS 15117 115kV CK1".

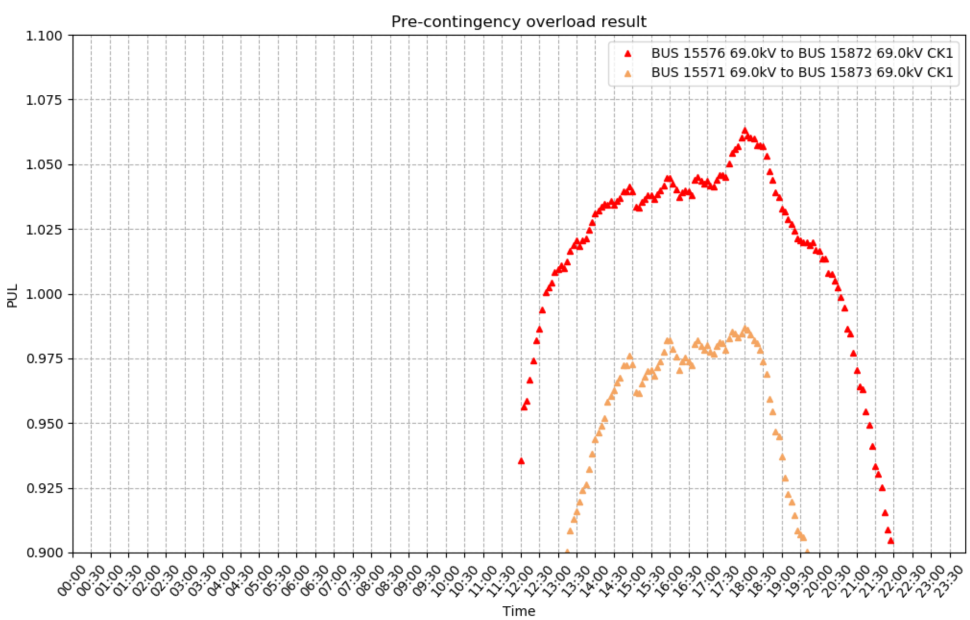

Figure 5.55 Pre-Contingency Overload Result - PUL (Scenario 3-5)

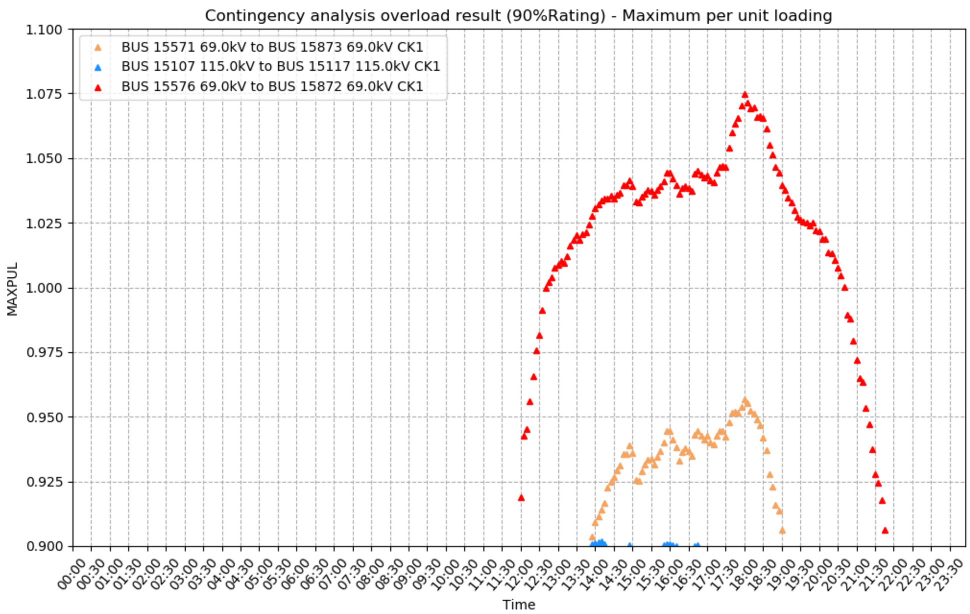

Figure 5.56 Post-Contingency Overload Result – MPUL (Scenario 3-5)

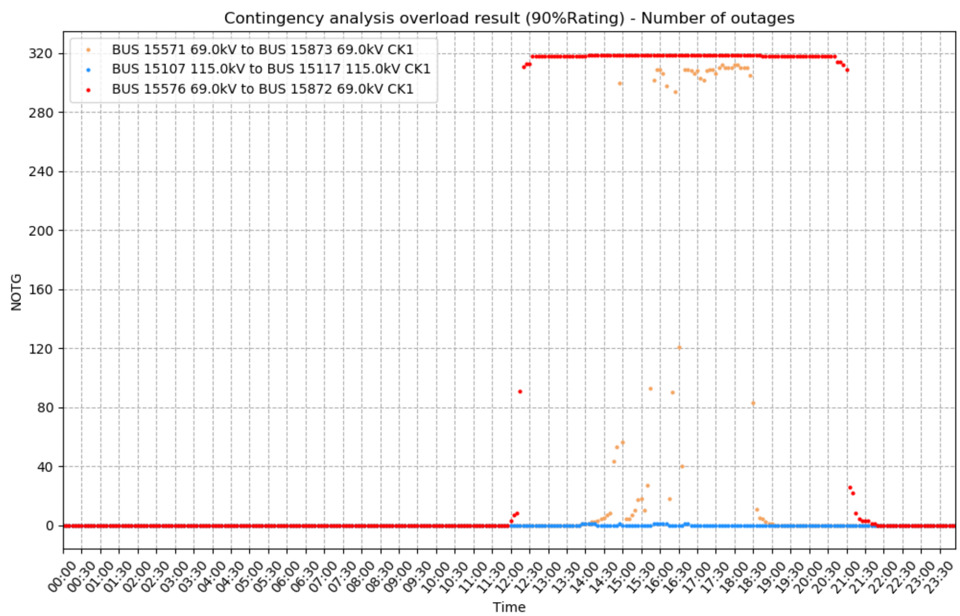

Figure 5.57 Post-Contingency Overload Result – NOTG (Scenario 3-5)

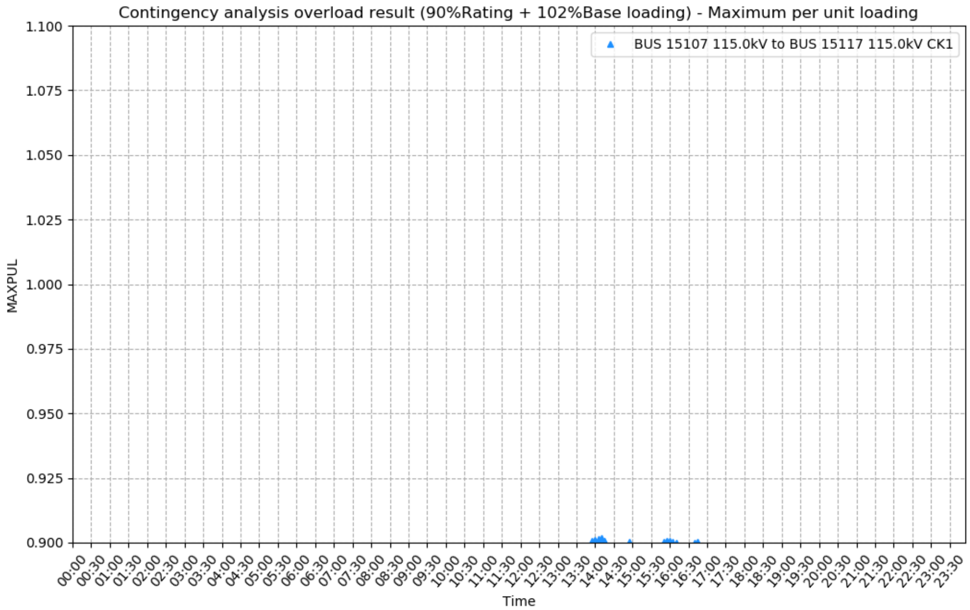

Figure 5.58 Post-Contingency Overload Result – NOTG (Scenario 3-5)

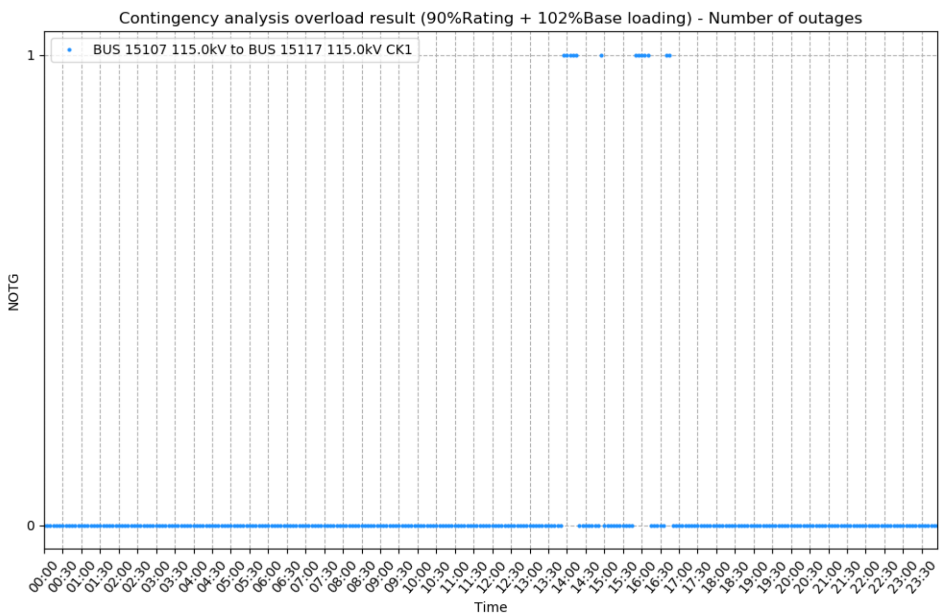

Figure 5.59 Post-Contingency Overload Result with 2nd Criteria – NOTG (Scenario 3-5)

5.4 Participation in the EIM

The basic operation of participating in the EIM, is to import the power from the western area in the morning hours and export power to the western neighboring area in the late afternoon hours. And the detailed flow chart of the program is shown in section 3.4.

In the following section, the result can be divided into three parts: the pre-contingency overload result, which is the overload of the base case in each time interval; the pre-contingency EIM overload result, which is the overload of the base case with tie line flow adjusted for EIM; the contingency result. At each time interval, there are multiple EIM cases that have different EIM flow, the pre-contingency EIM result only shows the maximum per unit loading of each overloaded branch among all the EIM flow cases, and a table that indicates which EIM flow cause the maximum loading will also be included in the following section.

5.4.1 Impact of Participation in the EIM

The base case used here is the same as that in section 5.1, there are no overloads in the time series pre-contingency power flow base cases as well as the EIM base cases. And compared to section 5.1.1, the same four transmission lines are overloaded, and the loadings of these four transmission lines are reduced after participating in the EIM.

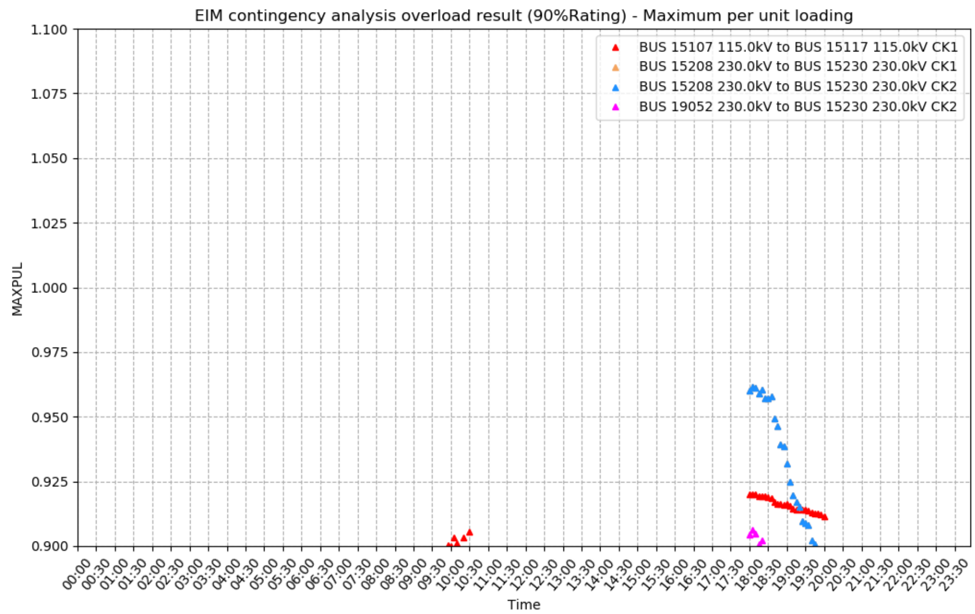

Figure 5.60 Post-Contingency Overload Result with Participation in the EIM – MPUL (Scenario 1-0)

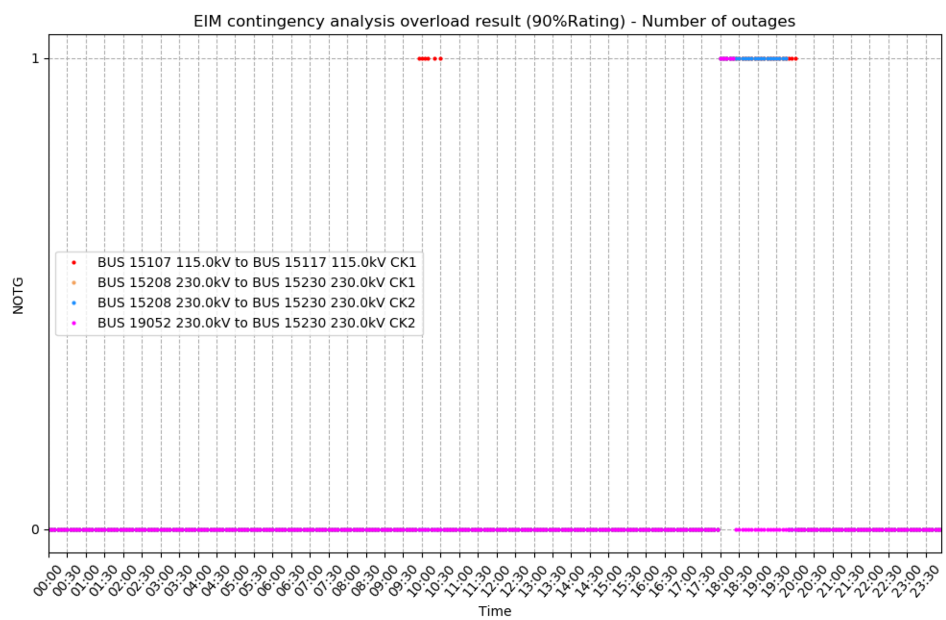

Figure 5.61 Post-Contingency Overload Result with Participation in the EIM – NOTG (Scenario 1-0)

5.4.2 Impact of Participation in the EIM with Transmission System Reinforcement

The same base case as in section 5.2 is used here, and the overloads in the base case time series are the same. Compared to the results obtained in section 5.2, there are no extra overloads caused by participation in the EIM.

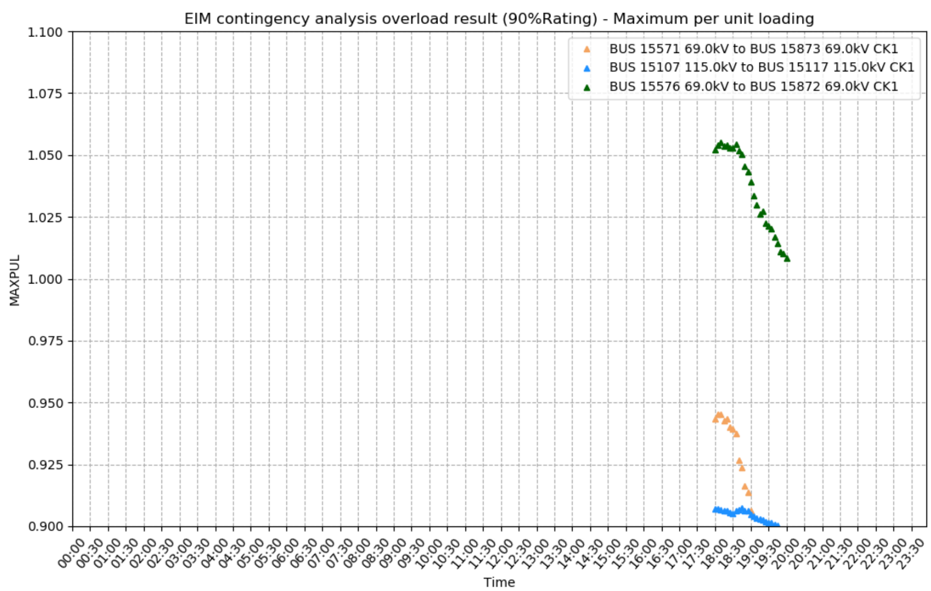

Figure 5.62 Post-Contingency Overload Result with Participation in the EIM– MPUL (Scenario 2-0)

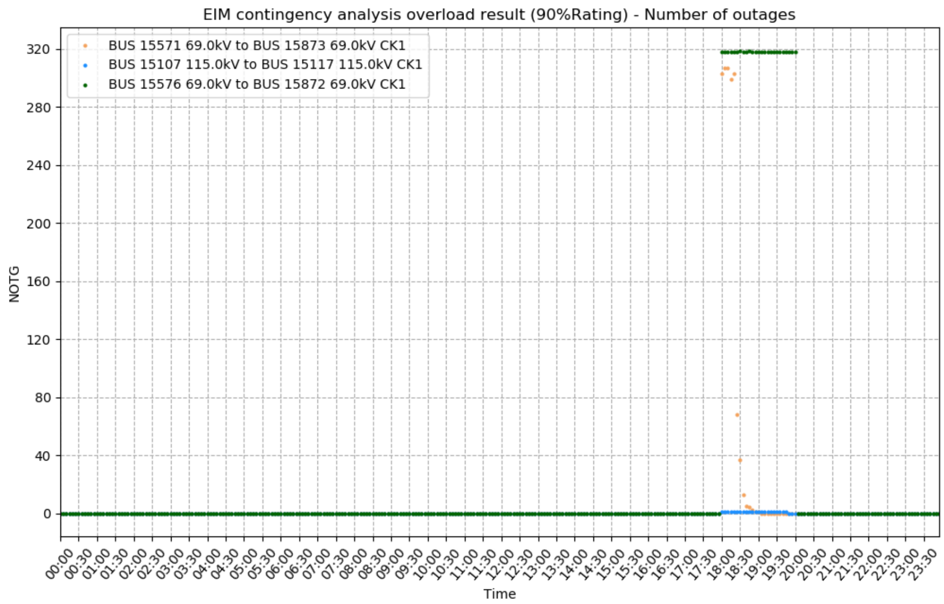

Figure 5.63 Post-Contingency Overload Result with Participation in the EIM – NOTG (Scenario 2-0)

6. CONCLUSION AND FUTURE WORK

6.1 Conclusion

In this project, a metric is developed to assess the flexibility of the transmission system using automated time series power flows. The flexibility metric provides an efficient numerical and visual analysis of the results generated from the program. Only the typical scenarios are chosen to be depicted in this thesis, but the TSPF program can always generate new scenarios of time series power flows.

A sensitivity analysis of the solar penetration has been conducted. PUL is plotted for all the pre-contingency cases including the cases with participation in EIM. The PUL index represents how the system performs in the base case without any outages. MPUL is plotted for all the contingency overloads and pre-contingency overloads for the EIM participation case (at each time interval, multiple flows are considered), compared to PUL for the base case, we note that there are new branches that could be overloaded as a result of outage and for such cases PUL quantifies the severity of the outage as well as the flexibility of the transmission system under this outage. From the results in the previous chapter, it is noted that in each time series power flow simulation, there is a maximum per unit loading (maxpul) among all the outages at all time which indicates how much allowance the system has, or how much the system has exceeded the limit, this represents the flexibility of the power system. NOTG evaluates the time series power flow results in an alternate manner, for instance, if NOTG nearly equals to the number of all the outages conducted for one branch, that is, this branch has already been overloaded in the base case. The larger the NOTG, the less flexibility the power system has.

The analysis incorporating the participation in the energy imbalance market has been conducted, and no overloads due to the participation in EIM are found. The participation in the EIM only affects the magnitude of loading on the branches to a limited extent, which also has the possibility of increasing the flexibility of the transmission system. In conclusion, the transmission system studied in this work has enough transmission capability and flexibility to operate after joining the EIM.

Comparing all the result figures in Chapter 5 with the Figures 3.3-3.6, it can be observed that the overloads mainly happen at heavy total load hours for the cases studied in this work, which makes sense since more power is delivered by the transmission system at heavier total load. The net load change in each time interval does not affect the transmission system flexibility, which verifies what is discussed in Chapter 2. The transmission system cannot provide flexibility to the power system, so it cannot respond to the net load change which requires flexibility from the power system. The flexibility required by the net load change is met by the conventional generators which are assumed to be flexible at the beginning of this work. However, the magnitude flexibility metric can be developed using the loading on the transmission component, which is evaluated by the capability margin for the existing transmission system.

Table 6.1 and Table 6.2 give a summary of the results obtained in Chapter 5. The relationship between the flexibility of the transmission system and the solar penetration is not linear, the increase in solar penetration may affect the transmission system's available flexibility both positively and negatively. Because the transmission flexibility availability is not solely dependent on the solar penetration but also largely dependent on the geographical location of the solar generation and the transmission component.

Table 6.1 Pre-Contingency Result in Chapter 5

Case		Branch	PML	Maxpul	Margin
I.Base	2	BUS 15571 69kV to BUS 15873 69kV CK1	15:50:00	0.93328	0.06672
	3		15:55:00	0.941218	0.058782
	4		15:00:00	0.95062	0.04938
	5		15:00:00	0.951043	0.048957
II.Base case with transmission reinforcement	0	BUS 15107 115kV to BUS 15117 115kV CK1	18:35:00	1.049803	-0.049803
	1		18:35:00	1.044736	-0.044736
	2		18:35:00	1.043589	-0. 043589
	3		18:35:00	1.037819	-0. 037819
	4		15:55:00	1.045713	-0. 045713
	5		15:55:00	1.045731	-0. 045731
III. case II with one coal unit retired	0	BUS 15107 115kV to BUS 15117 115kV CK1	15:55:00	1.054861	-0. 054861
	1		17:10:00	1.055313	-0. 055313
	2		17:00:00	1.066792	-0. 066792
	3		17:40:00	1.062167	-0. 062167
	4		17:50:00	1.064895	-0. 064895
	5		18:00:00	1.063257	-0. 063257

Table 6.2 Post-Contingency Result in Chapter 5

<table>
<tr><th colspan="2">Case</th><th>Branch</th><th>PML</th><th>Maxpul</th><th>Margin</th><th>NOTG</th></tr>
<tr><td rowspan="6">I.Base</td><td>0</td><td rowspan="6">BUS 15208 230kV to BUS 15230 230kV CK2</td><td>15:55:00</td><td>0.991678</td><td>0.008322</td><td>1</td></tr>
<tr><td>1</td><td>16:45:00</td><td>0.988819</td><td>0.011181</td><td>1</td></tr>
<tr><td>2</td><td>15:30:00</td><td>1.02453</td><td>-0.02453</td><td>1</td></tr>
<tr><td>3</td><td>15:45:00</td><td>1.009791</td><td>-0.009791</td><td>1</td></tr>
<tr><td>4</td><td>15:15:00</td><td>0.986268</td><td>0.013732</td><td>1</td></tr>
<tr><td>5</td><td>15:15:00</td><td>0.985413</td><td>0.014587</td><td>1</td></tr>
<tr><td rowspan="6">II.Base case with transmission reinforcement</td><td>0</td><td rowspan="6">BUS 15107 115kV to BUS 15117 115kV CK1</td><td>15:55:00</td><td>0.909873</td><td>0.090127</td><td>1</td></tr>
<tr><td>1</td><td>15:55:00</td><td>0.910589</td><td>0.089411</td><td>1</td></tr>
<tr><td>2</td><td>14:05:00</td><td>0.910827</td><td>0.089173</td><td>1</td></tr>
<tr><td>3</td><td>14:00:00</td><td>0.915804</td><td>0.084196</td><td>1</td></tr>
<tr><td>4</td><td>14:00:00</td><td>0.915976</td><td>0.084024</td><td>1</td></tr>
<tr><td>5</td><td>13:35:00</td><td>0.917223</td><td>0.082777</td><td>1</td></tr>
<tr><td rowspan="3">III. case II with one coal unit retired</td><td>3</td><td rowspan="3">BUS 15107 115kV to BUS 15117 115kV CK1</td><td>14:05:00</td><td>0.901969</td><td>0.098031</td><td>1</td></tr>
<tr><td>4</td><td>14:10:00</td><td>0.901998</td><td>0.098005</td><td>1</td></tr>
<tr><td>5</td><td>14:10:00</td><td>0.901957</td><td>0.098043</td><td>1</td></tr>
</table>

6.2 Future Work

In this thesis, only the thermal limits of the transmission lines and transformers are considered since only the active power data is available for the specific system used in this work. The voltage limits can also be combined into the metric if system reactive power is available, which gives a more comprehensive image of the system operating condition. Also, all the solar and load profiles used in the program are obtained from historical data, which may not accurately represent the exact future condition. Solar and load forecasting can be integrated into the proposed procedure, for example, using machine learning to generate predictions of the future load and solar profiles. In the TSPF program developed in this work, the dispatch of all the generating units follows an input priority dispatch order, which is only an approximation of the economic dispatch. For more accurate simulation, optimal power flow can be run for each time interval, which requires price information of all the conventional generators and any other cost information in the system.

The metric developed in this work is focused on the transmission network itself at a targeted solar penetration level with the solar generation fixed at certain locations in the network. The flexibility calculated by the metric is determined by the transmission system rating and the current operating state. The transmission flexibility is also sensitive to the location at which the solar resources are installed. Future work may combine both these factors to better estimate the overall flexibility of the transmission system.

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