ENGINEERING CONSULTING SERVICES

Final Report: Investigation of Total Failure of the Transmission System

Public Utilities Commission of Sri Lanka (PUCSL)

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1 Executive Summary

A total system failure occurred in the Sri Lankan Transmission Licensee's network on the 27th of September, 2015, at 23:57. The restoration of the power system took more than four hours. This sort of unexpected major failures in the transmission system has a significant negative impact on the continuity of power supply in the country. The Public Utilities Commission of Sri Lanka (PUCSL) requested explanations/information from the transmission licensee regarding this event.

Manitoba Hydro International (MHI) was contracted by PUCSL to study the event and provide recommendations. The study was conducted in close collaboration with engineers from PUCSL and the Ceylon Electricity Board (CEB).

1.1 Main Objectives of the Study

The following are the main objectives of the study:

- Identify the root cause of the failure;
- Determine whether the failure could have been prevented;
- Provide preventive actions and recommendations which will prevent or minimize the possibility of failures in the future.

1.2 Consultant's Analysis and Interpretation of the Event of September 2015

The dynamic response of the system following the event of September 2015 was captured in the transient recording provided to MHI by CEB.

Upon the tripping of the generating units, the system frequency dropped and, as expected, Under Frequency (UF) load shedding acted in an effort to stabilize the frequency.

The system was operating at a light load prior to the event. Thus, the system was vulnerable to overvoltage situations.

Load shedding and transformer on-load tap changer actions aggravate this condition due to the following reasons:

- The net (capacitive) reactive power generated by the lines will increase in response to the reduced loading.

- As the system voltage goes up, the transformer on-load tap changers (220/132 kV and 132/33 kV step-down transformers) act to regulate the low side voltage (LV side). A result of this action is an increased level of reactive power injection to the HV side of the system, As a result of the above actions, the system voltage in the high voltage network has reached levels that activated further tripping of equipment and the eventual system collapse. The system collapse of September 2015 was a ‘slow’ event, lasting nearly 3 minutes. This is a further indication of the influence of the tap changer action (which is a slow action) on the overall system response during this event.

These observations are consistent with the event recordings provided to MHI by PUCSL.

1.3 The Dynamic Simulation of the Event

PSS/E™ software-based dynamic simulations were used to meet the main objectives of this study.

The system model of the Sri Lankan power system was provided to MHI by CEB. MHI performed preliminary load flow studies (steady state) and had a number of discussions with CEB engineers to gain a good understanding of the system characteristics and the specific event background. The discussions also identified potential limitations of the System Dynamic models provided to MHI in the PSS/E™ format.

The simulation results based on the model provided by CEB were compared with the actual event recordings. The system response predicted by the model is far-removed from what was observed during the event. Specifically, the model predicts an extremely stable voltage response following the event. Thus, the model had to be adjusted. The ‘adjusted’ model followed key trends of voltage variations observed during the event. Two key adjustments were made to the model based on MHI’s past experience in similar situations:

- The tap action of transformers can have a significant impact in a ‘slow’ (also referred to as long-term) voltage instability situation. The model was updated by implementing the tap changer actions (based on information from CEB).

- Reactive power absorption limits of generators were adjusted. The recordings clearly indicated the gradual, uncontrolled voltage increase. This can only happen when generators (the only dynamic/reactive power regulating device in this system) reach their limits (exciters reaching their lower limit).

The model adjustment was a necessary part of the overall study. The important consideration was that the model showed the ‘same’ trends as those recorded following the generator tripping. This ’adjusted’ model was used to perform further dynamic studies to make overall conclusions and recommendation.

1.4 Conclusions and Recommendations

The follow are the main observations and conclusions of the study:

1. Based on MHI's extensive experience in similar situations, the 'adjusted' model sufficiently represents the Sri Lankan system for the purpose of examining the event of September 2015. However, the 'adjusted' model should not be used for general purpose system planning studies.

2. MHI strongly recommends updating the system planning study models:

   a. The dynamic data (Generator and generator control data of the Sri Lankan Power System Planning model) to be reviewed and updated based on accurate name plate information, test results and data gathered through site visits.
   b. The existing dynamic model is not suitable for long-term event analysis, such as the event under consideration. A proper model update, including transformer tap changers and specific load modeling, is recommended (i.e. induction motor models and composite load models representing actual load behavior should be used, instead of the static load model being used presently).
   c. A significant percentage of the load (especially during off peak) is provided by distributed generation (renewable) type resources (DGs). The response of these units is not included in the study model (both load-flow model and dynamic model). It is recommended to modify the study models and verify if the DGs have a significant impact on the system operation. The response of the DGs as a whole may have an impact on events, such as the system failure that MHI addresses in this study.

3. Based on generator ratings provided to MHI (steady state limits provided in PSS/E™ data format), it is very likely that the full reactive power capability of generators is not being utilized. The generator reactive power limits, as well as the actual settings that are currently in place, should be readily obtained from the respective generating stations. If the reactive power limits are not at their respective maximum/minimum values, this should be reviewed and adjusted, where possible. Thus, MHI recommends the following as an immediate action:

   - Check if generators are 'set-up' to provide voltage support (Voltage control mode of operation).
   - Discuss with independent generation owners how they can help the situation.
   - Make sure that the 'voltage control functionality' of generators is not unnecessarily curtailed (set at a lower value than what the generator is capable of).

4. As per the load flow data provided to MHI, the system steady state voltages on many 220 kV and 132 kV buses were above 105% (1.05pu). The international practice is to maintain the steady state voltage on the High Voltage network at or below 105%. Allowing a 110% voltage at steady state will bring the system devices dangerously close to their overvoltage protection limits.

5. It is recommended to maintain the system steady sate voltage within ± 5%. The present CEB criteria is ±10%. This can be achieved by mechanically switched shunt devices (reactors and capacitors). Simulations verified that this is a feasible solution to prevent system instability under similar events in the future. The size and location of such shunt devices should be determined through system studies once the model is updated and validated. Some potential short-term measures that can be investigated (must be studied before implementation) include the following:

    - As an interim measure, the steady state voltage during low load periods can be improved by 'tap staggering' of parallel transformers (although not recommended as a permanent solution);

    - Taking selected transmission lines out of service during low load periods (although not recommended as a permanent solution, as this action impacts overall system reliability). It should only be implemented if transmission reliability criteria (i.e. N-1 compliance) are not violated.

6. Shunt reactors are effective means of controlling steady state voltage, as well as improving the system dynamic response. The effectiveness of shunt reactor additions is demonstrated through simulations.

7. **Must Run Units:** Consider specifying 'must run units' for voltage support. This means, even if the customer load demands can be met with fewer generator units (example: A smaller number of units may be required at low load conditions at night compared to the number of units required during day time), keep a number of extra units running to support the power system recovery from a 'large' disturbance. This is a widely adopted international practice. Must-run units may be determined through a study. It is also recommended to review the spinning reserve policy currently adapted in system operation.

8. It is recommended to add disturbance recording devices at high voltage substations and generating stations. The current event was recorded at less than ten locations (recordings from just eight locations (132 kV and 220 kV) were available to MHI). Recordings from more locations in the system will help to analyze such events more accurately and thus provide insightful information on future actions (e.g. upgrades and operational practices).

Contents

2 Introduction

A total system failure occurred in the Sri Lankan Transmission Licensee's network on the 27th of September, 2015, at 23:57. The restoration of the power system took more than four hours. This sort of unexpected major failures in the transmission system has a significant negative impact on the continuity of power supply in the country. As per the provisions under Section 3(2) of the Sri Lanka Electricity Act, No.20 of 2009, Public Utilities Commission (PUCSL) is obligated to ensure that a coordinated, efficient and economical system of electricity supply is provided and maintained throughout Sri Lanka at all times.

PUCSL requested explanations/information from the transmission licensee under the condition 3(1) and 30(1) of Electricity Transmission and Bulk Supply License No. EL/T/09-002.

However, PUCSL is of the view that an expert investigation is required to identify the causes of the failure and possible actions to avoid reoccurrence of such failure in the future. MHI was contracted to study the event and provide recommendations. The study was conducted in close collaboration with engineers from PUCSL and the Ceylon Electricity Board (CEB).

2.1 The System Failure on the 27th of September, 2015

The following is the sequence of events that resulted in the total system failure:

1. Generator unit number 3 at Lakvijaya power station, which was delivering 280 MW and absorbing 28 MVAr, was tripped due to a mal-operation of the over-flux relay [1].
2. The Under Frequency (UF) load shedding scheme got activated. This resulted in shedding all the loads connected through stage 1 to 4 of load shed relays.
3. Generator unit number 2 at Upper Kothmale power station, which was delivering 15 MW and absorbing 11 MVAr, was tripped due to the activation of its over-flux relay.
4. Rantambe 132/220 kV grid transformer, New Anuradhapura 132/220 kV grid transformers 1 and 2 tripped due to the activation of the overvoltage relays.
5. Kotugoda 132/33 kV transformer, which was supplying 35 MW and 12 MVAr to 33 kV feeders, tripped.
6. Biyagama 132/220 kV grid transformers 1 and 2 tripped due to the activation of the overvoltage relays.
7. Kothmale generator unit 2, which was delivering 32 MW and absorbing 5 MVAr, tripped due to the activation of the over-flux relay.

Subsequently, the rest of the generator units connected to 132 kV and 220 kV networks tripped, causing the total system failure. The total system load[1] at this

[1] NCRE generators were supplying about 177 MW of active power, and loads this generation is supplying are not accounted for in this analysis and system modelling.

time was approximately 800 MW. It should be noted that the system was operating under an extreme condition, where one unit (Lakvijaya unit 3) was supplying about 30% of the total load. Thus, the tripping of this unit is a critical event.

Several important findings are made in a report [1] by analyzing the system measurements during the failure. Work presented in this report further analyzes the system behavior, employing dynamic simulations (based on PSS/E™ software) to identify the root cause of the failure and preventive actions to avoid future undesirable incidents.

3 Objectives

As per PUCSL requirements, the following are the main objectives of the study:

- Identify the root cause of the failure;
- Determine whether the failure could have been prevented;
- Provide preventive actions and recommendations which will prevent or minimize the possibility of failures in the future.

4 Methodology

The following study methodology was followed to identify the cause of the blackout and propose preventive actions:

1. Data and information, such as disturbance recordings, relay activation reports, including operating sequence, and pre-disturbance system operating conditions were collected and analyzed to establish events and system responses that likely had a major impact.
2. System response was analyzed using the PSS/E™ dynamic simulator. The simulation results were compared with system recordings to validate the simulation model.
3. The simulation model was adjusted.
4. Dynamic simulations were performed to identify the root cause behind the total system failure and determine whether the failure could have been prevented.
5. Additional simulations were performed to identify preventive actions and recommendations to prevent or minimize the possibility of similar system failures in the future.

5 Study Results

5.1 Initial Comparisons

The simulation results based on the model provided by CEB were compared with the actual event recordings in Figure 1 to Figure 3.

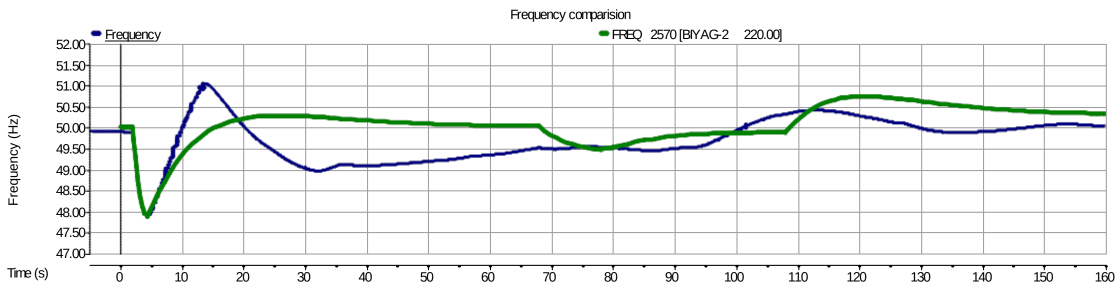

Figure 1: Comparison of the recorded (in blue) and simulated (in green) frequency profiles during the post-contingency window (just prior to the system collapse): 220 kV voltage level. Note that the frequency response of the model follows the actual recorded value closely during the first few seconds. This period is important for predicting load shedding.

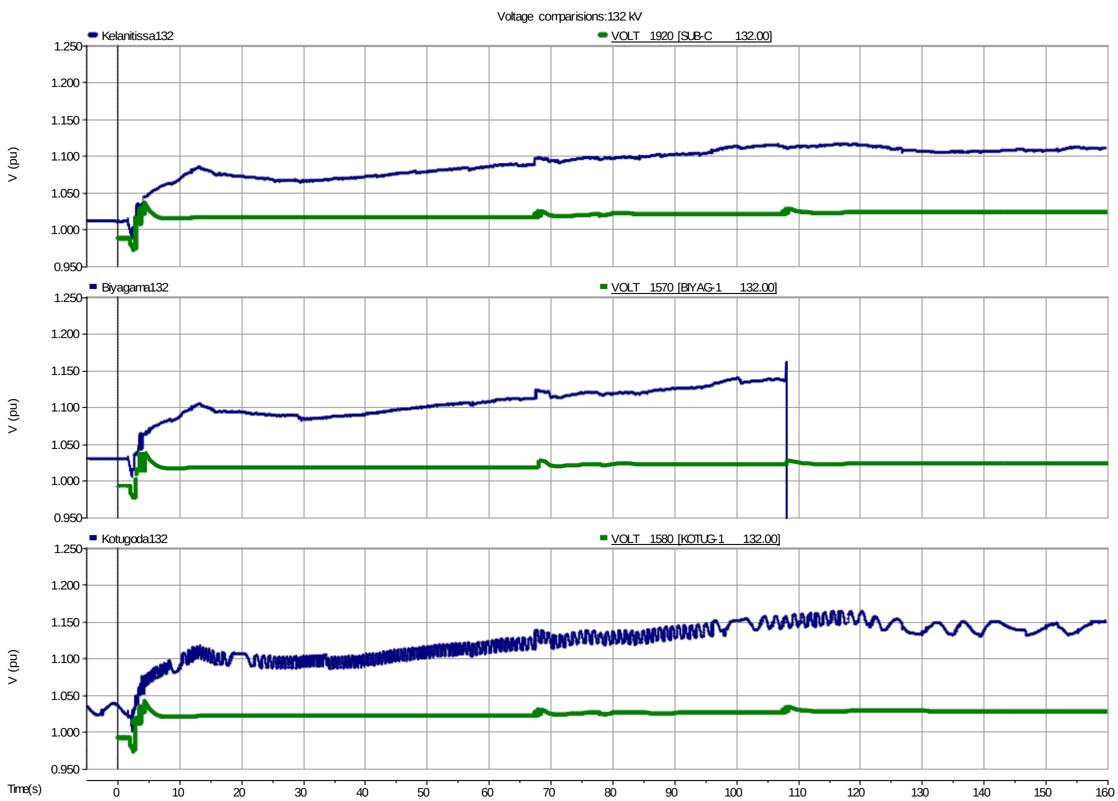

Figure 2: Comparison of the recorded (in blue) and simulated (in green) voltage profiles during the post-contingency window (just prior to the system collapse):132 kV voltage level

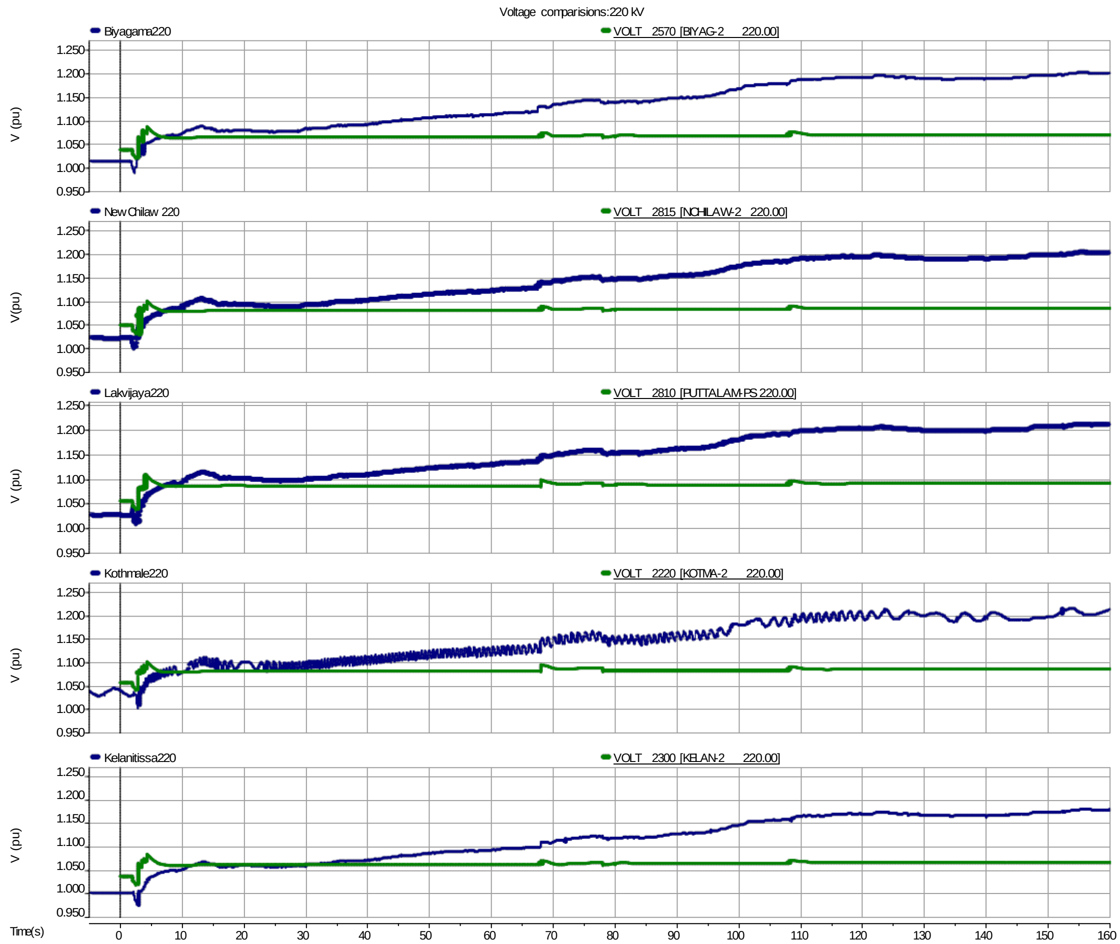

Figure 3: Comparison of the recorded (in blue) and simulated (in green) voltage profiles during the post-contingency window (just prior to the system collapse): 220 kV voltage level

The system response predicted by the model is far removed from what was observed during the event. The model does not depict the general trends of voltages observed during the post fault window. Since the eventual failure was a voltage-related phenomenon, attention should be on the voltage trends predicted by the model:

- Measured frequency and frequency obtained from simulations have roughly the same trend, although frequency values are much different in the post-fault window (just prior to the system collapse) following the event.

- The model predicts an extremely stable voltage response at 132 kV and 220 kV voltage levels, which is mostly flat in the post-fault window following the event. The actual measured voltages at the same buses show that the voltage is gradually increasing throughout the post-fault window, which causes tripping of various transformers and generator units due to the activation of overvoltage or over-flux protection.

- From the results of Figure 1 to Figure 3, it is clear that the voltages at all three levels (220 kV, 132 kV and 33 kV) are predicted to be well regulated as per the simulation model. This is not the case, and the measurements show that the voltages gradually increased.

Figure 4 shows the simulated voltage at selected locations for 33 kV, 132 kV and 220 kV voltage levels.

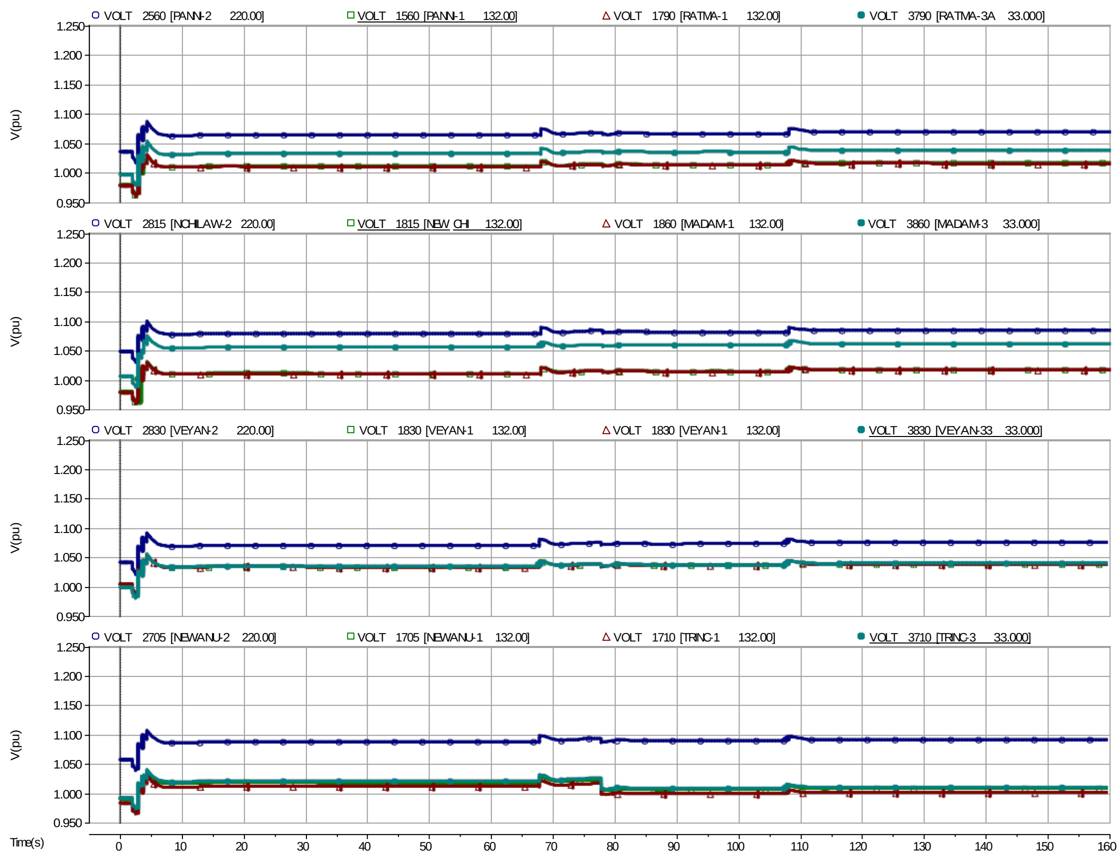

Figure 4: Voltage at 33, 132 and 220 kV buses at selected locations

As shown in Figure 4, the voltage profile at 33 kV voltage level is also flat similar to the 132 and 220 kV voltage levels.

The following observations were made based on the voltage profile shown in Figure 2 to Figure 4Figure 3:

- The almost flat voltage profile indicates a sufficient absorption of reactive power by the dynamic devices in the system. In the case of the Sri Lankan system, generators connected to the 132 kV and 220 kV levels constitute the only such devices.

- The slow increase in voltage captured in measurements may be a result of slow variation of transformer taps, where transformers have on-load tap changer with a controller. The auto tap-changers are available at most of 132 kV to 33 kV and 220 kV to 132 kV step-down transformers. The action of these auto tap-changers is to regulate voltage at their low voltage side bus bar. When the voltage of the low side of the transformer exceeds the high threshold of the transformer voltage band, a transformer tap is automatically adjusted in an effort to bring the voltage of the low side into the voltage band. This process will result in transferring the excess reactive power in the low side to high side[2]. In this case, reactive power transfer from low voltage network to high voltage network will further deteriorate the voltage condition at the 132 kV and 220 kV voltage levels.

Based on the observations listed above, the following decisions related to model 'adjustments' were made:

- The model was refined by implementing the tap changer actions of transformers equipped with auto tap changers.

- The reactive power absorption capability of generators, as predicted by the model, does not represent the practical situation. This is an important finding of the study. The exciter under-voltage limits in the simulation model were adjusted to obtain a closer match with actual recordings (in terms of general voltage variation trends).

5.2 Comparisons after Model Adjustments

The simulation results based on the model after the 'adjustments' ('adjusted model') are compared with the actual event recordings in Figure 5 to Figure 7.

[2] This is the expected outcome of transformer tap changer actions. The excessive reactive power should be absorbed by shunt devices such as generators, TCR (or SVC) or mechanically switched reactors in the high voltage network.

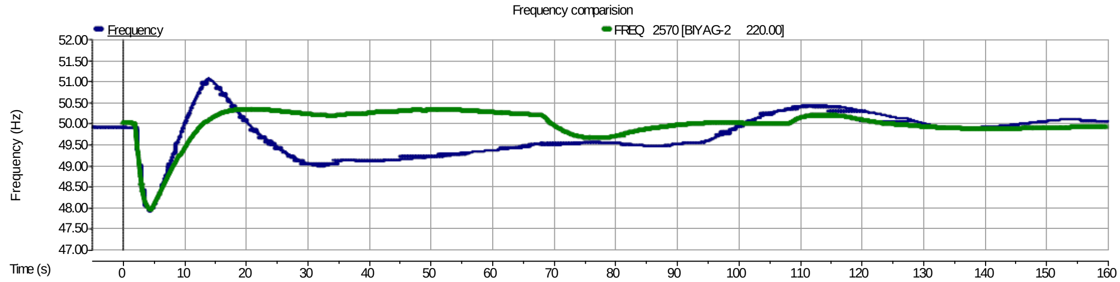

Figure 5: Comparison of the recorded (in blue) and simulated (in green) frequency profiles during the post-contingency window (just prior to the system collapse): 220 kV voltage level

The measured frequency and frequency obtained from simulations have roughly the same trend as before. No notable improvement in frequency comparison is observed.

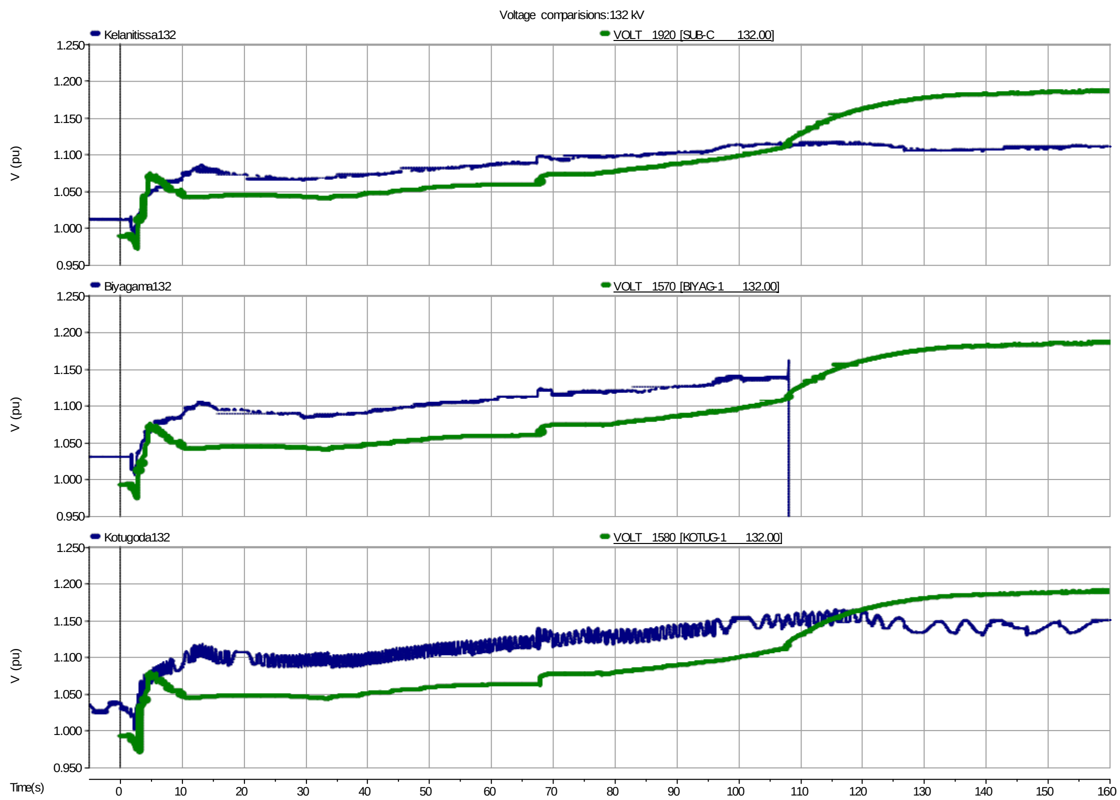

Figure 6: Comparison of the recorded (in blue) and simulated (in green) voltage profiles during the post-contingency window (just prior to the system collapse): 132 kV voltage level

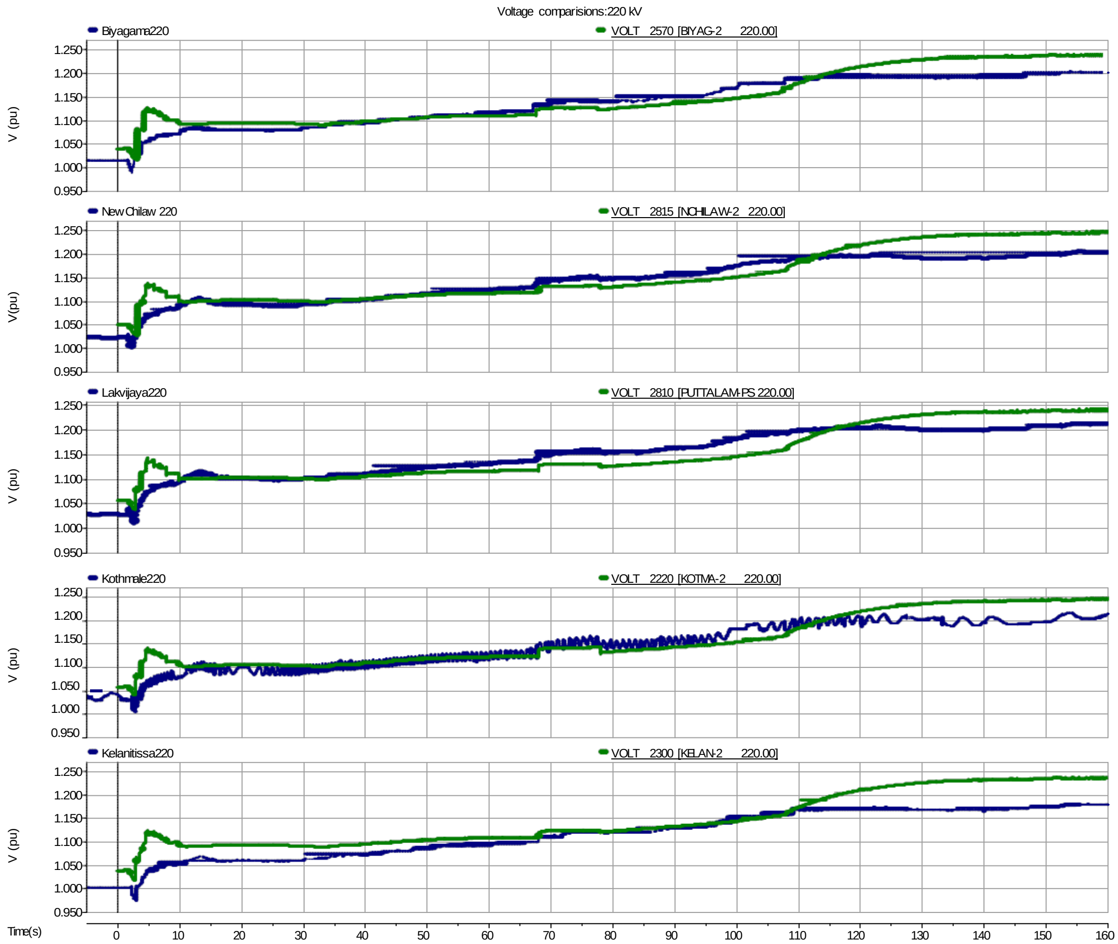

Figure 7: Comparison of the recorded (in blue) and simulated (in green) voltage profiles during the post-contingency window (just prior to the system collapse): 220 kV voltage level

Figure 6 and Figure 7 clearly demonstrate that the voltage response trends predicted by the `adjusted model' closely follow the field measurements.

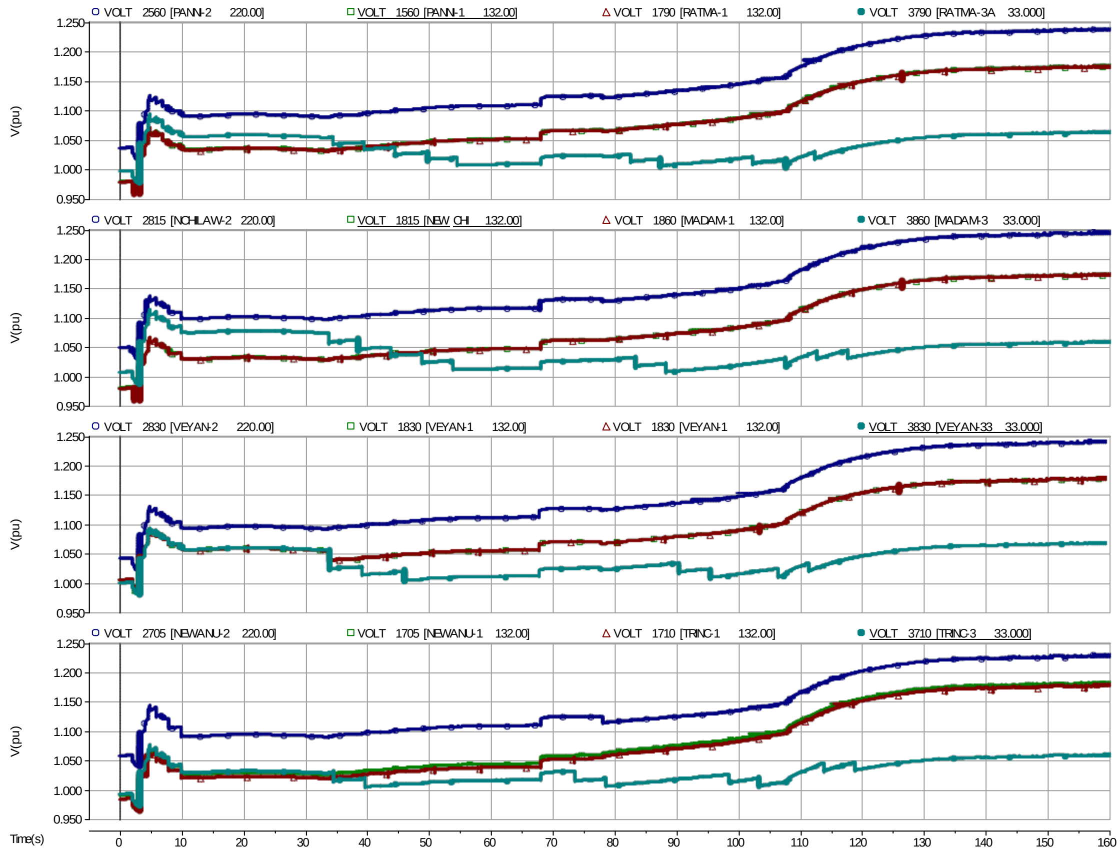

Figure 8 Voltage at 33, 132 and 220 kV buses at selected locations

Figure 8 shows the voltage variation at 33, 132 and 220 kV buses at selected locations. It should be noted that up to about 100 seconds, the 33 kV bus voltage is regulated due to the tap changer action. It should be also noted that the 132 kV and 220 kV bus voltages continue to rise during the same period. After about 100 seconds, the transformer taps have reached their limits.

The model adjustment was a necessary part of the overall study. The important consideration was that the model showed the same trends as those recorded following the generator tripping. This 'adjusted' model was used to perform further studies to make overall conclusions and recommendation.

Based on MHI's extensive experience in similar situations, the 'adjusted' model sufficiently represents the Sri Lankan system for the purpose of examining the event of September 2015. However, the 'adjusted' model should not be used for general purpose system planning studies. MHI strongly recommends reviewing and updating the dynamic data of the model based on accurate name plate information, test results and data gathered through site visits. The generator reactive power limits, as well as the actual settings that are currently in place, should be readily obtained from the respective generating stations.

5.3 Study of Mitigation Options

The impact adding shunt reactors was studied, and the results are shown in Figure 9.

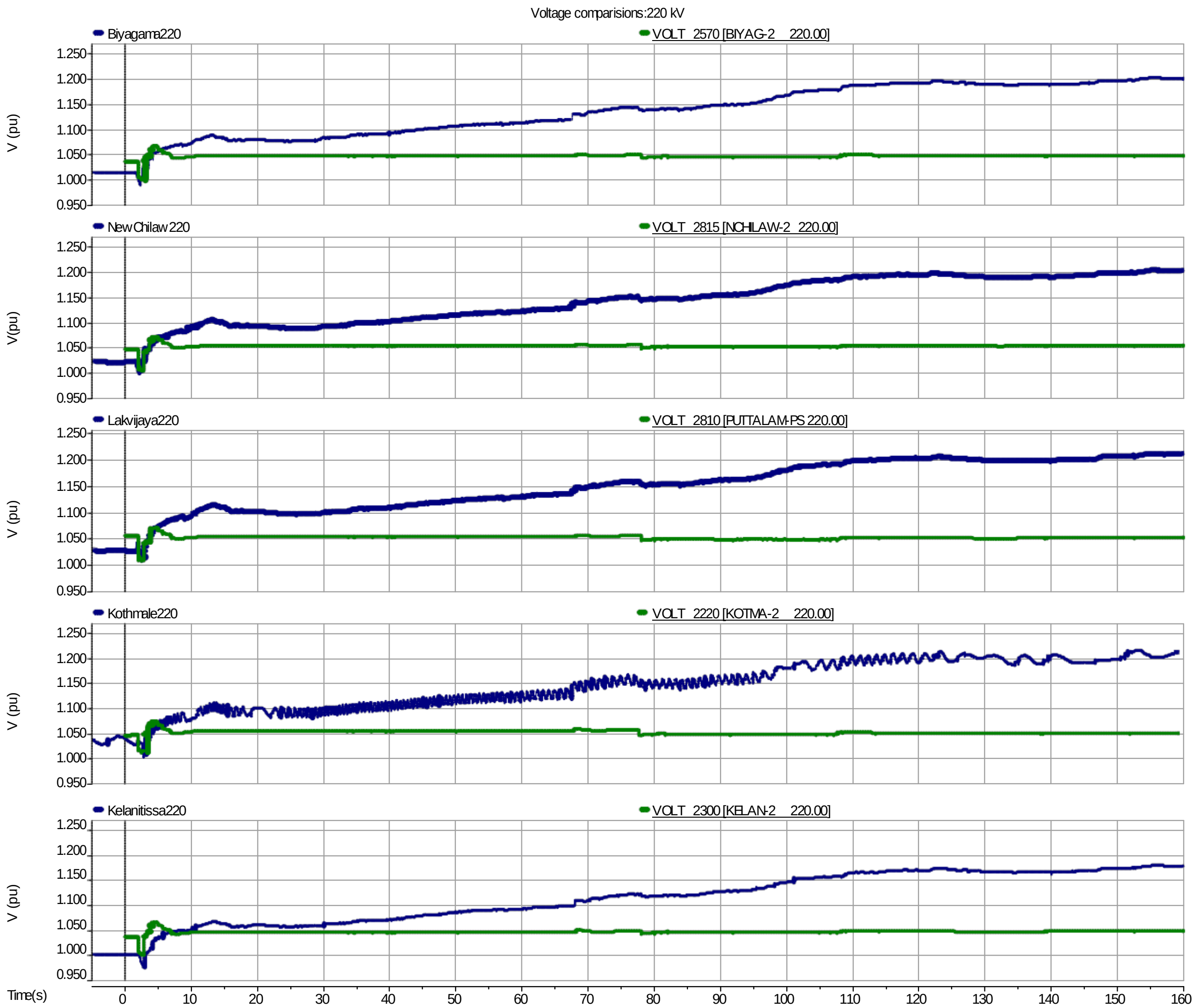

Figure 9: Impact of shunt reactors - Comparison of the recorded (in blue) and simulated (in green) voltage profiles during the post-contingency window (just prior to the system collapse): 220 kV voltage level.

To illustrate the effectiveness of the shunt reactors, two 50 MVAr reactors were included in the 220 kV network. As a result of this addition, the steady state voltage at 220 kV buses is at or below 1.05 pu. Dynamic simulations (using the modified model) showed a stable voltage recovery following the tripping of Lakvijaya unit 3 supplying 280 MW.

Another mitigation option is the proper utilization of available dynamic reactive power capacity of existing generators. In addition, installing dynamic reactive power devices, such as SVC (Static Var Compensator), will also be an option.

6 Conclusions

The follow are the main observations and conclusions of the study:

1. Based on MHI's extensive experience in similar situations, the 'adjusted' model sufficiently represents the Sri Lankan system for the purpose of examining the event of September 2015. However, the 'adjusted' model should not be used for general purpose system planning studies. MHI strongly recommends the following:

    a. The dynamic data (of the Sri Lankan Power System Planning model) to be reviewed and updated based on accurate name plate information, test results and data gathered through site visits.
    b. The existing dynamic model is not suitable for long-term event analysis, such as the event under consideration. A proper model update, including transformer tap changers and specific load modeling, is recommended (i.e. induction motor models and composite load models representing actual load behavior should be used, instead of the static load model being used presently).

2. Based on generator ratings provided to MHI (steady state limits provided in PSS/E™ data), it is very likely that the full reactive power capability of generators is not being utilized. The generator reactive power limits, as well as the actual settings that are currently in place, should be readily obtained from the respective generating stations. If the reactive power limits are not at their respective maximum values, this should be reviewed and adjusted where possible.

3. As per the load flow data provided to MHI, the system steady state voltages on many 220 kV and 132 kV buses were above 105% (1.05pu). The international practice is to maintain the steady state voltage on the High Voltage network at or below 105%. Allowing 110% voltage at steady state will bring the system devices dangerously close to their overvoltage protection limits.

4. It is recommended to maintain the system steady state voltage within ± 5%. The present CEB criteria is ± 10%. This can be achieved by utilizing mechanically-switched shunt devices (reactors and capacitors, as required). Simulation verified that this is a feasible solution to prevent system instability under similar events in the future. The size and location of such shunt devices should be determined through system studies once the model is updated and validated.

    - As an interim measure, the steady state voltage during low load periods can be improved by 'tap staggering' of parallel transformers (although not recommended as a permanent solution).

- Taking selected transmission lines out of service during low load periods (although not recommended as a permanent solution, as this action impacts overall system reliability).

5. Shunt reactors are effective means of controlling steady state voltage, as well as improving the system dynamic response. The effectiveness of shunt reactor additions is demonstrated through simulations.

9. **Must Run Units:** Consider specifying 'must run units' for voltage support. This means, even if the customer load demands can be met with fewer generator units (example: A smaller number of units may be required at low load conditions at night compared to the number of units required at the day time), keep a number of extra units running to support the power system recovery from a 'large' disturbance. This is a widely adopted international practice. Must-run units may be determined through a study. It is also recommended to review the spinning reserve policy currently adapted in system operation.

7 References

[1] "*Report on the total system failure occurred on 27th September 2015*", Additional General Manager- Cooperate Strategy, Ceylon Electricity Board, November 13, 2015.