FINDINGS OF THE COMMITTEE APPOINTED TO INVESTIGATE POWER SYSTEM FAILURES ON NOVEMBER 29, 2021 AND DECEMBER 03, 2021

MINISTRY OF POWER

SRI LANKA

Final Report
February 21, 2022

LIST OF ABBREVIATIONS

AGM	Additional General Manager
ANSI	American National Standards Institute
CB	Circuit Breaker
CEB	Ceylon Electricity Board
CT	Current Transformer
DC	Direct Current
DFR	Disturbance Fault Recorder
DGM	Deputy General Manager
FCB	Fast Cut Back
GCB	Generator Circuit Breaker
GS	Grid Substation
GWh	gigawatt-hour
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers of USA
IPP	Independent Power Producer
LECO	Lanka Electricity Company (Private) Limited
LP	Low Pressure
LVPP	Lak Vijaya Power Plant
NC	Normally Closed
NDEF	Non-Directional Earth Fault
NO	Normally Open
NSCC	National System Control Centre
OEM	Original Equipment Manufacturer
PRV	Pressure Relief Valve
PS	Power Station
PSM	Plug Setting Multiplier
pu	per unit
RMS	Root Mean Square
Rs or LKR	Sri Lankan Rupees
SCADA	Supervisory Control and Data Acquisition
SS	Substation
TMS	Time Multiplier Setting
UFLS	Under Frequency Load Shedding
UPS	Uninterrupted Power Supply
VT	Voltage Transformer

MEASURES AND WEIGHTS

^0C	degree Celsius
A	ampere
GWh	gigawatt-hour
Hz	Hertz
kHz	kilohertz
km	kilometre
kV	kilovolt
kWh	kilowatt-hour
ms	millisecond
Mvar	megavar
MW	megawatt
V	Volt

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ANNEXES

EXECUTIVE SUMMARY

On Friday, December 03, 2021, Sri Lanka's electric power supply grid experienced a total system failure, which was preceded by a partial failure affecting many parts of the country on November 29, 2021. The Secretary to the Ministry of Power by letter dated December 04, 2021 (Annex A) appointed our committee to study and report on the causes of the total power failure of December 03, 2021 and to recommend possible remedial actions that the Transmission Licensee Ceylon Electricity Board (CEB) should take to prevent such occurrences in the future. Later, by letter dated December 22, 2021 the Committee was asked to examine the partial failure on November 29. 2021 as well. It is our view that a closer examination of this incident was warranted, given that both incidents initiated from an earth fault on the Kotmale-Biyagama 220 kV transmission line.

The 70 km long Kotmale-Biyagama 220 kV transmission line is star-connected with the star point solidly grounded at the two ends, as are all 220 kV transmission lines in the CEB system. It employs *differential, distance, directional earth fault, over-current and earth-fault protection* as per the CEB's protection policy applicable to its 220 kV transmission network.

TOTAL SYSTEM FAILURE ON DECEMBER 03, 2021

The power system was operating normally on hydro-maximum mode on December 2021 with high hydro reservoir levels that resulted from heavy rainfall experienced in the preceding months. The large hydropower plants concentrated in the central region of the country were generating about 1,200 MW, or around 64% of the total demand of 1,875 MW at the time, with low use of coal and oil-fired thermal power plants. The double circuit 220 kV Kotmale-Biyagama transmission line bringing the bulk of Mahaweli hydropower to main load centers in the Western Province including Colombo was carrying approximately 654 MW at the time.

As per disturbance fault recorder (DFR) data made available to the Committee, the *differential protection* relay at the Kotmale end of circuit 2 of the Kotmale–Biyagama 220 kV transmission line had operated at 11:27:14 hrs. and tripped the phase B conductor from both ends. The cause of tripping had been indicated as an *earth fault*. The protective devices have operated as expected, causing the automatic opening of the circuit breakers of the faulty phase at both ends, initiating the procedure known as *automatic reclosure (auto-reclose)*. When auto-reclose function is activated, the tripped circuit breaker is set to remain open for a specified time in the event of a fault and return to close position, and to disconnect permanently if the fault persists. Accordingly, phase B would have re-closed from both ends, and the system should have resumed normal operation with no impact to the grid and customers, in the absence of a continued fault.

Unfortunately, while the *automatic reclosing* process was in progress accurately, another device not directly associated with line protection known as *end-fault* protection relay had issued an erroneous trip command from the Biyagama substation's 220 kV busbar protection system, causing the complete disconnection of circuit 2 and lockout of the circuit breakers at the Kotmale end, thus eliminating any possibility of circuit 2 returning to service through the auto-reclosing process. As will be described later in this report, the operation of the *end-fault* protection was unnecessary and unintended.

The tripping of circuit 2 from both ends, however, should have isolated the fault and the power system should have operated without further calamity, since the remaining circuit (circuit 1) had continued to carry the full load immediately upon the loss of circuit 2. However, this circuit too had tripped after approximately 22 seconds at 11:27:35, with the operation of *earth-fault* protection. As will be explained in this report, the tripping of circuit 1 also was unnecessary and was a result of erroneous configuration of its line protection relay.

The loss of this critical corridor evacuating hydropower from the Mahaweli Complex to load centres in the western parts of the country had caused a severe unbalance in the system—with excess generation in one section and insufficient generation in another. While the process of automatic load shedding designed to bring about a balance in such a situation had initiated and commenced removing customer loads in the Western sector, those measures had proven inadequate to restore balance. After the total loss of Kotmale–Biyagama 220 kV transmission line at 11:27:35 hrs., all generators and some critical transmission lines had tripped automatically. In approximately 34 seconds from the initial indication of fault (at 11:27:14 hrs.), all generators had tripped leading to complete collapse of the grid.

The indications of the initial fault on phase B of circuit 2 are consistent with those of a high impedance *earth fault*. CEB has not been able to identify the cause of this initial fault. The Committee understands that the cause of such non-persistent single-line faults is often difficult to identify as these faults clear within a very short period without leaving any traces.

PARTIAL SYSTEM FAILURE ON NOVEMBER 29, 2020

The partial failure on November 29, 2021, which was also initiated with the tripping of Kotmale-Biyagama 220 kV transmission line has revealed some similarities with the total failure of December 03, 2021.

On November 29, 2021, following what is suspected to be a single line-to-ground-fault of circuit 1 of the Kotmale-Biyagama 220 kV transmission line, phase R had reclosed after 934 ms. However, all three phases of circuit 1 had tripped from the Kotmale end by the activation of *end-fault* protection of busbar 01 of the Biyagama GS at 317 ms from the initial circuit breaker opening of phase R. The SIEMENS 7SS522 relay had issued an *end-fault* tripping signal that had locked out the circuit breakers, thus preventing the possibility of continued auto-reclose process.

The spurious operation of the *end-fault* protection of circuit 1 on November 29, 2021 as well as that of circuit 2 on December 03, 2021 (after the initial single-line-to-earth fault had cleared on both occasions) highlights an inherent weakness of the implementation of this protection scheme. End-fault protection is designed to provide protection in the event of an *earth fault* occurring between the circuit breaker (CB) and the current transformer (CT). CEB protection engineers informed the Committee that the spurious tripping initiated because of a faulty wiring in the relays at the Biyagama end, which they confirmed had already been corrected.

Hence, the Committee had no means of verifying whether these claim was true, or whether such "faulty wiring" did indeed exist in the first place.

The Committee cannot accept the reasons given by CEB's protection engineers for the erroneous operation of *end-fault* protection. However, the above revelations also presented the Committee with a serious uncertainty as to why the *end-fault* protection activated only on these two occasions (occurred in a space of 4 days in November and December 2021), followed by what appears to be a single-line-to-ground fault. The 220 kV protection system has been operating since 2014 and the alleged faulty wiring has taken place in early 2015 according to CEB's submissions to the Committee. There is only one other incident where *end-fault* protection had operated in the past. In any event, CEB has failed to investigate the erroneous activation of *end-fault* protection on the two occasions before December 03, 2021.

OBJECTIVES AND CONCLUSIONS

The main focus of this report is the Committee's efforts to establish the root cause of the power system failures on December 03, 2021 and November 29, 2021. This report is an attempt to describe the series of events that led to the two failures, submissions and analyses by the transmission system operator CEB, analyses conducted by the Committee on the specific events that caused the loss of the vital Kotmale-Biyagama 220 kV transmission line, and conclusions and recommendations aimed at preventing similar failures in the future.

We examined in detail the numerous written and oral explanations received from CEB officials on the possible cause (i.e., the initiating event) of the power failures on December 03, 2021 and on November 29, 2021, which in both cases is identified as an *earth fault* in a single phase. Despite many efforts, CEB officials have not been able to find definitive proof that would establish the occurrence of a single-line-to-earth fault.

While this situation can be acceptable given the past experience, the Committee has not found sufficient grounds to completely eliminate the allegation that the incidents on December 03 and November 29, 2021 could have been pre-planned, or caused by deliberate action, since material presented to this Committee by relevant branches of the CEB could not explain some key events such as the erroneous operation of *end-fault* protection and wrong configuration of line protection relay of the Kotmale-Biyagama 220 kV transmission line.

We have expressed our concerns and provided some recommendations on possible technical and procedural changes that we hope would help prevent the occurrence of a major failure from a single-line-to-earth fault in the future. We recommend a formal investigation by the law enforcement authorities assisted by independent IT experts to determine whether or not any human intervention has taken place.

1. OVERVIEW OF THE SRI LANKA POWER SYSTEM

Electricity has been accessible in Sri Lanka as isolated networks since 1895, using diesel generators in cities and using small hydropower generators in the tea industry. The national grid evolved over the past 70 years, beginning in 1950 with the installation of the first generators at Laxapana and the 66 kV transmission network. The transmission and distribution network were continuously upgraded and expanded to serve the entire country. About 7.3 million customers are presently served by the national grid across the country. The peak demand in 2020 was 2,717 MW, and the total electricity sold from the grid to customers was 14,261 GWh. Sri Lanka's per capita electricity consumption in 2020 was 650 kWh.

1.1. The Generating System

The country's existing generating network is mostly owned and managed by Ceylon Electricity Board (CEB), with the private sector owning a sizable portion of subsequent expansions. CEB owned all generation until 1996. Since 1996, the private sector has been engaged in the generation of electricity. The transmission network as well as about 90% of the distribution network continues to be owned and operated by CEB. By the end 2020, the country's generating system had about 4,265 MW of installed generating capacity of both conventional and renewable energy-based generation, excluding rooftop solar PV units which were estimated to be approximately 350 MW.

The country's generating system comprises[1]:

- Seventeen (17) hydro power plants owned by CEB
- One (1) wind power plant owned by CEB
- Ten (10) oil-fired thermal power plants owned by CEB
- One (1) coal power plant owned by CEB
- Six (6) oil-fired thermal power plants owned by independent power producers (IPPs)
- Seventeen (17) small wind power plants, 208 mini hydro power plants, 32 solar parks, and 14 biomass power plants, with a total installed capacity of 683 MW by the end 2020. These are power plants embedded in the distribution network, and they are non-dispatchable.

Using these generators, electricity is supplied to the national grid. Several generators would be operating at any given moment to meet the needs of customers and the reserve requirements. The following factors are considered when determining which generators should be operated.

For large and medium hydroelectric generators,

- Each power plant will be operated prioritizing the discharge of water for drinking and irrigation, based on a weekly schedule for water releases jointly agreed among the authorities on irrigation, agrarian services, water supply and electricity generation (CEB)

[1] Source: Statisitical Unit. Corporate Strategy & Regulatory Affairs Branch. Ceyon Electricity Board. *Sales and Generation Databook 2020*. 2021. Colombo.

- Water availability, to avoid reservoir spilling during periods of heavy rainfall or when heavy rainfall is expected

For oil-fired generators,
- Minimization of the operating cost
- Minimization of the starting and stopping the generators

For all major generators,
- The criteria for all grid substations to maintain the standard voltage levels
- Accommodating any scheduled or unscheduled maintenance

Renewable energy based embedded generators,
- Small hydropower generators, wind power plants, solar parks, and rooftop solar units are constantly operated to effectively maximize their contribution to the generating system while avoiding wastage of water, wind, or solar energy resources. All such power plants operate on must-run and must-take principles,

The general principle is that the generating system should be controlled in such a way that the cost of producing electricity is kept as low as possible. Economic dispatch planning is done over 12 months since rainfall is a primary driver of hydropower supply.

The institutional responsibilities are as follows:

- The transmission licensee of CEB operates the transmission system and so bears overall responsibility for maintaining the safe, reliable, and cost-effective operation of the whole generating and transmission system.
- The generation licensee of CEB owns and operates all of its power plants.
- Regarding IPPs, the appropriate owner operates their power plant under dispatch instructions of CEB.
- In the case of small power producers (SPPs, using mini-hydro, wind, solar parks and biomass), the relevant owner operates their plant independently of CEB. However, such power plants can only function while the related medium voltage distribution line (33 kV) is operational.

1.2. The Transmission System

The transmission system of Sri Lanka consists of a total of 3,160 km of transmission lines and 79 grid substations[2] (GSSs), including all the accompanying equipment. All major generating plants are connected to the national grid at 132 kV or 220 kV. Grid substations receive power at 132 kV or 220 kV, where power is stepped down to 33 kV (11 kV in some areas) and finally delivered to the distribution network.

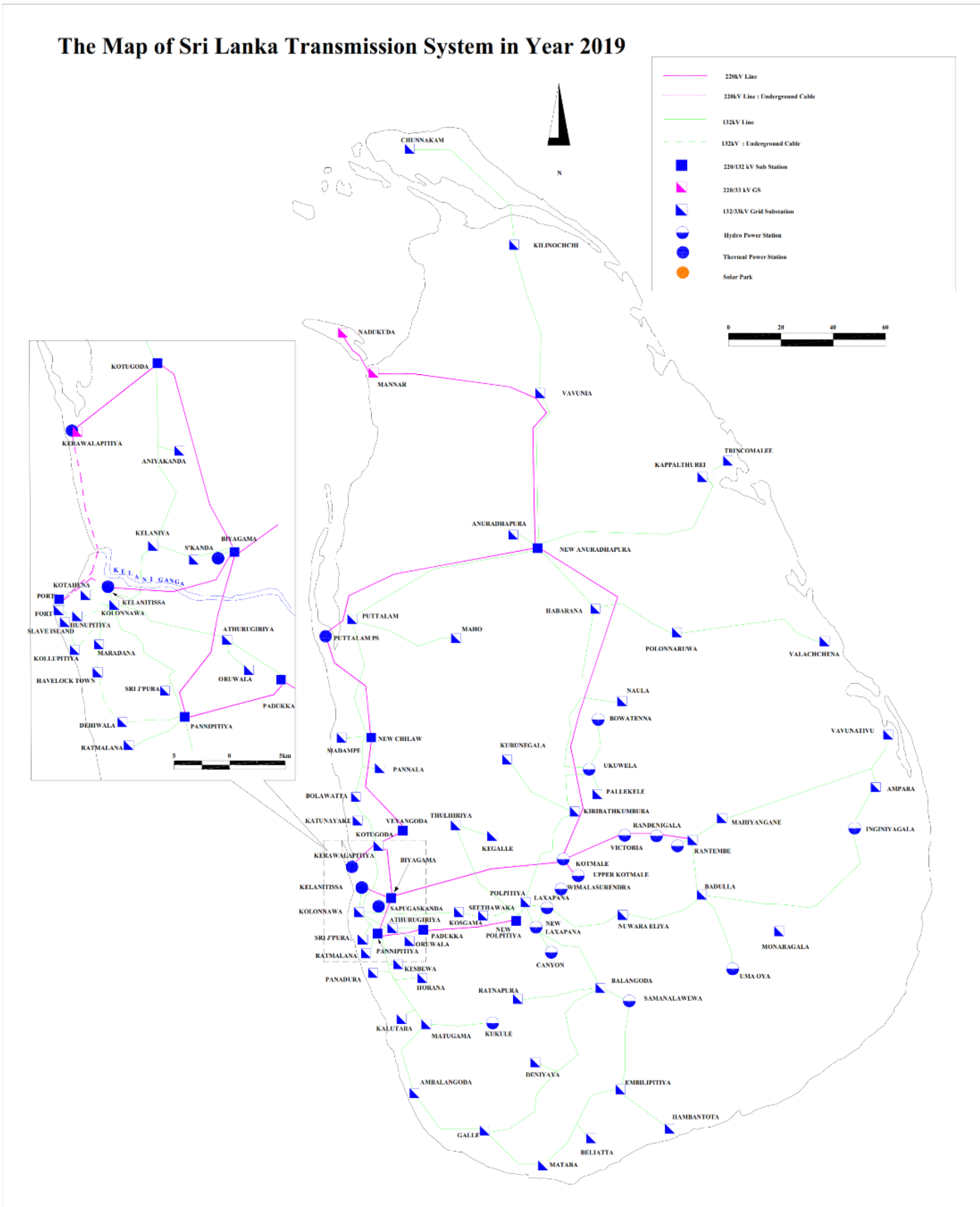
The transmission operator, CEB, is expected to manage the operation of all generators, transmission lines, and grid substations. Distribution lines originating at grid substations and running at 33 kV or below are the responsibility of regional and area operating units and are

---

[2] Source: Ceylon Electricity Board. *Statisitical Digest 2020*. 2021. Colombo.

not directly controlled by the transmission operator. Figure 1.1 shows the geographic layout of the generating and transmission network of Sri Lanka. All power plants, transmission lines, and distribution lines are interconnected. The “national grid” refers to this interconnected network of generating stations, transmission lines, distribution lines, and customers.

Figure 1.1 - Sri Lanka Generation and Transmission System



Note: All lines and substations shown in this map may not be operational at any given time.

Source: Transmission and Generation Planning Branch. Ceylon Electricity Board. Long Term Transmission Development Plan 2018 – 2027.

1.3. Distribution System

CEB owns and manages four out of five distribution regions of the country, while Lanka Electricity Company (Pvt) Ltd. (LECO) owns and manages the fifth distribution region.

The CEB distribution network consists of about 33,300 km of 33 kV lines, 2,400 km of 11 kV lines, and about 150,000 km of 400 V or 230 V lines[3]. The distribution network of LECO consists of about 1,000 km of 11 kV lines and 3,800 km of 400 V or 230 V lines[4]. Electricity is provided at 33 kV (or 11 kV) to medium and large industrial and commercial customers. Electricity is supplied to retail customers, including households, at 400 V (three-phase) or 230 V (single-phase), through road-side distribution lines.

1.4. Power System Security and Reliability

1.4.1. Security against outages of generation and transmission lines

The global minimum requirement for power system operation is that when any single element in the generating and transmission system fails to operate or malfunctions, the power supply to all consumers should remain uninterrupted. The overall system should be able to function without causing any equipment damage.

This single outage criterion is commonly known as the n-1 criterion, which states that there might be a large number (such as n) of elements in the generating and transmission network, and the network should be stable if one of these elements is out of service.

The declared security indication in Sri Lanka is the same single outage condition discussed earlier, but it only applies to the transmission system. If a distribution system breakdown happens at 33 kV or below, it is unavoidable that a customer or groups of customers will be without electricity. The large unit sizes of individual generators in Sri Lanka (the largest being 300 MW) in comparison with the demand, does not allow the system to be run by maintaining a generation mix that meets the n-1 reliability requirement. Hence, system operators depend on under-frequency load shedding[5].

Therefore, Sri Lanka grid does not meet the n-1 reliability criterion in generation since load shedding is required to overcome a sudden loss of a generator. However, the transmission network for the most part, meets the n-1 reliability criterion.

1.4.2. Security against the sudden change in customer demand

If there is an unexpected increase in customer demand, the generating system should be able to meet the demand without interrupting the service to that customer or any other customers. Such sudden increases may occur when an industry begins operations or when a distribution line is restored following an outage or malfunction. Sufficient spare generating

[3] Source: Ceylon Electricity Board. *Statisitical Digest 2020*. 2021. Colombo.
[4] Source: Lanka Electricity Complany (Pvt) Ltd. *Statisitical Digest 2021*. Colombo.
[5] An automatic mechanism installed at grid substations to disconnect pre-designated customer loads whenever a significant supply demand imbalance occurs due to tripping of a large generator.

capacity must be already in operation to meet the demand at the same time it is required. This criterion is called 'spinning reserve' since extra capacity must be spinning/rotating rather than stationary.

The system operator CEB decides how much spinning reserve is available at any moment. Spinning reserve consumes water and fuel while the energy output is small or zero, and hence incurs a cost. The usual spinning reserve retained in power networks across the world is about 10% of customer demand. The CEB policy is to maintain a spinning reserve of greater than 5% of gross generation at all times. However, if the predicted time of the violation is short, CEB's system operators are given the option of not initiating extra generation only to fulfill the spinning reserve requirement. The latter option was made exclusively for economic reasons, to avoid starting up more generations closer to severe demand peaks observed in the morning and evening, and merely to preserve the spinning reserve limitations.

Following extra security, the requirement is also typical in various nations throughout the world. If the largest generator in the generating system breaks unexpectedly, the other generators should be able to swiftly supply the customer requirements provided by the failed generator. As a result, it is typical to apply an extra security condition of maintaining a spinning reserve that is at least equivalent to the demand met by the biggest producing unit. However, this criterion does not apply to the Sri Lankan system because, when the largest generator trips (except during a high demand period), the system frequency always falls below a certain threshold, causing an automatic under-frequency load shedding to be active before the spinning capacity is used. Maintaining a higher spinning reserve of about 20% at all times, is extremely uneconomical. Besides, the power system has no spare capacity to allocate such a large share of capacity to be spinning.

Higher security levels, such as n-2 on the transmission network, a larger percentage of spinning reserve, and allowing a two-generator out scenario, may also be implemented but results in increased investments and running expenses.

1.5. Challenges in Operating the Power System

1.5.1. Necessities to maintain a power system

For the power system to operate safely, reliably, and economically, the System Operator should ideally have complete control over which generators are used to meet the customer demand. The system operator should have the following skills to efficiently run the system with a high degree of reliability:

Reliable information

- On the status of all equipment in the system
- On the operating status, such as the currents and voltages
- Demand forecast and historical information
- On factors contributing to demand and generation, such as weather and rainfall, and their forecasts
- On any special problems/concerns about equipment, such as limitations

Supervisory Control

- Remote operation of all critical equipment of the system
- Ability to remotely intervene to improve system reliability
- Online displays on widescreen (mimic diagram) and consoles
- Software tools to determine the most economical and safe mode of operating the system

Guidelines and Experience

- Clear guidelines on system operation
- Procedures in case of regular emergencies
- Experience in power plant and transmission operations
- Adequate experience in system operations
- Hands-on experience in managing emergencies

1.6. Constraints and Status of CEB Resources

With the addition of the new National System Control Centre (NSCC) to the system, most of the constraints faced by CEB in the past have been resolved. Based on the availability of supervisory control and comprehensive information on the status of the system, the switching on and off of the network can be performed effectively. With the improvement of increased system security and supervisory control and data acquisition (SCADA) network, the system can be examined for possible outages and how close it is to the most economical mode of operation.

2. SYSTEM FAILURE ON DECEMBER 03, 2021

The discussion in this chapter will focus mainly on the total system failure on December 03, 2021, while making appropriate reference, where necessary, to the partial failure on November 29, 2021. We will discuss and analyze the total system failure that occurred on December 03, 2021 commencing at 11:27:14, initiated with the following tripping sequence of the Kotmale–Biyagama 220 kV transmission line:

a) tripping and auto-reclosing of circuit 2 from the Biyagama end, and subsequent tripping of the same circuit from Kotmale end with the operation of end-fault protection;
b) followed by the tripping of circuit 1 of Kotmale–Biyagama 220 kV transmission line from the Kotmale end; and
c) tripping of circuit 2 of Kotmale-New Anuradhapura 220 kV transmission line from New Anuradhapura end.

The loss of both circuits of Kotmale-Biyagama 220 kV transmission line and the consequent rejection of 652 MW of generation from the system has led to a substantial drop in system frequency, eventually leading to a total system collapse from cascade tripping of all generators.

2.1. System Status before the Failure on December 03, 2021

The power system was in electrical and mechanical equilibrium just before the initial event, at 11:27:14 on December 03, 2021, with no noticeable fluctuations in voltages.

Weather

The weather reports on December 03, 2021 reveals that the highest temperature recorded in Biyagama area was 30°C with passing clouds. The humidity of the area was 75%, and the wind speed was 6 km/h (south-west)[6]. No rain was reported. Therefore, any possibility of lightning induced overvoltage conditions can be ruled out.

System Load

The total demand on the national grid at 33 kV and 11 kV busbars is recorded as 1,868 MW (refer Appendix 1) prior to the fault. Generation from an estimated installed capacity of 400 MW of rooftop solar PV units is not included in the total demand recorded at NSCC.

Generators

According to the data provided by NSCC, prior to the fault, all hydro units including those at the Laxapana, Mahaweli, and Samanala Complexes, apart from Ukuwela unit 2, Nillabe, and Inginiyagala units, were in operation, generating a total of 1,206 MW. Kelanitissa gas turbines and the combined cycle power plant were not in operation at the time of system failure, while

---

[6] timeandfdate.com, Past weather in Biyagama Sri Lanka – December 2021, Available [Online]: *https://www.timeanddate.com/weather/@1249863/historic?month=12&year=2021* (Accessed: January 2022)

Lak Vijaya Power Plant (LVPP) was providing 545 MW of power to the system. Both Sapugaskanda A and B power stations contributed 69 MW, while Uthuru Janani and Barge Power Plant delivered 11 MW and 45 MW to the system respectively. Renewable energy-based generation (other than rooftop solar) was 111 MW.

The active and reactive power share among the power plant groups before the fault are given in Table 2.1. Loading of each generator is given in Appendix 2.

Table 2.1 - Load Share in the Generating System before the Fault

Power Plant Group	Generation	
	Real Power (MW)	Reactive Power (Mvar)
Laxapana Complex	298	43
Mahaweli Complex	751	176
Samanala Complex	157	53
LVPP	545	194
Thermal Complex	124	88
Small Hydro (CEB)	3	-
Wind	1	3
Solar	15	2
Subtotal	**1,894**	**559**
Others	92	301
Total Generation	**1,986**	**860**
Spinning Reserve	155	8
Frequency Control	Kotmale Unit 2	

CEB = Ceylon Electricity Board, LVPP = Lak Vijaya Power Plant, Mvar = megavar, MW = megawatt

Transmission Lines

The transmission lines that tripped during the failure, and their loading levels prior to the failure are given in Table 2.2. Violation of thermal criteria was not observed for these transmission lines.

Table 2.2 - Transmission Line Current Loadings Prior to the Failure

Transmission Line Circuit	Rated Line Voltage (kV)	Current (A)	Loading %
Kotmale – Biyagama Circuit 2	220	768	50.1%
Kotmale – Biyagama Circuit 1	220	768	50.1%

Transmission Line Circuit	Rated Line Voltage (kV)	Current (A)	Loading %
Kotmale – New Anuradhapura Circuit 2	220	91	12.0%
Athurugiriya – New Polpitiya	220	NA	-
Athurugiriya – Polpitiya	132	134	30.3%
Kolonnawa – Kosgama	132	93	19.3%
Kolonnawa – Seethawaka	132	57	11.8%

Busbar Voltages

The relevant busbar voltages before the failure are listed in Table 2.33. The busbar voltages were within the stipulated limit of ±10% of the rated voltage prior to the failure.

Table 2.3 – Busbar Voltage and Variation before the Failure

Substation/Busbar	Nominal Voltage (kV)	Measured Voltage (kV)	Variation
Badulla	132	128.0	-3.0%
Balangoda	132	131.3	-0.5%
Biyagama 132 kV	132	133.5	1.1%
Galle	132	124.9	-5.4%
Kelanitissa 132 kV	132	131.6	-0.3%
Kelaniya	132	131.8	-0.2%
Kilinochchi	132	130.0	-1.5%
Kiribathkumbura	132	129.8	-1.7%
Kolonnawa	132	130.1	-1.4%
Kotugoda 132 kV	132	134.6	2.0%
Mathugama	132	128.9	-2.3%
New Anuradhapura 132 kV	132	131.8	-0.2%
New Chilaw 132 kV	132	131.0	-0.8%
New Laxapana	132	131.8	-0.2%
Pannipitiya 132 kV	132	129.3	-2.0%
Polpitiya	132	133.0	0.8%
Rantambe	132	127.9	-3.1%
Colombo I	132	131.4	-0.5%
Ukuwela	132	129.1	-2.2%

Substation/Busbar	Nominal Voltage (kV)	Measured Voltage (kV)	Variation
Biyagama 220 kV	220	201.5	-8.4%
Colombo I	220	208.1	-5.4%
Kelanitissa 220 kV	220	206.3	-6.2%
Kotugoda 220 kV	220	203.7	-7.4%
Lak Vijaya	220	218.7	-0.6%
New Anuradhapura 220 kV	220	219.2	-0.4%
New Chilaw 220 kV	220	210.7	-4.2%

2.2. The Failure of the Kotmala-Biyagama 220 kV Transmisison Line

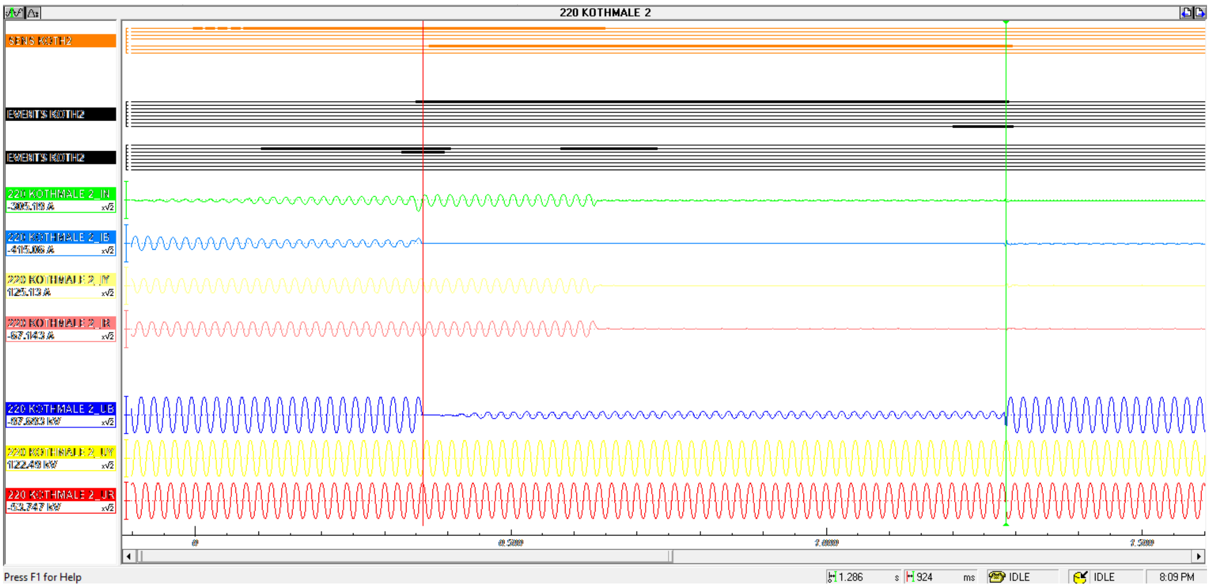
The double circuit Kotmale-Biyagama 220 kV transmission line employs Siemens Siprotec 5 7SL87 relay as Main 1 protection and Easergy MiCOM P545/546 relay as Main 2 protection, with all protection functions duplicated in both relays. This transmission line employs *differential, distance, directional earth fault, over current and earth fault* protection, in accordance with the policy adopted by the CEB for all 220 kV transmission lines (refer Annex D for all settings).

The differential protection relay of this line has a threshold of 400 A with instantaneous trip setting. Detection of a fault by the differential protection system initiates the process of auto-reclosure. During auto-reclosure following the detection of a single-line fault, the two remaining phases of the faulty circuit as well as all three phases of the healthy circuit will continue to carry the load current.

It appears that the failure has started with a fault on phase B (in RYB notation) of circuit 2 of this transmission line. According to the DFR (BEN6000; sampling frequency 5 kHz) reports at the Biyagama GS, on December 03, 2021 at 11:27:14, phase B current of circuit 2 has gradually decreased from approximately 740 A to 375 A while the neutral current has increased correspondingly from 88 A to 440 A. DFR Records also indicate that the differential protection relay at the Kotmale Substation of circuit 2 has operated and tripped phase B from both Biyagama and Kotmale ends, effectively isolating any fault that may have caused the initial high neutral current.

Records obtained from the BEN6000 DFR at Biyagama GS indicate that phase B circuit breaker (CB) of circuit 2 had initiated the auto-reclosure sequence. Following the opening of CB of phase B, the neutral current of circuit 2 had increased further to 600 A. This high neutral current could have been caused by the imbalance introduced by opening of phase B. It had continued to increase gradually up to 629 A, at which point all three phases of circuit 2 had tripped from the Kotmale end causing the CB lockout. This tripping had been caused by the activation of end-fault protection of Biyagama busbar 2, approximately 288 ms after the initial opening of CB of phase B. After this event, the CB of phase B at Biyagama end had reclosed, signifying the continuation and completion of the auto-reclosure sequence (after 924 ms from its initial opening). Records of BEN6000 DFR at Biyagama GS for the above scenario are reproduced in Figure 2.1.

Figure 2.1 – DFR Records of Circuit 2 of Kotmale- Biyagama 220 kV Transmission Line at Biyagama End on 3rd December 2021 at 11:27:14



Auto-reclosing is designed to overcome any transient fault, such as a tree touching the line momentarily and burning out, without tripping the line permanently. The faulty phase should open from both ends, reclose and hold if the fault is no longer present. The operation of end-fault protection relay at Biyagama was not expected while the auto-reclosing was in progress. We have determined that the combination of spurious operation of end-fault protection at Biyagama busbar and erroneous configuration of the line protection relay at Kotmale has been the principal cause of the total power failure on December 03, 2021. We have also determined that the same unintended operation of the end-fault protection at Biyagama GS had caused the Kotmale-Biyagama 220 kV transmission line to disconnect from the system, leading to a major breakdown affecting many areas of the country on November 29, 2021.

The phase B current and the corresponding neutral currents are consistent with those associated with a high impedance earth fault on phase B. The CEB has taken the position in its reports to the Committee that it was a primary side failure that caused this high neutral current as opposed to any other cause (such as faulty secondary equipment), in view of the identical current waveforms observed in the CT secondaries connected to the Main 1 relay (SIEMENS SIPROTEC 5 7SL87), Main 2 relay (Schneider Easergy MiCOM P546) and the DFR (BEN6000). CEB informed the Committee further that the primary side failure had been non-persistent since this circuit was re-energized successfully during the system restoration after the total failure.

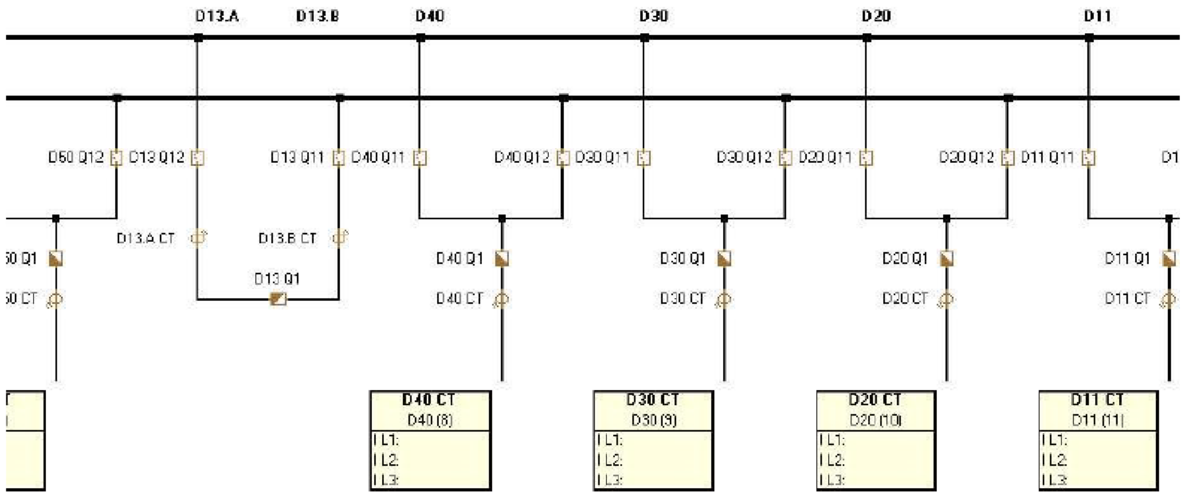
The Annex 1.3 of CEB's report to the Committee shows a detailed calculation of how the zero-sequence current above 400 A threshold had formed, considering the zero-sequence currents added from various connected circuits just before the fault. The summation (429.9 A) is very close to the actual zero-sequence current recorded in the fault (431.4 A). The Committee observed that the zero-sequence current has been increasing for a period of about 440 ms. The above explanation presented by the CEB is less than convincing for the following reasons:

The final answer depends on the exact time instant at which the neutral current is taken for the calculation. Since the DFRs at the two ends were not time synchronized, it is hard to agree that the calculated zero-sequence current matches its recorded value, unless it is shown to be matching over the entire period of 440 ms. Further, if the scenario explained by the CEB is indeed the reality, then it could have happened at any time in the past. However, no past records of similar incidents have been presented to the Committee. Therefore, the Committee cannot accept the calculated zero-sequence currents derived from various components in the Biyagama GS as the cause of the tripping of phase B of circuit 2 of Kotmale-Biyagama 220 kV transmission line. In the absence of a reasonable technical explanation backed by data, the Committee has concluded that the cause of the high neutral current prior to the fault to be indeterminate.

Failure in Circuit 2 of Kotmale-Biyagama 220 kV Transmission Line on December 03, 2021

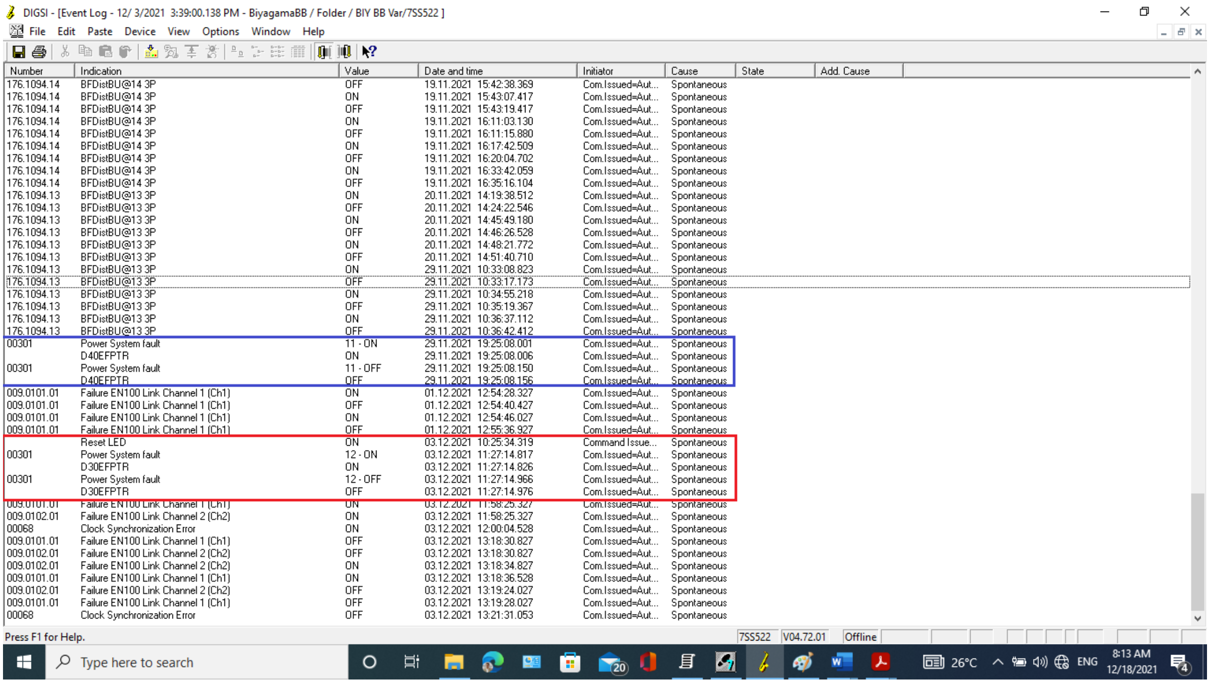
Part of the single-line representation of the Biyagama double busbar system obtained from the busbar protection relay software DIGSI V4.93 is shown in Figure 2.2. The feeder D30 on Bay 9 is the circuit 2 of Kotmale-Biyagama 220 kV transmission line, where D30Q11 is the Busbar 1 isolator and the D30Q12 is the Busbar 2 isolator, and the CT D30CT is on the line side after the CB indicated as D30Q1. The CT covers all 3 phases as indicated by IL1, IL2 and IL3 under D30(9).

Figure 2.2 - Part of the Busbar and Feeder Layout in Biyagama GS



As already discussed above, before the completion of the auto-reclosing of phase B of circuit 2, the end-fault tripping signal had been issued by the relay SIEMENS 7SS522 at the Biyagama GS, causing circuit 2 to be locked out at the Kotmale end. This event is marked as “Power System Fault/D30EFPTR ON at 11:27:14.826” highlighted in red in Figure 2.3, reproduced from the downloaded relay logs. The end-fault protection is designed to protect equipment in the event of an earth fault occurring between the CB and the CT, both of which are inside the Biyagama GS. The operation of end-fault protection of circuit 2 without an actual end-fault highlights a serious flaw inherent in the implementation of this protection scheme.

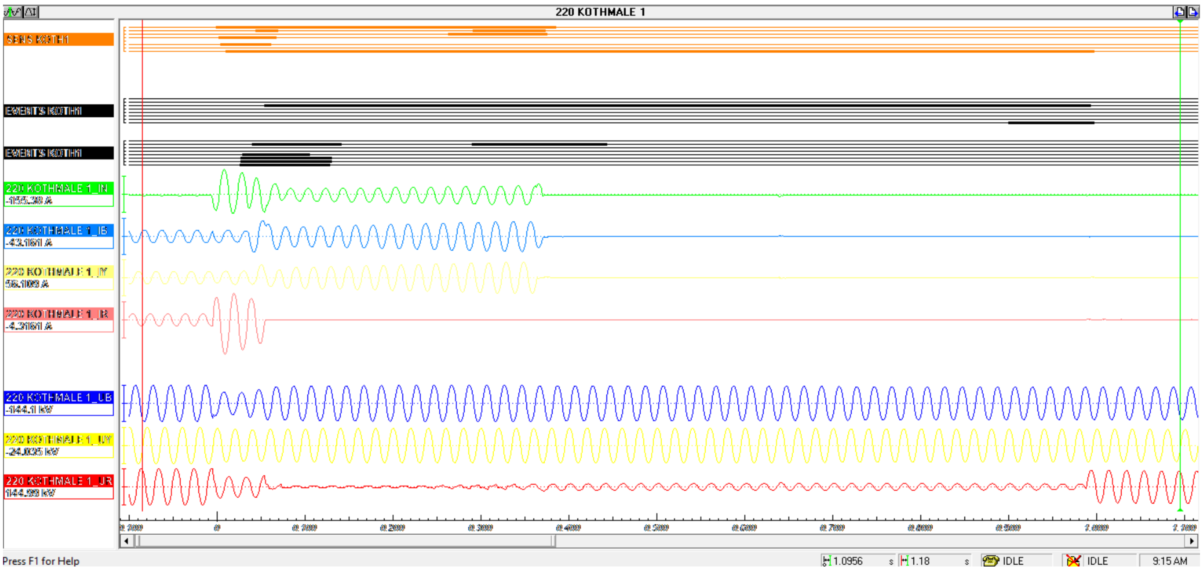
Figure 2.3 - Busbar Protection Relay Event Log of the Biyagama Substation Busbar 2



Number	Indication	Value	Date and time	Initiator	Cause	State	Add. Cause
176.1094.14	BFDistBU@14 3P	OFF	19.11.2021 15:42:38.369	Com.Issued=Aut...	Spontaneous		
176.1094.14	BFDistBU@14 3P	ON	19.11.2021 15:43:07.417	Com.Issued=Aut...	Spontaneous		
176.1094.14	BFDistBU@14 3P	OFF	19.11.2021 15:43:19.417	Com.Issued=Aut...	Spontaneous		
176.1094.14	BFDistBU@14 3P	ON	19.11.2021 16:11:03.130	Com.Issued=Aut...	Spontaneous		
176.1094.14	BFDistBU@14 3P	OFF	19.11.2021 16:11:15.880	Com.Issued=Aut...	Spontaneous		
176.1094.14	BFDistBU@14 3P	ON	19.11.2021 16:17:42.509	Com.Issued=Aut...	Spontaneous		
176.1094.14	BFDistBU@14 3P	OFF	19.11.2021 16:20:04.702	Com.Issued=Aut...	Spontaneous		
176.1094.14	BFDistBU@14 3P	ON	19.11.2021 16:33:42.059	Com.Issued=Aut...	Spontaneous		
176.1094.14	BFDistBU@14 3P	OFF	19.11.2021 16:35:16.104	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	ON	20.11.2021 14:19:38.512	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	OFF	20.11.2021 14:24:22.546	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	ON	20.11.2021 14:45:49.180	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	OFF	20.11.2021 14:46:26.528	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	ON	20.11.2021 14:48:21.772	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	OFF	20.11.2021 14:51:40.710	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	ON	29.11.2021 10:33:08.823	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	OFF	29.11.2021 10:33:17.173	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	ON	29.11.2021 10:34:55.218	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	OFF	29.11.2021 10:35:19.367	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	ON	29.11.2021 10:36:37.112	Com.Issued=Aut...	Spontaneous		
176.1094.13	BFDistBU@13 3P	OFF	29.11.2021 10:36:42.412	Com.Issued=Aut...	Spontaneous		
00301	Power System fault	11 - ON	29.11.2021 19:25:08.001	Com.Issued=Aut...	Spontaneous		
	D40EFPTR	ON	29.11.2021 19:25:08.006	Com.Issued=Aut...	Spontaneous		
00301	Power System fault	11 - OFF	29.11.2021 19:25:08.150	Com.Issued=Aut...	Spontaneous		
	D40EFPTR	OFF	29.11.2021 19:25:08.156	Com.Issued=Aut...	Spontaneous		
009.0101.01	Failure EN100 Link Channel 1 (Ch1)	ON	01.12.2021 12:54:28.327	Com.Issued=Aut...	Spontaneous		
009.0101.01	Failure EN100 Link Channel 1 (Ch1)	OFF	01.12.2021 12:54:40.427	Com.Issued=Aut...	Spontaneous		
009.0101.01	Failure EN100 Link Channel 1 (Ch1)	ON	01.12.2021 12:54:46.027	Com.Issued=Aut...	Spontaneous		
009.0101.01	Failure EN100 Link Channel 1 (Ch1)	OFF	01.12.2021 12:55:36.927	Com.Issued=Aut...	Spontaneous		
	Reset LED	ON	03.12.2021 10:25:34.319	Command Issue...	Spontaneous		
00301	Power System fault	12 - ON	03.12.2021 11:27:14.817	Com.Issued=Aut...	Spontaneous		
	D30EFPTR	ON	03.12.2021 11:27:14.826	Com.Issued=Aut...	Spontaneous		
00301	Power System fault	12 - OFF	03.12.2021 11:27:14.966	Com.Issued=Aut...	Spontaneous		
	D30EFPTR	OFF	03.12.2021 11:27:14.976	Com.Issued=Aut...	Spontaneous		
009.0101.01	Failure EN100 Link Channel 1 (Ch1)	ON	03.12.2021 11:58:25.327	Com.Issued=Aut...	Spontaneous		
009.0102.01	Failure EN100 Link Channel 2 (Ch2)	ON	03.12.2021 11:58:25.327	Com.Issued=Aut...	Spontaneous		
00068	Clock Synchronization Error	ON	03.12.2021 12:00:04.528	Com.Issued=Aut...	Spontaneous		
009.0101.01	Failure EN100 Link Channel 1 (Ch1)	OFF	03.12.2021 13:18:30.827	Com.Issued=Aut...	Spontaneous		
009.0102.01	Failure EN100 Link Channel 2 (Ch2)	OFF	03.12.2021 13:18:30.827	Com.Issued=Aut...	Spontaneous		
009.0102.01	Failure EN100 Link Channel 2 (Ch2)	ON	03.12.2021 13:18:34.827	Com.Issued=Aut...	Spontaneous		
009.0101.01	Failure EN100 Link Channel 1 (Ch1)	ON	03.12.2021 13:18:36.528	Com.Issued=Aut...	Spontaneous		
009.0102.01	Failure EN100 Link Channel 2 (Ch2)	OFF	03.12.2021 13:19:24.027	Com.Issued=Aut...	Spontaneous		
009.0101.01	Failure EN100 Link Channel 1 (Ch1)	OFF	03.12.2021 13:19:28.027	Com.Issued=Aut...	Spontaneous		
00068	Clock Synchronization Error	OFF	03.12.2021 13:21:31.053	Com.Issued=Aut...	Spontaneous		

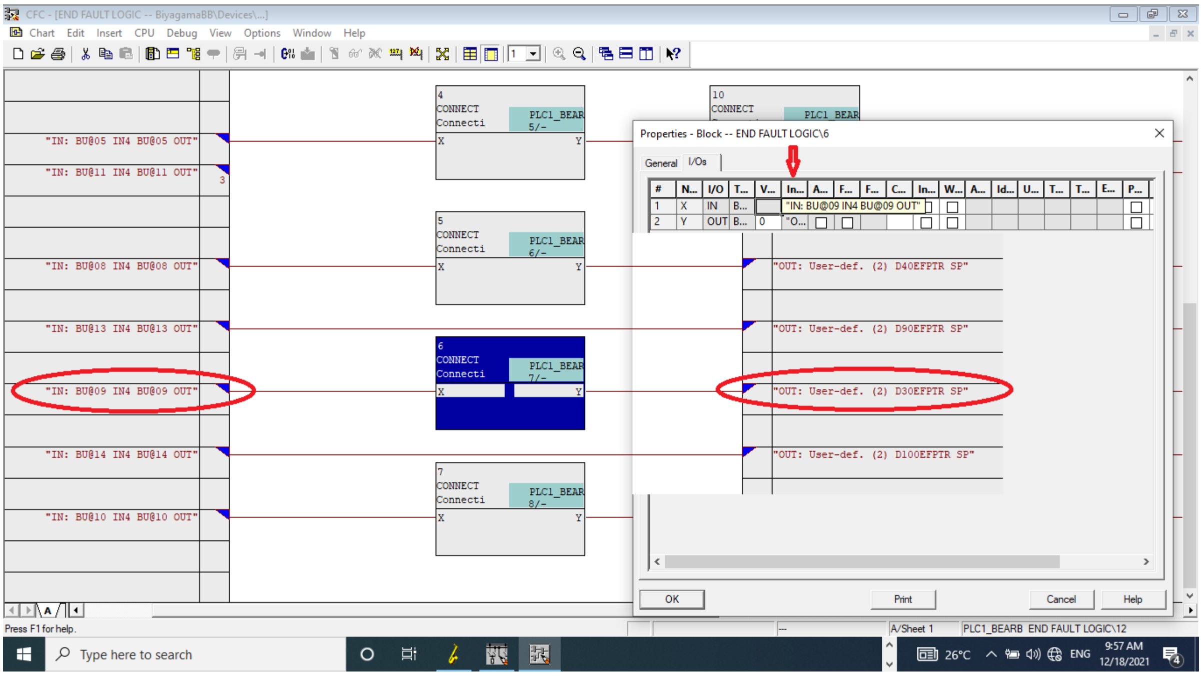
It can be seen that a similar tripping signal had been issued on November 29, 2021 (4 days before the incident on the December 03, 2021), highlighted in blue in Figure 2.3, following what is suspected to be a single-line-to-ground fault associated with phase R of circuit 1 of Kotmale-Biyagama 220 kV transmission line. In this instance, phase R had reclosed after 934 ms, by which time all three phases of this circuit had been tripped from the Kotmale end by the activation of end-fault protection of busbar 1 of the Biyagama GS (317 ms after initial CB opening of phase R). It has also caused lockout of the CBs, thus preventing the completion of auto-reclosure. The corresponding DFR records are shown in Figure 2.4, which clearly show the currents in all phases becoming zero before the CB of phase B recloses (the waveform at the bottom). In this case too, both circuits of the Kotmale-Biyagama 220 kV transmission line would have returned to normal service if the end-fault protection did not operate erroneously. It is unfortunate that the CEB's protection engineers had not commenced an immediate investigation into this spurious activation of end-fault protection on November 29, 2021. We can state with high degree of confidence that the total failure on December 03, 2021 could have been avoided, had such an investigation on the partial failure on November 29, 2021 been carried out and immediate remedial measures taken.

Figure 2.4 - DFR Records of Circuit 1 of Biyagama - Kotmale 220 kV Transmission Line at Biyagama End on 29th November 2021 at 19:25:07



The Committee studied the end-fault logic implemented in SIEMENS 7SS522 relay from the records in the relay accessed using DIGSI V4.93 software. Figure 2.5 shows the screenshot highlighting the output generated by the D30EFPTR using the relay function block. The properties of the function block reveal that only the neutral current (I_N) is taken as the input. Accordingly, when I_N exceeds a certain threshold, the end-fault tripping is activated.

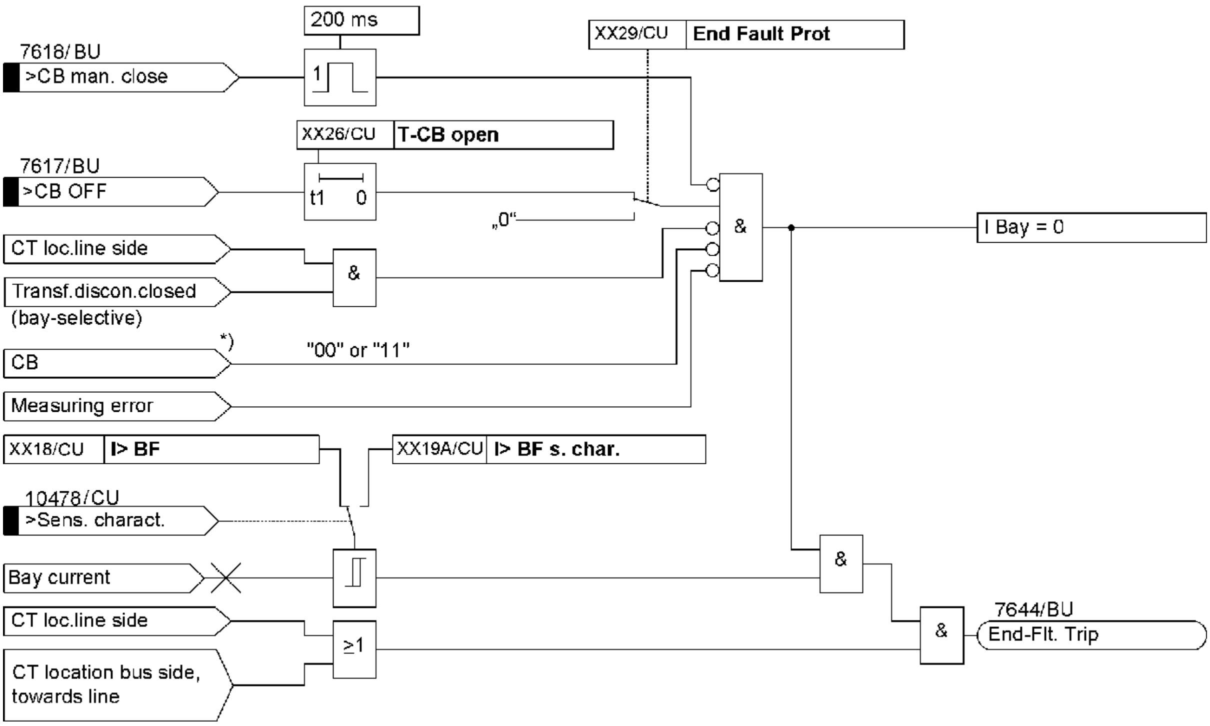
Figure 2.5 – End-Fault Function Implementation in the SIEMENS 7SS522 Relay



The operation manual of the SIEMENS 7SS522 relay confirms that the end-fault function is for the detection and disconnection of short-circuits between CT and CB of a line. The logic of the end-fault protection is reproduced in Figure 2.6. A prerequisite for the activation of end-fault protection is that the CB open state ”>CB OFF” (7617/BU) is marshalled to a binary input.

During the auto-reclosure operation, until the CB is closed and the feeder current is integrated into the busbar measurement again, the end-fault protection should remain blocked. The leading information of the CB CLOSE command is evaluated (">CB man.close" 7618/BU) and marshalled to a binary input. According to the relay manual (page 156), end-fault protection is blocked if the monitoring of the switching status feedback has detected a fault. However, it appears that despite the phase B fault having been detected and disconnected by SIEMENS 7SL87 relay (Main 1 line protection relay), initiating an auto-reclosure process, the status communication has not been correctly taken as an input. Such provision had not been present in the relay configuration at the time of the two incidents of November 29, 2021 (on circuit 1) and December 03, 2021 (on circuit 2). It is further proof that this matter should have received serious consideration of the CEB's protection staff without waiting for this Committee to raise the issue.

Figure 2.6 – End-Fault Function Implementation in the SIEMENS 7SS522 Relay Manual



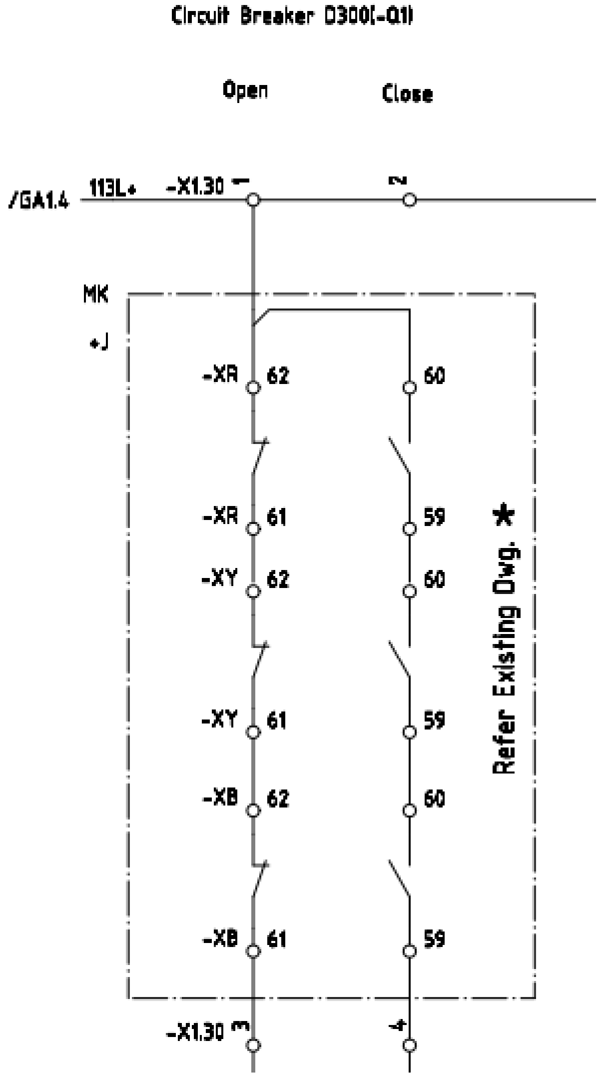
As-built circuit diagram of circuits 1 and 2 of Kotmale–Biyagama 220 kV transmission line supplied in 1986 by ASEA of Sweden (reproduced here from the original drawings) reveals that the CB positions of the three phases are collected using three series connected Normally-Closed (NC) auxiliary contacts as shown in Figure 2.7. According to the above implementation, the end-fault protection can operate when all 3 poles are open, all 3 NC auxiliary contacts are closed, and no other protection has operated already.

However, on December 03, 2021 at 11:27:14 in circuit 2 of Kotmale–Biyagama 220 kV transmission line,

(i) differential protection had operated,
(ii) only phase B was open at both ends, and
(iii) the auto-reclosure function of phase B was in progress.

Therefore, the conditions for the operation of the end-fault protection had not been satisfied. Yet, end-fault protection on circuit 2 at Biyagama GS had been activated, and a command had been issued to disconnect the circuit completely and to lockout the CB at the Kotmale end.

Figure 2.7 – As-built Circuit of Auxiliary Contacts of End-Fault Protection Supplied by ASEA in 1986



Explanation by CEB on the operation of End-Fault busbar protection

During the meeting held at the NSCC on the January 12, 2022, as well as in the subsequent report submitted to the Committee, CEB engineers stated that the CBs of circuits 1 and 2 at Biyagama GS in of Kotmale–Biyagama 220 kV transmission line had been replaced in the first quarter of 2015, after the completion of the protection development project by SIEMENS in 2014. However, no commissioning reports of such CB replacement or commissioning checks on the associated protection system at Biyagama GS, other than two unbundled files with hand written relay logic derivations for the two circuits, were made available to the Committee despite repeated requests. In subsequent reports and discussions, CEB engineers further revealed that during CEB's own investigations on the operation of the end-fault protection on November 29, 2021 and on the December 03, 2021 (after this matter was raised by the Committee), they had found the field wiring associated with the end-fault protection relay of busbar 1 and busbar 2 at Biyagama GS were as shown in Figure 2.8 and Figure 2.9 respectively. These wiring arrangements are markedly different to the original as-built drawings provided by ASEA in 1986. Further, CEB in its report to the Committee had attributed the alleged changes in the field wiring of the end-fault protection to a mistake made during the replacement of the CBs at Biyagama GS in circuits 1 and 2 of Kotmale–Biyagama 220 kV transmission line in early 2015.

Figure 2.8 - Actual Field Wiring of CB Open/Close Position Detection for End-Fault Protection Relay Operation in Circuit 1 of Kotmale-Biyagama 220 kV Transmission Line at Biyagama Substation (as Provided by CEB)

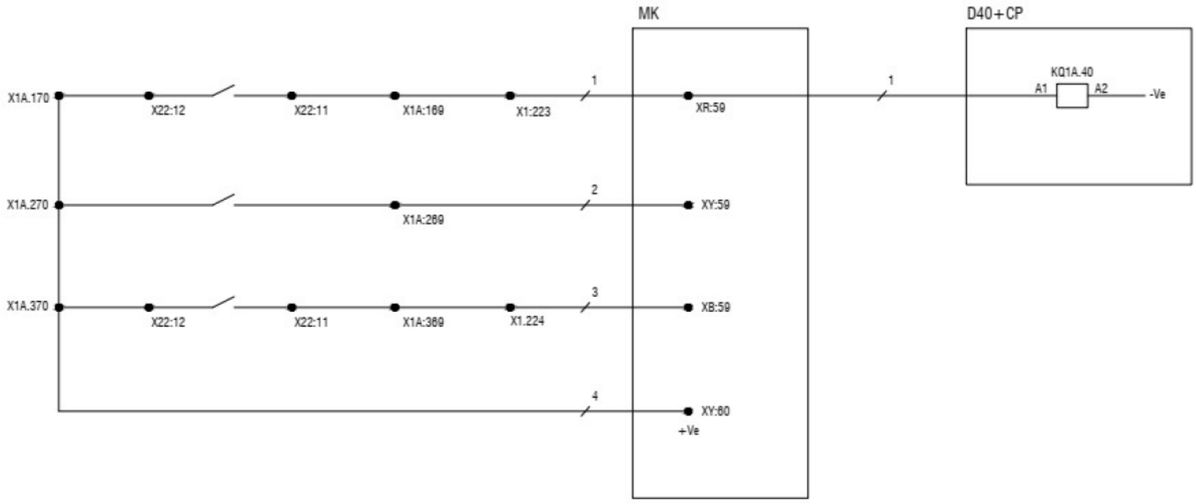
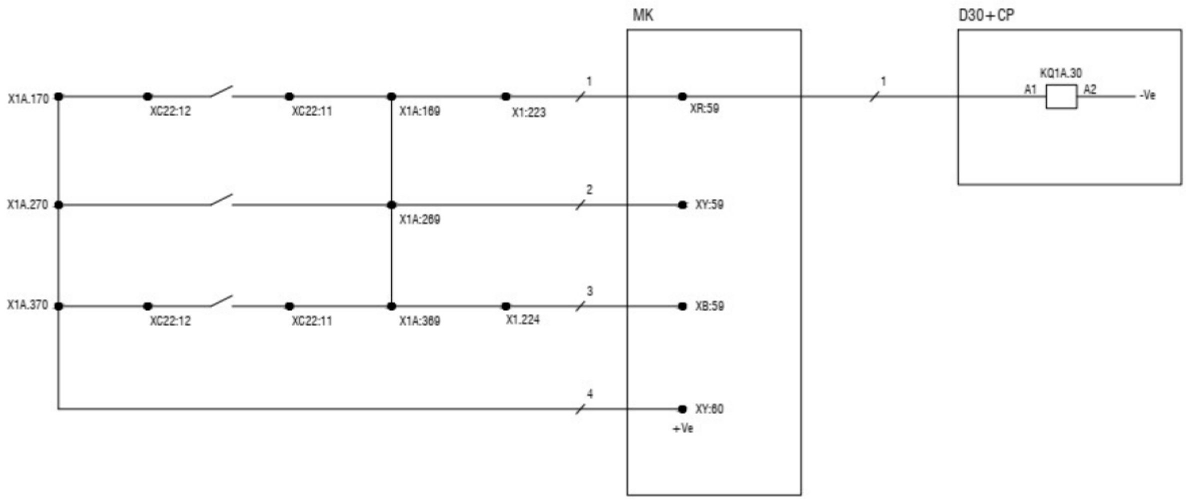


Figure 2.9 - Actual Field Wiring of CB Open/Close Position Detection for End-Fault Protection Relay Operation in Circuit 2 the Kotmale-Biyagama 220 kV Transmission Line at Biyagama Substation (as provided by CEB)



The Committee notes significant differences between the original as-built wiring (Figure 2.7) and the purported schematic diagrams CEB has presented to the Committee (Figure 2.8 and Figure 2.9). These discrepancies are enumerated below:

(i) Original wiring is based on NC auxiliary contacts which are closed when the corresponding CBs are open and vice versa, whereas Figure 2.8 and Figure 2.9 show Normally-Open (NO) auxiliary contacts.

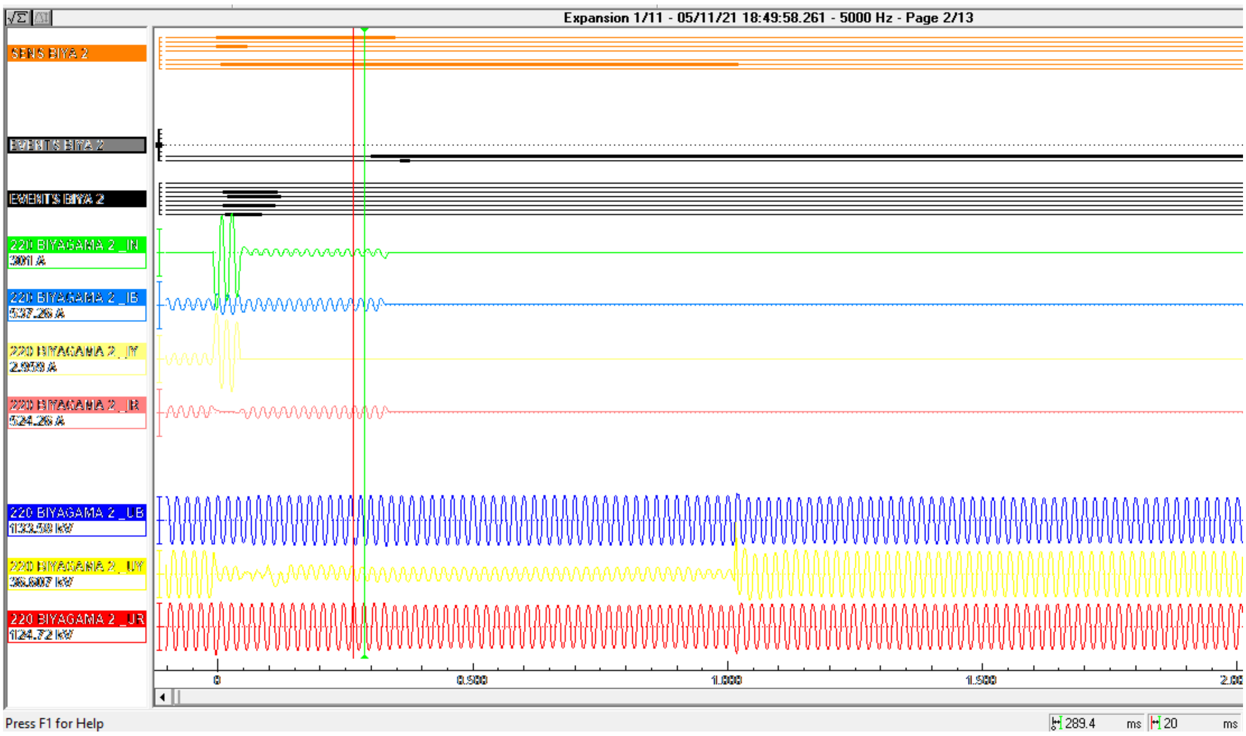
(ii) Original wiring takes the series connection of the NC auxiliary contacts, whereas the Figure 2.8 shows parallel connection of the NO auxiliary contacts. A logic truth table taking all possible CB position status into account in the R, Y and B phases shows that the approaches are completely opposite functionally, meaning that if any one of the CBs is open, then the CB position condition for the end-fault protection operation is satisfied in the case of the scheme provided by the CEB.

(iii) When comparing Figure 2.8 and Figure 2.9, corresponding to circuits 1 and 2, respectively, it is noted that NO auxiliary contacts in Figure 2.8 are connected neither in series nor in parallel, but only one phase is directly connected, making the CB position detection logic different between circuit 1 to circuit 2. Therefore, this cannot be correct because if the said auxiliary contact rewiring of circuits 1 and 2 in 2015 at the time of the CB replacement had referred to the same circuit diagram, then there could not have been any discrepancy between the wiring of the two CBs, even if the said diagram depicted wrong logic. In other words, circuit 1 wiring should have been identical to circuit 2 wiring irrespective of which of the two drawings had been followed.

CEB further stressed verbally and in writing that in addition to the CB open condition, another condition that had been considered for the operation of the end-fault protection was the currents in the healthy phases to be higher than 500 A. CEB used the examples below to highlight the significance of this latter condition.

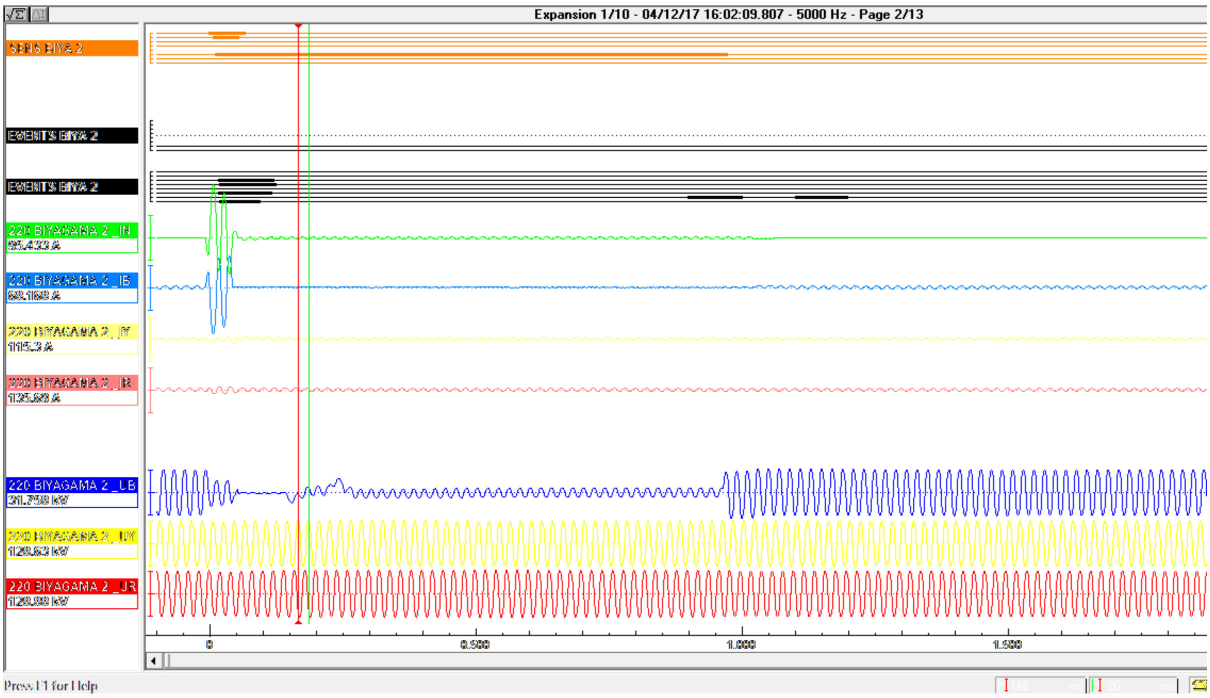
Example 1: End-fault protection operated with lockout in circuit 2 of Kotmale-Biyagama 220 kV transmission line at 18:49 on the May 11, 2021 following a phase Y to ground fault, where the currents in the healthy phases have been above 500 A. The corresponding record on the DFR is shown in Figure 2.10.

Figure 2.10 – DFR Record of Event in Circuit 2 of Kotmale-Biyagama 220 kV Transmission Line at 18:49 on May 11, 2021



Example 2: The end-fault protection did not operate in circuit 2 of Kotmale-Biyagama 220 kV transmission line at 16:02 on April 12, 2017 following a phase B to ground fault, where the currents in the healthy phases had been around 100-150 A, i.e., below 500 A. The corresponding record on the DFR is shown in Figure 2.11.

Figure 2.11 – DFR Record of Event in Circuit 1 of Kotmale-Biyagama 220 kV Transmission Line at 16:02 on April 12, 2017

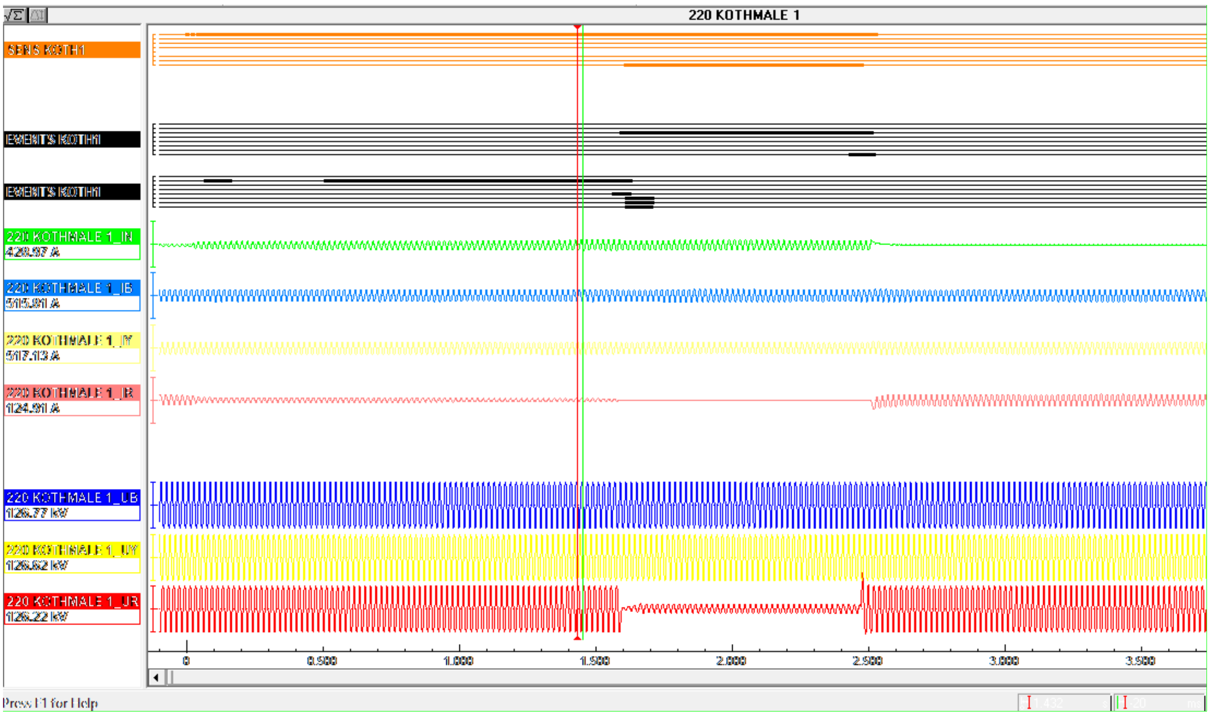


The manual of the SIEMENS 7SS52 relay that provides the end-fault protection function does not mention such a condition that the currents in healthy phases should be higher than 500 A or any other threshold for end-fault protection to operate. Instead, it does mention the condition that end-fault protection shall be inhibited in the presence of another fault. Accordingly, the end-fault protection should have been inhibited under the conditions that existed on December 03 and November 29, 2021 because differential protection of the faulty circuits had operated and the auto-reclosing procedure had commenced on both occasions.

Further, the report submitted by the CEB shows a case that resembles a high impedance earth fault in phase R of circuit 1 of Kotmale-Biyagama 220 kV transmission line that occurred at 11:38 on October 18, 2019, where the phase R (according to the field wiring circuit diagram in Figure 2.8 presented to the Committee; this is the only phase where the CB position is actively considered for the end-fault protection operation) protection had isolated the fault for a while and currents in the healthy phases were above 500 A, but the end-fault protection had not operated. The corresponding record on the DFR is shown in Figure 2.12. This latter observation further confirms that the healthy phase currents to be greater than 500 A is not a necessary condition for the operation of the end-fault protection.

For the foregoing reasons, the Committee cannot and will not accept the explanations provided by the CEB for the spurious operation of the end-fault protection in circuit 2 on December 03, 2021 (and on circuit 1 on November 29, 2021).

Figure 2.12 – DFR Record on Event in Circuit 1 of Kotmale-Biyagama 220 kV Transmission Line at 11:38 on the 18th October 2019



Failure in Circuit 1 of Kotmale-Biyagama 220 kV Transmission Line on December 03, 2021

According to the DFR (BEN6000–sampling frequency 5 kHz) at Biyagama GS, when phase B of circuit 2 of Kotmale-Biyagama 220 kV transmission line tripped at 11:27:14, the current in phase B of circuit 1 of Kotmale-Biyagama 220 kV transmission line had increased from about 800 A to 1200 A as should be expected, because the two circuits are connected in parallel. Once circuit 2 was disconnected completely from Kotmale end by the operation of end-fault protection, the bulk of the load previously carried by circuit 2 had got transferred to circuit 1. Thereater, currents in all three phases of circuit 1 had increased (phase R: from 777 A to 1350 A, phase Y: from 850 A to 1460 A and phase B from 1270 A to 1395 A), which is consistent with the expected behaviour when one of two circuits operating in parallel is disconnected. The report of the NSCC submitted to the Committee confirmed that the Kotmale-Biyagama 220 kV transmission line was operating under n-1 reliability criterion when circuit 2 of Kotmale-Biyagama 220 kV transmission line tripped with CB lockout at the Kotmale end. Accordingly, circuit 1 had carried the full load of both circuits once circuit 2 was isolated.

However, earth-fault protection on the otherwise healthy circuit 1 had operated after the system resumed normal operation, and tripped that circuit after 22.33 s.

Observations of the Committee on the tripping of Circuit 1

The information on the neutral current revealed in the downloaded DFR (BEN6000) records at Biyagama GS are given in Table 2.4 and the corresponding DFR records are shown in Figure 2.13. The BEN6000 records downloaded at Kotmale substation are given in Figure 2.14. According to these records, the pre-fault neutral currents recorded at the two ends are significantly different (162 A and 70 A for the two ends). The same observation was made when the Committee visited the NSCC on December 06, 2021, where it was observed that the values were 139 A and 61 A respectively for the two ends. This current off-set could have been due to a calibration error in the DFR (BEN6000) or mismatch of the CT secondary at the two ends, or a combination of both. The Committee requested the Ministry of Power to get the original equipment manufacturer (OEM) to check on this discrepancy and the OEM has submitted the calibration report confirming that there had been a calibration error and that has now been corrected.

Table 2.4 - Comparison of Neutral Current Records at Biyagama and Kotmale Ends of Circuit 1 of Kotmale- Biyagama 220 kV Transmission Line

Condition	Neutral Current (RMS) at Biyagama End (A)	Neutral Current (RMS) at Kotmale End (A)
Pre-fault	162	70
After phase B of circuit 2 had tripped by differential protection and before the entire line was tripped by end-fault protection	Starts at 504 and increases to 526	Starts at 478 and increases to 501
After circuit 2 was tripped by end-fault protection	173 initially and reduces to 167 later	83 initially and reduces to 78 later

A = ampere, RMS = Root Mean Square

Figure 2.13 – DFR Records of Circuit 1 of Kotmale- Biyagama 220 kV Transmission Line at Biyagama End on December 03, 2021 at 11:27:14

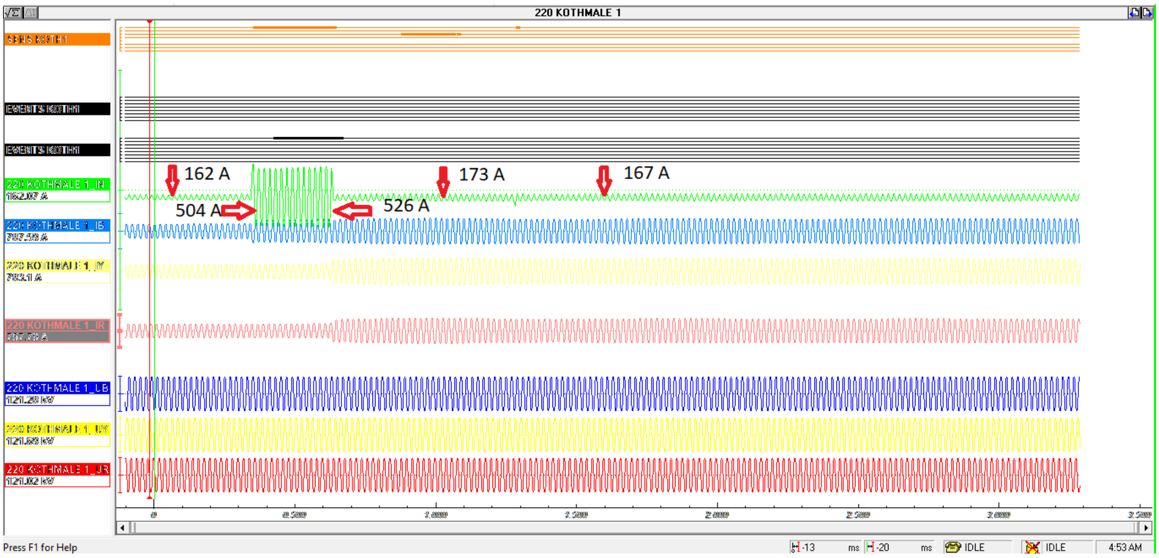
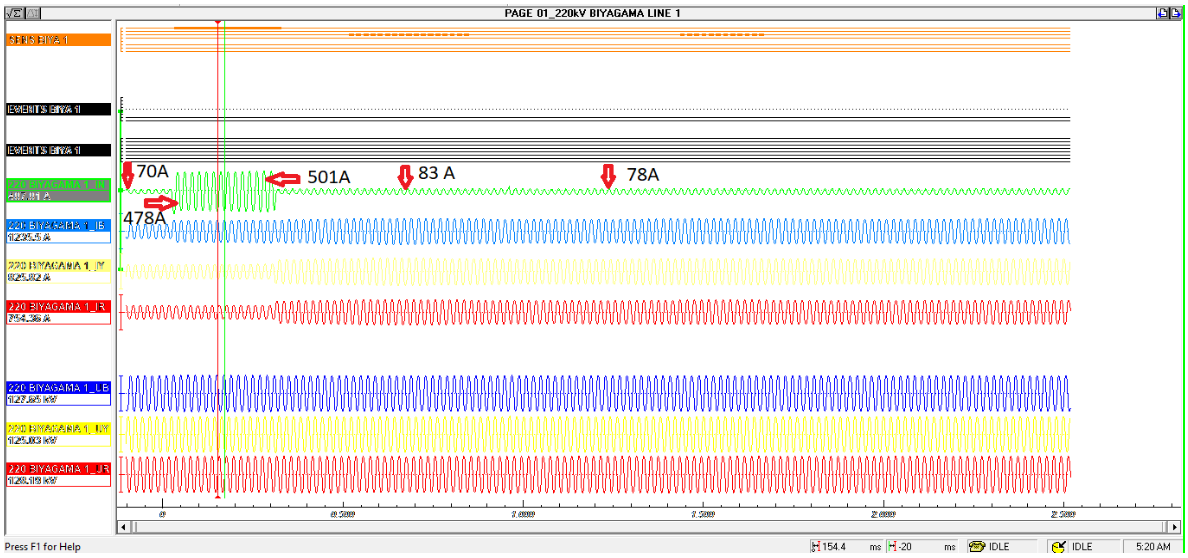


Figure 2.14 - DFR Records of Circuit 1 of Kotmale- Biyagama 220 kV Transmission Line at Kotmale End on December 03, 2021 at 11:27:14



The Committee learned from the CEB during deliberations that in the mutual line compensation wiring implemented in circuits 1 and 2, neutral of the circuit 1 is wired to the line protection relay of circuit 2 and vice versa. Therefore, the neutral current shown in Main 1 relay of circuit 1 is the actual neutral current of circuit 2. For protection operation, the neutral current of each circuit is calculated by the relay attached to that circuit.

Analysis of the fault in Circuit 1

Because of the possible calibration error of the DFR records, Contrade Viewer 4.5 SIEMENS AG software was used to access the SIEMENS 7SL87 relay setting file where the voltage, current and trigger signals can be viewed. Figure 2.15 shows the screenshot of fault records of the SIEMENS 7SL87 protection relay of circuit 1 as recorded in the relay. These records are consistent with the CEB's explanation that the neutral current shown in Main 1 relay of circuit 1 is the neutral current of circuit 2, since the current has become almost zero following the circuit 2 tripping.

Figure 2.15 – Main 1 Relay Disturbance Record of Circuit 1 of Kotmale-Biyagama 220 kV Transmission Line

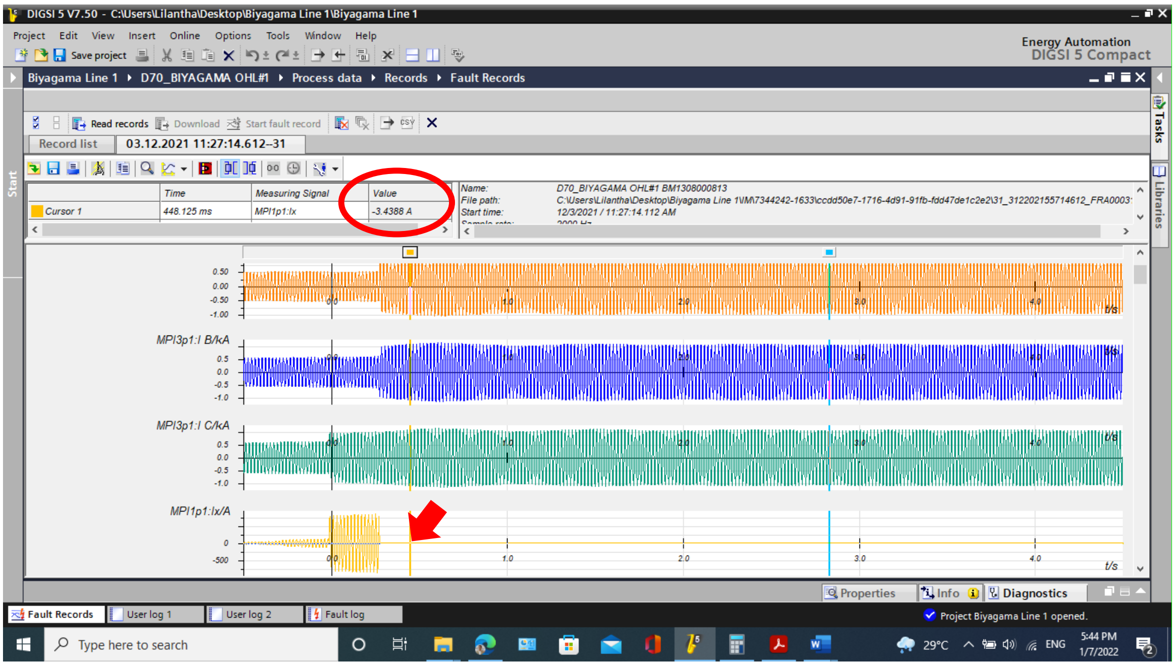
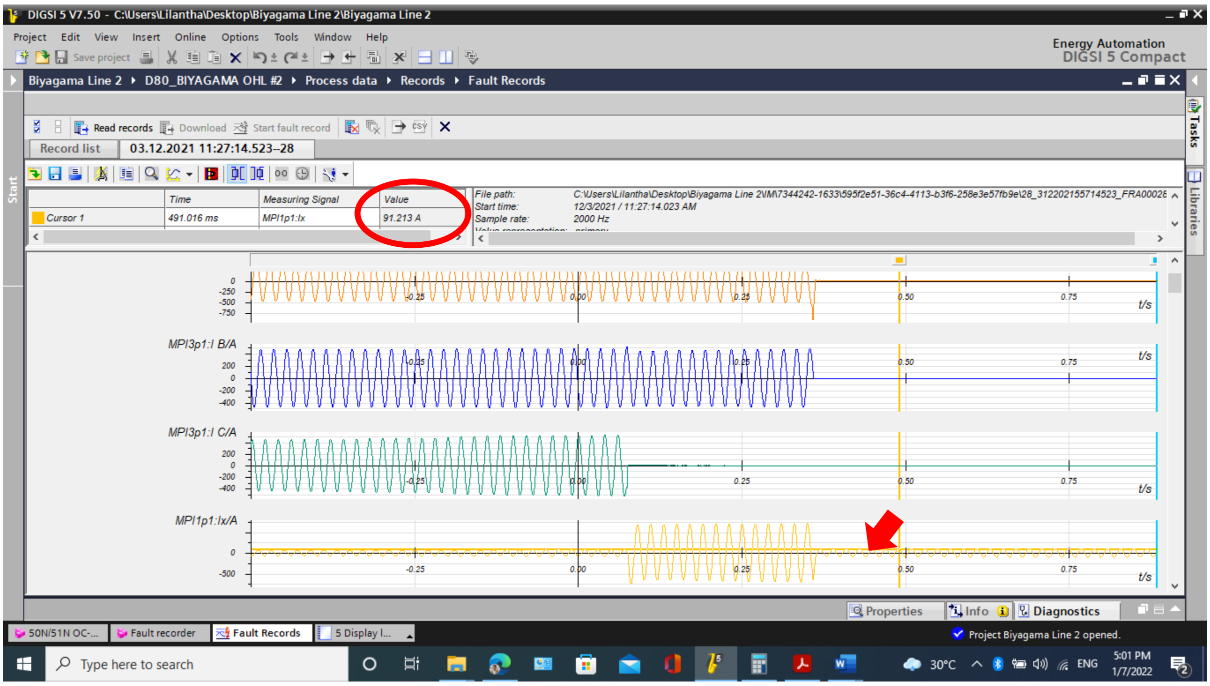


Figure 2.16 - Main 1 Relay Disturbance Record of Circuit 2 of Kotmale-Biyagama 220 kV Transmission Line



	Setting	Kotmale Substation, Biyagama 1 Bay	Biyagama Substation, Kotmale 1 Bay
Inverse T1	Mode (ON/OFF)	ON	ON
	Threshold (A)	0.04	0.04
	Characteristic curve	IEC normal inverse	IEC normal inverse
	Reset	Disk Emulation	Instantaneous
	TMS	0.38	0.41
Definite T1	Mode (ON/OFF)	ON	OFF
	Threshold (A)	0.825	0.825
	Dropout ratio	0.95	0.95
	Dropout delay (s)	0	0
	Operate delay (s)	1.1	1.1

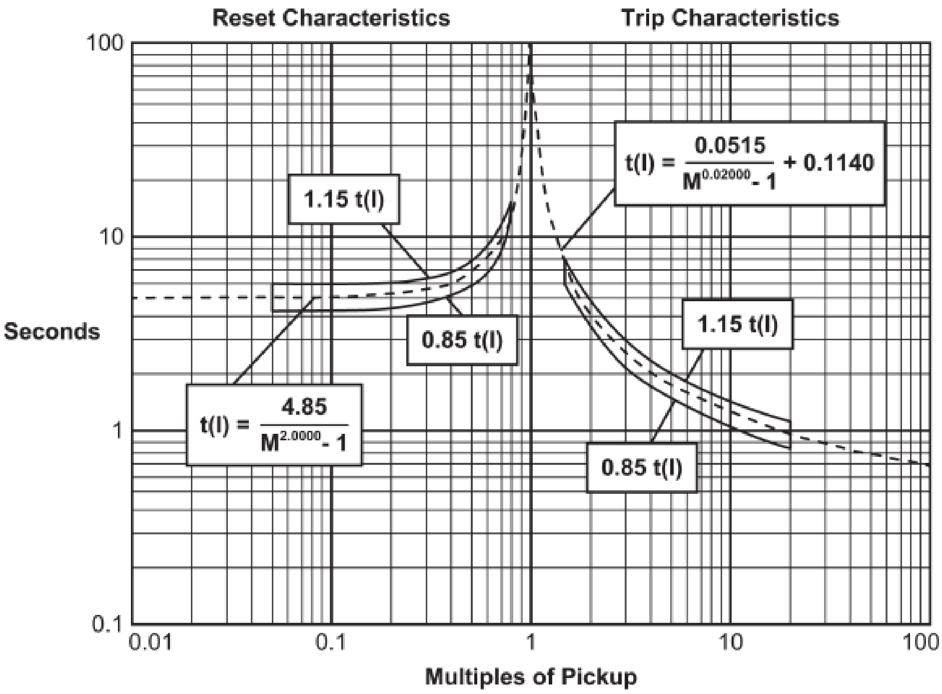
A = ampere, IEC = International Electrotechnical Commission, TMS = Time Multiplier Setting

The CEB in its report to the Committee, backed by the reply of relay OEM to its inquiry on the relay dropout characteristics, took the position that since the current did not drop below 58 A, the relay used the 110% of the threshold current to calculate the remaining time of the relay operation once the neutral current fell to 65 A from its 488 A pickup value. Hence, the earth-fault protection operation after 22.33 s has been explained by CEB.

However, neither the calculation by CEB nor the explanation by Mr. Ren YiQiang of SIEMENS Power Automation Limited (ea_support.cn@siemens.com), whose email has been quoted by CEB in the report to the Committee (who has been replying on behalf of the OEM of SIEMENS 7SL87), seems to have followed the IEC 60255-151 (IEEE Standard C37.112-2018), which is the standard pertaining to earth-fault relay resetting. The standard very clearly specifies the inverse time reset curve, whose Plug Setting Multiplier is below 1 (PSM < 1), which is very different to the IEC standard inverse time trip curve (PSM > 1) as reproduced from the standard[7] in Figure 2.17.

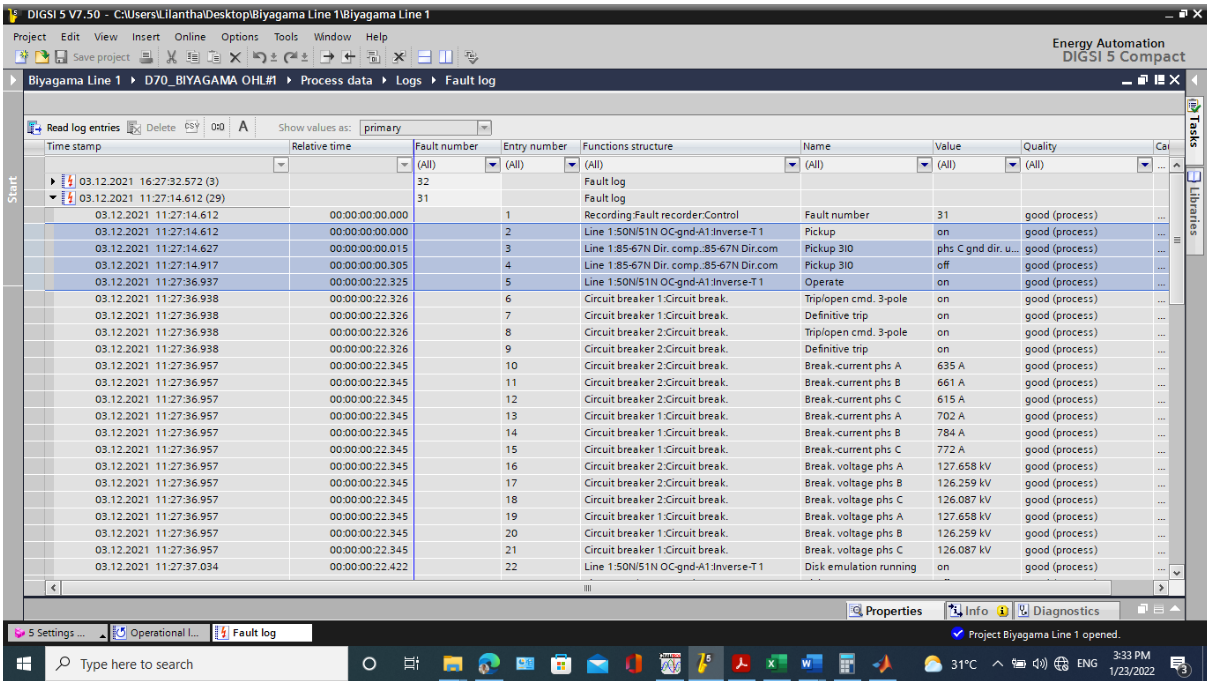
[7] the curve is reproduced from the standard without permission for academic pruposes.

Figure 2.17 - IEEE Standard C37.112-2018 for Over Current Relays



Hence, even though the answer for the tripping time calculated (22.33 s) agrees with the actual operating time with the associated tolerances, the method followed in the calculation does not comply with the reset characteristics in the industry standards. Nevertheless, the operation of the relay is recorded in the fault log of the relay as shown in Figure 2.18, which is consistent with information provided by BEN6000 at the Kotmale end for circuit 2.

Figure 2.18 - Fault log of SIEMENS 7SL87 Relay of Circuit 1 of Kotmale-Biyagama 220 kV Transmission Line at Kotmale Substation



Time stamp	Relative time	Fault number	Entry number	Functions structure	Name	Value	Quality
		(All)	(All)	(All)	(All)	(All)	(All)
03.12.2021 16:27:32.572 (3)		32		Fault log			
03.12.2021 11:27:14.612 (29)		31		Fault log			
03.12.2021 11:27:14.612	00:00:00:00.000		1	Recording:Fault recorder:Control	Fault number	31	good (process)
03.12.2021 11:27:14.612	00:00:00:00.000		2	Line 1:50N/51N OC-gnd-A1:Inverse-T 1	Pickup	on	good (process)
03.12.2021 11:27:14.627	00:00:00:00.015		3	Line 1:85-67N Dir. comp.:85-67N Dir.com	Pickup 3I0	phs C gnd dir. u...	good (process)
03.12.2021 11:27:14.917	00:00:00:00.305		4	Line 1:85-67N Dir. comp.:85-67N Dir.com	Pickup 3I0	off	good (process)
03.12.2021 11:27:36.937	00:00:00:22.325		5	Line 1:50N/51N OC-gnd-A1:Inverse-T 1	Operate	on	good (process)
03.12.2021 11:27:36.938	00:00:00:22.326		6	Circuit breaker 1:Circuit break.	Trip/open cmd. 3-pole	on	good (process)
03.12.2021 11:27:36.938	00:00:00:22.326		7	Circuit breaker 1:Circuit break.	Definitive trip	on	good (process)
03.12.2021 11:27:36.938	00:00:00:22.326		8	Circuit breaker 2:Circuit break.	Trip/open cmd. 3-pole	on	good (process)
03.12.2021 11:27:36.938	00:00:00:22.326		9	Circuit breaker 2:Circuit break.	Definitive trip	on	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		10	Circuit breaker 2:Circuit break.	Break.-current phs A	635 A	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		11	Circuit breaker 2:Circuit break.	Break.-current phs B	661 A	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		12	Circuit breaker 2:Circuit break.	Break.-current phs C	615 A	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		13	Circuit breaker 1:Circuit break.	Break.-current phs A	702 A	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		14	Circuit breaker 1:Circuit break.	Break.-current phs B	784 A	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		15	Circuit breaker 1:Circuit break.	Break.-current phs C	772 A	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		16	Circuit breaker 2:Circuit break.	Break. voltage phs A	127.658 kV	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		17	Circuit breaker 2:Circuit break.	Break. voltage phs B	126.259 kV	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		18	Circuit breaker 2:Circuit break.	Break. voltage phs C	126.087 kV	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		19	Circuit breaker 1:Circuit break.	Break. voltage phs A	127.658 kV	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		20	Circuit breaker 1:Circuit break.	Break. voltage phs B	126.259 kV	good (process)
03.12.2021 11:27:36.957	00:00:00:22.345		21	Circuit breaker 1:Circuit break.	Break. voltage phs C	126.087 kV	good (process)
03.12.2021 11:27:37.034	00:00:00:22.422		22	Line 1:50N/51N OC-gnd-A1:Inverse-T 1	Disk emulation running	on	good (process)

The Committee has determined that had the “Reset” of the relay of circuit 1 been configured to “Instantaneous” instead of “Disk Emulation”, the operation of the earth-fault protection “50N/51N OC-gnd-A1” upon the neutral current returning to 65 A would not have happened. In that case, circuit 1 would have survived, and the total power failure should have been avoided. The corresponding calculation is given below:

IEC normal inverse tripping time is calculated as;

$$t = 0.14\frac{TMS}{\left(\left(\frac{I}{I_{threhold}}\right)^{0.02} - 1\right)}$$

In this case $I_{threhold} = 80A, TMS = 0.38$.

Therefore, the tripping time with $I = 488\ A$ is

$$t = 0.14\frac{0.38}{\left(\left(\frac{488}{80}\right)^{0.02} - 1\right)} = 1.4446\ s$$

However, the current reduces to 65 A in 288 ms, which is less than 1.4446 s. Hence, if the relay “Reset” had been configured to “Instantaneous”, then the relay would not have operated as it did on December 03, 2021, thereby disconnecting the healthy circuit carrying the full-load current.

If the earth-fault protection “50N/51N OC-gnd-A1” of circuit 1 of Kotmale-Biyagama 220 kV transmission line did not operate after 22.33 s from the pickup, the power system would not have gone into a total collapse. This fact is evident from (a) the survival of circuit 1 for 22.33 s after phase B of circuit 2 of Kotmale-Biyagama 220 kV transmission line was completely isolated, and (b) the static load flow study conducted by the CEB in the presence of the Committee (Annex E).

The phase B of circuit 2 auto-reclosed from Biyagama end in 0.934 s from the circuit breaker opening. If not for the end fault operation, the Kotmale end of the phase B of circuit 2 would also have been closed at the same time. During the circuit breaker opening period, the initial neutral current seen by the circuit 1 would have been the same that appeared with the end fault operation. With the reset mode configured to “Disk Emulation”, there is a risk that earth fault protection of circuit 1 “50N/51N OC-gnd-A1” would have operated even without the operation of the end fault protection in circuit 2. Such a scenario would not have occurred if the reset mode had been configured to “Instantaneous”, because the auto-reclosure had operated in less time (0.934 s) than the associated tripping time (1.4446 s).

Hence, in this particular case, it is not the 80 A threshold setting that had caused circuit 1 to trip. It was the “Reset” configuration setting of “Disk Emulation” instead of “Instantaneous”, which has caused the tripping after 22.33 s. The CEB has failed to provide an explanation for choosing this setting only in the Kotmale end whereas the corresponding setting on the Biyagama end of the same circuit was set to “Instantaneous”.

The relay settings as recorded in the Kotmale substation and Biyagama GS are shown in Figure 2.19 and Figure 2.20 respectively.

Figure 2.19 - ***50N/51N OC-gnd-A1 Settings of SIEMENS 7SL87 in Circuit 1 of Kotmale-Biyagama 220 kV Transmission Line at Kotmale Substation***

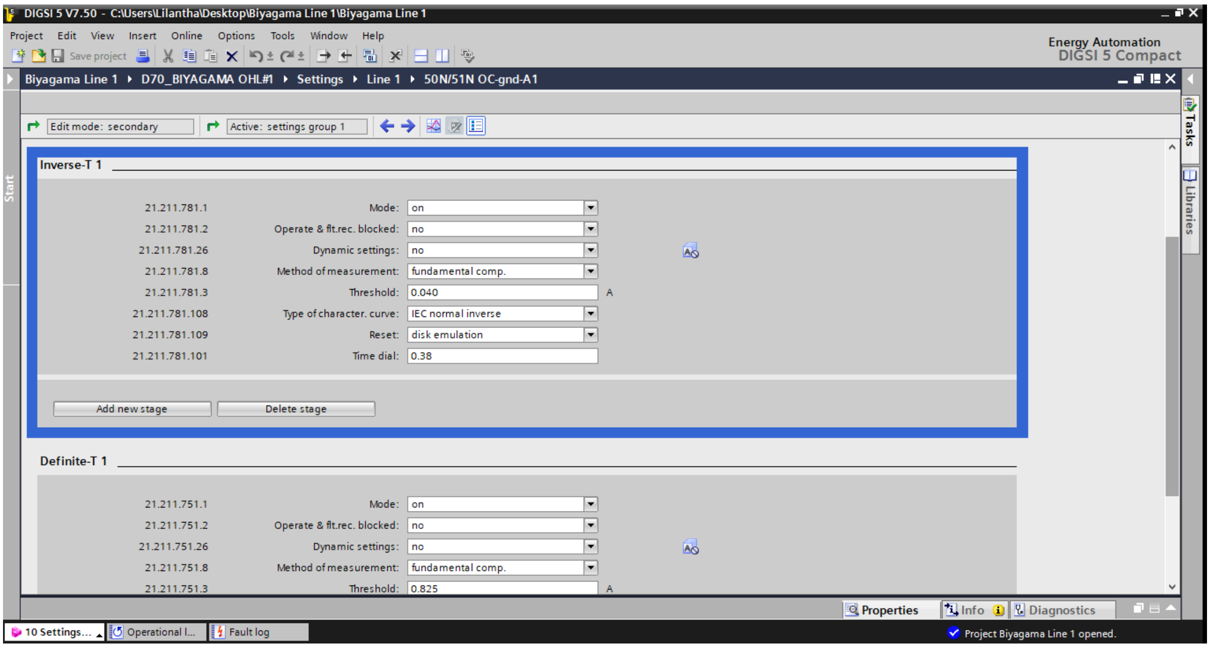


Figure 2.20 - ***50N/51N OC-gnd-A1 Settings of SIEMENS 7SL87 in Circuit 1 of Kotmale-Biyagama 220 kV Transmission Line at Biyagama Substation***

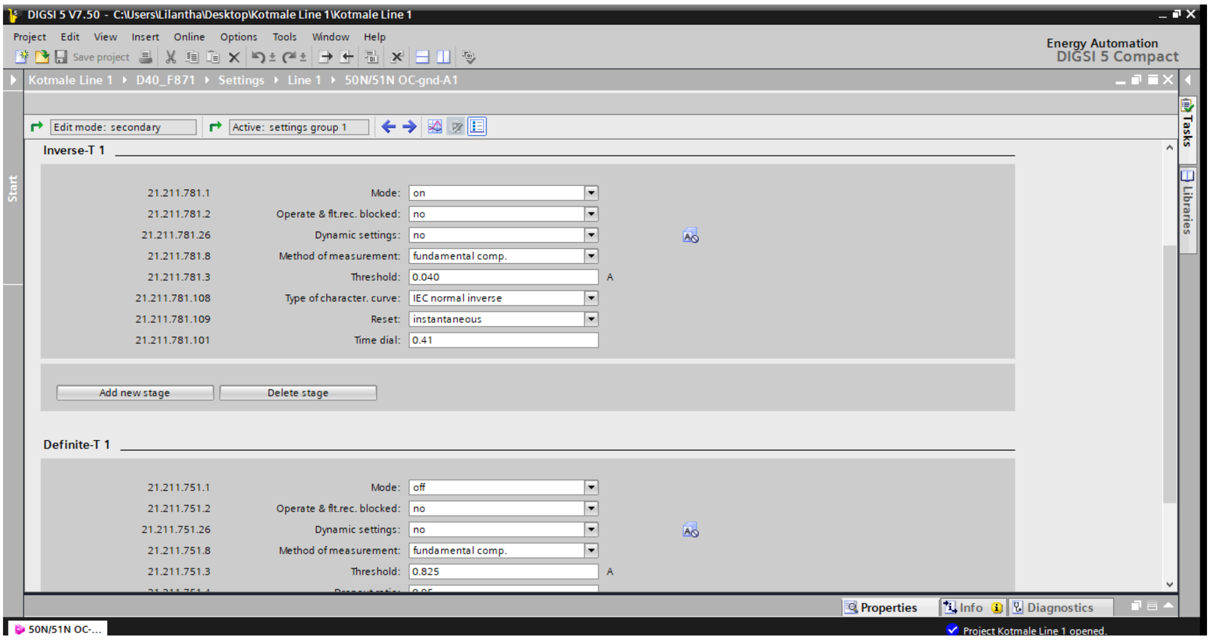


Figure 2.21 - Fault Trigger Signals on Circuit 1 of Kotmale- Biyagama 220 kV Transmission Line Obtained from SIEMENS 7SL87 relay at Kotmale Substation

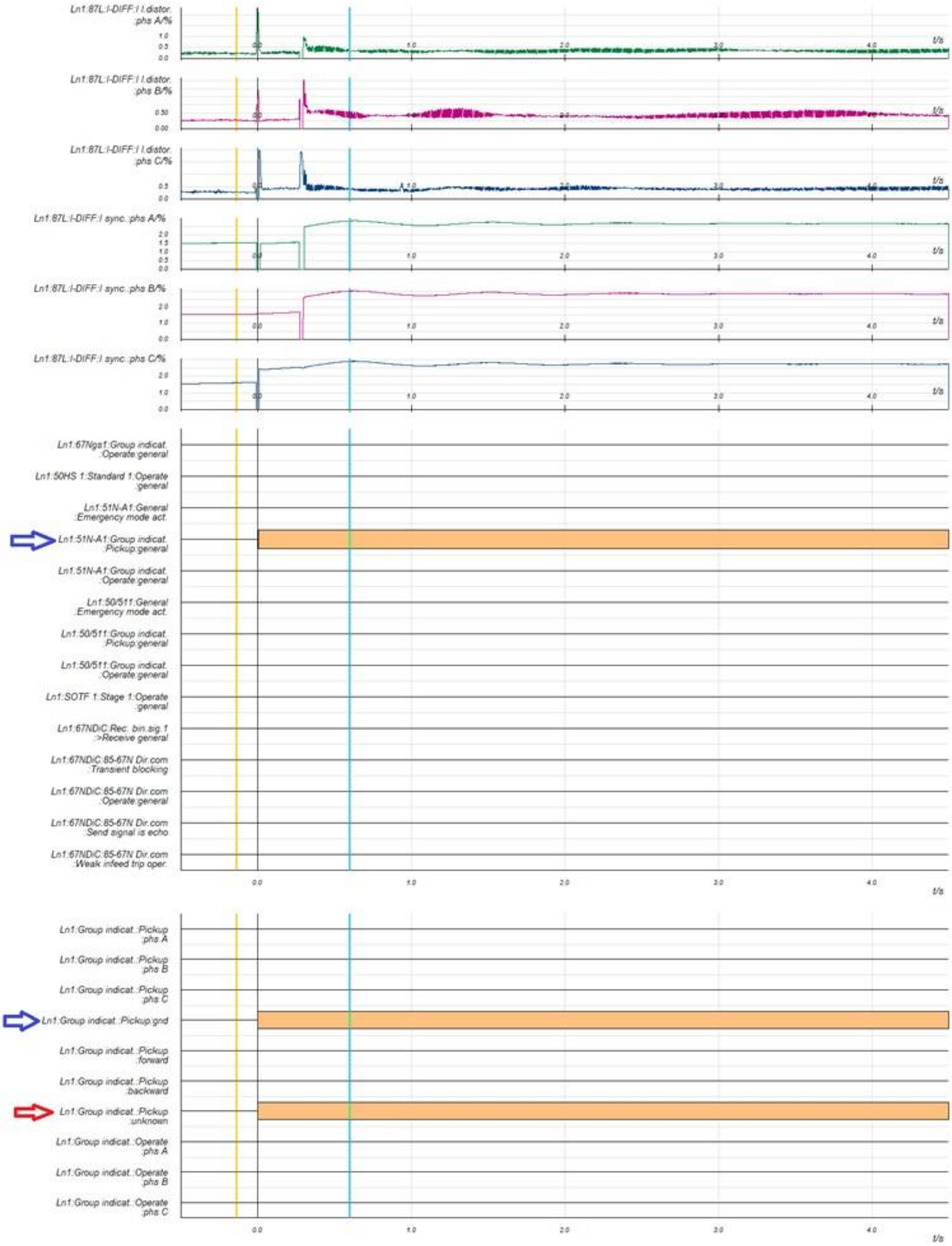
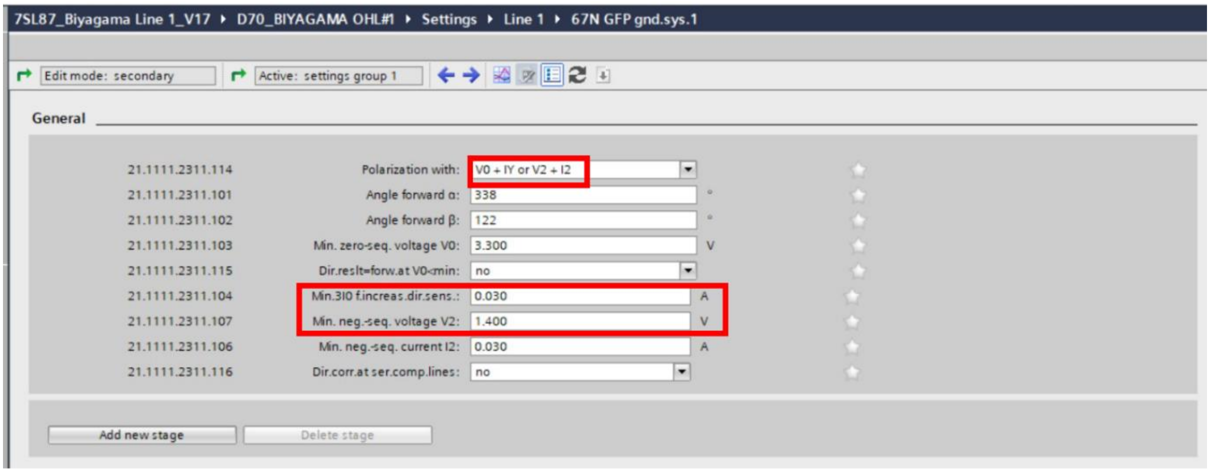


Figure 2.21 shows the fault trigger signals of the relay SIEMENS 7SL87 of circuit 1 of Kotmale-Biyagama 220 kV transmission line located at Kotmale substation. The neutral current is picked up by the earth-fault channel as seen towards the bottom in the waveform diagram as

"Ln1:51N-A1:Group indicat:Pickup:general" (marked in blue colour), "Ln1: Group indicat:Pickup:gnd" (marked in blue colour) as well as "Ln1: Group indicat:Pickup:unknown" (marked in red colour).

It is observed that "Ln1: Group Indicat: Pickup Unknown" signal has been detected due to one of the directional functions enabled in those relays that picked up the signal (also listed in the Fault Log in Figure 2.18), due to current margin but the determination of direction of the same current has failed. According to the event log generated by the relay at the same time, it can be seen in the log "Line 1:85-67N Dir. comp.85-67N Dir.com = Pickup 3I0 =phs C gnd dir. Unknown". Hence, it is confirmed that the directional earth-fault function has picked up but failed to determine the direction of the detected current. In the setting of the same function, it has been set "V0 +IY or V2 + I2" as the polarizing quantities for the directional decision. The same quantity is described as follows in the technical manual of the relay: "In the absence of neutral point measurement in the transmission line, the direction is determined based on the values of the magnitudes of the negative sequence voltage (V2) and current (I2) values". The relay settings of "85-67N Dir. Comp" are shown in Figure 2.22.

Figure 2.22 - Relay Settings of 85-67N Dir. Comp of Circuit 1 of Kotmale- Biyagama 220 kV Transmission Line Obtained from SIEMENS 7SL87 Relay at Kotmale Substation



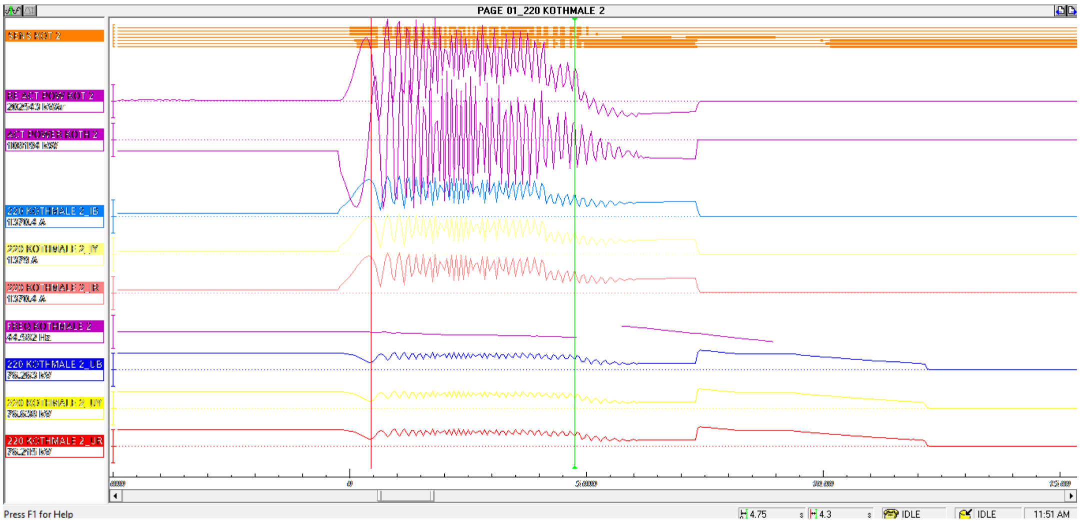
According to the relay settings, a negative sequence voltage of at least 1.4 V in the secondary (that is 2.8 kV in the primary with 2000:1 VT ratio) and negative-sequence current of at least 0.03 A in the secondary (that is 60 A in the primary with 2000:1 CT ratio) are required. According to the data of the DFR, although the negative-sequence current is higher than 60 A, the negative sequence voltage has never reached 2.8 kV. Hence, it is reasonable to deduce that the decision on the direction of the fault current flow in the relay will fail under the circumstances.

Failure in Circuit 2 of Kotmale-New Anuradhapura 220 kV Transmission Line

There are two 220 kV circuits of the 170 km long transmission line from Kotmale substation to New Anuradhapura GS. The CEB has stated in its report to the Committee that on December 03, 2021, circuit 1 of Kotmale-New Anuradhapura 220 kV transmission line had been switched off for scheduled project work. Hence, only circuit 2 was in operation on that day.

Figure 2.23 shows the frequency variation observed at New Anuradhapura GS, particularly in circuit 2 of Kotmale-New Anuradhapura 220 kV transmission line. It can be seen that the frequency there has decreased from 50 Hz to 44.5 Hz. Therefore, as far as circuit 2 of Kotmale-New Anuradhapura 220 kV transmission line was concerned, there had been a period of about 6 seconds during which the frequency at Kotmale end had been increasing from 50 Hz to 59.5 Hz and the frequency at New Anuradhapura end has been decreasing from 50 Hz to 44.5 Hz. Corresponding to the latter changes in the frequency, substantial fluctuation of currents and voltages, and hence of the active power and the reactive power in the circuit can be observed.

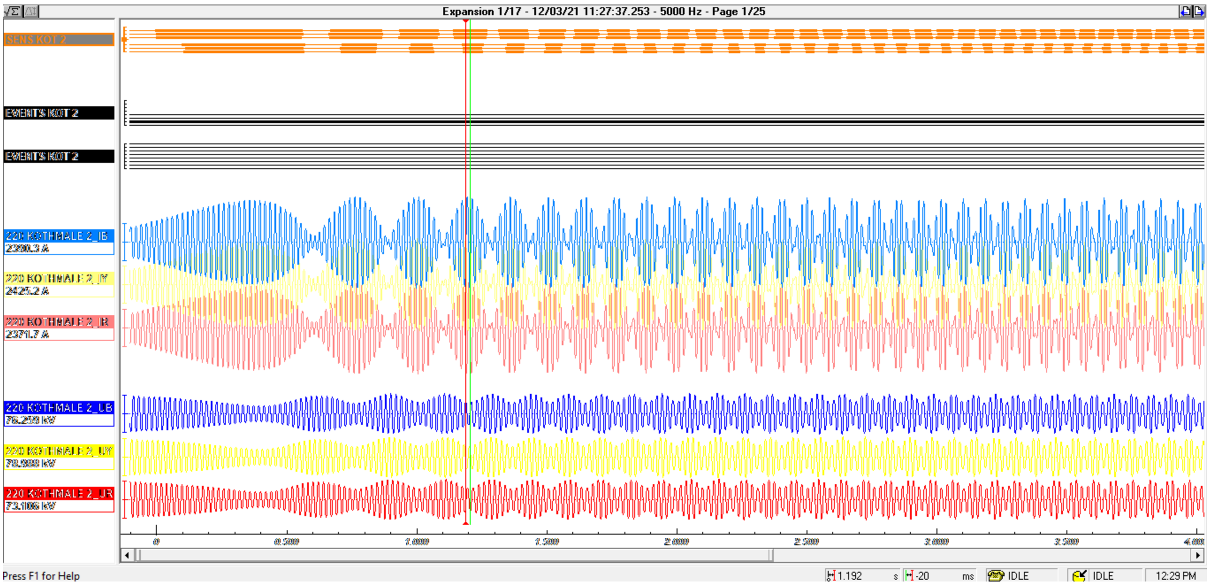
Figure 2.23 - Frequency, Currents, Voltages, Active Power and Reactive Power Variation of Circuit 2 of Kotmale-New Anuradhapura 220 kV Transmission Line



The waveforms in Figure 2.25 and Figure 2.23, which show the frequency, have been obtained using the slow DFR sampled at 20 Hz (in order to calculate the frequency, whose nominal value is 50 Hz, unless multilevel crossings are used, at least two complete cycles are needed to find the frequency using zero crossings reliably. Hence, it can be assumed that the DFR records obtained at 20 Hz sampling frequency provide reliable information). Figure 2.24 shows the voltage and current waveforms obtained by the fast DFR sampled at 5 kHz.

In Figure 2.24, it can be seen that voltage and current amplitudes oscillate so that the current varies in an envelope of 550 A to 2,400 A and the corresponding voltage fluctuation in an envelope of 129 kV to 75 kV. This 2,400 A and 75 kV combination crosses the overcurrent limit and the under-voltage limit of the circuit respectively, as seen in the DFR records. During this time, the overcurrent protection **Line 1:50/51 OC-3ph 1p 1:Inverse-T 1** has picked up 103 instances and another 20 instances with a gap of 4.56 s and circuit has been eventually tripped by the operation of the Zone 1 distance protection **Line 1:21 Distance prot. 1:Z 1** from New Anuradhapura GS.

Figure 2.24 - DFR record of Circuit 2 of Kotmale-New Anuradhapura 220 kV Transmission Line at New Anuradhapura GS



Responses of other elements of the Power System

Deputy General Manager (Generation Protection), in his report to the Committee, reveals the sequence of incidents as shown in Table 2.6, in which the time is manually synchronized with the DFR at Biyagama GS. The time values may be slightly different to those elsewhere in the report because the time synchronization was done manually.

Table 2.6 -Sequence of Incidents on Generation Substations and Power plants

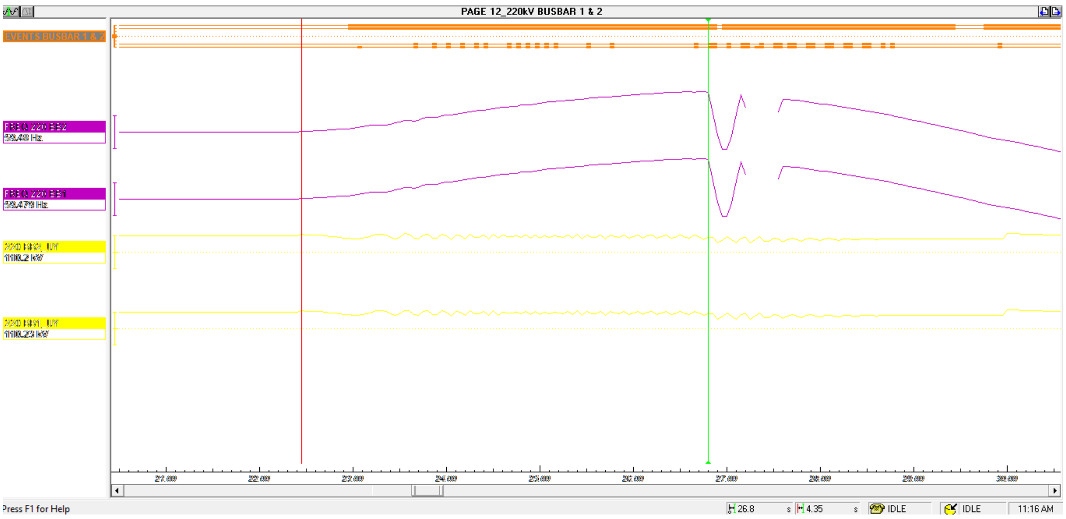
Event No.	Event	Time	DFR location	Reason
1	Kotmale-Biyagama circuit 2 phase B CB open from both ends	11:27:14.609	Kotmale SS	Differential protection operation
2	Kotmale-Biyagama circuit 2 phase R & Y Trip	11:27:14.885	Kotmale SS	End-Fault protection with CB lockout
3	Kotmale-Biyagama circuit 2 phase B CB close from Biyagama end	11:27:15.553	Kotmale SS	Auto reclosure operation
4	Kotmale-Biyagama circuit 1 trip at Kotmale end	11:27:37.005	Kotmale SS	Earth-Fault protection operation
5	Start of frequency increase at Kotmale end	11:27:37.005	Kotmale SS	Loss of loads via Kotmale-Biyagama circuits 1 and 2
6	Start of frequency decrease at Biyagama end	11:27:37.005	Kotmale SS	Loss of generation via Kotmale-Biyagama circuits 1 and 2
7	Victoria generator unit 1 trip	11:27:41.292	Protection relay	Over-frequency
8	Victoria generator unit 2 trip	11:27:41.294	Protection relay	Over-frequency
9	Lak Vijaya Power Plant (LVPP) unit 3 trip	11:27:41.331	LVPP	Under-frequency
10	LVPP bus coupler 2/3 trip	11:27:41.365	LVPP	Not recorded
11	LVPP-New Anuradhapura circuit 1 trip	11:27:41.365	LVPP	Current loss from LVPP

Event No.	Event	Time	DFR location	Reason
12	LVPP-New Anuradhapura circuit 1	11:27:41.365	Anuradhapura GS	
13	Kotmale generator unit 2 trip	11:27:41.381	Kotmale SS	Over-frequency
14	Kotmale generator unit 3 trip	11:27:41.381	Kotmale SS	Over-frequency
15	Kotmale generator unit 1 trip	11:27:41.399	Kotmale SS	Over-frequency
16	LVPP unit 1 trip	11:27:42.033	LVPP	
17	LVPP bus coupler 1/2 trip	11:27:42.068	LVPP	
18	LVPP – New Chilaw circuit 1 trip	11:27:42.068	LVPP	Current loss
19	Bus Bar 1,2 & 3 at LVPP & LVPP – ANU 1 & ANU 2	11:27:42.068	LVPP	Stator voltage loss
20	Kotmale – New Anuradhapura circuit 2 current zero	11:27:44.554	Kotmale SS	
21	Kotmale – New Anuradhapura circuit 2 trip	11:27:44.555	Anuradhapura GS	Distance protection operation
22	Victoria generator unit 3 trip	11:27:44.648	Protection relay	
23	Upper Kotmale hydropower station generator unit 1 trip	11:27:47.681	Protection relay	

DFR = Disturbance Fault Recorder, GS = Gird Substation, LVPP = Lak Vijaya Power Plant, SS = Substation,

Figure 2.25 shows the 220 kV busbar voltage and the frequency as recorded in the DFR at Kotmale substation. According to Figure 2.25, the frequency rises from 50 Hz to 59.5 Hz following the loss of circuits 2 and then circuit 1 of the Kotmale–Biyagama 220 kV transmission line.

Figure 2.25 - Variation of Frequency recorded at Kotmale Substation



Under-Frequency Load Shedding

Triggering from the tripping of circuit 2 of Kotmale-Biyagama 220 kV transmission line, and subsequently circuit 1 of Kotmale-Biyagama 220 kV transmission line and circuit 2 of Kotmale–New Anuradhapura 220 kV transmission line, the total generation lost by the remainder of the grid has been calculated at 652 MW. According to the NSCC, the total generation immediately before the failure had been 1,956 MW with spinning reserve of 155 MW (amounting to 7.9% of total generation, which is a reasonably good level). The loss of generation due to the failures is 33.3% of the total generation.

The NSCC records reveal that Under Frequency Load Shedding (UFLS) stages I, II, III, IV, V, V and df/dt have come into operation in various nodes in the National Grid. Details of respective feeders in each GS together with the operation time and the UFLS stages are given in the NSCC report to the Committee. The summary of the UFLS on the December 03, 2021 is given in Table 2.7.

Table 2.7 - Summary of Under-Frequency Load Shedding

UFLS stage	Shed load (MW)
I	105.6
II	123.8
III	122.0
IV	125.6
V	11.8
V or df/dt	38.9
df/dt	104.9
Total	632.6

MW = megawatt, UFLS = Under Frequency Load Shedding

As a percentage of the total generation, the total under-frequency loads shed is 32.3%. Hence, there was only 1% excess generation whose load could not have been shed, which is a good achievement.

2.3. Power Swing Scenario

The Control & Protection Branch of CEB in its preliminary reports 1 and 2 states that immediately after the tripping of circuits 1 and 2 of Kotmale-Biyagama 220 kV transmission line on December 03, 2021, power swings commenced and lasted for about 6 seconds and ended with the tripping of circuit 2 of Kotmale-New Anuradhapura 220 kV transmission line from the New Anuradhapura end with the operation of distance protection.

The power swing is attributed to the oscillations that had taken place between the two generating systems—one connected to the 220 kV network and the other to the 132 kV network. This phenomenon can be explained using the power-angle (P–δ) curves, where electrical power transferred between the two systems will be in accordance with the equation,

$$P = \left(\frac{V_S V_R}{X}\right) \sin\delta$$

where:

P = the power transmitted between the machines during the transient condition

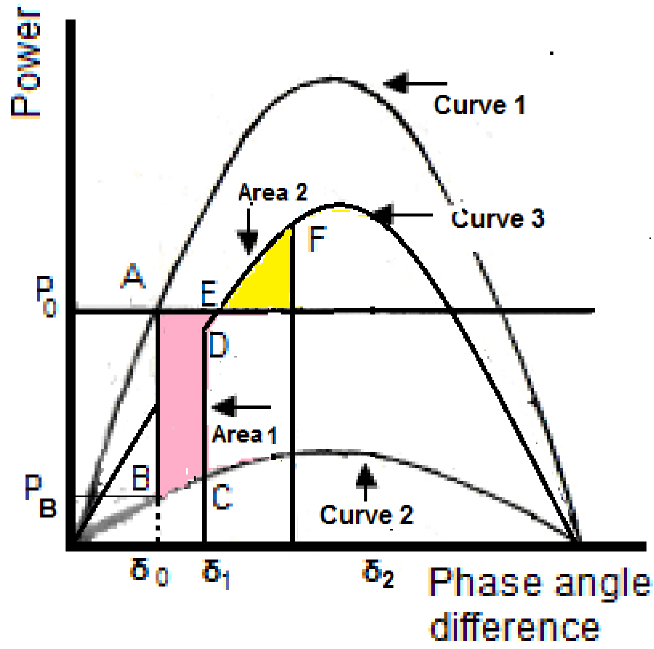
V_S= the voltage at the sending end or 220 kV side (LVPP end)

V_R= the voltage at the receiving end (group of generators connected to 132 kV system)

δ = the angle by which V_S leads V_R

Let us assume that the mechanical power input at LVPP be at P_0 on Figure 2.26. As the system had been in a stable state prior to the fault, mechanical input would have been equal to the electrical output of the generator.

Figure 2.26 - Power Angle Curve



During the fault, value of reactance X will be increased, hence the power transfer will be on a curve of lower amplitude compared to the curve 1. Let the new curve be the curve 2. Due to the lower power transfer of P_B, the operating point will now move to B from A. Power at the LVPP end will be a surplus denoted by ($P_0 - P_B$) and LVPP generators will speed up while the other group of generators will slow down. Hence, the angle δ increases along the curve 2 until the fault is cleared at point C, and the corresponding phase angle is δ_1.

From the moment the fault is cleared, curve 3 applies as the fault impedance is no longer present and the system impedance is higher compared to its original value. The new operating point will be D and still there will be a surplus of power at LVPP, and angle δ continues to increase along the curve 3. When the operating point passes point E, mechanical input from LVPP becomes less than the electrical output and LVPP machines will start to slow down while the other group will start to accelerate. However, LVPP machines will continue to speed up due to inertia, until they reach the point F where the two groups of machines will run at the same speed.

As there is a deficit at LVPP and a surplus in the other group, LVPP generators will now slow down and generators will oscillate around the point E and reach stability if the accelerating area (Area 1) is less than the decelerating area (Area 2).

Such oscillations cause large variations of voltages and currents, and depending on the response of protection relays and other power system controls, the system may remain stable and return to a new equilibrium state experiencing a stable power swing.

On the other hand, if the system cannot achieve transient stability, it will cause large separation of generator rotor angles, large swings of power flows, large fluctuations of voltages and currents, and eventually lead to a loss of synchronism between the two systems.

When that happens, the two systems will be in phase at one instant and in another instant will become 180^0 out of phase, the former giving rise to voltage maximums and current minimums and the latter creating voltage minimums and current maximums, as could be seen in the DFR records of circuit 2 of Kotmale-New Anuradhapura 220 kV transmission line in Figure 2.24. Hence, there has been a transient unstable power swing in circuit 2 of Kotmale-New Anuradhapura 220 kV transmission line, which had eventually led to the operation of distance protection and disconnection of the line.

2.4. Access to Relays

For circuits 1 and 2 of the Kotmale-Biyagama 220 kV transmission line, Main 1 (SIEMENS 7SL87) relay and Main 2 relay (Schneider Electric Easergy MiCOM P545/P546) have been provided, which duplicate the same primary protection functions (differential protection, distance protection, directional earth fault protection, etc.), and backup protection functions (overcurrent protection and earth fault protection, etc.), to ensure high reliability. As per the relay logs, except for the differential protection operation in phase B of circuit 2 of Kotmale-Biyagama 220 kV transmission line, there has not been any involvement of the Main 2 relays. In that case too, both Main 1 and Main 2 relays have operated in parallel.

In the original event data log of circuit 2 protection relay (Main 2) at the Biyagama end submitted by CEB (records up to March 2021), the Committee noted seven events labelled "User Logged Out on UI Level 1" on December 03, 2021 from 8:33:00.784 to 8:33.58.534 (over a period of nearly 1 minute), as reproduced in Figure 2.27.

Figure 2.27 - Part of the Main 2 Relay Event Log at Kotmale Substation on Kotmale-Biyagama 220 kV Transmission Line

Friday 03 December 2021 11:27:14.587 : Logic Inputs 1
Friday 03 December 2021 11:27:14.349 : Output Contacts1
Friday 03 December 2021 11:27:14.349 : IM64 Ch1 Output2 ON
Friday 03 December 2021 11:27:14.312 : Any Start ON
Friday 03 December 2021 11:27:14.312 : Started Phase N ON
Friday 03 December 2021 11:27:14.312 : IN>1 Start ON
Friday 03 December 2021 08:33:58.534 : User Logged Out On UI Level 1
Friday 03 December 2021 08:33:55.485 : User Logged Out On UI Level 1
Friday 03 December 2021 08:33:52.383 : User Logged Out On UI Level 1
Friday 03 December 2021 08:33:13.883 : User Logged Out On UI Level 1
Friday 03 December 2021 08:33:11.534 : User Logged Out On UI Level 1
Friday 03 December 2021 08:33:03.882 : User Logged Out On UI Level 1
Friday 03 December 2021 08:33:00.784 : User Logged Out On UI Level 1
Monday 29 November 2021 19:53:48.924 : TOC Active OFF
Monday 29 November 2021 19:53:48.752 : SOTF Active OFF
Monday 29 November 2021 19:53:48.549 : Logic Inputs 1
Monday 29 November 2021 19:53:48.530 : Logic Inputs 1
Monday 29 November 2021 19:53:48.425 : Pole Dead A OFF
Monday 29 November 2021 19:53:48.423 : Live Line ON
Monday 29 November 2021 19:53:48.420 : All Poles Dead OFF
Monday 29 November 2021 19:53:48.420 : Pole Dead C OFF
Monday 29 November 2021 19:53:48.420 : Pole Dead B OFF
Monday 29 November 2021 19:53:48.413 : Dead Line OFF
Monday 29 November 2021 19:53:48.253 : Logic Inputs 1

Easergy Studio

The Committee was surprised to learn that when the same Main 2 Relay records at Kotmale substation was accessed electronically using the Easergy Studio V9.3.0 on December 11, 2021, there were no records before 12:55:26.230 on December 03, 2021 for circuit 2 (reproduced in Figure 2.28) and no records before 10:15:23.951 on December 03, 2021 for circuit 1 (reproduced in Figure 2.29). This discovery was made just two days after receiving the records from the CEB as pdf files on the request of the Committee. The records downloaded from the relays were received in their respective file formats during the visit to Kotmale substation on December 11, 2021 and the explanation received on the missing records was that a possible overwriting may have taken place due to short internal memory storage capacity of the relay. However, CEB engineers have not shown us any statement in the manufacturer’s literature that confirmed this position. In addition, we also noted that the time zone of the clock used on these relays was GMT but not GMT+5:30 (applicable to Sri Lanka), which should have been corrected to ensure integrity of data recorded in different equipment.

Figure 2.28 - Main 2 Relay Records taken Electronically at Kotmale Substation on Circuit 2 of Kotmale-Biyagama 220 kV Transmission Line

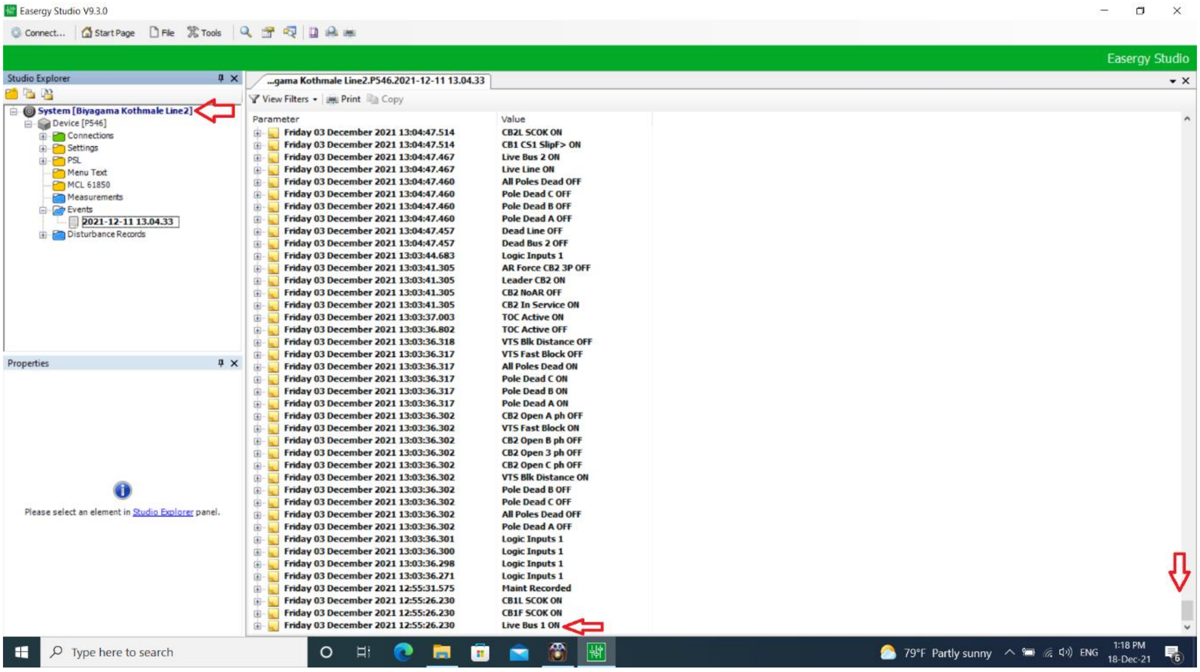
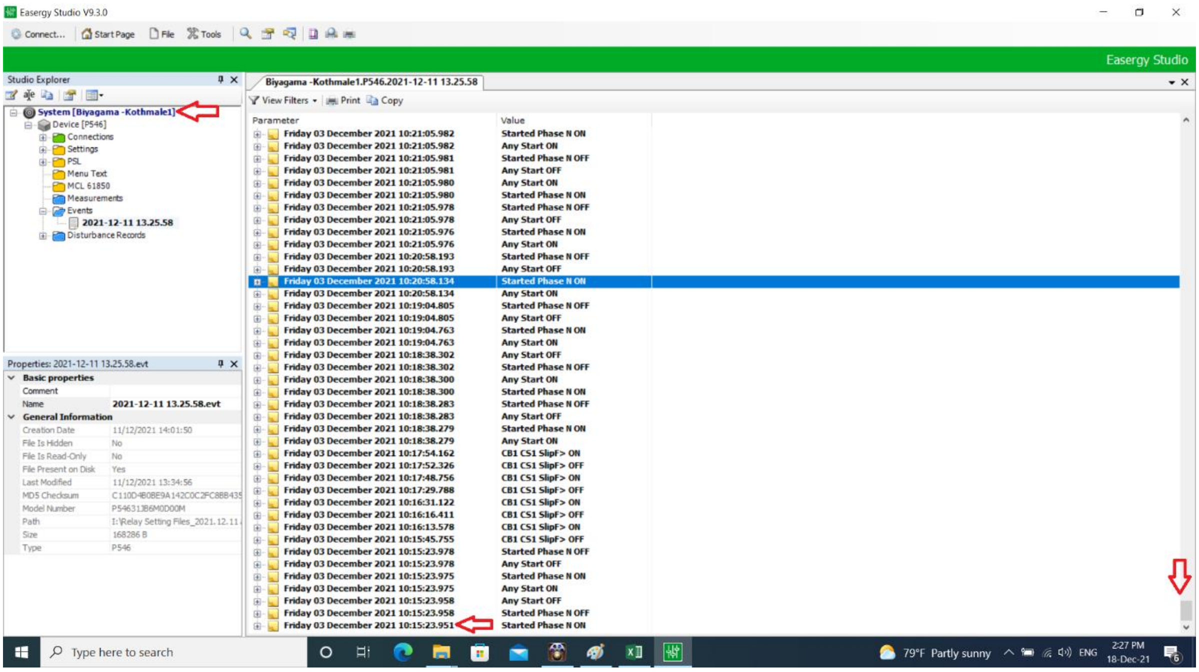


Figure 2.29 - Main 2 Relay Records taken Electronically at Kotmale Substation on Circuit 1 of Kotmale-Biyagama 220 kV Transmission Line



The set of privileges given to each access level as described in the Schneider Electric Easergy MiCOM P546 Technical Manual is reproduced in Figure 2.30. The Level 1 users have the permission to **Clear Event Records** and **Clear Fault Records**. It is pertinent to note that the data logs referred to earlier (Figure 2.27) indicate logout by a Level 1 user on December 03, 2021 on seven occasions. This position validates the Committee's assertion that an investigation of the possibility of any Level 1 users clearing event records and fault records is warranted.

Figure 2.30 - Privileges of each Access Level Extracted from the Technical Manual of the MiCOM P546

Access level	Operations enabled
Level 0 No password required	Read access to all settings, alarms, event records and fault records
Level 1 Password 1 or 2 required	As level 0 plus: Control commands, e.g. Circuit breaker open/close. Reset of fault and alarm conditions. Reset LEDs. Clearing of event and fault records.
Level 2 Password 2 required	As level 1 plus: All other settings

As these observations raise uncertainties whether the records have been altered, the Committee requested explanations from the CEB as well as the OEM. Accordingly, the CEB has sent the concerns as reproduced in Figure 2.31 and the responses received from the OEM forwarded to the Committee are shown in Figure 2.32. As can be seen in Figure 2.31 and Figure 2.32, the most critical concerns, i.e., 1, 2 and 7, have not been answered by the OEM. Hence, the Committee is unable to conclude on the access to the Main 2 relays.

Figure 2.31 - Concerns Raised at the OEM to Main 2 Relays

We would like to clarify following,

1. Even though "**User Logged Out On UI Level 1**" is recorded in the relay we couldn't find the "User Logged In" event. Could you clarify the reason?
2. As per clause 2.1.8 of the manual *"The Security Logs needs to store logs from each item of equipment. These logs are generated by the system, and cannot be edited by the user".* Is their system generated event to identify User Logged In events similar to "**User Logged Out On UI Level 1**"?
3. Can anyone delete "User Logged In event", if any?
4. Is it possible to delete Event log completely, ex. all the 1024 events?
5. Is it possible to delete part of the event log? Ex. selected events.
6. We identified the self-generated "Evt Unique Id" in each event. Can we use that "Evt Unique Id" numbers of the events to prove that in-between events were not deleted?
7. As per the available information during this time (Friday 03 December 2021 08:33) relay LEDs were cleared by using the "AAAA" password. Could you clarify why there are seven events within one minute?

Figure 2.32 - Responses to the Concerns in Figure 2.31 from OEM of Main 2 Relays

SE

Schneider Electric Customer Care <customercare.in@schneider-electric.com>

To Manoj WEERASEKARA

Cc GOUTHAM G; INDIKA ADIKARI; Akash Das; Bhaskar Sahu

Click here to download pictures. To help protect your privacy, Outlook prevented automatic download of some pictures in this message.

Dear Sir,

Greetings from Schneider Electric Customer care!!!!

Please below reply, We will update you for the other queries soon.

3. Can anyone delete "User Logged In event", if any?
No, not possible.

4. Is it possible to delete Event log completely, ex. all the 1024 events?
Yes, possible.
Removing the Battery will erase the disturbance records and events when the device will be powered Off.
To delete the disturbance records and events, removal of the battery and power Off the Micom relay during one minute.
Please note that removing the battery will not erase the settings.

5. Is it possible to delete part of the event log? Ex. selected events.
No, not possible.

6. We identified the self-generated "Evt Unique Id" in each event. Can we use that "Evt Unique Id" numbers of the events to prove that in-between events were not deleted?

Each event is identified with a unique number that is incremented for each new event so that it is possible to detect missing events as there will be a 'gap' in the sequence of unique identifiers.

For all further communication regarding this case, please reply directly to this email
Regards,
Bijay Kumar Sahoo

Further to the access to Main 2 relays, Main 1 relay access has been inquired by the Committee from the OEM through the following questionnaire on January 26, 2022, subsequent to several verbal communications through the Ministry of Power. The responses are given next to each query.

<u>Quote</u>

1. Whether the settings of the SIEMENS 7SL87 Transmission Line protection relays in the Kotmale-Biyagama 220 kV transmission line 01 & 02 located in Kotmale Power Station and the Biyagama Grid Substation have been changed between 1st November 2021 to 15th January 2022. The corresponding changes, if the settings have been changed.

   RESPONSE: **Any changes in settings are recorded in the relay and the same can be retrieved from the relay physically.**

2. Whether the settings of the SIEMENS 7SS52 Busbar protection relays in the Busbar 01 & Busbar 02 correcting to Kotmale-Biyagama 220 kV transmission line 01 & 02 have been changed between 1st November 2021 to 15th January 2022. The corresponding changes, if the settings have been changed.

   RESPONSE: **Any changes in settings are recorded in the relay and the same can be retrieved from the relay physically.**

3. Have any one of the above 6 relays mentioned in 1. and 2., been accessed either a) directly via the panel, b) remotely via a communication network or c) most importantly, indirectly through another relay, not necessarily a SIEMENS relay.

   RESPONSE:

a) **directly via the panel - This is recorded in the relay. The record can be retrieved from the relay physically.**

b) **remotely via a communication network - This is recorded in the relay. The record can be retrieved from the relay physically.**

c) **most importantly, indirectly through another relay, not necessarily a SIEMENS relay - It is not possible to change settings through another relay.**

4. If any of the answers to the 3 above is YES, then what actions have taken place in those relays after accessing them? Ex. Download data, edit records, delete records, change settings, delete settings, etc.

   RESPONSE: **We are not in a position to access any third-party data. However, this detail can be retrieved from the relay physically by an authorised person.**

   Download data - This data is not recorded

   Edit records - This data is not recorded

   Delete records - This data is not recorded

   Change settings - This data is not recorded

   Delete settings, etc. - This data is not recorded

5. Any other relevant information that the OEM thinks will be useful for the investigation.

   RESPONSE: **None.**

Unquote

Hence, the Committee concludes that the settings of the Main 1 relay of circuit 1 of Kotmale-Biyagama 220 kV transmission line, which tripped after 22.33 s from detecting an earth fault, were the original settings that prevailed well before the December 03, 2021 incident.

3. RESTORATION AFTER THE FAILURE

3.1. Introduction

Following the total system failure triggered in circuit 2 of Kotmale – Biyagama 220 kV transmission line, the system restoration has been started from Mahaweli system, Laxapana system, Samanala system and Colombo City system simultaneously.

Mahaweli system and Laxapana system have been synchronized from Kolonnawa GS. Mahaweli system and Colombo City system have been synchronized from Kelanitissa GS. The above system and southern system have been synchronized thereafter from Mathugama GS. According to the NSCC, the transmission network has been restored by 16:47 which is 5 hours and 20 minutes after the failure. The Committee observes nearly one hour gain in restoring the transmission network compared to the total system failure on the August 17, 2020, as a result of simulations training and trial runs carried out by the CEB. The first GS to be energized was Thulhiriya at 12:33 and the last GS to be energized was New Polpitiya at 17:54.

3.2. CEB Restoration Plan and Operating Policy

Mahaweli Complex: Mahaweli system restoration has commenced from Kotmale Unit 1, Victoria Unit 1 and the Upper Kotmale Unit 1 simultaneously as 3 separate islands at 13:05 hrs,12:27 hrs and 12:53 hrs respectively. The initial attempt of restoring from circuits 1 and 2 of Kotmale-Biyagama 220 kV transmission line have failed, and the process has got delayed because of the inability operating engineers at Kotmale PS to close the CBs at Kotmale substation. It was reported that for nearly 40 minutes, the CB was inoperable until the fault indication had to be reset manually at the Kotmale substation. Once this problem was solved and circuit 2 of Kotmale-Biyagama 220 kV transmission line was energized, the generators at Kotmale PS have been deployed to energize Biyagama GS and Kotugoda GS. The generators at Victoria PS have been deployed to energize Randenigala GS and Mahiyanganaya GS. The generators at Upper Kotmale have been deployed to energize New Anuradhapura GS and Kiribathkumbura GS. Further, Upper Kotmale has been deployed to energize 220 kV GS at LVPP via Kotmale and New Anuradhapura at 15:36 hrs.

Laxapana Complex: Initial restoration has started from the New Laxapana Unit 1 at 12:37 hrs but has failed with the tripping of the generator at 13:12 hrs. Thereafter, Laxapana system restoration has restarted simultaneously from New Laxapana Unit 1, WPS unit 1 and Polpitiya Unit 1 machines energizing Athurugiriya GS and Kolonnawa GS at 13:32 hrs,15:03 hrs respectively.

Samanalawewa PS: Samanalawewa system restoration has commenced simultaneously from Samanalawewa Unit 2 and Kukule Ganga Unit 2 as separate islands at 12:14 hrs. and 13:04 hrs. respectively. Initial five attempts from Samanalawewa generators have failed due to delayed exit from the failed automatic line charge mode at to manual line charge contributing to a significant delay in the process. For the 6th attempt, the grid synchronization of Samanalawewa Unit 1 has been successful at 14:49 hrs., which enabled energizing New Galle GS. Once Embilipitiya GS and Matara GS were also energized, those two substations had tripped at 16:11 hrs. as a result of the tripping of the Samanalawewa Unit 1. Thereafter, the entire southern system has been restored through Laxapana side by 16:30 hrs.

Colombo City: Colombo system restoration has started from Kelanitissa PS after starting GT-04 and GT-02 at 12:31 hrs and 14:15 hrs. respectively. Priority supply of Colombo City had been restored initially through Substation-J and Substation-H at 12:33 hrs. and 13:18 hrs. respectively.

3.3. Reasons for Delays in Restoration

The transmission network has been restored in 5 hours and 20 minutes from the triggering of the system failure. Several problems have contributed to the delays in the restoration. Table 3.1 lists the main contributors to the delay together with the identified reasons/explanations.

Table 3.1 - Main contributors to delayed restoration

NO	STATION	EQUIPMENT	Reason/Explanation
1	Kotmale PS	Kotmale Biyagama 220 kV Circuit 1	Pressure Relief Valve (PRV) operation in CB530 phase Y & therefore could not be closed until 14:16 hrs. However, it was later found no conditions have been satisfied to operate the PRV. Testing the PRV operation has delayed the restoration by 2 hours.
2	Kotmale PS	Kotmale Biyagama 220 kV Circuit 2	CB630 receiving trip signal from the protection panel. This tripping signal reset from the relay panel enabled closing the CB 630 at 13:04 hrs. The tripping signal has not been indicated in any of the panels in the control room, but only in the relay panel, which delayed the process by 50 minutes.
3	Embilipitiya	Samanalawewa Circuit 1	VT failure at 16:11 hrs since energizing at 14:49hrs.
4	Kelanitissa PS	Sapugaskanda Circuit 1	Unable to turn ON. No reason found.
5	Colombo Sub L GS	Kelanitissa underground cable	Unable to turn ON. No reason found.
6	New Laxapana PS	Generator 02	Generator differential protection operation since the initiation of the total system failure. This may be due to generator transformer over fluxing during the system frequency reduction during the total failure.
7	Samanalawewa PS	Generator 01	Delayed exit from the failed automatic line charge mode at 0.2 pu voltage to manual line charge at 0.8 pu voltage.
8	Samanalawewa PS	Generator 02	Delayed exit from the failed automatic line charge mode at 0.2 pu voltage to manual line charge at 0.8 pu voltage.
9	New Anuradhapura GS	48 V DC communication system	Inability to communicate through the hotline communication system

DC = Direct Current, GS = Grid Substation, kV = kilovolt, PRV = Pressure Release Valve, PS = Power Station, pu = per unit, V = volts, VT = Voltage Transformer

3.4. Remedial Actions Recommended

The nine cases which we believe have contributed to the delays in system restoration need to be studied in depth with a view to identifying the root causes, and rectified immediately. As reported by CEB, corrective action has been taken with respect to the cases 1 and 2 during the restoration process because it would have been hard to restore the system without the Kotmale-Biyagama 220 kV transmission line.

The committee notes that there has been no single reason for the operation of the Pressure Release Valve (PRV) in case 1, because it was eventually possible to close CB 530 after checking all essential steps but with no corrective action whatsoever. Hence, the PRV operation has only delayed the restoration by approximately 2 hours. Therefore, further investigation is recommended to examine whether the PRV operation was the result of a deliberate action.

In case 2 also, it is hard to believe the receipt of tripping signals not indicated in any of the panels in the control room, but only appearing in the relay panel at the GS, which is one floor down. If the problem was with the master RESET switch, then it should persist even now, and the maintenance engineers should be able to troubleshoot easily. Again, an investigation is recommended to determine whether this issue resulted from some planned action to delay the restoration of the supply.

Since the reasons for not being able to turn ON in cases 4 and 5 are not clear, it is recommended to investigate further and find the root cause.

In case 6, there should have been a persisting fault or a mal-operation of the differential protection relay as to why the Unit 2 could not be connected. It is recommended to investigate and find the exact reason in order to avoid it repeating in the future.

In cases 7 and 8, a thorough investigation is recommended to find the reason and any persisting hardware fault for the delayed exit from the failed automatic line charge mode to manual line charge mode in the embedded protection system, as this is a serious threat to the availability of the units to the grid. The investigations should also focus on the possibility of negligence on the part of operating staff that may have prevented the connection of Samanalawewa generators sooner.

It is recommended to investigate case 9 to ascertain whether the occurrence of this fault was due to a technical error, negligence or any other reason.

4. Lak Vijaya Power Plant

The Lak Vijaya Power Plant (LVPP) is the largest power station in Sri Lanka, with 3 generating units, each of gross generation capacity of 300 MW. Unit 1 was commissioned in 2011 and units 2 and 3 were commissioned in 2014. Coal is the primary fuel, while diesel is used during start and stop procedures. Coal is imported from several countries including Indonesia, and is procured on competitive bidding. CEB reported[8] that in 2020, LVPP provided 5,754 GWh (net) to the grid, an increase of 7.3% compared to the previous year. In 2020, LVPP provided 36% of net electricity generated and supplied to the grid, the largest share from a single power plant.

A power system disturbance or a fault within or outside LVPP may lead to the tripping of a generating unit or the transmission interconnection to the grid. Such tripping action can be triggered by the operation of,

(a) rate of change of frequency (df/dt) protection (ROCOF), low forward power protection, or manual opening of generator circuit breaker (GCB)
(b) any other protection system

Fast Cut Back: If the tripping is triggered by protection or actions listed in (a) above, the generating units control system has been configured to undergo a Fast Cut Back (FCB) procedure and switch over to operate on house load. This procedure has been established after the experience with the blackouts of 2015 and 2016. House load means the power requirements to operate its own support services and equipment, also known as auxiliaries, such as pumps, fans, and coal mills. An FCB event provides the opportunity (with certain limitations) to reconnect the generating unit separated from the grid and deliver power to the grid without requiring the generator to be shutdown. However, this mode of operation (on house load) has several major concerns: (i) the generating unit operates in an unstable regime with a load of about 20 MW, with boiler drum water level dropping to alarming levels, (ii) essential auxiliaries (bus A) do not include all cooling water pumps, causing the process steam cycle to be further unstable, (iii) the manufacturer does not recommend this mode of operation, since it causes undue stresses and leads to reduced lifetime of the power plant, especially the turbine.

Subsequently, the cooling effect drops and leads to increased back pressure on the low-pressure (LP) turbine. This back pressure may deflect and damage the LP turbine blades. To protect the LP turbine, the lead diaphragm, operating as one-off safety valve, ruptures to release the pressure. This rupture is destructive. Replacement of the ruptured diaphragm requires cooling down period of about one day, before any work begins. Furthermore, filling up the boiler drum requires it to be allowed to naturally cool down, to avoid large temperature gradients when water is filled up, and this process requires about 2 days. Therefore, even if FCB is successful but if the grid does not return within (typically) 30 minutes, the generating unit is required to move to an *uncontrolled complete shutdown*.

[8] Ceylon Electricity Board. *Statisitical Digest 2020*. 2021. Colombo

Complete Shutdown: If the outage is triggered by protection or actions other than those listed in (a) above, the generating unit controls are presently configured to move to shut down. Since auxiliary power is not available, this will be an *uncontrolled complete shutdown*.

If the power system disturbance causes the grid interconnection of LVPP to be lost (by opening of the main 220 kV breakers) such as during a total power outage, sustaining the generating unit on house load or moving the unit to shutdown is a challenge. The reason is that the power supply to auxiliaries is either unstable (during operation on household) or not available. Without power for critical auxiliaries, a safe shutdown of a generating unit is not possible.

Therefore, a unit FCB followed by a long duration of unstable operation (if the grid supply is not restored) or a unit that immediately moves to shut down can be put back on service only after several days.

4.1. Time to Restore, Previous Records and Damages

After a shutdown event (after FCB or without FCB), even if the grid supply is restored a few hours later, generating units of LVPP cannot be started immediately without rectifying the damages. It will take around 36 hours to replace the damaged LP turbine diaphragms and the cooling of boiler drum metal (to 210°C) will take about 3-4 days. Eventually, there will be 3–4-day delay in restoration of LVPP units even after the grid is back. The absence of 3×300 MW power to the system over 3-4 days causes significant financial loss to CEB, forcing CEB to dispatch oil-fired thermal generation at a significantly higher cost. Table 4.1 shows the duration to restart the first unit after replacement of LP turbine diaphragms and the estimated financial losses. The indicated cumulative loss for the seven incidents listed is estimated to be Rs 5,351 million. If the delay in restoration causes load shedding too, there will be further economic losses.

Table 4.1 - Failures of LVPP and Estimated Financial Losses

	Date of total power outage	Affected Units	Outage duration up to starting one unit (days)	Estimated energy lost (GWh)	Annual average fuel cost of LVPP (Rs/kWh)	Fuel cost of CEB's cheapest oil power plant (Rs/kWh)	Estimated minimum financial loss (Rs million)
1	8th August 2012	Unit 1 (Units 2 and 3 were still under construction	18.70	121.18	7.92	13.26	647.1
2	27th September 2015	Unit 3 (units 1 and 2 were not in operation at the time)	8.29	53.72	5.23	17.43	655.4
3	25th February 2016	Unit 1,2 and 3	3.18	61.82	4.73	17.50	789.4
4	13th March 2016	Unit 1,2 and 3	3.62	70.37	4.73	17.50	898.7

	Date of total power outage	Affected Units	Outage duration up to starting one unit (days)	Estimated energy lost (GWh)	Annual average fuel cost of LVPP (Rs/kWh)	Fuel cost of CEB's cheapest oil power plant (Rs/kWh)	Estimated minimum financial loss (Rs million)
5	15th October 2016	Unit 1,2 and 3	3.62	70.37	4.73	17.50	898.7
6	17th August 2020	Unit 1,2 and 3	3.87	75.23	6.78	17.26	788.4
7	3rd December 2021	Unit 1 and 3 (Unit 2 was not in operation at the time)	4.00	51.84	10.00	23.00	673.9
Total							5,351.6

GWh = gigawatt-hour, kWh = kilowatt-hour, LVPP = Lak Vijaya Power Plant, Rs = Sri Lankan Rupees
Source: CEB

Note: Estimated energy lost and minimum financial loss, are conservative estimates; data source for fuel costs are the respective statistical digests of CEB.

4.2. Auxiliary Power Requirements

When a generating unit at LVPP operates at full output (300 MW), total auxiliaries per unit amount to about 24.5 MW, organized into two busbars:

Auxiliary bus A: Installed capacity of equipment: 14.9 MW, Actual load: 13.2 MW

Auxiliary bus B: Installed capacity of equipment: 14.7 MW, Actual load: 11.3 MW

The following loads on 6 kV bus are essential loads in each unit for maintaining the minimum feed water circulation. These loads require to be powered through a reliable auxiliary generation scheme.

(i) 5 MW feed water pump operating on 6 kV
(ii) 2 MW cooling water pumps operating on 6 kV
(iii) 1.1 MW extraction pumps operation on 6 kV
(iv) 400 kW closed cycle cooling water pump operating on 6 kV
(v) 250 kW open cycle cooling water pump operating on 6 kV
(vi) 100 kW × 2 nos. vacuum pumps operating on 400 V
(vii) Other essential auxiliary loads connected to 400 V

The total capacity of essential loads is around 8 MW per unit and even a momentary interruption of power supply to these essential loads will be critical for the well-being of the unit.

4.3. CEB Proposals to Establish Auxiliary Power

CEB presented a list of 11 options to resolve the issue of auxiliary power (see Annex F).

Ten options out of 11 options are based on designs that require continuous operation of auxiliary generators, which is not economical and infeasible from the control point of view. The preferred option was stated to be option 11: rotary Uninterrupted Power Supply (UPS) along with a diesel power plant.

Since this solution needs to be applied at medium voltage network of LVPP where there can be higher system disturbances, rotary type UPS have been recommended by CEB's technical committee. It can be used to supply both active and reactive power requirements of LVPP auxiliary loads.

4.4. Trial Run to Obtain Auxiliary Power from Upper Kotmale

CEB has conducted trials on the possibility of securing the Upper Kotmale-Kotmale-New Anuradhapura-LVPP transmission route to transfer power from Upper Kotmale power station to LVPP in short duration, in the event of a grid failure and when the LVPP units are serving the house load after a FCB operation.

Although the restoration process was successful, the trial has taken 1 hour and 38 minutes to restore the LVPP followed by a total system failure. Therefore, CEB reported to the committee that securing power from Upper Kotmale power station to LVPP is not suitable, given that LVPP units cannot be held in the house load mode for such a long period.

4.5. Recommendations

Loss of LVPP for at least 3 days is a repeated occurrence after a total power failure. The estimated financial loss, if oil-fired generating capacity is available, is at least Rs 200 million per day for all three units. If oil-fired generation is not available, there will be larger economic losses owing to several days of load shedding. CEB requires to urgently reach a conclusion on the correct strategy and solution to resolve the issue in this 8-year-old power plant, which has several decades of service ahead.

The committee recommends CEB to consider the following:

(i) procuring a control system to assist in managing the drum water level during FCB mode operation following a system disturbance,
(ii) installation of a turbine-driven steam-based feed pump, and
(iii) procuring a facility to provide auxiliary power to achieve a safe shutdown.

5. IMPLEMENTATION OF RECOMMENDATIONS BY PREVIOUS COMMITTEES ON POWER FAILURES

Recommendations of committees that investigated five total system failures/outages since 2015, are listed below.

Recommendations have been numbered continuously across the failures and outages, for the convenience of referencing during discussions and follow-up.

On the request of the committee, the CEB completed columns II and III. The present committee recommendations based on the observations are given in Section 7 of this report. A report on the failure in March 2016 is not available.

5.1. Power System Failure on 27th September 2015

I	II	III
Recommendation	**Status of implementation as of 31 Jan 2022 (provide the precise status of each subsection)**	**Timeline to implement any remaining actions (State the planned action, target date and person responsible)**
1. Economic dispatch forecast and daily reports		
1.1 Economic Dispatch Plan Forecast is a vital plan that guarantees fair play, ensures transparency and maximize efficiency. Hence, suitable provisions shall be included in the relevant circulars and immediately implemented, to streamline such procedures.	1.1 Completed	
1.2 Immediate action should be taken to ensure that var loads are shared by all the generators in a fair and a pragmatic manner.	1.2 Remedial actions taken (Reactive power sharing)	
1.3 Data on reactive power shall be included in the SCC summaries and reports.	1.3 Already implemented	
1.4 PUCSL should play its role as the regulator to ensure that generation dispatch is most fair and done at the least cost.	1.4 Daily data including day ahead forecast is directly sent to PUCSL by SCC.	
2. Dynamic devices for reactive power compensation		Pannipitiya – May 2022 Biyagama – December 2022
2.1 CEB plans to install SVCs at Galle and Pannipitiya GSs, it is a timely proposal. These are high-cost devices, and type, location and capacity must have been decided by the CEB after careful study.	2.1 100 MVAR Capacitor Bank (MSCDN) at Pannipitiya & 100MVAR Static Synchronous Compensator (STATCOM) at Biyagama under construction. These installations are resulting from the Long-Term Transmission Plan	
2.2 PUCSL as the regulator is duty bound to study such reports in detail before allowing the Transmission Licensee to recover the relevant costs from consumers.	2.2----	
2.3 CEB shall take appropriate action to ensure that reactive power compensation devices that are already in the system, are in proper working order.	2.3 This is being attended to as per available resources	
3. Reactive power management		
3.1 CEB/PUCSL shall explore the possibility of finding suitable solutions to the reactive power problem, by way of electricity tariffs, possibly	3.1 100MVAr Reactor at New Anuradhapura GSS-and 50MAr Reactor at Mannar GSS is already	

I	II	III
Recommendation	**Status of implementation as of 31 Jan 2022 (provide the <u>precise</u> status of each subsection)**	**Timeline to implement any remaining actions (State the planned action, target date and person responsible)**
through charges on reactive energy to encourage large electricity consumers to produce their reactive power requirements 3.2 Provide incentives to Distribution Licensees to manage their reactive power needs 3.3 Ensure higher load growth during the off-peak hours, thus filling the valleys in the daily load curve, as low load conditions during such periods give rise to increased leading MVAr.	commissioned and in operation to control the steady state over voltage situation at low loads 3.2 ------ 3.3 Reactive power management is carried out by SCC including switching off certain lines, running some Generators for Var controlling etc.	
4. Load shedding scheme 4.1 No load shedding scheme will be able to shed load to achieve an exact balance. It appears that this scheme has shed load more than required. A review of the scheme to improve its performance is essential**.**	4.1 Review of the load shedding scheme is done continuously; and monitored and adjusted if required and the UFLS scheme is now operating as desired. This is a continuous process.	
5. NCRE 5.1 177MW of NCRE had been connected to the system at the time of the failure and appears to have got tripped due to the abnormal situations prevailed in the system. A complete study should be undertaken to determine the effect of the loss of such large share of generation, and suitable measures should be proposed to make use of this valuable resource, whilst maintaining the system stability and security at the desired levels**.**	5.1 Several measures have been taken: SCC has developed inhouse, an NCRE monitoring system which is under implementation. Mannar wind plant operating on semi dispatchable mode. Effects of VRE to synchronous islanded power grids were not fully studied and known by 2015. Optimum level of NCRE to be added to system is now not decided following planning studies but are forced by policy. Hence, NCRE needs to be added now even before the grid is "ready" for large asynchronous penetration. CEB commenced carrying out what is called "RE integration study" along with every generation planning cycle starting in 2015. However, the government policy changed regularly creating a need to carry out fresh RE integration studies too to catch up with every policy change. CEB was issued with another new policy guideline containing 70% RE by 2030 policy (and no more Coal development) in January 2022. CEB had already commenced RE integration studies to this new policy. According to the Grid Code, all generators including RE generators/machines need to stay in the system during a fault. This requirement is mentioned as	

I Recommendation	II Status of implementation as of 31 Jan 2022 (provide the precise status of each subsection)	III Timeline to implement any remaining actions (State the planned action, target date and person responsible)
	LVRT (Low Voltage Ride-Through) capability of the generators and the extract from the Grid Code. In order to ensure the system stability during such a disturbance, above LVRT requirement mentioned in the Grid Code needs to be enforced for the new RE generators	
6. SCC A state-of-the-art SCC is an urgent necessity. CEB should ensure that the proposed SCC is commissioned very early without delay.	6 Completed.	
7. LVPP Non-technical issues have arisen in the management of LVPP unit 3. The operation of No3 generator has been contracted to a Chinese company and does not operate directly under the direction of the CEB. This affects the smooth operation of the power plant and resolved immediately.	7 -------	
8. Restoration 8.1 Colombo city supply: Considering the importance of restoring power to Colombo, it is very important to have more than one option to promptly restore the Colombo city supply 8.2 Expedite the commissioning of frequency control mode of operation of KCCP, to keep as an option to restore Colombo in a total or partial failure. **8.3** Explore the possibilities of using Westcoast power (IPP) to restore the Colombo supply and to keep the provision as standby option on restoration after a total or partial failure.	8.1 Multiple options are been implemented. i.e.: 3x35 MW Gas turbine procurement with specific capability to restore Colombo city is in progress. At present, at Procurement Appeal Board after CAPC decision. SCC has tested restoration with available Generators at Kelanitissa PS. 8.2 Frequency control tested and already practiced during dry period. Colombo restoration tested. 8.3 This is yet to be addressed as there are related commercial issues.	8.1 3x35MW Commercial Operation expected in July 2023.

5.2. Power System Failure on 25th February 2016

I Recommendation	II Status of implementation as of 31 Jan 2022 (provide the precise status of each subsection)	III Timeline to implement any remaining actions (State the planned action, target date and person responsible)
9. Protection Philosophy 9.1 Carry out a complete study to identify the changes needed to protection philosophy to	9.1 Settings of important lines and transformers have been checked.	

I	II	III
Recommendation	**Status of implementation as of 31 Jan 2022 (provide the precise status of each subsection)**	**Timeline to implement any remaining actions (State the planned action, target date and person responsible)**
ensure an improved performance from the protection system with special focus on: (i) the need for out of step relaying (OOS) scheme and adopting a suitable scheme if such a need is established, (ii) adopting a more advantageous transfer tripping scheme for the transmission distance relaying, (iii) employing feeder differential relays as a main protection for all transmission lines, where fibre optic cables are available, (iv) use of high speed single pole auto-reclosing for all 132 kV transmission lines and their timing, (v) basing over-current protection on fault protection and not on continuous thermal ratings, (vi) the necessity of giving consideration to the transient performance of instrument transformers when selecting such equipment.	(i) CEB does not have experience on implementation of out of step relaying (OOS) in transmission lines and this shall be studied with the assistance of external experts. (ii) CEB now uses advanced Fibre based tele protection schemes and use of PLC is being phased out gradually. (iii) Specification has been updated to implement differential protection as main protection in all transmission lines. (iv) Single phase Auto Reclosing cannot be implemented in 132kV lines since circuit breakers are not designed for single pole operation (v) Over current settings of critical lines were revised based on a detailed study carried out by Transmission design branch.	
10. Power system reliability/stability 10.1 Review all over current protection relay settings to ensure better protection function performance. 10.2 Standardize all protection equipment after a proper assessment of all existing equipment. 10.3 Urgently procure and commission a state-of-the-art asset management program to ensure proper maintenance of the assets. 10.4 Carry out thorough dynamic studies and make all necessary changes to the PSS settings if required to ensure the best use of Power System Stabilizers (PSS) already incorporated to synchronous generator excitation controllers. 10.5 Strengthen the 220/132kV link at Rantembe with a second 105MVA transformer. As an interim measure, consideration should be given to disconnect an equivalent load from the 132kV southern network, with the tripping of the Rantembe transformer. 10.6 Carry out the necessary studies to improve the performance of the power swing blocking feature of the distance relays.	10.1 Important 220kV lines have been reviewed. 10.2 Chapter 5 of the CEB Tender Specification (for Control & Protection Scheme) has been updated and released for implementation. 10.3 Computerized Maintenance Management System has been procured and in place. 10.4 ------- 10.5 Second 220/132kV Interbus Transformer at Rantembe is already in operation since Aug 2018. 10.6 Settings of Power swing blocking feature of the distance relays have been reviewed and a general guideline for settings has been established	

I	II	III
Recommendation	**Status of implementation as of 31 Jan 2022 (provide the precise status of each subsection)**	**Timeline to implement any remaining actions (State the planned action, target date and person responsible)**
10.7 Review the under-frequency load shedding scheme on regular basis. 10.8 Carry out necessary studies and take necessary measures to mitigate the effects of lightning strikes. 10.9 Evaluate the transient performance of the current transformers presently in use in the transmission system.	10.7 Done and continuously monitored. 10.8------ 10.9------	
11. LVPP Power Complex 11.1 It is very evident that the power system, at least when operated as being done at present, becomes unstable under transmission system transient fault conditions. This makes the LVPP machine speeds to increase and gives rise to power swings as well as the triggering of the Over-speed Protection Controller (OPC). Ascertain the fact that one of the key roles of OPC at LVPP is to bring about improvement in power system transient stability, but Committee was unable to find any evidence to confirm that OPC settings have been determined based on system stability studies. 11.2 With single phase opening and reclosing of 132kV transmission lines, this rise of LVPP machine speed can be arrested and also maintaining transient stability and also preventing islanding. 11.3 Action taken by LVPP engineers to activate “Fast cut back mode” on the operation of the OPC for one machine, is a step in the right direction, but should be considered strictly as an interim measure. **11.4** Commission a study on the use of OPC in the LVPP machines, preferably with manufacturers and experts who have in-depth knowledge in the subject.	11.1 OPC settings reviewed and implemented by Generation Protection Branch. 11.2 Single phase Auto Reclosing cannot be implemented in 132kV lines since circuit breakers are not designed for single pole operation 11.3 Already implemented by Gen. Prot. Branch. 11.4 ---	
12. Restoration **12.1** Restoration has not encountered any problems due to system inadequacies, and the only delay has been delay involved in energizing Embilipitiya and Hambantota GSS. Cause for this delay should be established and remedial action need to be taken immediately.	12.1 New Restoration guideline already implemented.	
13. General 13.1 Provide opportunities to CEB engineers to actively participate in these studies and implementing a suitable scheme to enable them to serve in specialized departments for a minimum definite period. 13.2 Standardize failure reports delivered from power stations so that they are in the same format and contain all information, especially accurate data on protection relay operations.	13.1 This is being practiced to the level possible in the organizational context. 13.2--------	

5.3. Power System Failure on 3rd February 2020

I	II	II
Recommendations	**Status of implementation as of 31 Jan 2022 (provide the <u>precise</u> status of each subsection)**	**Timeline to implement any remaining actions (state the planned action, target date and person responsible)**
14. Coordination 14.1 The committee recommends that direct coordination and communication between the Ministry of Power and Energy, CEB, CPC, Treasury on financial and other administrative matters be revitalized, and comply with the regulatory conditions in view of being an utility operating in a regulated environment, and, which appears to be highly lacking in the current setup. 15. **Data:** 15.1 The committee understands that the CEB/System Control Center data are still generated with manual intervention. This came to the light when the committee observed two versions (Annex 22 of report) of generation summary on the 4th Feb. 2020, which is critically connected to the incident on the 3rd Feb. 2020 and the significant discrepancy observed between the Day Ahead Economic Dispatch and the Actual System Dispatch data. Therefore, the committee highly recommends an efficient computerized information management system for this purpose be implemented with immediate effect. Further, the committee highly recommends CEB to explore the optimum use of the Supervisory Control and Data Acquisition (SCADA) systems of all power plants in the country whose information can be used in real-time by the CEB/System Control Centre to optimize the generation subjected to cost, availability and other constraints.	14.1 In the internal CEB context, all Heads of licensee & other divisions including their staff are properly communicated and updated continuously to operate in the regulated environment time to time as per the requirements stipulated in the six licenses issued by the Public Utilities Commission of Sri Lanka to CEB. 15.1 Already implemented and continuously reviewed and improvements are made.	
16. Procedures at SCC: **16.1** The committee also observes that there is poor "Workflow" practice at the system control operations where there was no clear evidence of proper flow of authority, tasks, steps, people in making the final decisions of operations at corporate level which are highly economical and socially sensitive business operations. Thus, it is recommended to revisit the workflow practice ensuring best practiced quality assurance and accountability aspects. Manual intervention at the System Control in deciding the optimum combination of electricity supply sources at a given time should be minimized as per the global practice. This will not only help minimizing the possible room for potential manipulations but also will save the	16.1 SCC has prepared documentation for all procedures and duty lists and submitted to PUCSL for further review. CEB is at present following these procedures and also the dispatch planning & operations are carried out using two software systems. i.e., SDDP for medium term and long-term planning and NCP for short term.	

I	II	II
Recommendations	**Status of implementation as of 31 Jan 2022 (provide the precise status of each subsection)**	**Timeline to implement any remaining actions (state the planned action, target date and person responsible)**
country's Rupees Billions on electricity generation costs.		
17. Economic impact: **17.1** The committee notes that as estimated by the PUCSL in 2018, the cost of unserved energy is USD 0.745/kWh and thus the impact to the economy with respect to the curtailment of 1.4 GWh on the economy is around LKR 188 million and thus CEB to make informed decisions related to conducting rotational load shedding taking all elements into account in view of the nature business that CEB is engaged in.	17.1 This is being done taking in to account the multitude of effects and stakeholders.	
18. Dispatch auditing: **18.1** As it is also noted that there no evidence of appropriate mechanism in place for dispatch auditing of the Licensee and thus strongly recommended to initiate immediate action in view of dispatch auditing in line with the guidelines of PUCSL that would enable monitoring and verification of the performance of the Licensee. Whether it is intentional or unintentional even a small margin of error, costing the country dearly which runs into billions of rupees. Room for manipulation cannot be simply ignored in this area.	18.1 Continuous self-assessment is done as directed by PUCSL. All relevant data is available and any independent entity can conduct the Energy / dispatch Audit.	
19. Implementation of plans: **19.1** Due to long start up and shutdown sequences as well as stability reasons, it is customary in any power system to keep thermal power plants as the generation base and add hydro power with relatively shorter start up and shutdown sequences for peaking. However, in the Sri Lankan context, a substantial portion of the thermal generation uses expensive fuel such as Diesel and HFO. Therefore, the committee highly recommends to initiate actions to implement the generation options stipulated in the approved long-term generation plans to meet the future energy demand which is on the rise significantly. For more details of the available options, the authorities may refer the CEB Long Term Generation Expansion Plan 2018-2037.	19.1 LTGEP studies have always considered this.	

5.4. Power System Failure on 17th August 2020

I	II	III
Recommendation	**Status of implementation as of 31 Jan 2022 (provide the precise status of each subsection)**	**Timeline to implement any remaining actions (state the planned action, target date and person responsible)**
20. Maintenance procedures		
20.1 Establish a properly benchmarked robust maintenance and work permit granting protocols, employing robustly framed operating practices for maintenance on safety critical and his risk operations. (time frame: immediate)	20.1 Improved permit-to-work system is adopted while performing maintenance activities in the Transmission network.	
20.2 Plan the maintenance work taking the holistic picture of the power network under strict supervision of properly qualified, professionally trained, experienced and skilled personnel. (time frame: immediate)	20.2 Holistic picture is-visible to SCC and by granting interruptions it is verified that SCC has considered it. It is to be noted that this failure occurred during, and since then CEB too has been working in, a restricted context due to the COVID pandemic.	20.2 Maintenance plan is 1 year rolling plan. Plan is available to SCC for 1 year ahead.
20.3 Establish a risk management mechanism in order to determine the proper mix of preventive measures and mitigation levels, considering the related risks, in view of the robustness of the operations and maintenance protocols. (time frame: short-term)	20.3 Condition monitoring and assessing of healthiness of major components in the Transmission network are in the development process to assess and reduce the risk of sudden failures of such equipment Important information required for risk management such as maintenance/break down history, trending of important parameters is progressively entered and made available with the implementation of the Computerized Maintenance Management System of Transmission division. To avoid operational risk & mal operations, a permit system & Common Activity Schedule (CAS) has been introduced. To avoid any preliminary work risk or unauthorized operation during maintenance, Maintenance Activity Schedule (MAS) has been prepared & already in practice A risk management policy for CEB has been drafted. It has to go through the approval process	
20.4 Revitalize the asset management framework of CEB in view of overcoming potential deficiencies and fostering the overall culture of asset management (time frame: short-term)	20.4 Computerized Maintenance Management System is being implemented to manage technical assets in Transmission Division	
20.5 Work toward the Long-term Generation Expansion Plan in line with the current	20.5 However, the regular change of government policy is creating a need to	

<table>
<tr><th>I</th><th>II</th><th>III</th></tr>
<tr><th>Recommendation</th><th>Status of implementation as of 31 Jan 2022 (provide the <u>precise</u> status of each subsection)</th><th>Timeline to implement any remaining actions (state the planned action, target date and person responsible)</th></tr>
<tr><td>government policy, considering the future requirements. (time frame: short-term)</td><td>carry out fresh LTGEP studies to catch up with every policy change. CEB was issued with another new policy guideline containing 70% RE by 2030 policy (and no more Coal development) in January 2022. Accordingly, CEB is currently carrying out studies in view of submitting the LTGEP 2023-2042 in June 2022.</td><td></td></tr>
<tr><td>20.6 Review the existing generator df/dt protection scheme at Lak Vijaya power plant in view of working out new df/dt setting(s) for all three generator units, and consequently conduct a comprehensive verification exercise of the protection system and related protection coordination in highly vulnerable areas, across the entire network. (time frame: suitably designated)</td><td>20.6 Lak Vijaya Protection System has been reviewed by CEB on the approval of the AGM Generation.
The new settings are
<table>
<tr><td>Unit</td><td>01</td><td>02</td><td>03</td></tr>
<tr><td>df/dt (Hz/s)</td><td>2.25</td><td>2</td><td>2.05</td></tr>
<tr><td>Enable frequency (Hz)</td><td>50.75</td><td>50</td><td>50.5</td></tr>
<tr><td>Delay timer (ms)</td><td>150</td><td>0</td><td>150</td></tr>
</table>
Settings of Important 220kV lines and Inter Bus Transformers have been reviewed.
Overall protection scheme review is planned.</td><td></td></tr>
<tr><td>20.7 Use the existing dynamic transmission system model to perform dynamic system analysis on the reported case. (time frame: immediate)</td><td>20.7 ----</td><td></td></tr>
<tr><td>20.8 Synchronize all clocks in the national grid with the GPS clock so that the data logged is consistent and deploy digital fault recorders with sufficient rate to capture the generator frequency data (time frame: immediate)</td><td>20.8 GPS clock of Digital Disturbance Recorder at Kotmale power station was repaired with the help of Original Equipment Supplier. Time synchronization in Victoria PS has been completed. New GPS clock has been installed at LVPP to cater the DCS Ovation control system. Unit 2 & 3 station DFR are working properly with the old GPS clock. However, Unit 1 station DFR is not yet time synchronized due to a software issue, which is being investigated by the LVPP staff. Generator protection system of LVPP is time synchronized. Design stage of time synchronization of all other power plants has also been completed.</td><td></td></tr>
<tr><td>20.9 Study and identify the best mode of governor controls and settings to facilitate fast system restoration. (time frame: immediate)</td><td>20.9 A new control mode was studied, identified and recommended for Kotmale PS and Victoria PS turbine governors by a committee appointed by AGM Generation and currently the proposal is</td><td></td></tr>
</table>

I	II	III
Recommendation	**Status of implementation as of 31 Jan 2022 (provide the precise status of each subsection)**	**Timeline to implement any remaining actions (state the planned action, target date and person responsible)**
	in the implementation stage. All those governors involved in initial system restoration were tested and adjusted if required in existing control modes after the system blackout according to the instructions of the AGM Generation. After that system restoration trials were carried out from different stations successfully and it confirms that available governors are capable enough for stable system restoration process. SCC conducted several real time trial restorations for all parts (Mahaweli, Laxapana, Samanalawewa, KPS and Kukule systems separately) and identified the issues and included to the restoration guideline.	
20.10 Investigate better means of using past daily loading records of feeders with a suitable to identify more accurate demand to essential in system restoration. (time frame: short-term)	20.10 Implemented.	
20.11 Explore the possibilities of using Kerawalapitiya combined cycle power plant or explore any other potential solution through a proper investigation in view of restoring power to Colombo city. (time frame: immediate)	20.11 Using West Coast Power Plant is yet to be addressed as there are related commercial issues. However as described above in 8.1 & 8.2, other measures have been investigated and being implemented.	
20.12 Update the system restoration manual through accurate dynamic simulation studies of the system, so that the system can be restored reliably using it as a guide. (time frame: immediate)	20.12 Already updated with the results of several trial operations carried out and used the same for the restoration of the total failure occurred on 3rd Dec. 2021.	
20.13 Provide continuous professional training to system control center (SCC) personnel to become expert in their duties, and to be disciplined to follow and handle emergency situations at their highest competency level. (time frame: short)	20.13 By doing periodical trail restorations and field visits to Power stations, SCC is doing the continuous professional development. Few restoration trials were carried out based on different stations as mentioned below. The staff involved in the system restoration activities could have gathered vast experience and trained themselves by actively participating those trials. 1. Restoration Biyagama from Victoria and Kotmale PS 2. Restoration of LVPP auxiliary supply from Upper Kotmale PS and Kotmale PS 3. Restoration of southern part from Samanalawewa PS and Kukule Ganga PS	

I	II	III
Recommendation	**Status of implementation as of 31 Jan 2022 (provide the precise status of each subsection)**	**Timeline to implement any remaining actions (state the planned action, target date and person responsible)**
	4. Restoration of Kolonnawa and Kelanitissa from Laxapana PS. However, the context of COVID 19 outbreak has to be taken in to account.	
20.14 Expedite the already initiated process of exploring the possibility of optimum auxiliary power at Lak Vijaya power plant as recommended in previous committees (time frame: immediate)	20.14 SCC had carried out trail restoration of Auxiliary supply by using Upper Kotmale-Kotmale via Anuradhapura switching station. The same was practiced during the recent total failure incident on 3rd Dec.2021. But time taken for this restoration of LVPP is significant and may not be feasible and an alternative arrangement has to be adopted.	
20.15 Revisit the load shedding scheme of the Sri Lanka power system in view of meeting the present system conditions. (time frame: short)	20.15 Load shedding scheme is continuously monitored and is working in a proper way.	

6. SUMMARY AND CONCLUSIONS

The power system was operating in a healthy state on December 03 and November 29, 2021, with some generators and circuits taken out of service owing to maintenance requirements and for construction work.

The sequence of key events leading to the total power failure on December 03, 2021 are the following:

(a) At 11:27:14, an *earth fault* in phase B conductor on the circuit 2 of Kotmale-Biyagama 220 kV transmission line was detected by the protection system.
(b) While the *automatic-reclosing* process was in progress to restore the faulty phase conductor, all three phases of the circuit were automatically tripped from Kotmale and the circuit breaker at the Kotmale end was locked out, thus removing circuit 2 from service.
(c) With circuit 2 now out of service, power transfer from Kotmale substation to Biyagama GS successfully shifted to the remaining healthy circuit (circuit 1). Power flows elsewhere in the grid readjusted to the new situation.
(d) However, after operating for about 22 seconds in this configuration, circuit 1 too tripped automatically, thus cutting off the power flow from Kotmale substation to Biyagama GS.
(e) As a result, some segments in the power system (notably the Central Province) was having surplus power generation while elsewhere in the system (notably the Western province) there was in deficit.
(f) Built-in protection systems automatically operated to shut down lines and generators, to prevent damage to equipment from the consequences of this sever unbalance, because the automatic load shedding could not restore balance.
(g) By approximately 11:27:48 (34 seconds after the first detection of the alleged *earth fault* on circuit 2) all generators and transmission lines were totally out of service.

6.1. Primary Cause of the Fault on Circuit 2 of Kotmale-Biyagama Transmission Line

Conclusion: The primary cause for the fault that subsequently initiated several events, finally leading to the total power failure has not been established.

Description: The total power failure on December 03, 2021 has been triggered by the tripping of phase B of circuit 2 of Kotmale–Biyagama 220 kV transmission line. Records analysed by the Committee indicate features consistent with an *earth fault*. Among typical primary causes for such short-term non-persistent faults are equipment weaknesses, wayleaves, weather-related events, and animal or human activity. The probable primary cause for the apparent *earth fault* of phase B provided by CEB after inspecting the line was not considered credible by the Committee. The Committee accepts that for some intermittent faults on transmission lines, the primary cause may sometimes be difficult to establish. However, the Committee can rule out weather related causes (such as lightning), wayleave issues (as confirmed later by CEB's maintenance staff), and equipment weakness (as no such weakness or failure has been reported, or repetition of *earth fault* has been experienced to date by CEB).

6.2. Action to Isolate the Faulty Phase B of Circuit 2

Conclusion: The automatic line protection system responded correctly to the apparent *earth fault* detected, opened the CBs from both Kotmale and Biyagama ends and initiated the auto-reclosing procedure on the faulty phase. The faulty phase was indeed restored automatically, but only from Biyagama end, because the spurious activation of the *end-fault* protection at the Biyagama busbar protection system caused the tripping and lockout of the Kotmale circuit breakers.

Description: Phase B protection system identified a significant difference between the incoming current and the outgoing current in the line, isolated it by simultaneously opening the CBs at Kotmale end and at Biyagama end, and initiated the *auto-reclosing*. This process was to complete in about one second, and restore the faulty phase B back into service. However, an *end-fault protection* signal issued automatically from Biyagama GS caused all three phases of circuit 2 to disconnect at the Kotmale end prematurely, whereas the Biyagama CB of phase B reclosed successfully in 924 ms, thus reconnecting the circuit from the Biyagama end. As there was no indication of persistent fault, the circuit should have resumed normal operation if not for the unexpected isolation of all three phases at the Kotmale end.

6.3. Unexpected Tripping of Circuit 2 of Kotmale-Biyagama Transmission Line

Conclusion: Circuit 2 of Kotmale–Biyagama 220 kV transmission line was automatically but unnecessarily tripped from Kotmale end caused by an erroenous *end-fault* protection signal issued from the Biyagama GS.

Description: Circuit 2 of Kotmale–Biyagama 220 kV transmission line has tripped automatically by the operation of *end-fault* protection in the bus bar 2 of Biyagama GS. This tripping occurred while the *auto-reclosure* was already activated and was in progress, which would have cleared the fault in phase B and restored the faulty circuit back to service.

The field wiring in the control panel to indicate CB positions input to *end-fault* protection was not compatible with the original as-built circuit diagram provided by the contractor ASEA, Sweden in 1986 at the time of commissioning this line. Furthermore, the nature of the discrepancy in the field wiring,as reported by CEB, was not identical between circuit 1 and circuit 2 at the time of the December 03, 2021 incident.

CEB engineers reported to the Committee on January 21, 2022 that a faulty wiring of the *end-fault* protection realy at Biyagama was the cause of spurious activation of *end-fault* protection at Biyagama. This information was shared with the Committee, however, after they had "corrected" the alleged error in wiring. There is no photographic or independent eyewitness evidence on what existed before the alleged corrections were effected and the actual corrections made to the circuits. According to the reported information, some major changes to the wiring as well as the auxiliary circuit components have been done on December 26, 2021 and on January 02, 2022, with no regard to the ongoing investigative process.

6.4. Inadequate Investigation of Two Similar Previous Incidents

Conclusion: If the similar unexpected tripping of these circuits (although those events did not escalate to a total failure) twice before the December 03, 2021 incident were investigated shortly thereafter, the alleged error in wiring could have been identified and corrected, thus preventing the total failure on December 03, 2021. This inference is particularly true of the similar incident four days before, on November 29, 2021.

Description: No investigation or examination has been conducted by CEB on the unwanted and unexpected operation of *end-fault* protection on May 11, 2021 and on November 29, 2021. This inaction displays the negligence and carelessness on the part of CEB to investigate the maloperation of its protection system. Had the two previous incidents been investigated in detail, the alleged error in wiring could have been discovered at that time and the total failure on December 03, 2021 could have been avoided.

6.5. Loss of Circuit 1 of Kotmale-Biyagama Transmission Line

Conclusion: After circuit 2 was lost, the subsequent loss of circuit 1 could have been avoided if the *earth fault* relay of circuit 1 had been configured for “Instantaneous” reset. CEB has not been able to explain why this setting had been configured as “Disk Emulation” reset at the Kotmale end while the setting at the Biyagama end of the same circuit has been on “Instantaneous” reset.

Description: After circuit 2 of Kotmale–Biyagama 220 kV transmission line was completely isolated from the system, circuit 1 had continued to operate, meeting the n-1 reliability criterion followed by CEB for operating its transmission assets. After 22.33 seconds, however, this circuit too got automatically tripped due to the operation of *earth-fault* protection. The neutral current caused by the fault in phase B of circuit 2 had triggered the Main 1 relay of circuit 1 because the two lines were operating in parallel. However, with circuit 2 tripping completely in 288 ms had caused the *earth fault* current in circuit 1 to decrease to 65 A (below 10% of the threshold setting of 80 A). The *earth fault* relay would have generated a trip command in 1.4 s if an earth fault actually prevailed on circuit 1. However, the *earth fault* relay had operated and caused circuit 1 to trip after a relatively longer duration of 22.33 s from its first triggering. CEB presented calculations to confirm that given the threshold current setting of 80 A and reset characteristics were set to “Disk Emulation”, the tripping duration of 22.33 s was possible. While CEB’s position may explain the tripping of circuit 1, the Committee is of the view that if reset characteristics of the relay had been set to “Instantaneous” instead of “Disk Emulation”, circuit 1 would not have tripped and the consequent total power failure could have been prevented.

We state with confidence that if not for the flawed tripping of circuit 1 of Kotmale–Biyagama 220 kV transmission line in 22.33 s after the loss of circuit 2, the total system failure on December 03, 2021 would not have occurred.

Except for the phase B of circuit 2 of Kotmale–Biyagama 220 kV transmission line, in all other occasions, the trip commands have been issued from Main 1 relays. The Main 2 relay has operated only in the operation of differential protection in response to the *earth fault* of phase B of circuit 2.

6.6. Unexplained Records of User Access to Some Relays

Conclusion: Records of user access to the Main 1 relays (which operated to trip the line) can be explained, but there are unexplained records of access to the Main 2 relay. The Main 2 relay operated during this incident only for the differential protection in phase B of circuit 2, which was a successful operation.

Description: The Main 1 relays protecting circuits 1 and 2 of Kotmale–Biyagama 220 kV transmission line have not been accessed on December 03, 2021 to edit records, delete records, change settings or delete relay settings. However, they have been accessed after system restoration for downloading data, which the Committee accepts to be a reasonable requirement for CEB's internal investigations.

However, the Main 2 relay of circuit 2 of Kotmale–Biyagama 220 kV transmission line has been accessed on December 03, 2021 with Level 01 privileges and logged out seven times over a period of 1 minute at 8:33 am. The corresponding records of logging-in could not be located. The purpose of such accessing could not be explained by CEB. The OEM too has not provided a firm answer on the same issue.

6.7. Power Swings that Led to the Collapse of the Total Power System

Conclusion: The power system moved through large power swings between the western area with generation deficit and the central and other areas with surplus generation. The consequent operation of various protection systems of generators and transmission lines caused the generating system to undergo cascade tripping.

Description: After tripping of circuits 2 and 1 of the Kotmale–Biyagama 220 kV transmission line, the frequency at Kotmale substation busbars has increased to about 59 Hz (System 1, indicating a surplus of generation), while the frequency in the load centre in Colombo (System 2) has dropped. The system has lost its ability to return to normal operation, with the two systems being in phase at one instant creating voltage maximum and current minimum, and 180 degrees out of phase at another instant creating voltage minimum and current maximum. This phenomenon is evident in circuit 2 of Kotmale-New Anuradhapura 220 kV transmission line, which tripped subsequently by the operation of *distance protection* from the New Anuradhapura GS.

With over-frequency in most generators in the Mahaweli Complex (isolated from loads) and under-frequency in the generators still feeding the load centre, consequent to the tripping of both circuits of Kotmale–Biyagama 220 kV transmission line, circuit 2 of Kotmale–New Anuradhapura line could not maintain transient stability, resulting in the system collapse through cascade tripping of generators.

Unit 3 and Unit 1 of LVPP had been tripped by the operation of the C*omposite Low Voltage Over Current* protection as a result of transient instability. The Unit 2 of LVPP had not been operating on that day (released for planned maintenance work).

6.8. Restoration of Auxiliary Power to LVPP

Conclusion: After the total blackout, restoration of auxiliary power to LVPP has taken at least 2 hours and 30 minutes, a duration too long for a safe shutdown of the power plant.

Description: Auxiliary power restoration at LVPP from Upper Kotmale power station and Kotmale power station has been previously achieved in 1 hour and 38 minutes during a trial operation. However, after the total power failure on December 03, 2021, restoration of auxiliary power to LVPP has taken 4 hours and 9 minutes according to NSCC, whereas some reports to AGM (Generation) stated this had been achieved in 2 hours and 30 minutes. In either case, the duration had been too long to prevent generators of LVPP from being forced to undergo an unsafe shut down, causing the rupture of safety mechanisms that requires 3 to 4 days to restore.

6.9. Unexpected Failures of Equipment Causing Delays to Full Restoration

Conclusion: The NSCC has commenced system restoration simultaneously from the sub-systems in Mahaweli, Laxapana, Samanalawewa and Colombo. The transmission network had been restored by 16:47 hrs, which is 5 hours and 15 minutes from 11:27 hrs. There has been one hour saving in the duration to restore the transmission system compared with the previous total system failure on the August 17, 2020.

Description: The main contributors to the restoration delays have been (a) Kotmale power station due to unexpected PRV operation in a CB of the circuit 1 of Kotmale-Biyagama 220 kV transmission line, (b) failure to indicate receipt of fault signal at CB of circuit 2 of Kotmale-Biyagama 220 kV transmission line at the Kotmale end, (c) VT failure at Embilipitiya on Samanalawewa circuit 1, (d) unknown errors in Sapugaskanda-Kelanitissa circuit 1 and Kelanitissa-Colombo Sub L 220 kV underground cable , (e) Generator 2 differential protection operation in the New Laxapana power station, (f) synchronizing problem due to delayed exit from the failed automatic line charge mode to manual line charge mode in Generators 1 and 2 of Samanalawewa power station, and (g) the hotline communication failure in the 48 V DC communication system in the New Anuradhapura GS.

7. RECOMMENDATIONS

Explanation 1: The primary cause for the non-persistent fault in phase B of circuit 2 of Kotmale-Biyagama 220 kV transmission line, which subsequently initiated a sequence of events, eventually leading to the total power failure, has not been established. Such non-persistent faults in power systems make up the majority of faults experienced in transmission systems, and the cause of such faults are often difficult to determine. The Committee is satisfied with the explanation and data CEB provided on the criteria it has been following for selecting faults reported for further investigation. However, the initiating event (single-line fault) would not have led to any major consequence on December 03, 2021, let alone a total system failure, if the following two major events did not take place: (a) unnecessary operation of the *end-fault* protection and tripping circuit 2 with CBs lockedout while auto-reclosing was in progress and (b) unnecessary operation of the *earth fault* protection of circuit 1 of Kotmale-Biyagama 220 kV transmission line at 22.33 s after triggering, while the fault current had decreased below 10% of the threshold in 0.288 s after triggering. There are two scenarios, which could have led to the subsequent events (a) and (b).

i. the non-persistent fault in phase B may have been due to a *natural cause* and the protection system settings and configuration that prevailed at the time of the incident enabled subsequent events (a) and (b).
ii. the non-persistent fault in phase B was *man-made*, knowing that the protection system settings and configuration that prevailed at the time of the incident would lead to the subsequent events (a) and (b).

The single-line fault may have been a natural cause. Further, the unintended operation of *end-fault* protection of busbar protection at Biyagama may have been the result of faulty wiring that existed for many years, as may have been the wrong configuration of the line protection relay of circuit 1. However, before arriving at this conclusion definitively, the Committee needs to eliminate the possibility of human intervention of deliberate action in any one of the three events—*earth fault* on phase B of circuit 2, alleged faulty wiring of busbar protection system of Biyagama GS, and wrong configuration of line protection relay (Main 1) of circuit 1 of the Kotmale-Biyagama 220 kV Transmission line.

The Committee has not seen sufficient evidence to eliminate scenario ii above. Among the reasons for the Committee's decision in this regard are the following:

a) No explanations were received either from CEB or the OEM on the Level 01 privilege access to Main 2 relay, which was also activated in parallel to Main 1 relay for the operation of the differential protection in phase B of circuit 2.
b) Alleged changes made to the control wiring of *end-fault* protection and current settings of *earth fault* protection subsequent to the total failure on the December 03, 2021 were notified to the Committee only after such changes were made. CEB was unable to produce any evidence of the changes made or the existence of such faulty wiring.

Recommendation 1: A formal investigation by the law enforcement authorities supported by independent IT experts if necessary is recommended to determine whether or not any human intervention has taken place.

Explanation 2: LVPP plays a key role in the electric power system in Sri Lanka owing to its capacity. Being a coal-fired power plant, it has many operational complexities, which demands an uninterrupted power supply to auxiliary equipment. When producing 300 MW, the auxiliary power requirement is around 30 MW, obtained from the generated power itself. However, in an emergency, the non-essential auxiliaries can be eliminated temporarily and each unit will need approximately 12 MW to maintain essential auxiliaries. Hence the minimum auxiliary power needed for LVPP is 36 MW and it should be available in less than 30 minutes from an emergency, to prevent an unsafe shutdown.

Based on the previous committee recommendations, internal studies, and other expert opinion, CEB plans to install diesel generators to obtain auxiliary power in an emergency. However, this measure will only cover the scenario where the turbines go to FCB mode. Furthermore, CEB has tried auxiliary power restoration at LVPP from Upper Kotmale power station and Kotmale power station and achieved successfully in 1 hour and 38 minutes during the first successful trial. However, the subsequent incident on December 02, 2021 has taken 2 hours and 30 minutes in the best case.

Recommendation 2: Expedite the procurement of an auxiliary power supply solution for LVPP to cover critical failure situations. The estimated investment is minimal compared with technical, financial, and economic merits. It is further recommended to conduct a few more trials to secure power via Upper Kotmale power station and Kotmale power station and establish the best possible restoration duration achievable, which would support the missing failure scenarios in the former solution.

Explanation 3: In studies conducted by CEB on the request of the Committee to analyse power flows in the transmission network revealed that even in the absence of circuits 1 and 2 of Kotmale–Biyagama 220 kV transmission line, the system would have remained stable if Kotmale-New Polpitiya-Padukka-Pannipitiya 220 kV transmission connections (presently under construction) were in operation.

Recommendation 3: Expedite the construction of the Kotmale-New Polpitiya-Padukka-Pannipitiya 220 kV transmission line segments and commission them without delay so that the probability of future total system failures owing to the loss of the critical Kotmale-Biyagama 220 kV transmission line could be reduced.

Explanation 4: In restoring the transmission system, the following were identified as causes of delays with no identified reasons: (i) PRV operation in a CB of circuit 1 of Kotmale-Biyagama 220 kV transmission line in Kotmale substation (ii) unindicated fault signal receipt of a CB of circuit 2 of Kotmale-Biyagama 220 kV transmission line, (iii) unknown errors in Sapugaskanda-Kelanitissa circuit 01 and Kelanitissa - Colombo Sub L 220 kV underground cable, (iv) delayed exit from the failed automatic line charge mode to manual line charge mode in Generators 1 and 2 of Samanalawewa power station, and (v) the hotline communication failure in the 48 V DC communication system in the New Anuradhapura GS.

Recommendation 4: Conduct an internal investigation by CEB to find the exact causes of delays in the restoration at each point identified and rectify them immediately. Call explanations from everyone who held responsibilities at installations where those delays occurred and take necessary actions if the investigations reveal that the staff had not performed adequately to ensure safe and fast restoration of the system.

Explanation 5: It has been noted that there have been obvious discrepancies in some of the settings of the protection relays in the Kotmale-Biyagama 220 kV transmission line. For example: 1) the *earth fault* threshold of circuit 2 in Kotmale end is 150 A while it is 80 A in the Biyagama end, 2) Reset mode of *Earth-Fault* protection in circuit 1 is "Instantaneous" at the Biyagama end and "Disk Emulation" at the Kotmale end.

Recommendation 5: Study and revise protection relay settings, first in the critical Kotmale–Biyagama circuits in both primary protection, backup protection in Main 1 and Main 2 relays, and later in the entire 220 kV network.

Explanation 6: Assessing CEB's position on why the *end-fault* protection in circuit 2 and *earth-fault* protection in circuit 1 operated unnecessarily and unexpectedly, alleged errors in wiring of control circuits and wrong settings of relays, respectively, have prevailed for at least five years, without being detected.

Recommendation 6: Conduct regular inspection of the functioning of the auxiliary circuits of CBs in addition to maintenance testing of CBs, and take corrective action, if necessary, to ensure their correct functioning under all designed scenarios. Conduct an independent investigation to uncover reasons for erroneous settings and alleged faulty wiring of the protection system of Kotmale-Biyagama 220 kV transmission line, including reason as to why such errors had not been discovered or investigated for many years. As part of this investigation, identify who is responsible for maintaining the protection system, including the preparation of procedures/protocols for investigating and preventing reported faults and erroneous settings.

Explanation 7: At present, most of the DFRs and numerical relays at various locations in the network are not time synchronized. Therefore, DFRs should be checked and manually synchronized if errors are found. According to CEB, this process has commenced based on the previous committee recommendations, but has not been completed yet.

Recommendation 7: Expedite the process of synchronizing disturbance fault recorders and numerical relays installed at all grid substations.

Explanation 8: It has come to the light that most of the investigations and analysis into the operation of the protection equipment were initiated only after the Committee inquired about them at various stages of the investigation. However, the Committee believes that the CEB should have been proactive and come up with detailed explanations backed by scientific proof on the operation of such equipment, analysis, and actions needed to prevent future mal operations (if necessary) as part of its investigative process.

Recommendation 8: Strengthen the post-analysis process of the operations of the assets such as the generators, transformers, transmission lines, their protection systems, etc., to ensure that unexpected operations are identified at the first instance, studied in detail, and corrective measures are taken.

Explanation 9: A model of the network with acceptable accuracy is not available with CEB to simulate the transient behaviour of the national grid during an event such as that of December 03, 2021. Such a model would enable the analysis of transient behaviour under various contingencies.

Recommendation 9: Complete all missing models and parameters of the main and sub-components of generators, transformers, transmission lines, etc., enabling accurate transient studies covering the entire power grid of Sri Lanka.

Explanation 10: This report carries the analyses and findings of the Committee, and a narrative of events that led to the total failure on December 03, 2021. The Committee believes the contents of the report will be useful the CEB, the engineering community, administrative officials and the general public at large.

Recommendation 10: Publish this committee report on the websites of CEB and Ministry of Power immediately. Publish the CEB's response to the contents of the report within a month of releasing this report to the public. Conduct a seminar hosted by the Institution of Engineers Sri Lanka (IESL), with the participation of the Committee, Ministry of Power and CEB, to enable the knowledge sharing across the wider engineering community of the country. This Committee recommends reconvening the Committee once in 3 months, to review the progress of the implementation of its recommendations.

Recommended time-line:
Web publication of the report: Immediate
CEB's response to the report on the Web: by 21 March 2022
MOP to request IESL to host the seminar: February 2022
Seminar to be conducted: March 2022
Committee to be reconvened by end May 2022 and in three-monthly intervals thereafter, to review progress

Continuation of Recommendations of Previous Committees

Explanation A: Redundancy in spinning reserves and transmission lines must be increased to enable network components such as generators, transformers, and transmission lines be released for their routine, annual and other periodic maintenance. Operating such network components without attending to maintenance places the network and its stakeholders at great risk.

Recommendation A: Implementing the 20 year Least Cost Long Term Generation Expansion plan, 10-year Transmission Network Expansion plan and 5-year Distribution Development plan without delays, to ensure the network carries adequate redundancy comparable with international best practices.

Explanation B: Selecting the least cost generation source is not fully automated and reasonable human intervention still happens unlike many systems in other countries. The need for independent dispatch audit by an external source has been discussed by previous committees to ensure transparency. Even the slightest miscalculation could mean loss of rupees billions per annum.

Recommendation B: Ministry of Power, Public Utilities Commission of Sri Lanka and CEB may take actions to conduct independent dispatch audits through competent external parties perhaps jointly with government audit, to enhance the transparency of the process.

Explanation C: Even if CEB directly borrows from agencies like ADB, World Bank, etc., for its development projects, those are received on sovereign guarantees making it a contingency liability of the state. Therefore, proper coordination of all these is urgently needed to make CEB a financially viable and efficient entity.

Recommendation C: It is highly recommended to prioritize various developments proposed by different divisions based on the resource availability.

Signed by

Signed by

1.	Prof. Lilantha Samaranayake Department of Electrical & Electronic Engineering Faculty of Engineering, University of Peradeniya (Chairman of the committee)	
2.	Dr. Tilak Siyambalapitiya Managing Director, Resource Management Association (Pvt.) Limited (Member of the committee)	
3.	Dr. M. N. Susantha Perera Additional Secretary (Policy, Technical & Research), Ministry of Power (Member of the committee)	
4.	Mr. E. A. Rathnaseela Additional Director General, Department of National Planning (Member of the committee)	
5.	Mr. Sugath Dharmakeerthi Additional Secretary, Ministry of Power (Member of the committee)	
6.	Mr. Nalinda Illangakoon Vice Chairman, Ceylon Electricity Board (Member of the committee)	
7.	Mr. Andrew Nawamani Additional General Manager (Generation), Ceylon Electricity Board (Member of the committee)	

	Active Power Demand (MW)	Reactive Power Demand (Mvar)
Maliboda	0.0	0.3
Wewalwatta	-4.6	0.3
Wimalsurendra	-9.6	0.3
Ampara	35.5	10.5
Ukuwela	34.9	14.0
Vavuniya	5.7	3.7
Mahiyanganaya	5.5	3.9
Mannar	6.5	1.9
Kelanithissa	26.6	12.3
Kerawalapitiya	30.8	16.7
Naula	23.9	3.9
Monaragala	7.5	3.9
Beliatta	12.0	5.6
Nawalapitiya	2.5	4.8
Hambantota	22.6	10.0
Horana	42.2	18.0
Katunayake	25.1	11.1
Maho	14.5	7.4
Polonnaruwa	13.7	4.0
Vaunathive	12.1	0.0
Pallekele	15.0	9.5
Kosgama	48.0	25.8
Seethawaka	24.8	14.4
Nuwara eliya	-1.2	8.1
Thulhiriya	27.3	13.8
Kegalla	17.6	11.4
Kolonnawa gis	51.3	7.6
Kolonnawa stanly	35.2	14.1
Pannipitiya	56.7	26.5
Biyagama-1	47.3	18.0
Biyagama-2	22.2	8.5
Kotugoda-1	41.1	7.9
Kotugoda-2	32.3	17.4
Sapugaskanda	60.7	30.7
Bolawatta	57.9	25.6
Badulla	9.6	4.9
Balangoda	5.5	6.8
Deniyaya	2.3	4.6
Galle	60.8	24.8
Embilipitiya	13.6	4.5
Matara	38.3	19.2

	Active Power Demand (MW)	Reactive Power Demand (Mvar)
Kurunegala	51.8	21.5
Habarana	18.7	11.4
Anuradhapura	15.3	7.0
Newanuradhapura	22.0	12.8
Trincomalee	25.4	5.4
Kilinochchi	9.3	0.0
Chunnakaum	24.1	9.2
Ratnapura	-6.1	6.3
Kiribathkumbura	31.3	13.7
Valachchenai	11.9	3.3
Ratmalana	56.6	36.0
Matugama	36.0	11.8
Puttalam	33.0	12.9
Aturugiriya	32.7	13.3
Veyangoda	44.1	23.2
Sri Jayawardanepura	47.4	18.4
Panadura	59.7	38.5
Madampe	35.0	17.6
Kelaniya	38.8	16.3
Ambalangoda	29.2	13.4
Dehiwala	32.4	15.4
Pannala	45.5	21.6
Aniyakanda	20.5	10.9
Colombo M	14.4	4.5
Colombo N	8.2	1.8
Colombo L	14.2	5.5
Colombo I	39.2	12.3
Colombo A	41.2	13.3
Colombo E	24.9	10.5
Colombo F	15.9	4.5
Colombo C	22.2	10.8
Total	**1868.2**	**839.4**

Mvar = megavar, MW = megawatt
Source: National System Control Centre

Appendix 2 – Active and Reactive Power Generation of Power Plants Prior to the Failure

Generating Unit	Active Power (MW)	Reactive Power (Mvar)
Victoria 1	80.0	15.9
Victoria 2	80.3	19.1
Victoria 3	80.3	9.4
Randenigala 1	61.1	11.4
Randenigala 2	62.5	11.3
Rantambe 1	27.3	5.5
Rantambe 2	27.5	5.0
Kotmale 1	57.1	17.9
Kotmale 2	58.4	17.6
Kotmale 3	57.7	15.6
Nillambe	0.0	0.0
Ukuwela 1	20.1	3.9
Ukuwela 2	0.0	0.0
Bowathenna	39.4	2.0
Upper Kotmale 1	40.0	20.9
Upper Kotmale 2	39.9	20.3
Moraghakanda	19.2	0.5
Moragolla	0.0	0.0
New Laxapana 1	50.2	16.0
New Laxapana 2	50.3	16.5
Polpitiya 1	44.3	4.4
Polpitiya 2	43.7	-1.3
Old Laxpana 1	9.6	0.6
Old Laxpana 2	9.7	0.5
Old Laxpana 3	9.6	0.8
Old Laxpana 4	12.4	0.5
Old Laxpana 5	12.2	0.4
Canyon 1	15.2	1.6
Canyon 2	20.4	1.6
Wimalasurnedra Power Station 1	10.0	0.6
Wimalasurendra Power Station 2	10.0	1.0
Broadlands 1	0.0	0.0
Broadlands 2	0.0	0.0
Samanalawewa 1	39.8	23.4
Samanalawewa 2	40.2	19.3
Kukule 1	39.0	4.9
Kukule 2	38.5	5.0
Udawalawa	2.9	0.0
Inginiyagala	0.0	0.0
Kelanitissa Power Station GT 1	0.0	9.5
Kelanitissa Power Station GT 2	0.0	9.3
Kelanitissa Power Station GT 4	0.0	13.2

Generating Unit	Active Power (MW)	Reactive Power (Mvar)
Kelanitissa Power Station GT 5	0.0	0.0
Kelanitissa Power Station GT 7	0.0	0.0
Kelanitissa Combined Cycle GT	0.0	0.0
Kelanitissa Combined Cycle ST	0.0	0.0
Sapugaskanda 1	0.0	0.0
Sapugaskanda 2	15.6	8.0
Sapugaskanda 3	0.0	0.0
Sapugaskanda 4	0.0	0.0
Sapugaskanda 5	8.8	4.1
Sapugaskanda 6	0.0	0.0
Sapugaskanda 7	8.9	4.7
Sapugaskanda 8	8.7	3.7
Sapugaskanda 9	8.8	4.6
Sapugaskanda 10	0.0	0.0
Sapugaskanda 11	9.0	4.9
Sapugaskanda 12	9.0	3.8
Barge	44.6	22.7
Uthuru Janani	10.6	-0.4
Lak Vijaya Power Plant 1	271.2	98.3
Lak Vijaya Power Plant 2	0.0	0.0
Lak Vijaya Power Plant 3	273.4	96.1
Asia power	0.0	0.0
Sojitz	0.0	0.0
Ace-Matara	0.0	0.0
Ace-Embilipitiya	0.0	0.0
West Coast GT 1	0.0	0.0
West Coast GT 2	0.0	0.0
West Coast Steam	0.0	0.0
Northern Power	0.0	0.0
Aggreko-Pallekele	0.0	0.0
Aggreko-Galle	0.0	0.0
Vpower-Hambantota	0.0	0.0
Vpower-Horana	0.0	0.0
Altaaqa-Mahiyanganaya	0.0	0.0
Altaaqa-Polonnaruwa	0.0	0.0
50MW of DPP_KPS_THULH	0.0	0.0
50MW of DPP_KPS_KOLON	0.0	0.0
50MW of DPP_KPS_MATU	0.0	0.0
Kilinochchi Wind 01	0.0	0.0
Kilinochchi Wind 02	0.0	0.0
Norochcholai Wind	1.4	3.0
Seguwanthivu/Vidathamuni	0.0	0.0
Senok Wind	0.0	0.0

Generating Unit	Active Power (MW)	Reactive Power (Mvar)
Ace Ambewela Wind	0.0	0.0
Musalpitti Wind	0.0	0.0
Hambantota Solar	15.1	1.5
Welikanda Solar	0.0	0.0
Mannar Wind	0.0	0.0
Total	**1894.0**	**558.9**

GT = Gas Turbine, Mvar = megavar, MW = megawatt
Source: National System Control Centre