Response of CEB to the Final Report of the committee appointed by the Ministry of Power to investigate power system failures on November 29, 2021 and December 03, 2021

25 March 2022

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1 Introduction

CEB is being one of the largest utilities in Sri Lanka which was established in 1969 continued to supply electricity to the entire country at present with the support of other licensing IPPs and LECO. One of the prime duties of CEB is to run its system with minimum failures and less burden to its customers. The same has been addressed in the Corporate Plan 2019-2023 of CEB in customer perspectives and subsequently being implemented through Board approved Annual Action Plans yearly.

2 Failure History and Present Status

History Records in CEB since 2001 to 2020 reveals that a total of twenty (20) total failures happened within a period of nine (9) years since 2001 to 2009. However, CEB was successful in limiting the number of total failures to four (4) within a period of eleven (11) years since 2010 to 2020. This momentous improvement was achieved due to utmost commitment of its employees through the responsibilities entrusted to them mainly in the subjects of Planning, Designing, Implementation, Operation & Maintenance etc. This was achieved in presence of many restrictions including lack of funds for development of generation, transmission and distribution infrastructure (CAPEX) including the financial limitations imposing time to time on recurrent expenditure (OPEX) in the approved annual budgets and limitations in human resources. Nevertheless, CEB has paid its attention on the past committee recommendations made on some of the failure incidents occurred in between 2010 to 2020 and possibilities of implementation. Accordingly, necessary actions were taken to implement/initiate to implement some of the recommendations which are not financial sensitive as well as no network disturbances are required.

Meanwhile, two power failures were occurred in the CEB power system respectively on 2021-11-29 and 2021-12-03. As a result, Secretary to the Ministry of Power has appointed a committee to investigate the incidents and report committee recommendations to prevent similar incidents future.

As a responsible utility, CEB assisted the Chairman of Committee including members in all possible ways by ***giving written and oral facts, arranging site visits, access to equipment etc.,*** in finding sequence of events leading to the total failure, issues related to system restoration including the primary cause of failure. CEB is of the view that the committee must be appreciated in completion of the assigned task within a short period of time professionally and conveying us its findings and recommendations for CEB's response.

While appreciating again the effort taken by the Committee to investigate in depth the operation of the protection schemes during the system failure, CEB has observed that the Committee has reached some of the very critical conclusions based on inaccurate assumptions / interpretations.

Since we have found numerous technical errors in the report as highlighted in following comments, it is recommended to review the CEB's responses in just and equitable manner.

3 CEB Responses to Executive Summary

3.1 Executive Summary – Comment 1 (Page xi)

Quote:

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.

Unquote

CEB Response:

Nature of the faults that occurred in the Biyagama – Kothmale 220kV transmission lines on 2021-11-29 and 2021-12-03 are completely different.

On November 29, 2021,
Biyagama - Kothmale Line 1: **R phase -E fault**, Magnitude of the current ~2.3 kA
Biyagama - Kothmale Line 2: **R phase- B phase -E fault** Magnitude of the current ~3 kA.

On December 03, 2021
Biyagama - Kothmale Line 2: **B phase -E fault**, Magnitude of the current ~ 0.5 kA
Biyagama - Kothmale Line 1: Sustained zero sequence current ~70A subsequent to the tripping of the parallel line.

CEB has provided evidence, based on the fault recorders in the relays and digital disturbance recorders, to substantiate the presence of an actual fault in the primary side. Committee has sought definitive proof for the cause of the primary fault, while acknowledging the fact that transient faults do not leave permanent proof in most of the cases. CEB has submitted evidence of a fire directly under the transmission line coinciding with the time of the fault and located within 5% of the calculated distance whose smoke could have triggered a flash over to a nearby vegetation resulting in a high impedance fault which was adequate to operate the line differential protection in Main 1 relays. On the other hand, definitive proof of the cause of the fault on November 29th is not available, though it is quite clear that a simultaneous fault of the magnitude of 3kA involving multiple phases of both 220kV circuits cannot be man-made.

3.2 Executive Summary – Comment 2 (Page xi)

Quote:

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.*

Unquote

CEB Response:

We are strongly of the view that we have submitted enough evidence to the Committee to eliminate the possibility that the physical error in wiring is planned and deliberate to cause the two failures as summarized below.

1. It is CEB itself who brought to the attention of the committee that there is an error in field wiring. If the error in wiring is deliberate such revelation would not have given.
2. CEB shown records to the committee (pertaining to drawings and connection diagrams used for the circuit breaker replacement in Kothmale Line 1 & 2 in 2015) that this error was in existence even in construction drawings that dates back to 2015. Thus, it is clear this error is not recent and hence not carried out to cause the recent two failures.
3. Committee too acknowledged the fact that there were previous tripping incidents, long before 2021-11-29 and 2021-12-03 incidents, caused by the inappropriate operation of tripping logic due to this error in physical wiring. This is additional proof that the error in wiring was in existence (but unknown to CEB).

"Wrong configuration of line protection relay of Kothmale - Biyagama 220kV Transmission Line" – This is an inaccurate statement based on wrong interpretation of the reset characteristic setting as explained in the report. **Minimum drop out differential for protection class CTs is 15mA**. This will be 30A primary when CT ratio is 2000/1A. This results in the drop out value of 58A when the setting is 80A. (80*1.1-30) irrespective of reset characteristic. Hence the reset setting of Disk Emulation or Instantaneous will not have any impact on the tripping of Line 1 as incorrectly mentioned in multiple occasions in the report.

3.3 Executive Summary – Comment 3 (Page xi)

Quote:

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.

Unquote

CEB Response:

As the concluding remark of the Executive Summary, the committee recommends a formal investigation by the law enforcement authorities assisted by independent IT experts to determine whether or not any human intervention has taken place. However, we are compelled to strongly defer on this conclusion based on the following :

1. The committee has accepted the fact that settings of Main 1 relays have not been tampered with in their statement in Page 40.

2. However, the committee has mis-interpreted the false "User Logged Out " events in Main 2 relay as a deliberate attempt to tamper the Main 2 relay, which could not hold true after receiving the OEM explanation on 2022-02-11. Further the Main 2 relay has **not issued any tripping** on 2021-12-03.

4 CEB Responses to Chapter 2

4.1 2.2 Failure of Kothmale - Biyagama transmission Lines (Page 12)

Quote:

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.

Unquote

CEB Response:

The CEB submitted the above calculation to prove that there has been an actual fault in the primary side NOT as "the cause of the tripping of phase B of circuit 2". The message which CEB needed to covey was that Zero Sequence current flowing out of Kothmale Circuit 2 from 220kV Bus Bar of Biyagama GSS is equal to Zero Sequence Current flowing in from all other Circuits connected to 220kV Bus Bar of Biyagama GSS. (viz. Kirchhoff's current law [1st Law] states that the current flowing into a node [or a junction] must be equal to the current flowing out of it.)

Further the Protection Engineers never rely on the time synchronization of DFR's at two ends of a transmission line for failure analysis, since the same can be performed more reliably by manually identifying the synchronized points of the wave forms.

4.2 2.2 Failure of Kothmale Biyagama transmission Lines (Page 14)

Quote:

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 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 (IN) is taken as the input. Accordingly, when IN exceeds a certain threshold, the end-fault tripping is activated.

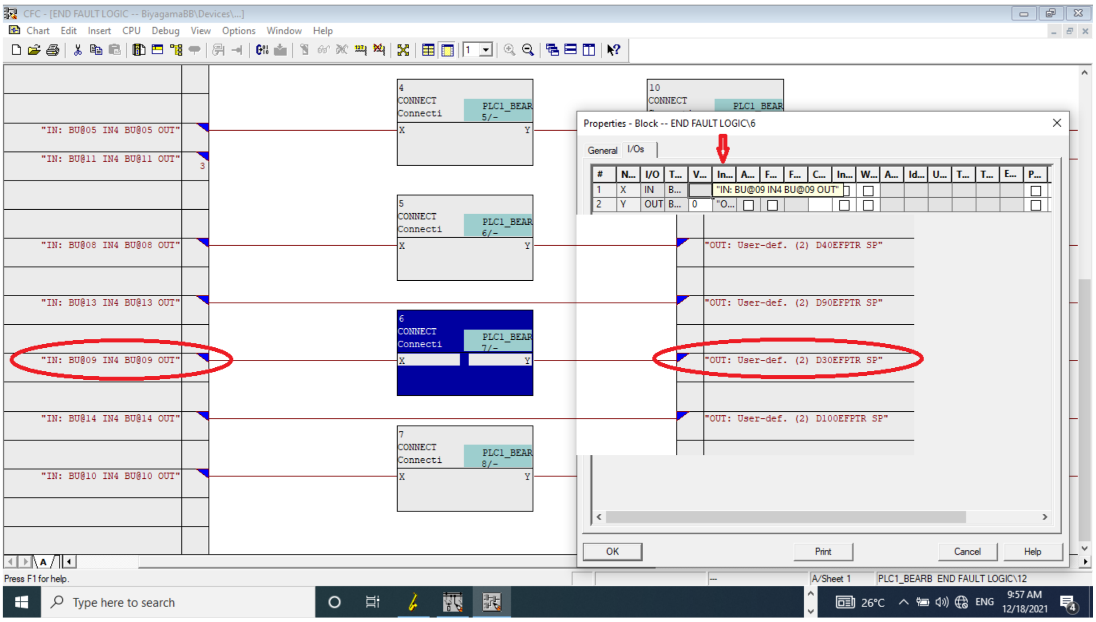

Figure 4.2-1 CFC logic diagram of End-Fault Function Implementation in the SIEMENS 7SS522 Relay

Unquote

CEB Response:

In Siemens 7SS52 BusBar Protection Scheme, the trip decision of End Fault Protection (EFP) is carried out by the Bus Bar Protection Bay Unit of each 220 kV bay. Anyhow, these bay units are not compatible with the IEC61850 protocol which has been the one used in Biyagama to provide information of the relays to the Substation Automation System (SAS). So, the busbar central unit which is compatible with IEC61850 protocol has been used to provide the operation of end fault protection indication of each bay to the existing SAS by taking the same information of the bay unit to the central unit through a proprietary protocol existing between the two relays. So, the CFC logic diagram depicted in the committee report is only used to send the indication of end fault operation of each bay unit to BB central unit and thereby to the SAS. The input “IN: BU@09 IN4 BU@09 OUT” in the left side of the Figure is used as the 4th digital signal of bay unit 09 (Kothmale 02) shared with the central unit. The text “IN: ” has been used to represent an input in the CFC logic diagrams & the same “IN: ” can be clearly seen in front of all the inputs in CFC logic sheets as well.

Accordingly, the Committee has misinterpreted a CFC Logic used for communication between bay units and central unit and determined that End Fault Protection depends on a neutral current (IN) which is not true.

4.3 2.2 Failure of Kothmale - Biyagama transmission Lines (Page 15 and Page 20)

Quote:

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.

Unquote

Quote:

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.

Unquote

CEB Response:

Generally, the "CB Close Command" is taken to the end fault logic as a leading information of a probable CB closure. That input is very important as there is a possibility that during a CB close operation, the busbar relay might capture the bay current just with the closing of the CB but before receiving the "CB Closed" status feedback to the relay and issue a trip command erroneously by it's the end fault logic. So, once the Busbar relay detects an issuing of a "CB close command", the end fault protection will be inhibited for a 200ms delay by the relay as a precautionary measure to allow receiving the "CB Closed" status feedback to the relay.

The 7SS52 relay technical manual doesn't mention a condition that end-fault protection shall be inhibited in the presence of another fault (meaning power system fault) as stated by the Committee as well. The statement "The end fault protection is blocked if the monitoring of the switching status feedback has detected a fault." in the relay manual refers to the failure of the CB status feedback to the relay, not about a power system fault. It seems the committee has mis understood the "switching status feedback fault" to a "power system fault". Following table illustrate the same in the relay manual.

Table 4.3-1 Alarms related to the circuit breaker status

Binary input			Status of the circuit breaker	Alarm
CB OPEN	CB CLOSED	CB CLOSE command		
0	0	0/1	Failure	"CB fault $01" (FNo. 176.1136/CU)
0	1	0	Closed	Closed
0	1	1	Closed by CLOSE command	"CB fault $01" (FNo. 176.1136/CU)
1	0	0/1	Open	Open
1	1	0/1	Failure	"CB fault $01" (FNo. 176.1136/CU)

As per the below logic diagram, the end fault protection of the SIEMENS 7SS52 relay uses "Bay Current" value for the operation of the end fault protection. It uses the current value of "I>BF" setting as the threshold value for the end fault protection, which is 500 A in this case. Further, under the section "5.3.2 Setting Notes" related to the "Circuit Breaker Failure Protection" in the same manual, it is clearly mentioned that the parameter "I>BF" is also used for the function "End Fault Protection".

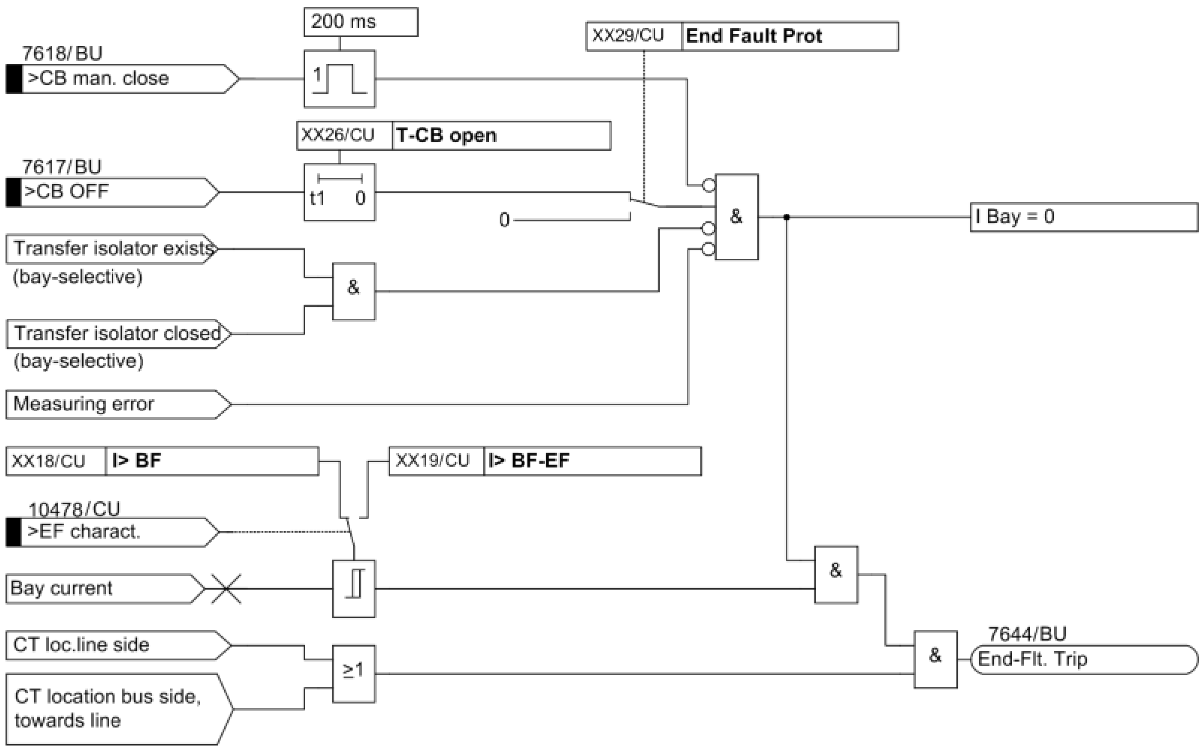

Figure 4.3-1 End Fault Protection Scheme Block Diagram

While CEB agree with the Committee that End Fault Protection should have received serious consideration of protection staff but as per CEB explanation submitted above the following statements made by the Committee with regard to End Fault Protection Scheme are not correct.

- End-fault protection function does not mention that the current should be higher than 500 A or any other threshold for end-fault protection to operate.
- The end-fault protection should have been inhibited under the conditions that existed on failures occurred on 2021-11-29 and 2021-12-03.

4.4 2.2 Failure of Kothmale - Biyagama transmission Lines (Page 26)

Quote:

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" (in the signed report "Disk Emulation").

Unquote

CEB Response:

Minimum drop out differential for protection class CTs is 15mA. This will be 30A primary when CT ratio is 2000/1A. This results in the drop out value of 58A when the setting is 80A. (80*1.1-30) irrespective of reset characteristic. Hence the reset setting of Disk Emulation or Instantaneous will not have any impact on the tripping of Line 1 as incorrectly mentioned in multiple occasions in the report.

4.5 2.4 Access to relays (Page 35)

Quote:

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.

Unquote

CEB Response:

CEB has noted that the Committee has made an incorrect determination that Main 2 Differential Protection Relay has operated on 2021-12-03.

None of the Main 2 (MiCOM) relays have operated during the incident on 2021-12-03. In line 2, the differential current is around 520A. As per the algorithm of differential function of Main 2 relay, fault has not entered the tripping region.

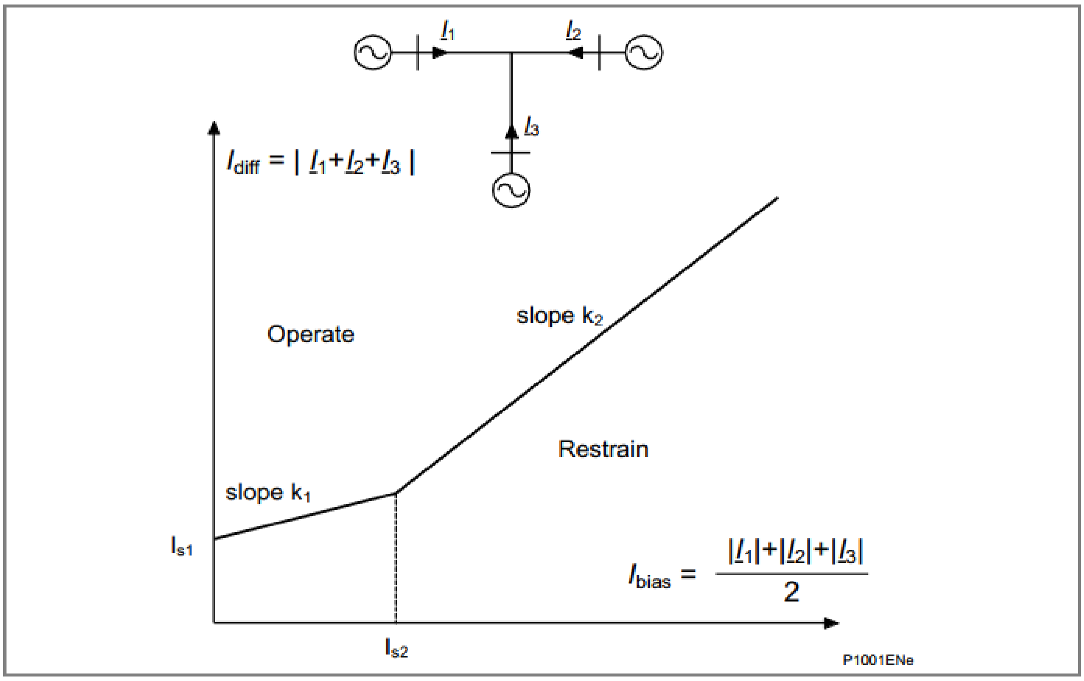

Figure 4.5-1 Relay bias characteristic

Table 4.5-1 Calculation related to Tripping Characteristic of Main 2

Relay Settings							
Kothmale End				Biyagama End			
Is1	Is2	Slope K1	Slope K2	Is1	Is2	Slope K1	Slope K2
0.2	2	30%	150%	0.2	2	30%	150%
CT Ratio Biyagama					2000		
CT Ratio Kothmale					2000		
Faulty Phase (in R,Y,B notation)					B Phase		
Total Current Biyagama B Ph (A)					868		
Total Current Kothmale B Ph (A)					359		
Bias Current(A)					613.5		
Min Primary Diff. Cur Requirement for Tripping(A)					584.05		
Diff. Current Observed (A)					540		

As per the above calculation Differential Current Observed (540 A) does not exceed the Min Primary Diff. Cur Requirement for Tripping (584.05 A).

Accordingly, Main 2 relays in circuit 2 did not operate, which is also further confirmed by the analysis of relay events and disturbance records of Main 2 relays, in contrary to the statement of the Committee that both Main 1 and Main 2 relays have operated in parallel for the fault in Biyagama - Kothmale circuit 2.

4.6 2.4 Access to relays (Page 36)

Quote:

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.

Unquote

CEB Response:

Initially, events of Main 2 relays were not downloaded since they have not operated during this incident. Later, when it was downloaded all records were available in correct order. Further the OEM has confirmed that event lists cannot be partially deleted.

4.7 2.4 Access to relays (Page 37/38)

Quote:

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.

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.

Unquote

CEB Response:

This erroneous conclusion of the Committee is due to the fact that they have not received OEM's response on time. However, CEB has submitted the complete answers received from OEM to the Committee/Ministry with AGM (Transmission)'s letter dated 2022-02-18. Response received from OEM is reproduced below.

Atten: Eng. P. H. Hendahewa
Additional General Manager (Transmission)
Office of the Additional General Manager - Transmission
Ceylon Electricity Board
4th Floor
No 50, Sir Chittampalam A. G Mawatha,
Colombo 02,
Sri Lanka

Technical Query on Schneider Transmission Line Protection Relay (Model MICOM P545)
Ref: AGM(Tr)/DGM(Tr.C&P)/CE(PS) dated 15th January 2022

We Schneider Electric, thank you for the technical queries and pleased to clarify as below.

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?

If there is prolonged inactivity by the user after a successful logging into the relay (example during setting change) then the relay would be by default go to Access level-1 (User Logged Out On UI Level 1) **after 15 min** (pls see below fig) **complying the Cybersecurity compliant. However, If the user has set the password for Level-1 then the relay will go to Access level-0** (User Logged Out On UI Level 0) **by default.**

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"?

Ans: Yes, we cannot edit the events manually. The "User logged In" events will occur when we try to login the relay by entering the password under System Data or when we change the settings in the relay using password.

3. Can anyone delete "User Logged In event", if any?

No, it is not possible to delete any single event like "User Logged In event**" as mentioned in the relay manual as per Cyber Security compliance.**

4. Is it possible to delete Event log completely, ex. all the 1024 events?

- **Deleting of events are possible by 3 ways as follows**

  1) Through HMI, under Submenu Record Control --> Clear Events
  2) Through Easergy studio, supervise device --> Clear Events (Refer attached file-clear events)
  3) By removing batteries and turning of the relays.

  Please note partially deleting events are not possible.

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http://www.schneider-electric.com

Schneider Electric

5. Is it possible to delete part of the event log? Ex. selected events.

Ans: No, we cannot partially delete the 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?

Ans: Yes correct, the unique ID confirms us if there is any missing events in between. As long as the unique ID sequence of events appeared, it is assured that the events are not missed out.

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?

Ans: Someone pressed the clear button from the password option window in the system data menu of the relay continuously which leads the relay to "UI logged out" event appears continuously.

Video link for reference: https://schneider-electric.box.com/s/e0mqcogii4d8b7wlgbxl23g6mzpai8jb

Thank you

Schneider Electric Lanka (Pvt) Ltd

Indika Adikari
In the capacity of: GM-Power Systems
Date: 11th February 2022

5 Lak Vijaya Power Plant

5.1 4.5 Recommendations

Quote:

Loss of LVPP for at least 3 days is a repeated occurrence after a total 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:

Procuring a control system to assist in managing the drum water level during FCB mode operation following a system disturbance,

Installation of a turbine-driven steam-based feed pump, and

Procuring a facility to provide auxiliary power to achieve a safe shut down.

Unquote:

CEB Response:

CEB notices that committee has recommended three tasks as a solution to resolve the auxiliary supply issue of LVPP during a grid failure. Before to comment on solution, CEB wishes to explain the FCB operation of Lak Vijaya Plant as follows for proper understanding of the system.

LVPP Fast Cut Back (FCB) operation (House load operation)

Under normal operation, LVPP unit is able to supply its auxiliary requirement while delivering power to national grid. In an event of blackout due to an external fault (and not due to any operation of unit Protection) LVPP generator is able to deliver its house load by disconnecting from the grid. In this mode, unit is operating in islanding mode to control the frequency and voltage. Earlier, FCB operation was not successful and with improvements those have been done to the system, FCB operation was able to stabilize.

FCB mode is activated only by three schemes;

- Due the operation of rate of change of frequency (df/dt) protection
- Low forward power protection (this scheme is implemented in the protection system as well as control system)
- Manual opening of generator circuit breaker

In addition to this unit 02 of LVPP is set to go into FCB, if its OPC (over speed protection control) had operated at 3,078 rpm.

To safe shutdown of the machine, Generator should be stopped while keeping the supply to house loads. Therefore, house load should be transferred to some other source without any interruption before stopping the generator. Even though a separate power supply system is arranged, most important part is to transfer house load to that separate power supply without any interruption.

With the above detailed explanation CEB comments on three recommendations under section 4.5 (page 47 of the committee report) are given below;

(i)- Procuring a control system to assist in managing the drum water level during FCB operation following a system disturbance;

LVPP Units have a control system supplied with the power plant construction. The OEM of the system is Emerson Process Management; the product name is Ovation, which is a reputed and largely used control system in coal power plants. During the past, the Control System has always safeguarded the LVPP units.

Machines installed in LVPP, has designed to run at full capacity as base load plants. Therefore, three element drum water level control system has been implemented to control the drum water level at higher and stable loading conditions. It is a proven and optimized technology used by most of the power stations.

But when it operates in low load, no sophisticated drum water level control has been designed due to the fact that the unit has been not designed to run continuously in low load condition. In low load conditions like in start-up and FCB, drum level is controlled by the operator manually. In such low flow instances, the flow readings from the sensors are also not accurate since the flow changes are below the accuracy class of the instruments.

Major reason to fail the FCB operation in prior occasions was the drum level control (in low load). Shrink and swell effects in the boiler dominate in low load conditions. Therefore, while the unit is in FCB mode, disturbance to the main steam pressure was studied and actions were taken to minimize such disturbances to stabilize the drum water level. With that improvement, drum level control was improved while in FCB mode.

Purchasing of new water level control system will be an added advantage in FCB mode. But water level control system could not operate independently without controlling many other associated sub systems. Therefore, purchasing a new standalone drum water level controlling system is not practical, since it cannot work independently. However, if an integrated, proven, standard solution is available for boiler drum level control during a FCB situation, it will be an advantageous. Considering the requirement to integrate the new boiler drum water level control system with existing instruments, sub systems and the Emerson Ovation DCS, the procurement shall be conducted from the OEM of the Existing DCS (subjected to the condition that they too can provide such an updated, proven and standard system) to control boiler drum water level during a dynamic situation like FCB.

(ii) Installation of turbine-driven steam-based feed water pump.

Present configuration consists of 3 number of electrical driven feed water pump having the capacity of 5.4 MW each. Two numbers of pumps are operated when the unit is run at 300 MW. The pumps are capable to continue operation during the FCB mode operation.
Installation of steam-based feed water pump alone is not a complete solution to avoid the consequence occurred during total failure in the absence of auxiliary power for other critical sub systems in the water steam cycle.

Introducing an additional steam driven pump now into the existing system is complex and technically not feasible due to the following reasons.

1. Steam driven pump demands larger space. It consists of large size of pipe line, hydraulic driven governing system, bearing lubricating system and cooling system. Also, it’s difficult to connect new line to the existing system since existing pipe lines are in very compact space. Practically there is no space in the turbine hall.
2. Even though steam exists in the boiler after blackout tripping, it may not be qualified to admit in to the pump. Before admitting steam in to turbine of the steam driven pump, steam quality (Pressure, temperature, degree of superheat etc.) should be maintained.
3. Exhaust of the turbine of the steam driven pump should be dumped to a separate condenser as existing main condenser cannot be used during a blackout.
4. The existing steam requirement is designed without considering the requirement of Steam driven BFPs, hence there can be a drop in the total efficiency. Normally steam driven BFP are introduced to enhance the efficiency of the cycle and generator net output at the design stage.
5. Even the turbine of Steam driven BFPs is designed to run at a scenario of unit tripping due to blackout, it should have some steam flow rate to heat up the unit to load it quickly. Therefore the

auxiliary system of Steam driven BFPs (lube oil, cooling, hydraulic system and separate condenser) should be in running condition using separate uninterrupted power supply.

Installing of new Steam driven BFPs will affect the fundamental design of the steam cycle and hence it will reduce the efficiency of the unit. Considering the above facts and since it is not a complete solution for blackout tripping, installing of new Steam driven BFPs is not a total solution.

(iii)Procuring a facility to provide auxiliary power to achieve a safe shutdown

Auxiliary power supply for LVPP could not be readily procured from the open market and it requires immense R &D works to be performed before any feasible solution is attained and this solution has to be an in-house technical solution with the support of original equipment manufacturer (OEM). Since this power plant has many complicated control systems, it is necessary to refer to the design institute of the power plant through the EPC contractor and need to get their recommendations for the technical solution. Since this power station is very vital and auxiliary supply solution is a major modification, it is not advisable to go for a technical solution without having consent of the design institution. The procuring of the system can be started afterward. Details of the proposals and the present progress will be discussed under the **CEB's Response for Recommendation No.2** of the committee report.

6 CEB Response to Summary and Conclusions

6.1 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.

CEB Response:

While we agree that a snapshot of the system indicates that system was in a stable state, we do not agree that the system is healthy as under mentioned contingencies could have resulted in a total collapse of the system.

If a double circuit multiphase or three phase fault is occurred in Biyagama – Kothmale Line 01 and 02 and

1. Fail to auto reclose due to failure of equipment to properly operate due to available system conditions (such as delayed operation of Protection Relay, Circuit breaker etc.)

2. Fail to auto reclose due to Check Synchronizing function is not giving clearance to close the circuit breakers as a result of difference in phase angle or difference in frequency between two ends of the line compared to setting.

Note: The phenomena explained in the above item no. 2 was observed for partial failure occurred on 2021-11-29 in Biyagama – Kothmale Line 02. This line got tripped and auto-reclosed from Kothmale end but check synchronizing conditions were not met at Biyagama end and therefore auto-reclosing was not allowed from Biyagama end. The details of frequency recorded in Ben Digital Disturbance Recorders are as follows.

At the time the auto-recloser tried to close the line i.e. after about 0.8 sec

Frequency at Biyagama Bus Bar	- 49.991 Hz
Frequency at Kothmale Bus Bar	- 50.473 Hz
Frequency Difference	- 0.482 Hz (Setting in the Relay is 0.1 Hz)

In order to improve the system reliability under the above contingency condition CEB has initiated an alternative Transmission corridor between Mahawali Complex Power Plants located in central province and Load Centre in Western Province via Kothmale-New Polpitiya – Padukka – Pannipitiya 220 kV Line. Therefore, until such Transmission Links are in place, we cannot say the system is operating in a healthy condition under maximum hydro running condition.

In the present transmission planning context, we do not plan the system to be stable under N-2 contingency criteria. System was stable at steady state condition prior to transmission line trippings. However, it does not mean that system is at healthy state prior to tripping of Kotmale-Biyagama circuit 01 as transmission network is being operated as number of radial circuits although it is designed to be operated as ring network. If transmission network is operated as ring network, it is impossible to maintain the N-1 reliability criteria of some critical transmission lines due to delaying of number of critical transmission line projects. Consequently, system is prone to frequent major/total system failures in case of tripping of critical transmission lines. Making system into few radial networks, reliability of sub networks is compromised to achieve the overall system reliability. Under those circumstances, it is not reasonable to justify that system is running in healthy condition.

6.2 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).*

CEB Response:

CEB has provided evidence, based on the fault recorders in the relays and digital disturbance recorders, to substantiate the presence of an actual fault in the primary side. Committee has sought definitive proof for the cause of the primary fault, while acknowledging the fact that transient faults do not leave permanent proof in most of the cases. CEB has submitted evidence of a fire directly under the transmission line coinciding with the time of the fault and located within 5% of the calculated distance whose smoke could have triggered a flash over to a nearby vegetation resulting in a high impedance fault which was adequate to operate the line differential protection in Main 1 relays. On the other hand, definitive proof of the cause of the fault on November 29th is not available, though it is quite clear that a simultaneous fault of the magnitude of 3kA involving multiple phases of both 220kV circuits cannot be man-made.

Summary of findings by CEB on the fault which triggered the tripping of Biyagama – Kothmale Line 02 are as follows:

- Biyagama – Kothmale Line 02 tripped due to a transient high resistant earth fault.
- The information recorded in Digital Disturbance Recorders and Relays installed at Biyagama Grid Substation and Kothmale Power Station are sufficient to prove that there was an actual primary earth fault.
- When analyzing the past trippings of 132kV and 220kV Lines it was found that most of the time (around 95%) physical evidence for primary cause of the fault is not found.

Detailed analysis of this incident by CEB which has also been submitted to the committee is reproduced below.

Kothmale – Biyagama line 2 has tripped due to the occurrence of C phase (in ABC notation) to Earth fault (Differential current of 521 A) in the primary side. This fault current has been recorded in Main 1, Main 2 relays and the BEN6000 Digital disturbance recorder at Biyagama GSS. The recorded waveforms from these equipment are shown below:

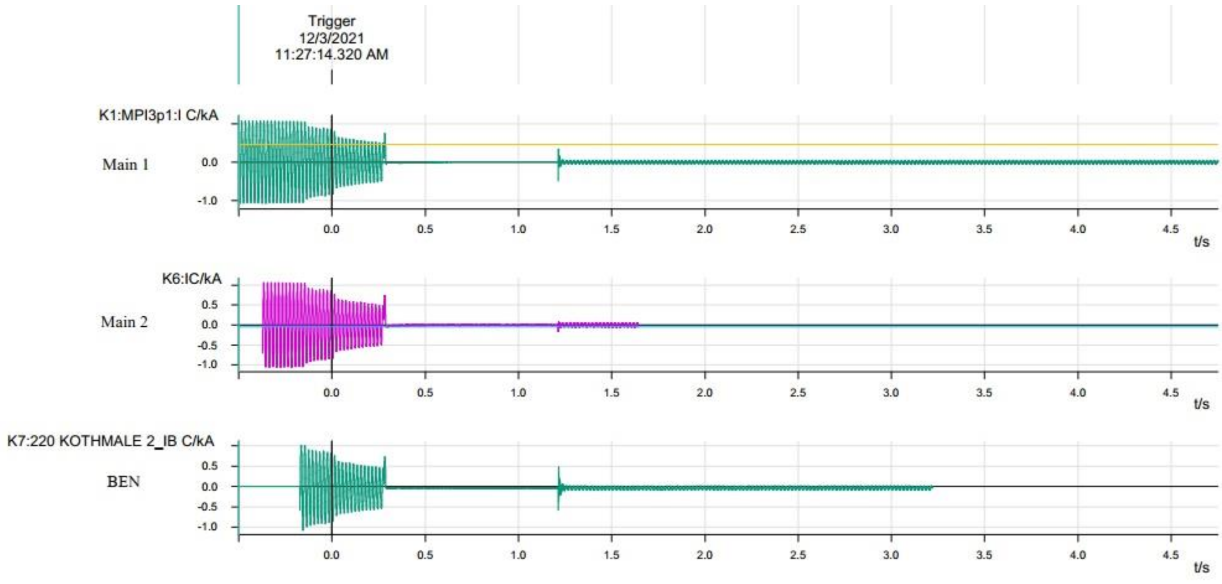


Figure 6.2-1 Current waveforms seen by Main 1 relay, Main 2 relay and DDR at Biyagama GSS – Kothmale line 2 C phase (in ABC notation)

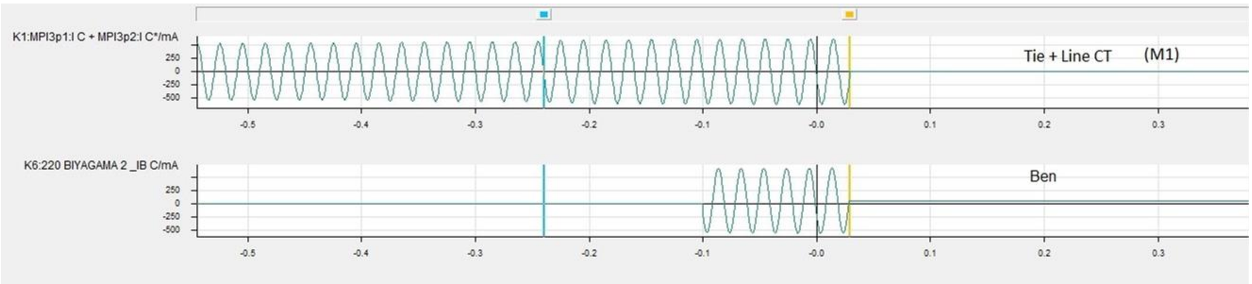


Figure 6.2-2 Current waveforms seen by Main 1 relay and DDR at Kothmale PS – Biyagama line 2 C phase (in ABC notation)

The Main 1 Protection Relay and BEN6000 Digital Disturbance Recorder at Kothmale have also recorded the fault current fed into C phase (in ABC notation) to Earth fault. Screen shots of all the available waveforms of this incident recorded in different devices in both ends of the line are included in Annex 6.1-1.

In above two figures, the waveforms have been arranged with respect to the waveform that consist longest pre fault information. Pre fault recording of each device are as below.

M1 – 0.5 seconds memory before trigger
M2 – 0.66 seconds memory before trigger
DFR – 0.1 seconds memory before trigger

A differential current above 400A will instantaneously trigger a tripping of the circuit breakers of both ends of the line.

Zero sequence current fed to the fault from Biyagama end is approximately 431.36A and a zero sequence current of 89.91A could be observed in the fault records in Kothmale end of Line 2. Additionally, it is observed that the summation of zero sequence currents observed in all connected 220kV bays at Biyagama GSS prior to the tripping of Kothmale line 02 closely equals the zero-sequence current flowing in Kothmale line 2. This zero-sequence current has been cleared with the tripping of phase C which confirms that there has been an actual earth fault in the primary side of Biyagama Kothmale line 02. (Please see Annex 6.1-2 for detailed calculation of zero sequence currents)

Accordingly, there is sufficient information from secondary equipment to decide that there has been an actual earth fault in the primary equipment. Further the fault is a transient in nature and the faulty phase has reclosed successfully from Biyagama end. Transient faults may not leave any physical evidence and hence the digital disturbance records available in secondary equipment is used for failure analysis.

Such transient faults may be caused by flash over due to lightning, way leaves, contact with kites, surface flash over / creepage of insulators due to dust, salt, smoke created by fires close to the transmission line. Etc.

As per the information submitted by the DGM (O&MS South), there is physical evidence of a man-made fire directly under the line which could very well be the possible cause of the tripping. This fire was located very close to the tower number 138 which is located 21.23km from Biyagama end. Photographic evidence of the fire is provided in Annex 6.1-3. Above mentioned facts confirm this incident could have led to the fault as reported in available DFR records etc.

It is noted that only Phase C (in ABC notation), which is the bottom conductor, has tripped in this incident. Additionally, as per the witness statements the timing of the fire matches the tripping time of the transmission line. Based on the fault currents calculated distance to the fault is approximately 24.1 km from Biyagama GSS. (Fault distance calculation provided in Annex 6.1-4) Accuracy of the calculation is limited due to the low fault currents involved, the errors in available line parameters and the measurement errors of CTs & CVTs. The O&MS staff has inspected the suspected range of the transmission line based on the initial calculated distance provided by the staff of C&P branch. As per calculation done by C&P Branch using the information collected from the Protection Relays the location of the fault is close to the location of fire. Considering the total length of the line, 70km, actual location of the fire lies within 5% error margin. However, fault impedance in this incident is very high. Hence flash over directly to the ground (through tower) cannot be considered in this case. Likely possibility is a flashover to a nearby tree. A case study of a similar incident involving a very high resistant fault in a 525kV transmission line in Brazil is attached in Annex 6.1-5.
(*https://ieeexplore.ieee.org/document/4982523*).

The Committee has failed to justify the reason why the compelling evidence presented by CEB supported by DFR records, cannot be considered credible enough to be counted as a probable primary cause for the apparent earth fault of phase B of circuit 2.

As per the data available on the faults occurred in the Biyagama – Kothmale transmission lines, it is apparent that in all trippings involving transmission line faults, which is 19 in total, at least one end has reclosed successfully. Hence all of them have been transient faults. When the line has reclosed from one end, the system operation engineer can close the breaker at the end with permanent tripping without any issue. Hence the involvement of Operation and Maintenance engineers is minimum and it is highly unlikely that any physical evidence of the cause of line faults would ever be found. There is no recorded information of physical evidence for any of the above incidents.

A similar incident in which a high resistive fault, smaller than the load current, causing the operation of differential protection could be observed on 2019-10-18, in which the line has reclosed. (Please refer figure given below)

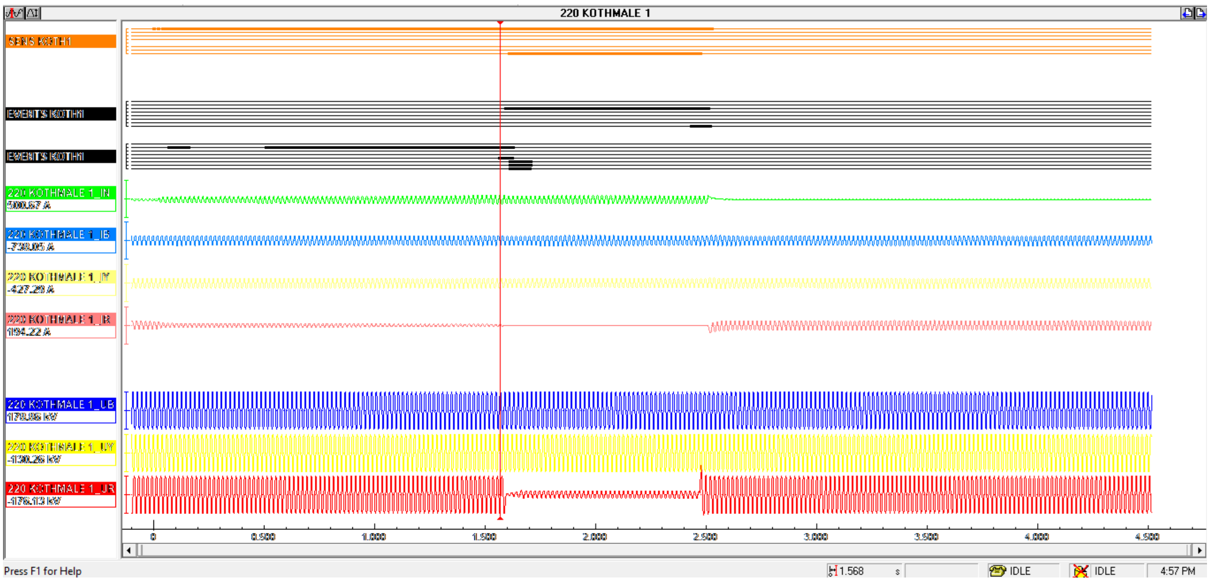


Figure 6.2-3 Ben 6000 DDR record of Kothmale line 1 at Biyagama GSS at 11:38hrs on 2019-10-18

As per the data obtained from transmission hotline maintenance unit for the period 2018-2021, there has been only 2 incidents in which the nature of the fault has been identified, out of all the trippings of the 220kV transmission lines in CEB network.

Table 6.2-1 Summary of Breakdowns -220kV Lines

No	Year	Total No of 220kV line trippings	Number of Breakdowns in which cause identified by hotline unit
1	2018	11	0
2	2019	18	0
3	2020	25	0
4	2021	28	2

Further a summary of breakdowns of all incidents involving 220kV and 132kV transmission lines is given below. This clearly demonstrate that majority of line trippings are of transient in nature and physical evidence may not be available.

Table 6.2-2 Summary of breakdowns of all incidents involving 220kV and 132kV transmission lines since 2018

Year	Total no. of transmission line trippings	Number of Breakdowns in which cause identified by hotline unit	Percentage (Nature identified)
2018	300	11	3.67%
2019	247	8	3.24%
2020	185	2	1.08%
2021	210	8	3.81%

Finally, **CEB considers there is a serious lapse in the Committee Report** due to the fact that non consideration of man-made fire under the line with other circumstantial evidence viz. photographs obtained from the site of fire, time of the fire matches with time of Total Failure, location of the fire directly under the line, physical distance to location of fire matches approximately with the distance calculation done using current and voltage waveforms recorded in the protection relays, the bottom conductor at the location of fire is C phase (in A,B,C notation) and protection relays have also reported C phase to ground fault. Etc. **as a possible primary cause for the line fault**.

6.3 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 erroneous 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 relay 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.

CEB Response:

CEB has provided all available evidence in relation to the error in field wiring which resulted in the unintended operation of end fault protection. We wish to state the following in that regard.

1. In the preliminary report submitted to the committee on 2021-12-09 CEB itself had stated that there appear to be a discrepancy in the End Fault Protection Scheme. Further CEB had also requested permission to investigate and rectify the observed discrepancy in the end fault protection scheme of the busbar protection relay at Biyagama GSS. This document seeking the permission to investigate and RECTIFY the error has been duly informed to Total Failure Investigation Committee.

2. As there is an ongoing investigation CEB had refrain from carrying out any rectification work immediately in order to maintain statuesque until the Committee visits the sites.

3. The Committee had visited the relevant sites by 2021-12-11 and had collected all the evidences related to the incident.

4. Thereafter CEB staff were granted permission to investigate and rectify the fault as mentioned under #1 above as keeping possible error in the scheme could lead to a similar total failure. (The Committee never instructed CEB not to carry out any changes/rectification work pertaining to equipment connected to failure despite being informed of the CEB intention to do so under #1 above.)

5. Thereafter the visiting CEB staff had observed an error in physical wiring containing the circuit status information and rectified it at site on 2021-12-26 and 2022-01-02. This has been duly reported and recorded. Thereafter it has been reported to the Committee as well on 2022-01-07.

6. CEB later found confirmation that this error in wiring was in existence even in commissioning drawings that dates back to 2015, eliminating the suspicion that this change in wiring has been carried out recently/deliberately.

7. The above list of incidents clearly indicates that CEB has acted transparently and had kept the Committee duly informed of all its actions and conclusions.

6.4 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.*

CEB Response:

General failures occurring in the transmission network that do not escalate up to a major or total failures are not being analysed up to the same extent of a total failure due to limitation of available resources and time. CEB admit that had these individual incidents have been analysed up to that extent this issue could have been identified earlier.

6.5 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.

CEB Response:

While we appreciate the analysis done on the configuration of earth fault relay of circuit 1 by the Committee, we cannot agree on following two points.

1. It is inaccurate to say that loss of circuit 1 could have been avoided if the earth fault relay of circuit 1 had been configured for "Instantaneous" reset. Reset characteristic comes in to picture when the current reaches drop off threshold value. When the pickup setting is at 80A, the drop off value is 58A irrespective of the fact whether reset setting is instantaneous or disk emulation.

   Minimum drop out differential for protection class CTs is 15mA. This will be 30A primary when CT ratio is 2000/1A. This results in the drop out value of 58A when the setting is 80A (80*1.1-30) irrespective of reset characteristic. Hence the reset setting of Disk Emulation or Instantaneous will not have any impact on the tripping of Line 1 as incorrectly mentioned in multiple occasions in the report.

   CEB staff tested the performance of the Earthfault Protection function and confirmed the following by simulating the zero-sequence current observed during the Total Failure using Omicron test set.

   (a) Relay operating time is around 22 seconds.
   (b) Relay pickup threshold is 88A when pickup current is set for 80A

(c) Relay drop-off current is 58 A when pickup current is set for 80A

Further it was confirmed that above test results do not change whether the relay reset characteristics is set for instantaneous or disk-emulation

2. It is incorrect to say that Main 2 relay has operated during the Earthfault in circuit 2. None of the Main 2 Schneider Protection Relays were operated in Biyagama – Kothmale Line 01 and 02 on this day.

6.6 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.

CEB Response:

CEB observed that the statement of the Committee, the Main 2 relay has operated is incorrect. As Main 2 relay has never operated, any access to Main 2 relay has no relevance to the incident. However the Committee has made an erroneous conclusion based on the following event list of Main 2 Schneider Protection Relay of Biyagama – Kothmale Line 02 at Biyagama GSS, where 7 logged out attempts were observed within one minute interval on this day at 8.33 am.

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

Figure 6.6-1 Event List of Main 2 Schneider Protection Relay of Biyagama – Kothmale Line 02 at Biyagama GSS

CEB investigation on these events found that no one has accessed the Main 2 relay of Kothmale line 2 at Biyagama GSS at the mentioned time on 2021-12-03 using the password. The event "User Logged Out On UI Level 1" correspond to pressing "Clear" button on relay seven times to clear relay LED indications.

The CRO had pressed "Clear" key from the HMI of the relay seven times within one minute period, when HMI was at "Password" selection option window of the "System Data" menu. This event has been confirmed by recreating using a relay of similar model by the staff of Protection Systems Unit.

Further it has been confirmed that there has not been any deletion of relay events by examining the continuous unique id of each event.

6.7 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.*

CEB Response:

Safe shut done of LVPS is required only if units are running on house load. However, during the failure occurred on 2021-12-03, LVPS unit 01 and 02 had tripped completely. Hence, there was no such urgent requirement to extend the supply to LVPS. However, it has been decided to start the LVPS unit 02 which was under maintenance. Accordingly, later, LVPS requested to energize the Norochchole 220kV bus. Thus, Auxiliary supply extension process started around 12.30 hrs.

One Upper Kotmale unit and one Kotmale unit were used for the LVPS auxiliary supply restoration during the trial. Minimum active power required to run the above two machines in stable is around 40 MW. Two units were used to enhance the capability of the generators to absorb the total reactive power generated by Kotmale- New Anuradhapura and New Anuradhapura-Lakvijaya 220kV circuits (42 Mvar). However, during the restoration process on 2021-12-03, two Upper Kotmale units had to be used instead of one Kotmale and one Upper Kotmale unit. The total minimum load requirement for the two Upper Kotmale units to run in stable mode is 60 MW. Therefore, more time was elapsed to energize more GSS to add more loads.

Further, Kotmale two 220kV bus bars had to be separated and one bus bar was used for Biyagama supply restoration and other bus bar was used for LVPS supply restoration. Although bus bar separations and 220kV line isolations were pre-arranged during the trial, It took more time during real condition than in trial restoration process. One has to consider that during the trial, there are Engineers/ESS/ Staff on standby at relevant GSS, however during the actual restoration such staff is not available and only the normal staff is available. Further, during a trial all prerequisite system requirements are made available, which cannot be done in an actual situation

6.8 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.*

CEB Response:

Responses for issues; (a) to (g) in the description above are given below.

(a) *Kotmale power station due to unexpected PRV operation in a CB of the circuit 1 of Kotmale-Biyagama 220 kV transmission line -* This is explained under Recommendation 4 – Delays in Restoration, item (*i)*

(b) *Failure to indicate receipt of fault signal at CB of circuit 2 of Kotmale-Biyagama 220 kV transmission line at the Kotmale end* - Control & Protection Branch of Transmission Division is planning to establish an alarm indication for the operation of CB lockout relay at circuit 2 of Kotmale-Biyagama 220 kV transmission line at the Kotmale Power Station.

(c) *VT failure at Embilipitiya on Samanalawewa circuit 1*,

(d) *unknown errors in Sapugaskanda-Kelanithissa circuit 1 and Kelanitissa-Colombo Sub L 220 kV underground cable -* Response for issues related to item (c) and (d) are given below.
Though the committee report mentions about possible delays in restoration due to suspected technical faults in Substation L, Embilipitiya and Kelaniya (mentioned as Kelanitissa due to oversight) grid substations, no such technical faults were found at the particular locations. In any case issues from these substations have not resulted in a significant delay in the restoration process.

(e) *Generator 2 differential protection operation in the New Laxapana power station -*
New Laxapana Unit #02 generator had tripped on under frequency protection (81U). However, while unit was in shut down sequence there was an operation of unit differential protection (87U).

The reason for operation of 87U protection could be due to large internal currents drawn by main transformer due to over fluxing condition.

Since after an operation of differential protection in a generator or/ transformer, it is a mandatory requirement and practice in CEB (and world over) that all equipment in the zone of protection, are inspected and tested for any failure/damage. These basic tests have cause delays to release the unit for system restoration.

However further studies too are underway by relevant branches to find the reasons for larger currents at over fluxing condition.

(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 -* This is explained under Recommendation 4 – Delays in Restoration, Item (iv)

(g) *Hotline communication failure in the 48 V DC communication system in the New Anuradhapura GS.*

The communication channel for the hot line telephone is provided via the Fiber Optic Multiplexer of type FOX 615 at New Anuradhapura GS. It has been powered up with the 48V DC auxiliary supply system (with a 110 Ah Battery bank and a battery charger). Upon the failure of AC supply at GS on that day, the Fiber Optic Multiplexer had been powered up by the battery bank for around duration of 2 hours. The battery bank has drained after two hours of time and the power supply for the Fiber Optic Multiplexer has been lost. But it has restarted after 5 minutes with the availability of auxiliary supply to the GS. Therefore, the hotline telephone of the New Anuradhapura GS has failed for about 5 minutes duration.

7 CEB Responses to Recommendations

7.1 Recommendation 1 – Formal Investigation

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.

CEB Response:

There is no basis for this recommendation since it has been based on inaccurate assumptions.

1. **(a) unnecessary operation of the *end-fault* protection -**

   The very fact that there were two similar previous incidents of operation of end fault protection, including on 2021-05-11, negate the fact that it has been intentionally done. As per Control and Protection Branch investigation, this erroneous wiring had occurred during the time the circuit breakers were installed in 2015. Further the Marshalling Kiosks related to erroneous wiring are locked and keys are kept under the custody of Control Room Operator. Hence there cannot be any unauthorized access to this equipment without informing the operational staff on duty at Grid Substation. i.e. CRO and Security staff.

2. **(b) unnecessary operation of the *earth fault* protection of circuit 1 of Kotmale- Biyagama 220 kV transmission line due to alleged wrong configuration of the line protection relay of circuit**

This is a completely inaccurate statement based on wrong interpretation of the reset characteristic setting as explained in the report. Minimum drop out differential for protection class CTs is 15mA in Siemens 7SL relays. This will be 30A primary when CT ratio is 2000/1A. This results in the drop out value of 58A when the setting is 80A. (80*1.1-30) irrespective of reset characteristic. Hence the reset setting of Disk Emulation or Instantaneous will not have any impact on the tripping of Line 1 as incorrectly mentioned in multiple occasions in the report.

3. **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.**

It has to be noted that Main 2 relay has not been tripped during this incident. CEB has explained this fact to the Committee which has not been given due consideration.

CEB wish to explain that during any of these events no one has accessed the Main 2 relay of Kothmale line 2 at Biyagama GSS at the mentioned time on 2021-12-03 using the password. This has been officially informed to the committee by way of the letter from OEM.

The event "User Logged Out On UI Level 1" correspond to pressing "Clear" button on relay seven times to clear relay LED indications.

The CRO had pressed "Clear" key from the HMI of the relay seven times within one minute period, when HMI was at "Password" selection option window of the "System Data" menu. This event has been confirmed by recreating using a relay of similar model by the staff of Protection Systems Unit.

Further it has been confirmed that there has not been any deletion of relay events by examining the continuous unique id of each event.

4. **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).**

Approach of the committee is evident in the executive summary of the report in which it is mentioned ,

Quote

"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.***"**

Unquote

However, nature of the faults occurred in the Biyagama – Kothmale 220kV transmission lines on 2021-11-29 and 2021-12-03 are completely different.

On November 29, 2021,

Biyagama - Kothmale Line 1: R phase -E fault, Magnitude of the current ~2.3 kA

Biyagama - Kothmale Line 2: R phase- B phase -E fault Magnitude of the current ~3 kA.

On December 03, 2021
Biyagama - Kothmale Line 2: B phase -E fault, Magnitude of the current ~ 0.5 kA
Biyagama - Kothmale Line 1: Sustained zero sequence current ~70A subsequent to the tripping of the parallel line

CEB has provided evidence, based on the fault recorders in the relays and digital disturbance recorders, to substantiate the presence of an actual fault in the primary side. Committee has sought definitive proof for the cause of the primary fault, while acknowledging the fact that transient faults do not leave permanent proof in most of the cases. CEB has submitted evidence of a fire directly under the transmission line coinciding with the time of the fault and located within 5% of the calculated distance whose smoke could have triggered a flash over to a nearby vegetation resulting in a high impedance fault which was adequate to operate the line differential protection in Main 1 relays. On the other hand, definitive proof of the cause of the fault on November 29th is not available, though it is quite clear that a simultaneous fault of the magnitude of 3kA involving multiple phases of both 220kV circuits cannot be man-made.

The committee is of the view that they do not have any reasons to eliminate the cause as mentioned in scenario ii above, whereas CEB notes that the Committee has not found out any conclusive evidence to support the assumption that non-persistent fault in phase B was deliberately man-made.

However, CEB has no objection in carrying out an investigation after reviewing the CEB's Response by an independent protection expert.

7.2 Recommendation 2 – Auxiliary Power Supply for LVPP

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.*

CEB Response: Action by Addl.GM(Generation) / Plant Manager (LVPP)

Providing Auxiliary Power to LVPP from Upper Kotmale Power Station (UKPS)

Two trials have been performed to provide auxiliary power supply from UKPS to LVPP in the following instances.

1. 6 kV Bus Bar of LVPP was energized from the power supply from UKPS on 2020-12-03.
2. Unit #2 of LVPP was shutdown using the auxiliary power from UKPS on 2021-10-22.

At the first instance, Unit 02 of UKPS was started at 12.48 hrs. and the supply was extended to LVPP at 14.15 hrs. The time taken to energize 6 kV Bus Bar from UKPS is 1 hour and 27 minutes.
At the second instance, Unit 01 of UKPS was started at 14.00 hrs. and Unit 2 of LVPP was synchronized to UKPS power supply at 15.38 hrs. The time taken to synchronize Unit 02 of LVPP to power supply of UKPS is 1 hour and 38 minutes. The Unit 2 of LVPP was safely shutdown.
Time taken for both occasions are more than the OEMs recommended time for FCB mode operation, which is 30 minutes. Hence, this cannot be considered as a better solution for supplying auxiliary supply to LVPP. CEB will carry out further trials once the power system returns to a normal situation. However, in view of the criticality of LVPS, such auxiliary supply may not be a feasible option in a stressed situation, as experienced during the recent restoration process carried out.

Alternative Solution for Providing Auxiliary Supply to LVPP:

Two technical committees (TCs) have been appointed to find a technical proposal & solution for auxiliary power for LVPP.

In 2016, the first TC was appointed for this purpose and TC had studied 11 options in depth and arrived at a decision that the last option (Option No. 11) was the most technically feasible option as per the conditions prevailed at that time. The committee had submitted the report in September 2016 for implementation. However, the recommendation made by this technical committee regarding Option No. 11 was not implemented; mainly due to the cost, the complexity and outage requirements.

In 2021, the second TC was appointed to study the possibility of providing Auxiliary Power to Lak Vijaya Power Plant during blackout based on the Option No. 11 proposed by the first TC. This TC has submitted the report on 24^{th} January 2022 to AGM (Gen) with few modifications in Option 11 and is waiting for the approval to take the next steps.

The latest proposal, Option 11 hereafter referred as "**Technical Proposal for Auxiliary Supply of LVPP**" is summarized below;

Description	Option 11 ("**Technical Proposal for Auxiliary Supply of LVPP**")
Solution	• Emergency Diesel Generators with Rotary type UPS (without separate critical 6kV bus)
Capacity of Diesel Generators	• 36 MW (Three Units with 12MW capacity each)
Capacity of Rotary UPS	• 30 MW (Three Units with 10 MW capacity each)

Other requirements to fulfill	• Need to make considerable modifications in existing control system logics. • Need longer plant outages
Total Estimated Cost	• LKR 09 Billion

Note: The literature survey shows that backup supply schemes with Rotary Based UPS system are used in data centers, financial institutions, broadcasting, telecommunication networks, airports, healthcare facilities, continuous process production sites and applications where high quality power is needed. However, there is no proof for the application like power plants where huge dynamic loads are used.

Accordingly, present TC has requested further six months for finalizing and recommending the above proposal to the Management.

CEB is of the view that getting the consent of OEM of LVPP is essential before to process the above proposal. Therefore, once the TC is recommended the proposal, it is necessary to obtain the consent for the conceptual design from OEM. Thereafter, CEB may proceed for the detail design that could be done with the assistance of OEM and consultants.

Once the required designs are over and approvals are obtained from the Board, the remaining procurement and implementation process could be commenced. A descriptive Road Map for the procurement and implementation shall be prepared for following major events by the Project Management Unit appointed for this task after principal approval is received from the Board.

1. Preparing bid documents.
2. Obtaining necessary funds.
3. Land selection.
4. Conducting EIA study (If necessary) and Environmental Protection License.
5. Obtaining approval from PUCSL.
6. Calling Bids and obtaining SCAPC approvals
7. Physical implementation works.
8. Testing and Commissioning.

7.3 Recommendation 3 – Strengthening of Transmission Network

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.*

CEB Response

Action by

1. **Addl.GM(Projects),**
2. **PD (NTDND&EIP),**
3. **PM (NTDND&EIP – Package 3) and**
4. **PM (CENEIP3)**

(i) Kotmale-New Polpitiya 220kV transmission line

As of today this has been delayed by almost one year mainly due to the effects of changes in the scope of work, delay in land clearences, other effects due to Covid outbreak etc., and reschedulled to complete it by September 2022 subjected to release of tower locations by Forest Department and Land Reform Commission by end March 2022.

(ii) New Polpitiya-Padukka 220kV transmission line

New Polpitiya – Padukka 220kV Transmission Line was commissioned in year 2020.

(iii) Padukka-Pannipitiya 220kV transmission line

All constructions were completed. One circuit of the transmission line between Padukka GS and Pannipitiya GS energized. The CEB has obtained all necessary approvals from the relevant authorities for the construction of transmission line as per the Electricity Act. However, a land owner residing at Arawwala objecting to cut coconut trees which are under the transmission line (other circuit) without having required safety clearance for energizing.

Though the DS has granted approval to cut these coconut trees the land owner did not allow CEB to enter in to the land. As the land owner is strongly objecting to cut trees, CEB filed a case in the Magistrate Court under case no.28947 and the case was dismissed by the Court stating that Transmission Licensee has no right to enter in to this land as per the Electricity Act.

Since CEB has no alternative solution to energize the 2nd circuit , this decision was challenged at the Court of Appeal by CEB and now being heard at the Court of Appeal under case no. CA PHC (APN) 96/2021.The other circuit cannot be energized until the decision of the Court of Appeal case no. CA PHC (APN) 96/2021 is given. Scheduled Date of Completion cannot be declared due to the ongoing Court proceedings. Remaining circuit of the transmission line can be energized within 3 days, if Court decides in favor of CEB.

CEB has written to MoP long before for necessary amendments to SLE Act but no action has been initiated yet. Removal of unnecessary legal and procedural barriers which hamper the completion of projects timely must be an utmost task of the relevant authorities when emphasized by the utility.

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.*

CEB Response: Action by Addl.GM(Generation) / Addl.GM(Transmission)

Item (i) - Operation of Pressure Relief Valve (PRV) in the Circuit Breaker (CB) of Kotmale - Biyagama 220kV Line 01 (CB 530) at Kotmale Switchyard during the Total Failure occurred on 2021-12-03 at 11:27 hrs;

During the system failure on 2021-12-03, CB 510, CB 530, CB 610 and CB 630 were opened in the Kotmale 220 kV switch yard. Therefore, an inspection was carried out to check the condition of the Circuit Breakers before energizing. There were no outer abnormalities in CB 510, CB 610 and CB 630. However, in CB 530, it was observed the operation of Pressure Relief Valve (PRV) in phase “Y”.

This is a Minimum Oil type Circuit Breaker. The Pressure Relief Valve (PRV) or Overpressure valve of a Circuit Breaker operates when the pressure in the breaking unit of CB is increased beyond its defined safe pressure range.

Hence, in case the PRV of a 220kV Circuit Breaker is operated it is the standard practice to check the CB for its healthiness before energizing. The aim of this practice is to prevent any further damages to the unit as well as for the safety of other switchyard equipment in the vicinity of the CB due to a subsequent catastrophic failure. Accordingly, the CB is checked for any physical abnormalities and Contact resistances of the Breaking units of all phases are checked whether they are in the acceptable range together with their oil level and Nitrogen pressure.

Actions Taken after the operation of the PRV

Due to PRV operation in Phase Y of CB 530, it was decided to further check the condition of the phase “Y” of CB 530. A summary of steps followed during the process were indicated below;

- CB 530 was properly isolated by opening and locking Disconnector Switches, DS 531 and DS 532 and earthing CB 530.
- Then oil levels and nitrogen pressures were checked in all six chambers. Oil levels and nitrogen pressures were within acceptable ranges.
- Then, contact resistances of all three phases were checked and they were also within the acceptable range.
- Physical abnormalities were also checked, especially in “Y” phase “A” side in which the PRV was operated.

Since there were no abnormalities observed and oil levels and Nitrogen pressures were in acceptable ranges, it was decided that the CB 530 was safe for the operation.

Accordingly, after confirming the safety of the operation of the breaker, all the alarms were reset & Kotmale - Biyagama Line 01 was energized from Kotmale end by switching on the CB 530 at 14:16 hrs.

Item (ii) - Unindicated fault signal receipt of a CB of circuit 2 of Kotmale-Biyagama 220 kV transmission line

Control & Protection Branch of Transmission division is planning to establish an alarm indication for the operation of CB lockout relay at circuit 2 of Kotmale-Biyagama 220 kV transmission line at the Kotmale Power Station.

Item (iii) - Though the committee report mentions about possible delays in restoration due to suspected technical faults in Substation L, and Kelaniya grid substations (mentioned as Kelanitissa due to oversight), no such technical faults were found at the particular locations. In any case issues from these substations have not resulted in a significant delay in the restoration process.

Item (iv) - Delayed Exit from Failed Automatic Line Charge Mode to Manual Line Charge Mode in Generators 1 & 2 of Samanalawewa Power Station (SWPS)

There are no two line charge modes in SWPS as automatic and manual; instead there are two methods as explained below;

- Starting the restoration using reduced line voltage (0.2pu) to charge the transmission lines is called line charge mode. As per the recommendations given by the committee appointed to investigate the system failure in 2020-08-17, trial run on restoration of southern system was planned and there had been certain modifications to the control and protection system, in order to facilitate this new restoration process of southern system. After these modifications a successful restoration trial was done by CEB. This new restoration proposal was to line charge up to Galle GSS, through Embilipitiya and Matara GSS.

- Typical restoration process using 0.9 pu line charge voltage is called as islanded mode in SWPS and it had been the older practice , and the line charging was done up to Embilipitiya GSS.

<u>Reasons for failure in line charge mode and reasons for delayed switching to islanded mode:</u>

Once the modification to the control and Protection system was done and after the above mentioned successful trail, Generation Protection Branch has done further modification to under voltage protection function considering the safety of plant and equipment which would otherwise be hindered if an operator has inadvertently forgotten to exit from the line charge mode.

On 2021-12-03, this modified logic in the protection system has mal-operated during the line charge operation. After the failure of second attempt at restoration using line charge mode at 12:35 hrs SWPS staff consulted Generation Protection branch for their advice on the repeated failures. When the cause for failures was identified as the maloperation of the modified logic in the protection system, SWPS staff immediately turned off the line charge mode and started the restoration process using islanded mode (active power control and voltage regulation were done manually) at 13:25 hrs.

On 2021-12-26, staff of PG branch has rectified the error in the logic and has configured and tested. A new alarm was introduced in SCADA to warn the operator, if he has forgotten to exit from the line charge mode.

Item (v) - Hotline communication failure in the 48 V DC communication system in the New Anuradhapura GS

As per the records the DC communication system has been down only for 5 minutes.

Accordingly, CEB is of the view that there is no reason to carry out further investigations on these five; (i) to (v) issues since what happened is clear and the time taken are reasonable.

7.4 Recommendation 5 – Check and Review the Protection Settings in 220kV Network

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.*

CEB Response – Action by Addl.GM(Transmission) / DGM(Control & Protection – Transmission)

Considering the sensitivity of 80A earth fault setting in 220kV transmission lines with high load currents, immediate action has been taken to revise the pickup setting in critical lines including Biyagama – Kothmale lines. However, it should be noted that disparities can exist in some settings of protection relays in two ends of a transmission line due to various reasons and the discrepancies mentioned in Explanation 5 has no bearing in the correct operation of the protection scheme except for the fact that the pickup setting 80A has not been adequate due to persistent zero sequence currents, a phenomenon which has not been previously identified.

CEB acknowledge the necessity to review all protection settings in the transmission network and rehabilitate some of the existing schemes. This work has been initiated even before the total failure and a TOR has been prepared to carry out this work with the assistance of external experts and the TOR was forwarded to funding agencies viz. ADB and USAID to check the possibility to obtain funds.

On 2022-01-05, AGM (Transmission) has given concurrence to include Review of Protection Settings in the ongoing USAID energy program. Accordingly, this has been discussed with Chemonics, the local contractor appointed by USAID. They have requested details of the protection schemes of the CEB network which CEB has provided and the discussion to finalize the scope of work is being carried out.

CEB will take action to implement this as a project and also will seek the possibility of utilizing CEB funds in the event the assistance from funding agencies is not forthcoming

Similar consultancy assignment was discussed with ADB after the total failure on 2020-08-17, under the Technical Assistance received with Power System Reliability Strengthening Project which was not materialized.

7.5 Recommendation 6 – Regular Inspection and Testing of Circuit Breakers, Protection Relays etc.

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.*

CEB Response – Responsible by Addl.GM(Transmission) / DGM(Control & Protection – Transmission) / DGM(AM – Transmission) / DGM(O&Ms – North) / DGM(O&Ms – South)

CEB admits that there had been an erroneous wiring in Local Control Cubicle/Marshalling Kiosk of the Circuit Breaker with regard to the "Open" position which is shared with Control Panel and Protection Panels. This resulted in the incorrect operation of the End Fault Protection Scheme at the Biyagama Grid Substation. The reason for the oversight is possibly due to referring to an inappropriate wiring diagram, during the replacement of the circuit breakers of the two lines. It is noted that the scheme has been properly implemented and tested by the contractor of the protection modernizing project. However, the wiring diagrams referred in later stage are not the same updated version nor the original ASEA as built drawing but an unrevised copy of the originally submitted ASEA drawing. Protection modernization project at Biyagama grid substation was implemented in 2014 and Circuit breakers were replaced in 2015 by the O&Ms Branch.

However, it is also noted that during the concerned period of circuit breaker replacement, Protection Unit then existed had been under restructuring process. In addition, the installations have been done within short period due to the criticalness of the said two lines, consequently might have missed the proper scheme test. Further, even at present, it is not possible to completely carry out routine maintenance activities of the Control and Protection relays as planned due to the severe shortage of staff. CEB is contemplating the possibility of outsourcing part of the routine maintenance activities due to this reason.

In general, there is an established procedure to follow in CEB when an equipment is tested, commissioned, energized and taken over. In the process, officials in the Projects, Constructions, O&Ms, Protection, Communication, System Control and finally Asset Management Branches are involved in time to time until the installation is completely energized and taken over. However, CEB is of the view that the procedures currently adopted by the aforesaid branches have to be revisited and shall be updated for fool proofing and thereby to minimize to such an erroneous wirings and similar things in the future installations.

Accordingly, CEB expects to initiate necessary actions to reinforce the protocols of existing construction, testing & commissioning, energizing, taking over etc., with the guidance of Corporate Strategy Division. A road map will be prepared after the initial discussions with Corporate Strategy, Transmission, Projects and Generation Divisions.

7.6 Recommendation 7 – Synchronizing of Protection Relays and DFRs

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.*

CEB Response:

Transmission Division – Action by Addl.GM(Transmission) / DGM(Control & Protection – Transmission)

Process of calibration and time synchronizing of digital disturbance recorders has been expedited in Transmission Division. This work has already been completed in some of the critical stations. viz. Biyagama Grid Substation, Kothmale Power Station, New Anuradhapura Grid Substation, Norochcholai Power Station. A road map for this work will be prepared after discussion with the OEM for remaining stations once the financial position of CEB is improved. The time synchronization of numerical relays will be checked during the routine maintenance work.

Current status of Generation Division – Action by Addl.GM(Generation) / DGM(Protection Generation)

Only numerical relays of Lak Vijaya, Upper Kotmale, Kukule Ganga and UJPS power stations were time synchronized by the respective OEMs, the inception, and Protection Generation Branch has completed time synchronization of Victoria power station. PG Branch already started this process in 2021 and procurement of equipment related to time synchronization in KCCP (ST), Kotmale, Randenigala, Rantambe, Samanalawewa, Canyon, Udawalawe and Iginiyagala has been initiated and this project will be completed in 2022.

However, protection systems of other plants such as Laxapana, Wimalasurendra, Polpitiya, Ukuwela and Bowatenna are to be upgraded due to obsolescence and time synchronization facility will also have to be accommodated with this replacement. A road map will be given when the financial position of CEB is improved.

7.7 Recommendation 8 – Strengthening the Failure Analysis Process

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*

CEB Response: Action by Addl.GM(Transmission) / DGM(Control & Protection – Transmission)

During the past, CEB has taken steps to improve the failure analysis processes even under the limited available resources, especially the lack of engineers. Activities of the Control and Protection Branch were adversely affected by the migration of experienced engineers and delays in recruitment of new engineers.

In the event of a total failure the key task of the Control and Protection Branch is to identify the root cause of the failure and inform the NSCC the findings of the initial analysis to assist the restoration process. During the total failure that occurred on 2021-12-03, staff of Tr. Control and Protection Branch immediately carried out post fault analysis based on the DFR records and relay events. All tripping incidents including the tripping of 132kV lines were analyzed and the clearance was given to NSCC to energize those equipment. However, since it was identified that there was an issue in the tripping of Biyagama - Kothmale lines, an outage was requested from the NSCC to carry out further investigation immediately during the night off peak on 2021-12-03. Based on the initial investigation, it was identified the requirement to revise the Earth Fault pickup setting and the requirement to investigate the direct inter-trip signal to avoid possible repetition of the fault. Initial concurrence for the line outage was received from the NSCC and staff were arranged to carry out the investigation and testing. But at the last moment this work could not be carried out due to an special instruction issued by CEB. As per the advice of the Higher Management, Control & Protection Branch staff were not allowed to enter Biyagama and Kothmale substations.

Later during the process of detailed investigation, important activities carried out by the Control and Protection Branch are explained below.

(a) Tripping of Biyagama – Kothmale Line 01 by Backup Earthfault Protection function of Main 1 (Siemens 7SL87) Relay at Kothmale Power Station.

It was identified that the tripping of backup Earth fault protection is due to a high persistent zero sequence current in the network and identified that it could trip the line again. Therefore, the Control & Protection Branch recommended to increase the Earth fault current setting to around 160 A to avoid relay mal-operation and requested approval of CEB management by submitting a Draft Failure Report dated 2021-12-03. This report was also submitted to the Committee on 2021-12-06.

(b) Operation of End Fault Protection Scheme

The Control and Protection Branch identified the incorrect operation of End Fault Protection by analyzing the events recorded in the Bus Bar Protection Relay. This information and requirement of further investigation by visiting Biyagama Grid Substation was conveyed to CEB Management and Independent Investigation Committee by Draft Failure Report dated 2021-12-09.

After the visit by the Independent Committee to Kothmale Power Station and handing over of data related to Total Failure, the management gave clearance to execute above two recommendations and staff of the Control and Protection Branch completed the above listed two activities without further delay.

CEB agree with the recommendation of the Committee to 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. In this regard it is necessary to allocate additional resources to Control and Protection Branch viz. allocation of additional engineers, organizing protection related training to staff etc.

However, CEB cannot agree with the explanation for recommendation as staff of Control & Protection Branch was actively supported the NSCC in the restoration of total failure occurred on 2021-12-03 by analyzing the protection related tripping of the transmission network and shared the findings with NSCC. Further the draft Failure Report dated 2021-12-03 the Control and Protection Branch has informed the management to increase the Earth Fault setting of 80A in Biyagama - Kothmale Line. Also, the incorrect direct trip from End Fault Protection was identified in draft Failure Report dated 2021-12-09 and has shared to CEB management and the Committee.

7.8 Recommendation 9 – Dynamic Model of the Network

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

CEB Response: Action by Addl.General Manager(Transmission) / DGM(Transmission & Generation Planning)

The requirement for system dynamics parameters were arisen during the analysis of power system failure occurred in 2015. This was because, it was unable to model the system voltage behavior during this disturbance. This was mainly due to the absence of proper exciter model in the dynamics system model (a typical simplified excitor model was used to that date). Therefore, as a recommendation it was decided to carry out generator testing for all the system generators and update the generator, governor, excitor models.

As a first step, with the help of Manitoba hydro consultants together with BC Hydro, generator testing was carried out in 2016 for four generators (initially it was planned to test two thermal power plants and two hydro power plants, but due to unavailability of outages at that time, it was only carried out for following generators) as follows,

1. Sapugaskanda Unit 8
2. New Laxapana Unit 2
3. Victoria Unit 2
4. Samanalawewa Unit 2

And also, it was planned to continue this by capacity building for generator testing and model tuning from respective branches.

From this generator testing procedure CEB received a new governor model and an excitor model for each of the four generators including a parameter update for the generator model in 2017. Since then, these model parameters were incorporated into the dynamic system file.

In order to complete this task, it needs to be carried out for all the generators in the system. However, this was not progressed due to following reasons,

- Unable to take outages for generators (specially Lakvijaya coal power plant which is the largest unit of the system):
- Lack of funding to continue the testing to remaining generators to carry out testing procedure and formation of the dynamic system file.
- Proper knowledge transfer To prepare the PSSE support dynamic system file from the derived generator parameters to relevant branches is still not sufficient.
- Limited availability of Engineers and dedicated work group specifically to carry out this task, which needs to be repeated periodically.

In addition to the dynamic system model update, it is also required to update the static system model to a more accurate level. The static model was prepared using the theoretical calculations and updated by transmission planning branch using snapshots of the Realtime system which was provided by system control center. However, it was observed that there are some mismatches when compared with actual reactive power flow.

Therefore, it is required to ascertain the following static system models by carrying out testing the same,

- Transmission lines
- Transformers

Transmission Planning Branch needs to carry out this with the help of Transmission Protection, Transmission O&M and Transmission Asset Management Branches and thus involves much time and resources.

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

7.9 Continuation of Recommendations of Previous Committees

Recommendation A – Implementation of Generation Plan and Transmission Plan

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.*

CEB Response: Action by GOSL/ Ministry of Power/ CEB Board, Addl.GM (Transmission)

CEB has always tried its best to implement the Generation & Transmission Plans and will continue to do so. However, financial constraints and external issues during project implementation have hampered the progress of implementation of the two plans,

Most Prioritized Transmission System Bottlenecks/Issues and Solutions (Planned, Under Construction Reinforcements) are listed in the table below.

Table 7.9-1 Transmission System Bottlenecks/Issues and Solutions (Planned, Under Construction Reinforcements)

No	Issue	Solution	Project
01	Single circuit outage of Biyagama – Kothamale 220kV transmission line will overload the other circuit	Construction of Padukka Pannipitiya and Padukka-New Polpitiya 220 kV transmission lines	Clean Energy & Network Efficiency Improvement Project
		Construction of Kotmale -New Polpitiya 220 kV transmission line	National Transmission and Distribution Network Development and Efficiency Improvement Project -I
02	Low voltage and transmission line overloading due to the single circuit outage of Polpitiya – Kiribathkumbura 132kV transmission line will overload the other circuit.	Capacity enhancement of Polpitiya – Kiribathkumbura-New Habarna 132kV transmission line	National Transmission and Distribution Network Development and Efficiency Improvement Project -I
03	Transmission line bottlenecks exist in Colombo and suburban area	Construction of Veyangoda Kirindiwela – Padukka 220 kV transmission line and related 132kV transmission line	National Transmission and Distribution Network Development and Efficiency Improvement Project -I
		Construction of Padukka Pannipitiya and Padukka-New Polpitiya 220 kV transmission lines	Clean Energy & Network Efficiency Improvement Project
04	Low voltage and transmission line overloading due to the single circuit outage of Habarana – New Anuradhapura 132kV transmission line and Habarana – Polonnaruwa 132kV transmission line	Construction of New Habarana 220/132 kV switching station with 132 kV transmission line re-arrangement	Habarana - Veyangoda 220kV Transmission Project
05	Low voltage at Southern province and transmission line overloading due to the single circuit outage of New Laxapana – Balangoda 132kV transmission line and Samanalawewa –	Construction of New Polpitiya – Hamabantota 220kV transmission line	Green Power Development & Energy Efficiency Improvement Investment Programme (Tranche 2)
		Construction of Hambantota – Matara 132kV transmission line	Power System Reliability Strengthening Project

No	Issue	Solution	Project
	Embilipitiya 132kV transmission line		
06	Low voltages and transmission line overloading due to the single circuit outage of Pannipitiya - Panadura T 132 kV transmission line outage	Construction of Padukka - Horana 132kV transmission line	Green Power Development & Energy Efficiency Improvement Investment Programme (Tranche 2)

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.*

CEB Response: Action by Addl.GM(Transmission) / DGM(System Control) / DGM(Engineering Audit)

Draft Merit Order Dispatch Procedure (final draft) is under review with CEB , PUCSL and its Consultant. It has been decided to conduct a Dispatch Audit through an independent party/firm which will be managed by Engineering Audit Branch, CEB. The TOR for Dispatch Audit Guide Line is currently being developed by engineers attached to NSCC. SAID has agreed to provide financial and other assistance for the Dispatch Audit. Hence it is expected to conduct the audit with the assistance of USAID.

As discussions on this are in progress, it is difficult to determine the timeline of the assignment at the moment. Time line with milestones for implementation could be provided once the relevant discussions are over.

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.*

CEB Response : Action by GOSL / Ministry of Power / CEB Board / FM / Addl. GM (CS) / DGM(CS&RA)

CEB directly borrows from ADB, ICBC, HNB and People's Bank for project financing but not from World Bank. CEB has obtained the treasury guarantees for the borrowings from the above banks. Further, loan service is done by the CEB.

There is no argument for prioritizing the projects and implementation based on the availability of resources including the urgency of requirement. Accordingly, various developments proposed by the divisions are usually prioritized and listed in CEB-Annual Action Plans mainly based on the urgency of requirement, availability of financial and human resource requirements for implementation etc.

Current Financial Resources Status

Profit/(Deficit)

By end 2021, CEB (Transmission Licensee) carried an LKR 378 Billion persistent gap over 2016-2021. The accumulated total Debt as per Bulk Supply Transaction accounts which would have been recommended by PUCSL on CEB's repeated subsidy requests and to be provided by the Treasury is given below. Nevertheless, End User Tariff was not adjusted since 2013 to bear the cost increased to date.

	2013	2014	2015	2016	2017	2018	2019	2020	2021	Tot. Subsidy from 2016
Profit/ (Deficit) BLKR	26.3	(30.5)	2.0	(58.4)	(80.9)	(43.1)	(101.9)	(45.9)	(45.6)	(378.0)

Outstanding Payables as at 31st December 2021by CRB (Transmission Licensee)

The outstanding payables owed to suppliers: thermal power producers, fuel suppliers and renewable energy suppliers are as follows.

No.	Items	Amount (MLKR)
1	Independent power producers - Thermal Oil (with delay interest)	38,869
2	NCRE	17,115
3	Ceylon Petroleum Corporation (with delay interest)	82,256
4	Total Major Creditors	138,240
	Total	276,480

Current Human Resource Availability Status

According to the approved cadre of CEB, it is required to have total of 26783 employees at present. However as of 31st December 2021 the human resource availability in CEB is 22367 in all three categories; permanent, casual and contract. There is a deficit of 4416 employees at present and that affects the performance of all the divisions in CEB. This may further aggravate due to the Board Decision No.: 21.19.335 dated 2021-11-15, to stop all external recruitments for a period of 2 years.

Under such circumstances, to make CEB a financially viable organization and also to implement plan developments in priority order it is necessary to grant subsidies monthly for deficits and expediate granting approval for one of the Board Approved Tarif Proposals already submitted to the Ministry of Power and PUCSL in February and March 2022 and do HR recruitments timely.

8 Conclusion

Under the circumstances, progress of the planned development works including implementation of some of the recommendations of this committee and earlier committees has to be compromised due to the persisting resource constraints. Therefore, it is essential to expediate the necessary actions by the relevant authorities to fulfill Financial, HR and other requirements and remove Legal and Procedural barriers at earliest.

Accordingly, CEB highly appreciates the Committee if suitable recommendations are initiated in addition to the ten (10) Recommendations made in achieving the committee expectations efficiently.

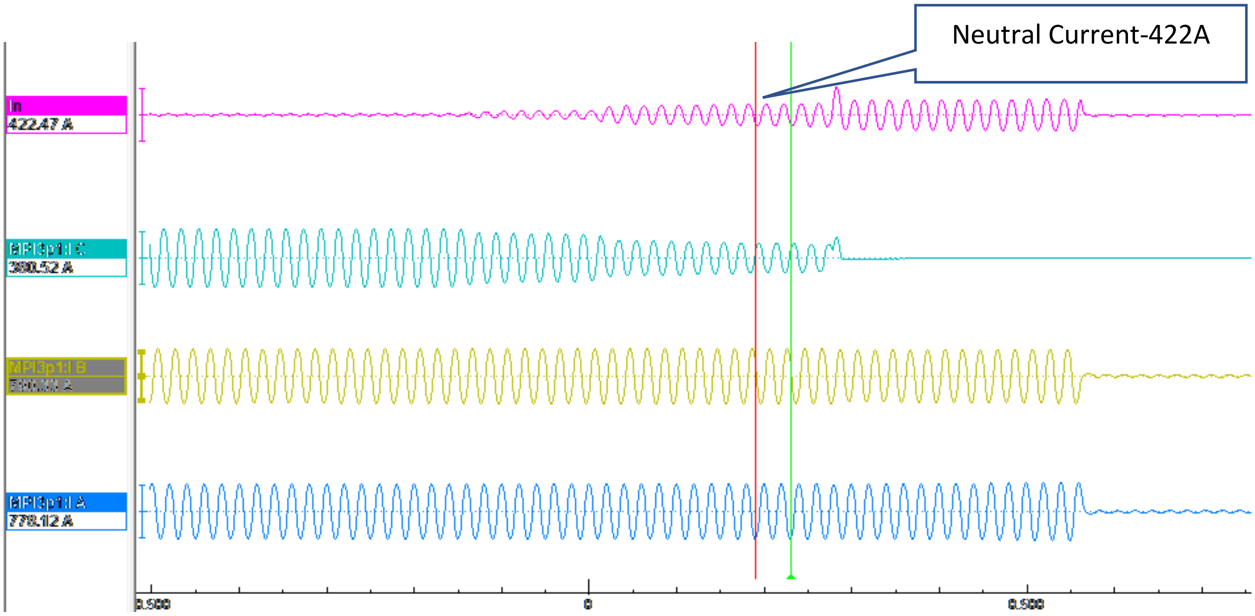
Further, Addl.GM(Generation), Addl.GM(Transmission), Addl.GM(Projects) and other Heads of Branches are instructed to monitor and report the progresses of their respective items in the CEB's response (this report) to GM,CEB once in every two months (1st reporting on 29th April 2022). Addl.GM(CS) is also instructed to review the progress immediately and shall forward his opinion and necessary recommendations to GM(CEB) for further improvements of progress.

Eng. (Dr.) DCR Abeysekara
Actg. General Manager
Ceylon Electricity Board.

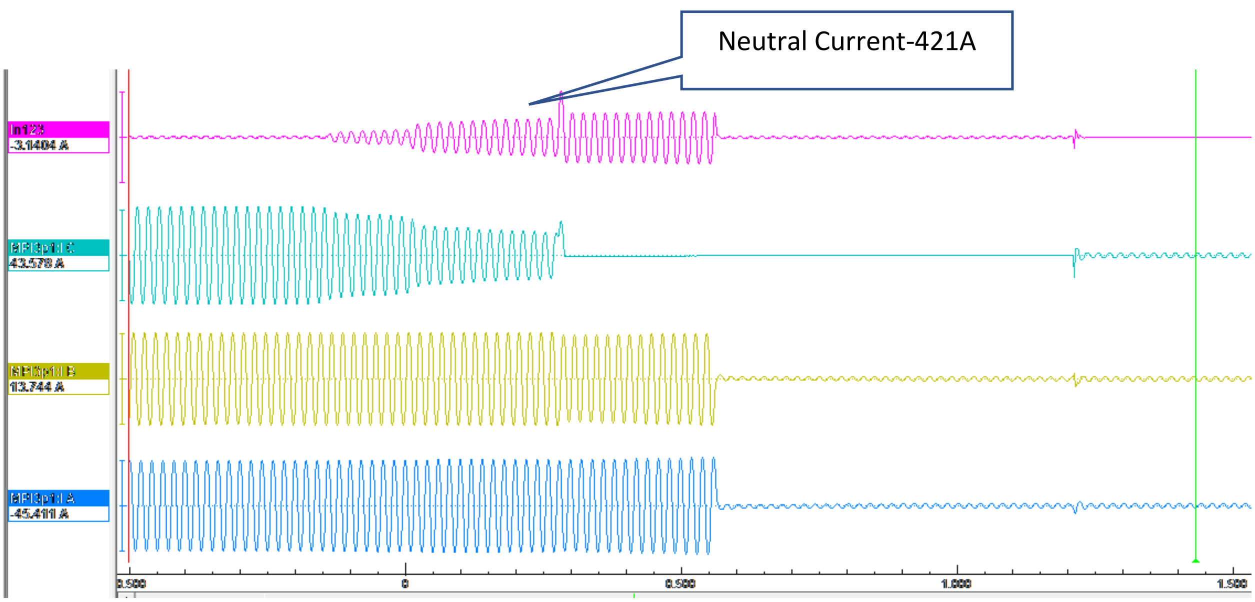
25th March 2022

Annex 6.1-1
Screenshots of waveforms of fault current recorded in different devices

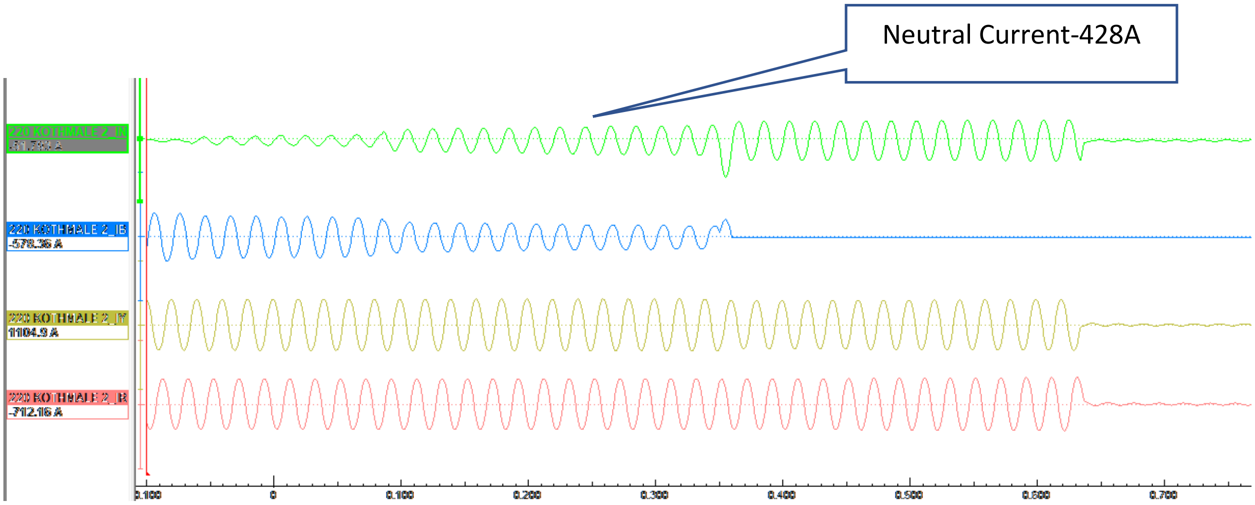
Current Waveform Record from Main 1 Protection Relay of Kothmale Line 2 at Biyagama Grid Substation



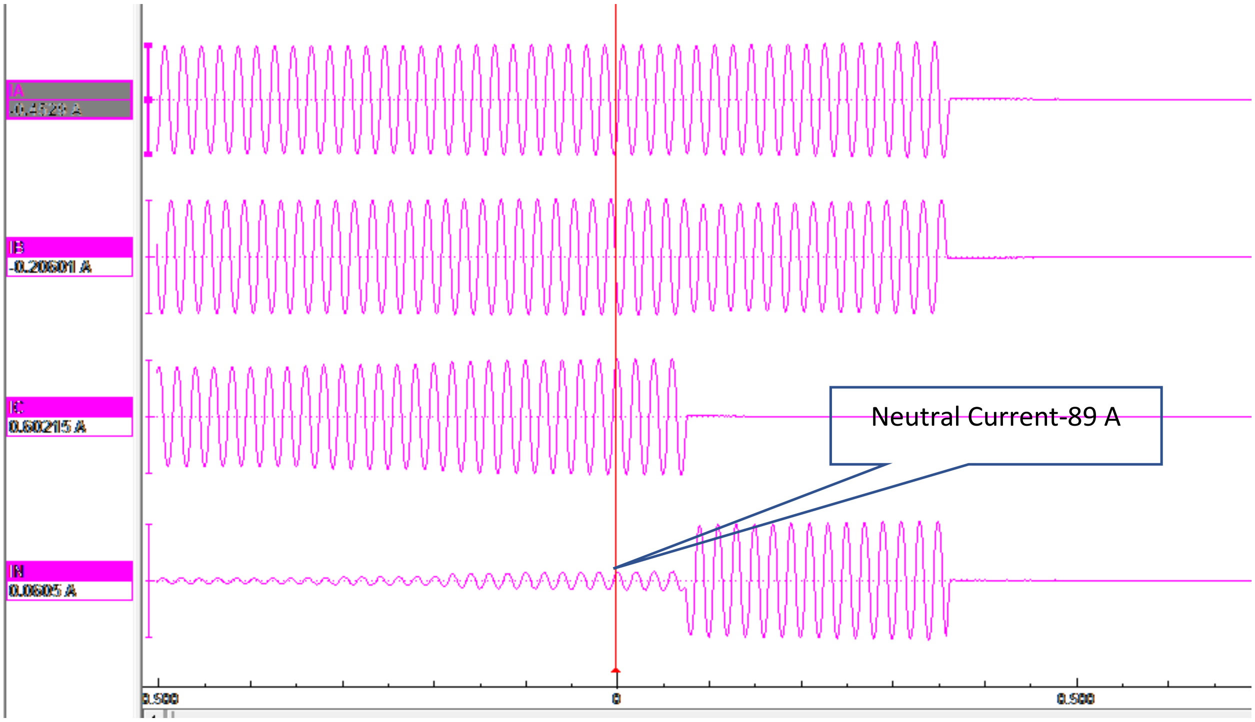
Current Waveform Record from Main 2 Protection Relay of Kothmale Line 2 at Biyagama Grid Substation



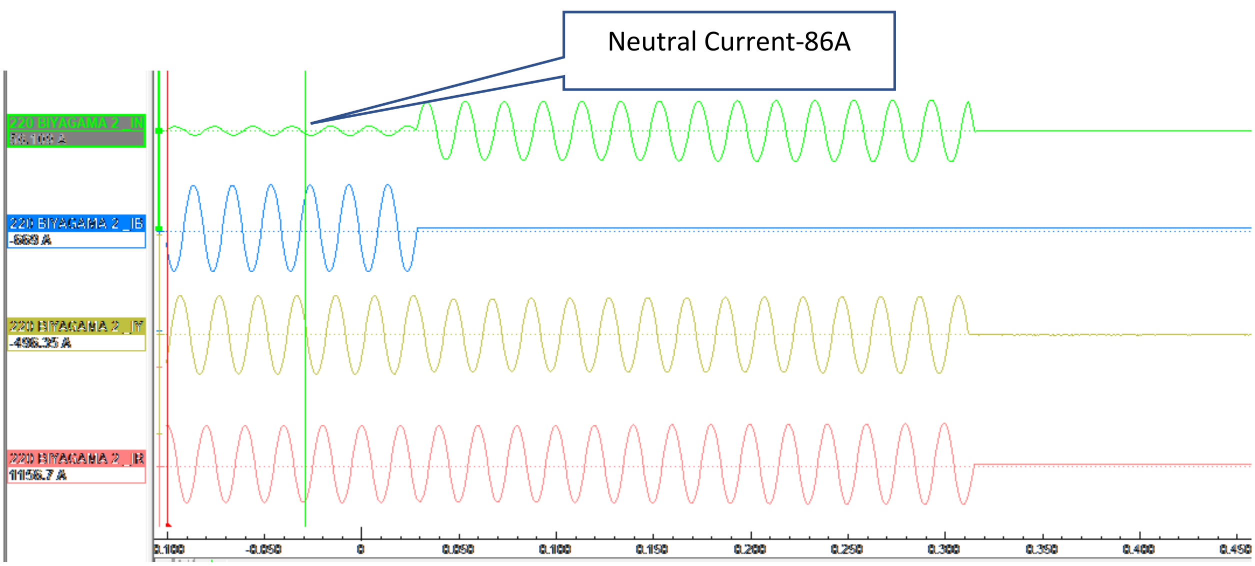
Current Waveform Record from BEN DDR of Kothmale Line 2 at Biyagama Grid Substation



Current Waveform Record from Main 1 Protection Relay of Biyagama Line 2 at Kothmale Grid Substation



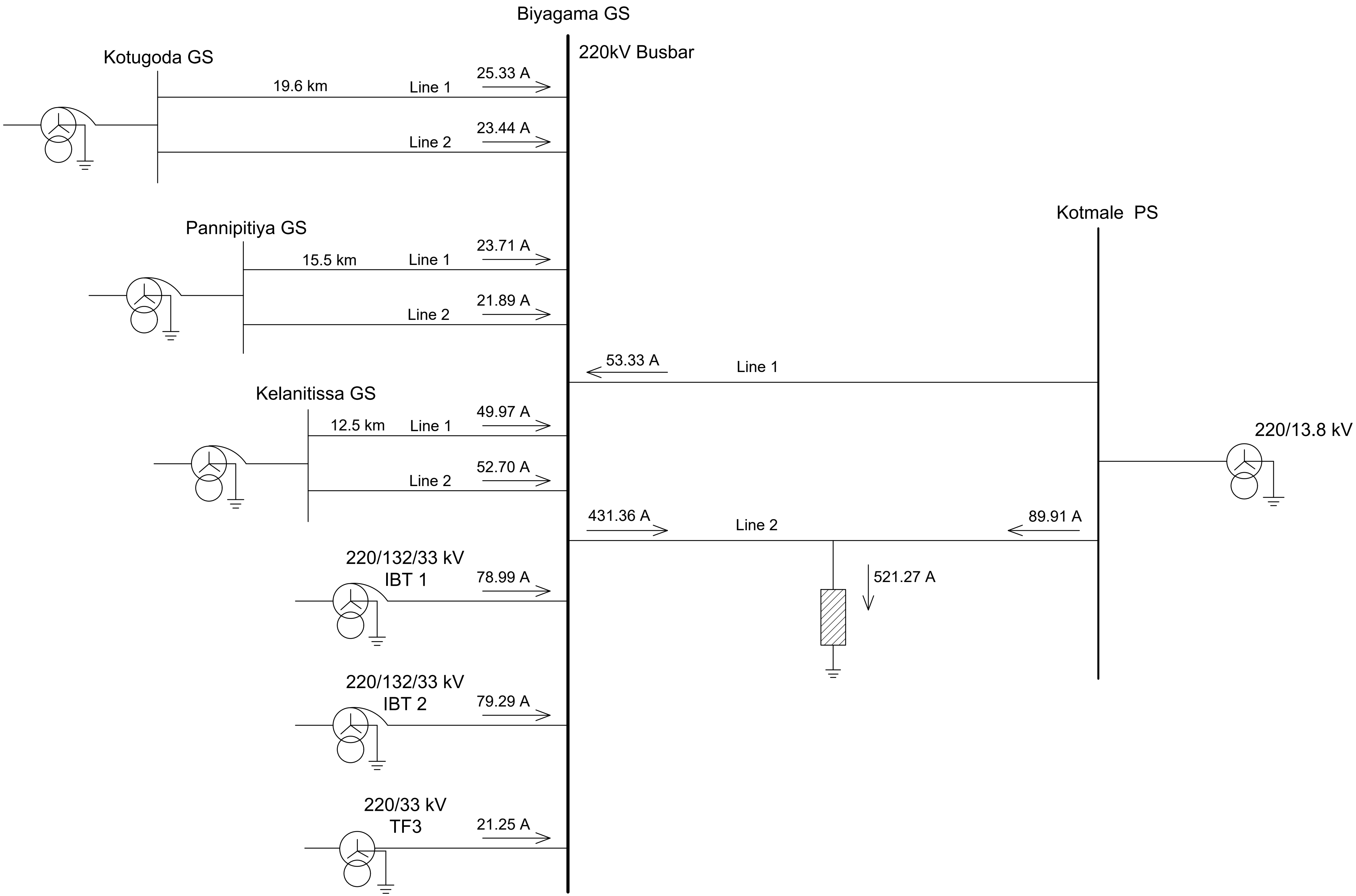
Current Waveform Record from BEN DDR of Biyagama Line 2 at Kothmale Power Station



Annex 6.1-2
Detailed calculation of zero sequence currents

Zero Sequence (3I0) Current distribution
of
220 kV Busbar of Biyagama GS

Zero Sequence (3I0) Current distribution - 220kV Biyagama Busbar



Biyagama GS –
Zero Sequence (3I0) Current

Time = 11:27:14.5724 before 87L tripping

Kothmale Line 2	=	**431.36 A**
Kothmale Line 1	=	53.337 A
Pannipitiya Line 1	=	23.716 A
Pannipitiya Line 2	=	21.892 A
Kotugoda Line 1	=	25.332 A
Kotugoda Line 2	=	23.445 A
Kelanitissa Line 1	=	49.972 A
Kelanitissa Line 2	=	52.701 A
IBT 1	=	78.997 A
IBT 2	=	79.299 A
220/33 kV TF 3	=	21.256 A
220/33 kV TF 4	=	0 (OFF)
Total	=	**429.947 A**

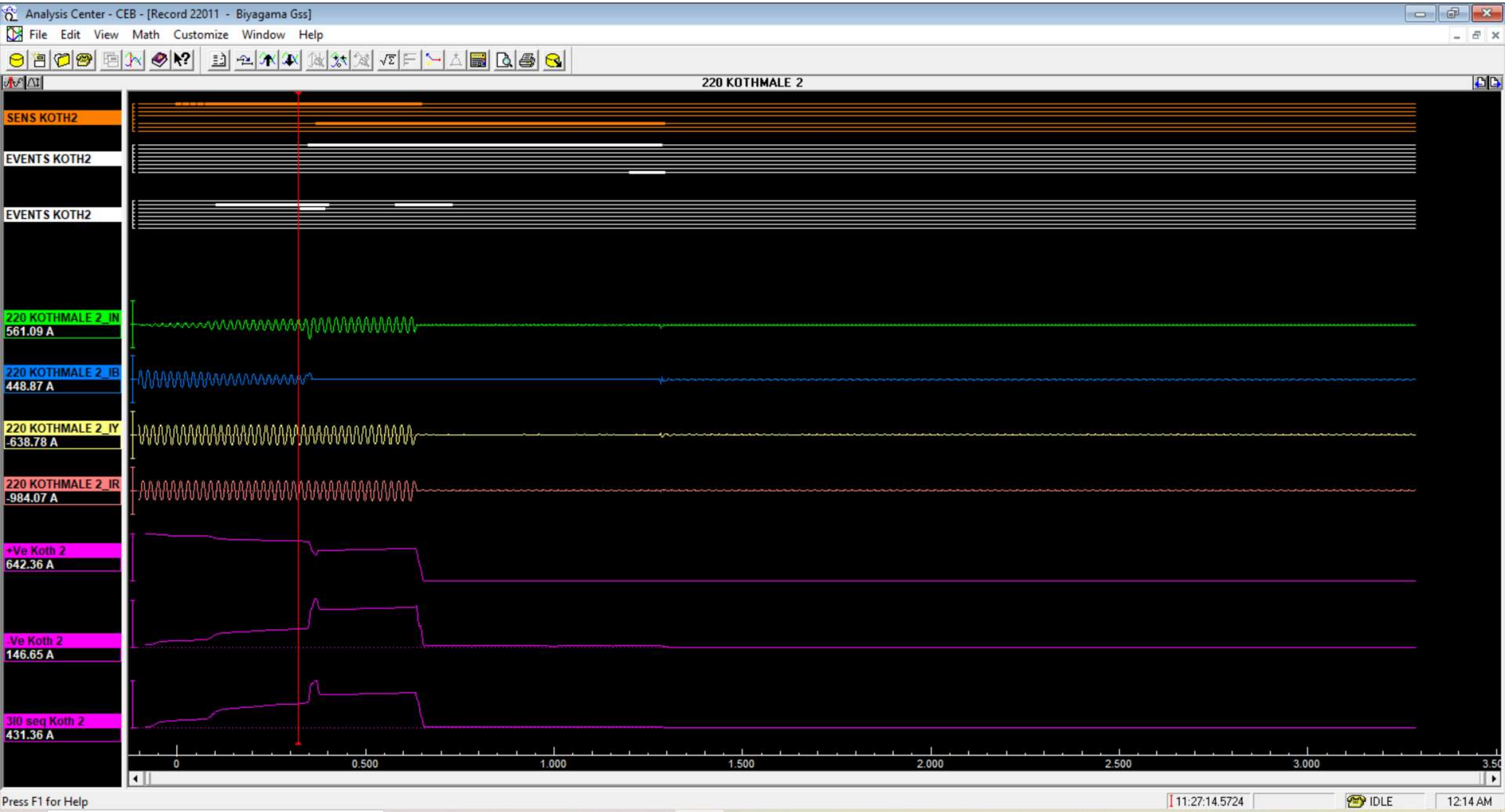
Kothmale Line 2 current = Total of other Bays current

Kothmale PS –
Zero Sequence (3I0) Current

Time = 11:27:13:2811 before 87L tripping
(This time equals to the Biyagama BEN time 11:27:14.5724)

Biyagama Line 1	=	55.186 A
Biyagama Line 2	=	89.912 A

Biyagama GS BEN Records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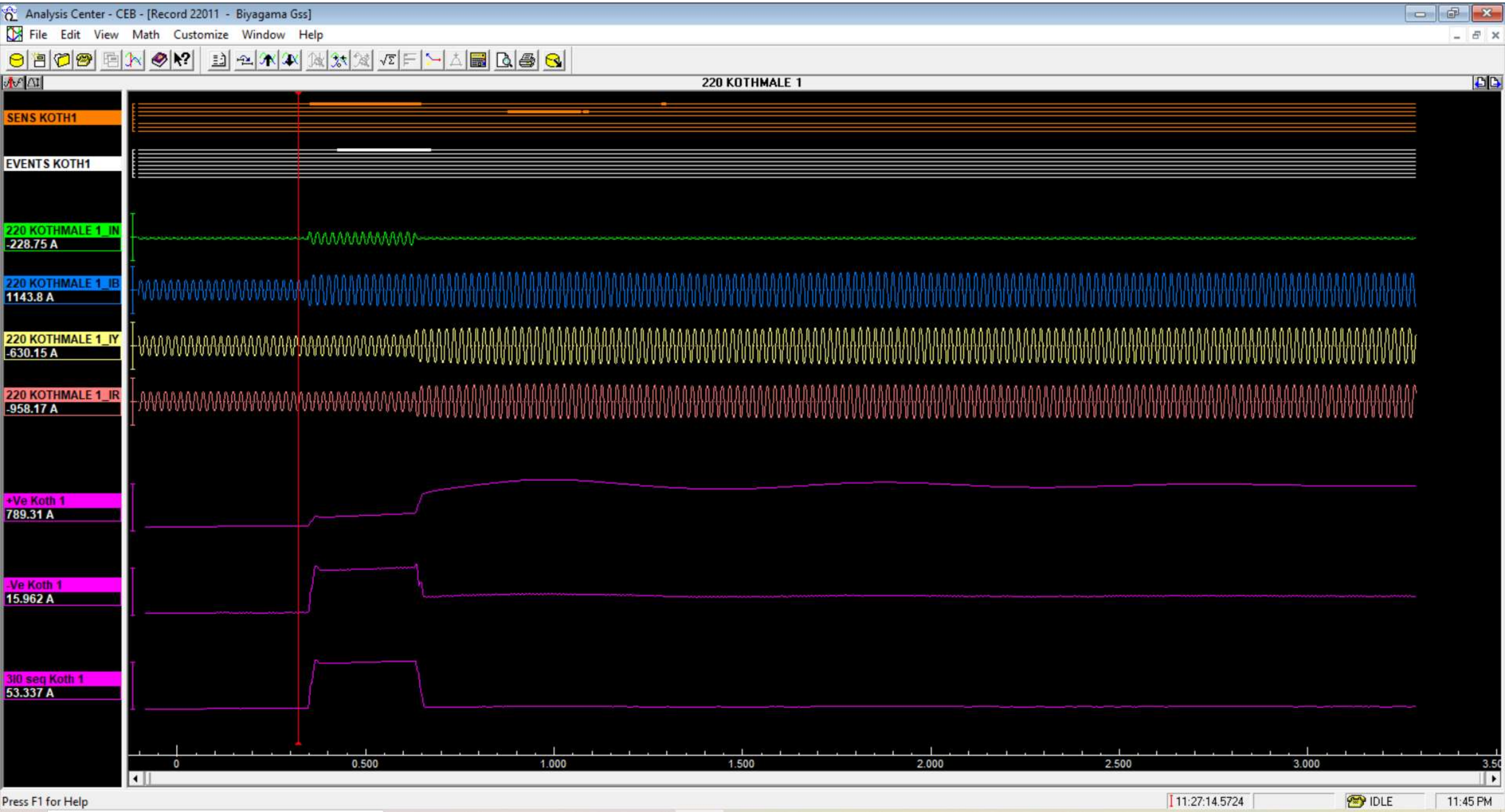
SENS KOTH2
EVENTS KOTH2
EVENTS KOTH2
220 KOTHMALE 2_IN
561.09 A
220 KOTHMALE 2_IB
448.87 A
220 KOTHMALE 2_IY
-638.78 A
220 KOTHMALE 2_IR
-984.07 A
+Ve Koth 2
642.36 A
-Ve Koth 2
146.65 A
3I0 seq Koth 2
431.36 A
0
0.500
1.000
1.500
2.000
2.500
3.000
Press F1 for Help
11:27:14.5724
IDLE
12:14 AM



Analysis Center - CEB - [Record 22011 - Biyagama Gss]
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SENS KOTH1
EVENTS KOTH1
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220 KOTHMALE 1_IB
1143.8 A
220 KOTHMALE 1_IY
-630.15 A
220 KOTHMALE 1_IR
-958.17 A
+Ve Koth 1
789.31 A
-Ve Koth 1
15.962 A
3I0 seq Koth 1
53.337 A
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1.000
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2.500
3.000
Press F1 for Help
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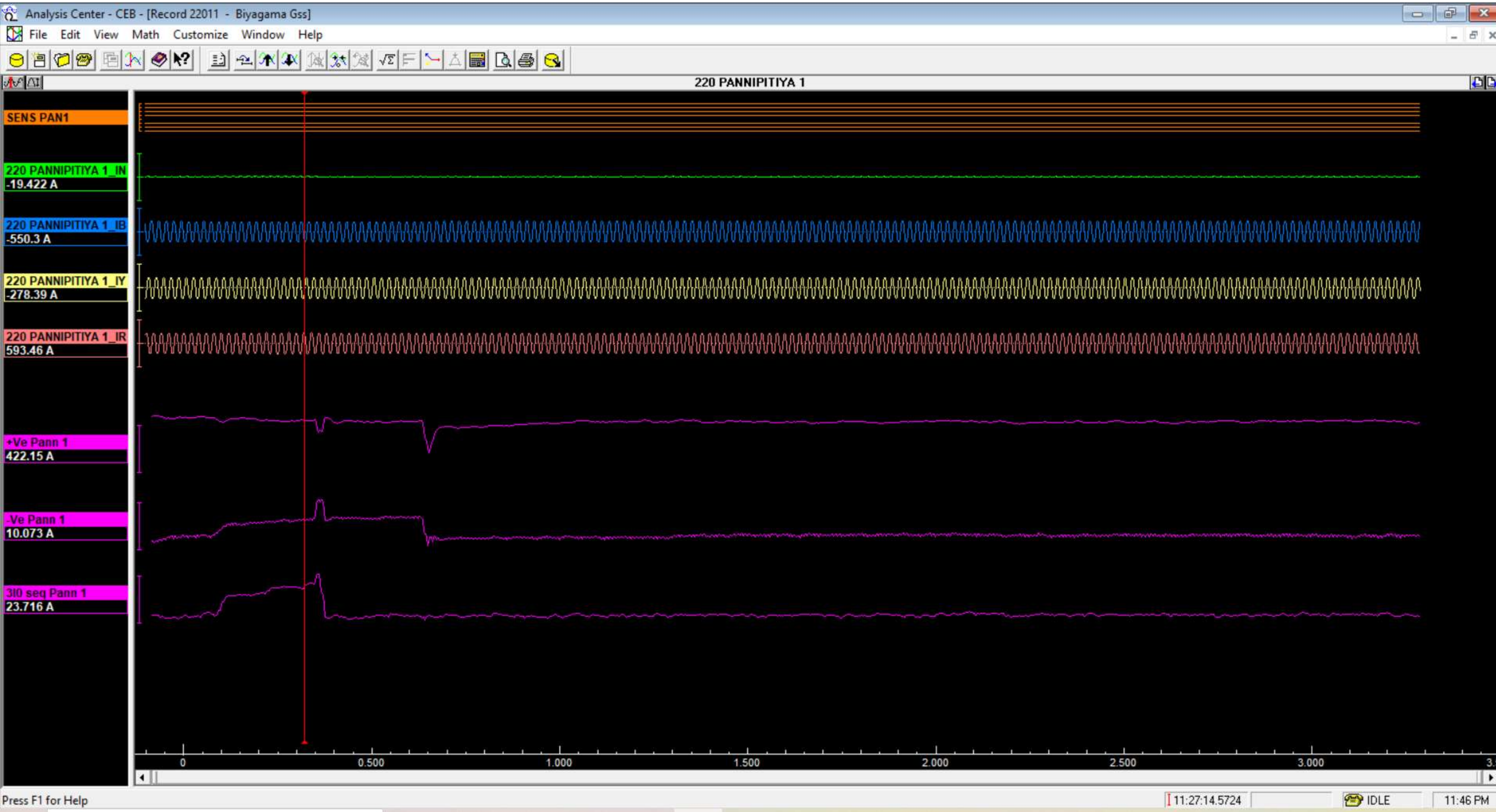
11:45 PM



Analysis Center - CEB - [Record 22011 - Biyagama Gss]
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SENS PAN1
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220 PANNIPITIYA 1_IB
-550.3 A
220 PANNIPITIYA 1_IY
-278.39 A
220 PANNIPITIYA 1_IR
593.46 A
+Ve Pann 1
422.15 A
-Ve Pann 1
10.073 A
3I0 seq Pann 1
23.716 A
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2.500
3.000
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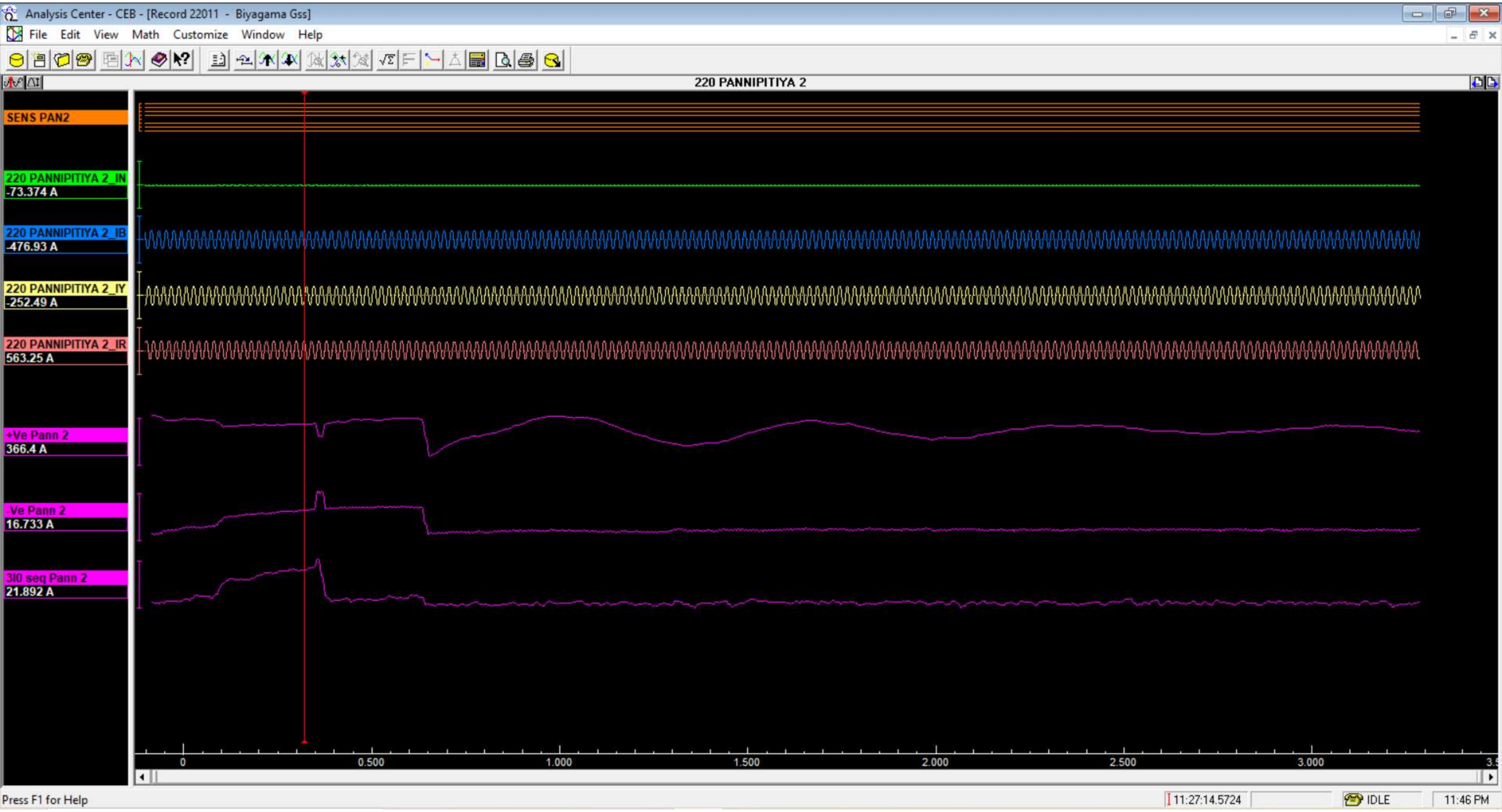
11:46 PM



Analysis Center - CEB - [Record 22011 - Biyagama Gss]
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220 PANNIPITIYA 2
SENS PAN2
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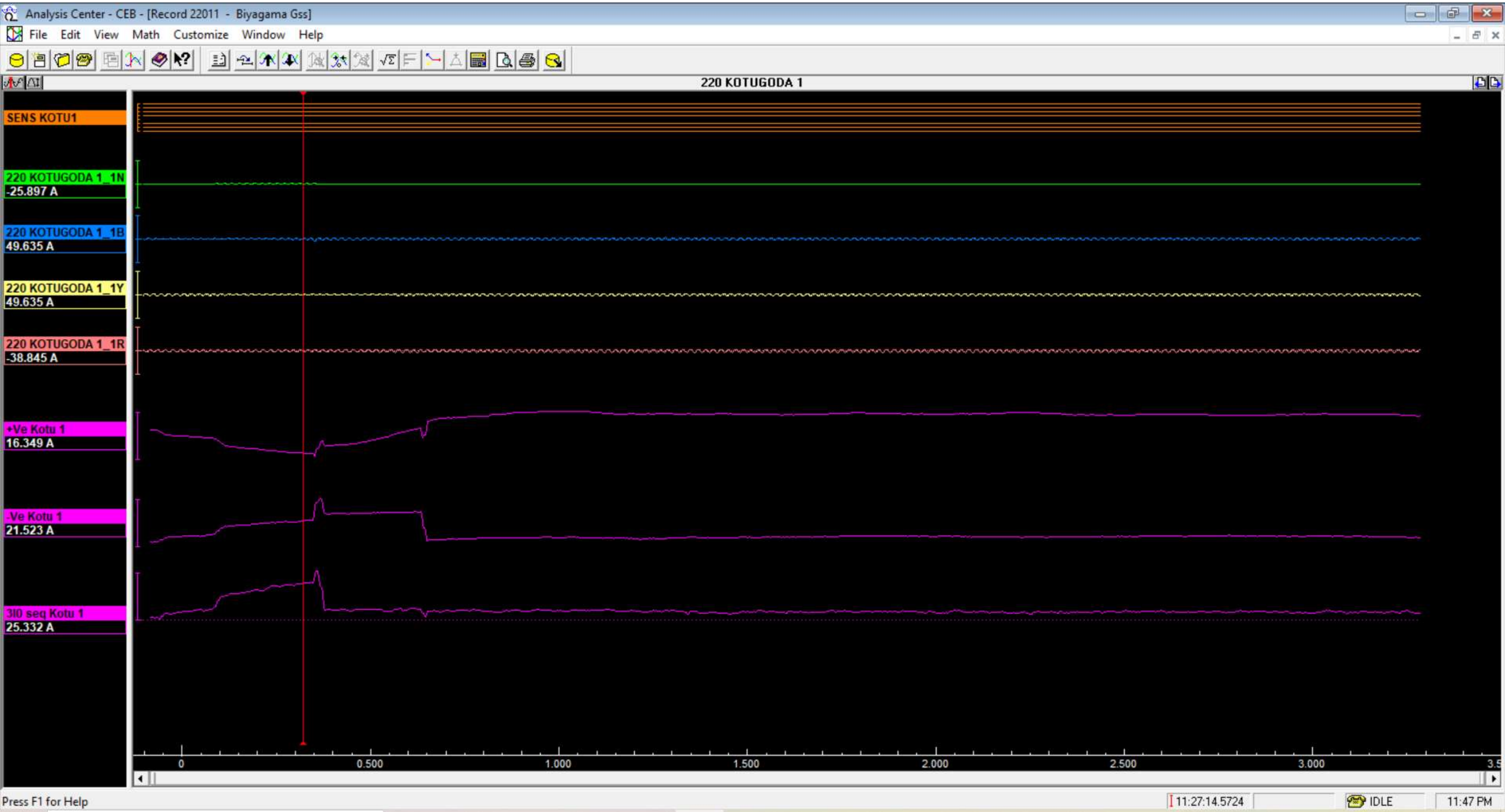
220 PANNIPITIYA 2_IB
-476.93 A
220 PANNIPITIYA 2_IY
-252.49 A
220 PANNIPITIYA 2_IR
563.25 A
+Ve Pann 2
366.4 A
-Ve Pann 2
16.733 A
3I0 seq Pann 2
21.892 A
0
0.500
1.000
1.500
2.000
2.500
3.000
Press F1 for Help
11:27:14.5724
IDLE
11:46 PM


Analysis Center - CEB - [Record 22011 - Biyagama Gss]
File Edit View Math Customize Window Help
220 KOTUGODA 1
SENS KOTU1
220 KOTUGODA 1_1N
-25.897 A
220 KOTUGODA 1_1B
49.635 A
220 KOTUGODA 1_1Y
49.635 A
220 KOTUGODA 1_1R
-38.845 A
+Ve Kotu 1
16.349 A
-Ve Kotu 1
21.523 A
3I0 seq Kotu 1
25.332 A
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2.500
3.000
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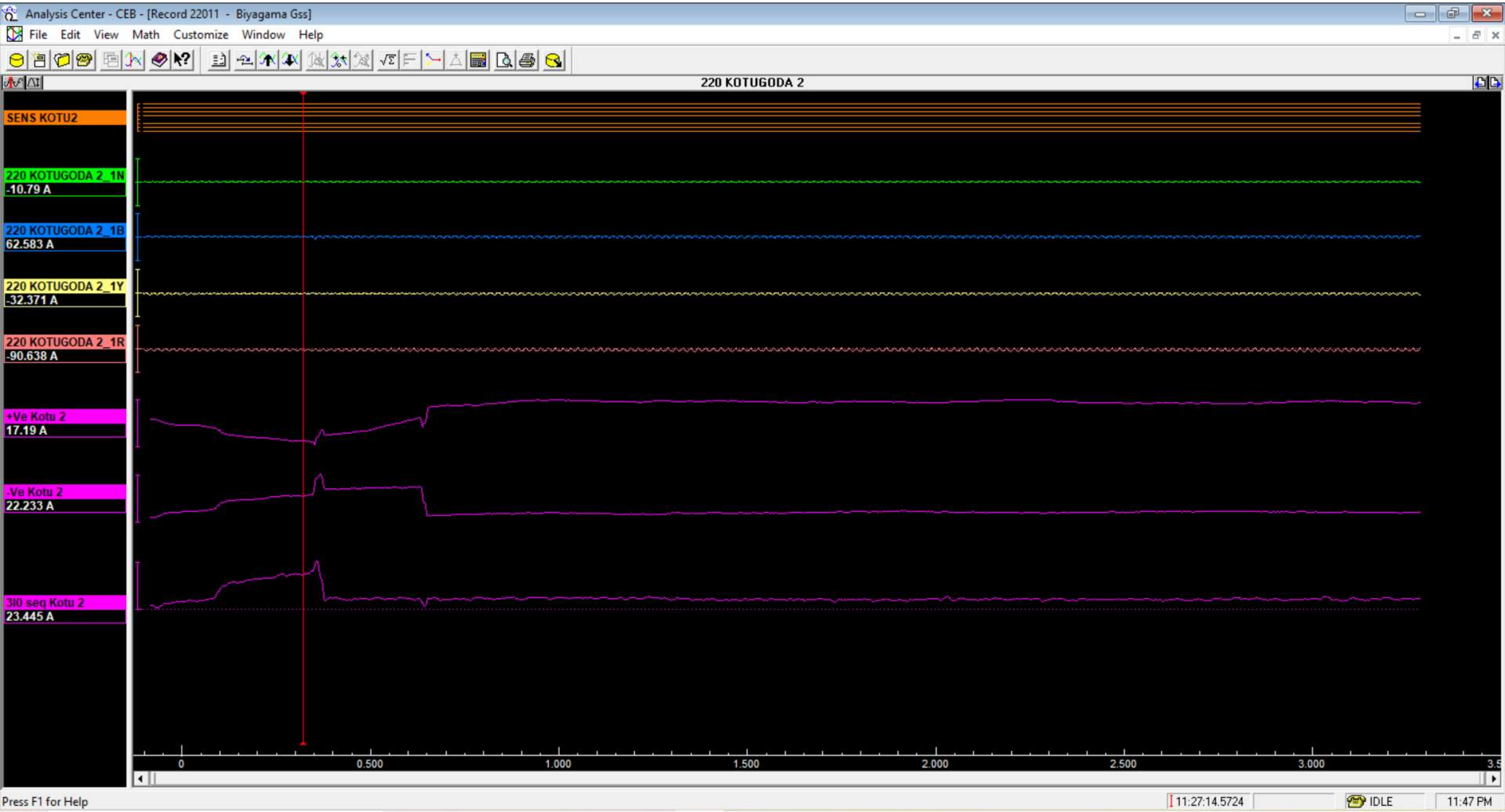
IDLE
11:47 PM



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220 KOTUGODA 2_1B
62.583 A
220 KOTUGODA 2_1Y
-32.371 A
220 KOTUGODA 2_1R
-90.638 A
+Ve Kotu 2
17.19 A
-Ve Kotu 2
22.233 A
3I0 seq Kotu 2
23.445 A
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2.500
3.000
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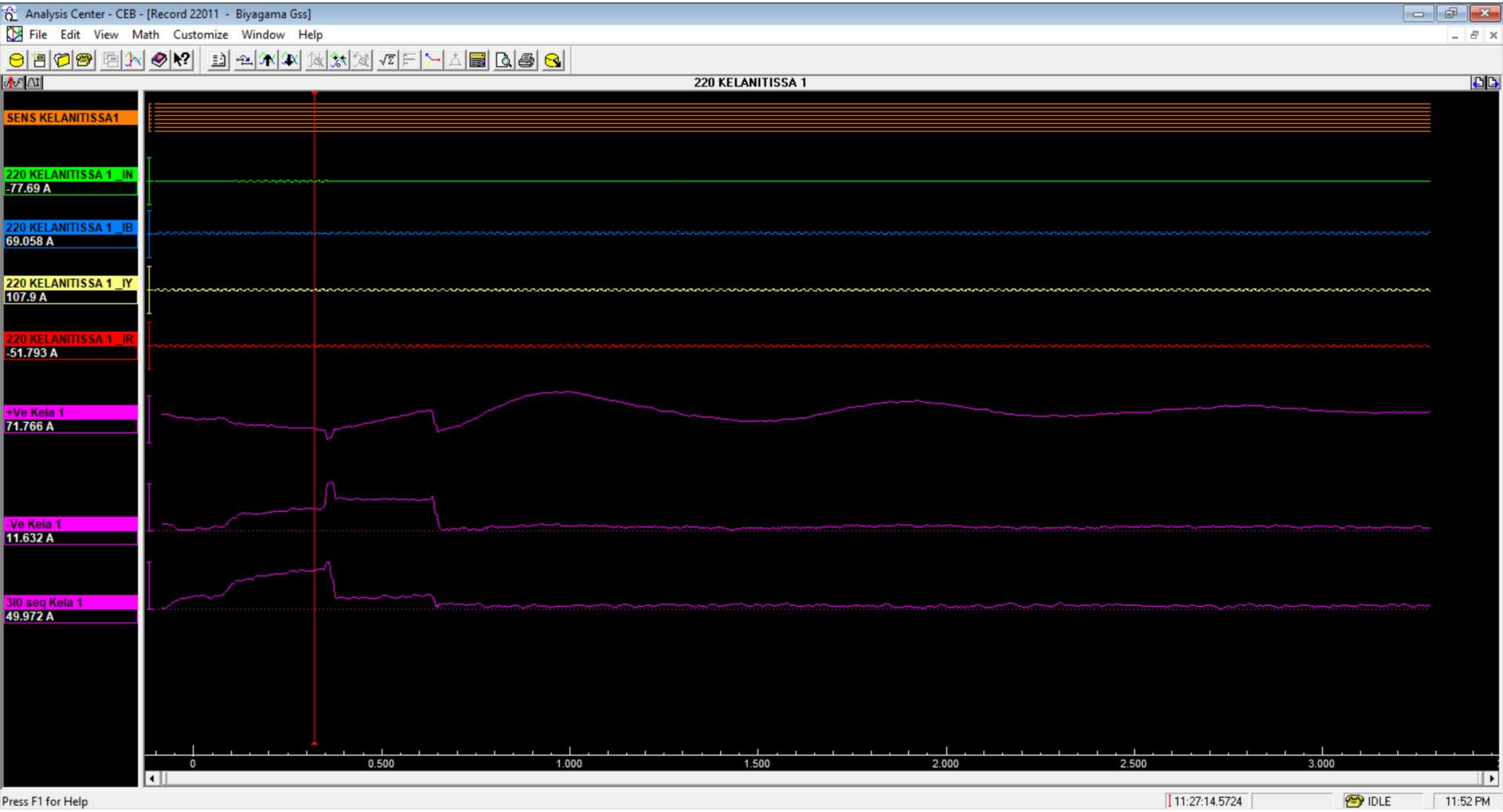
IDLE
11:47 PM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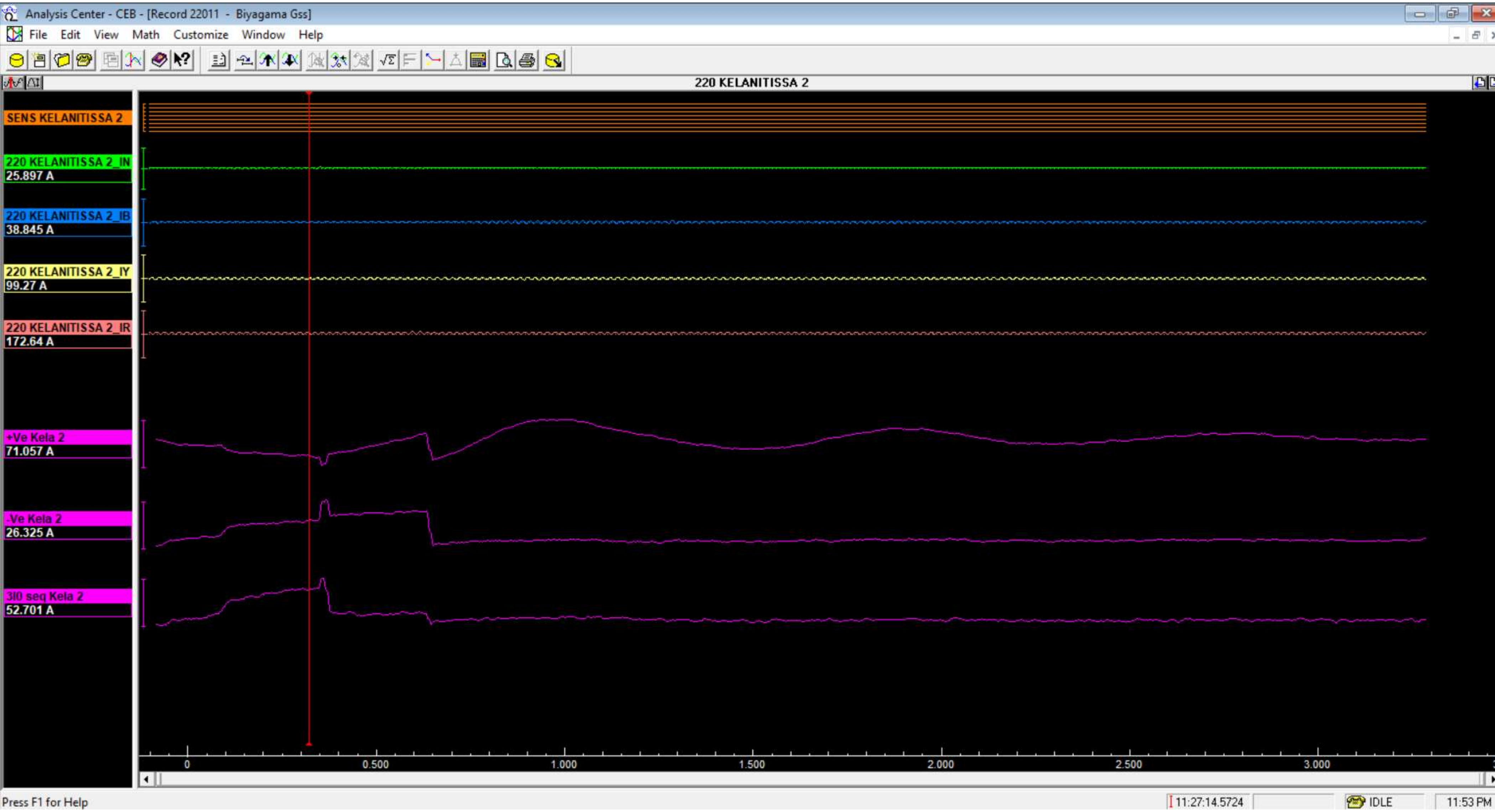
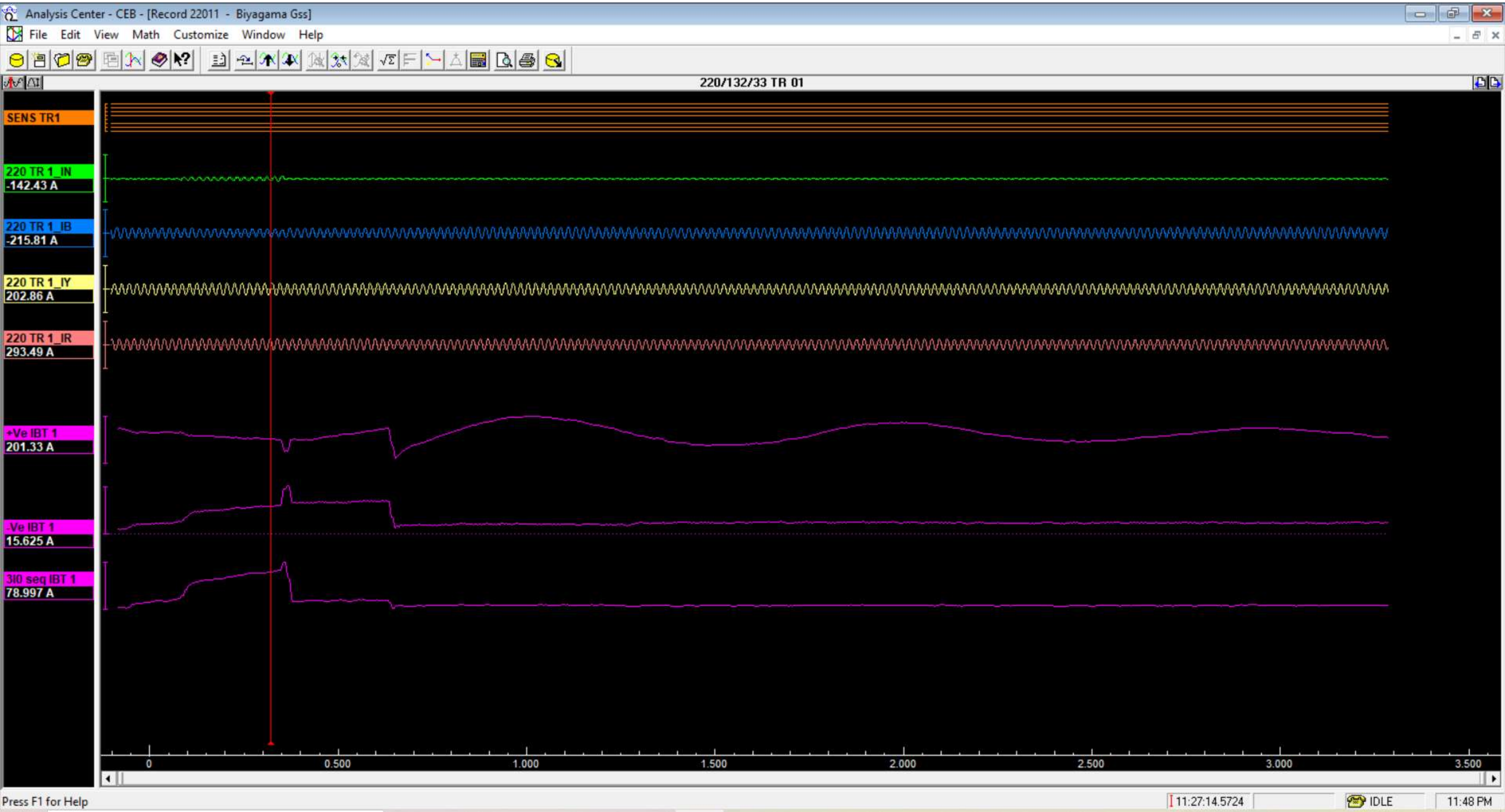
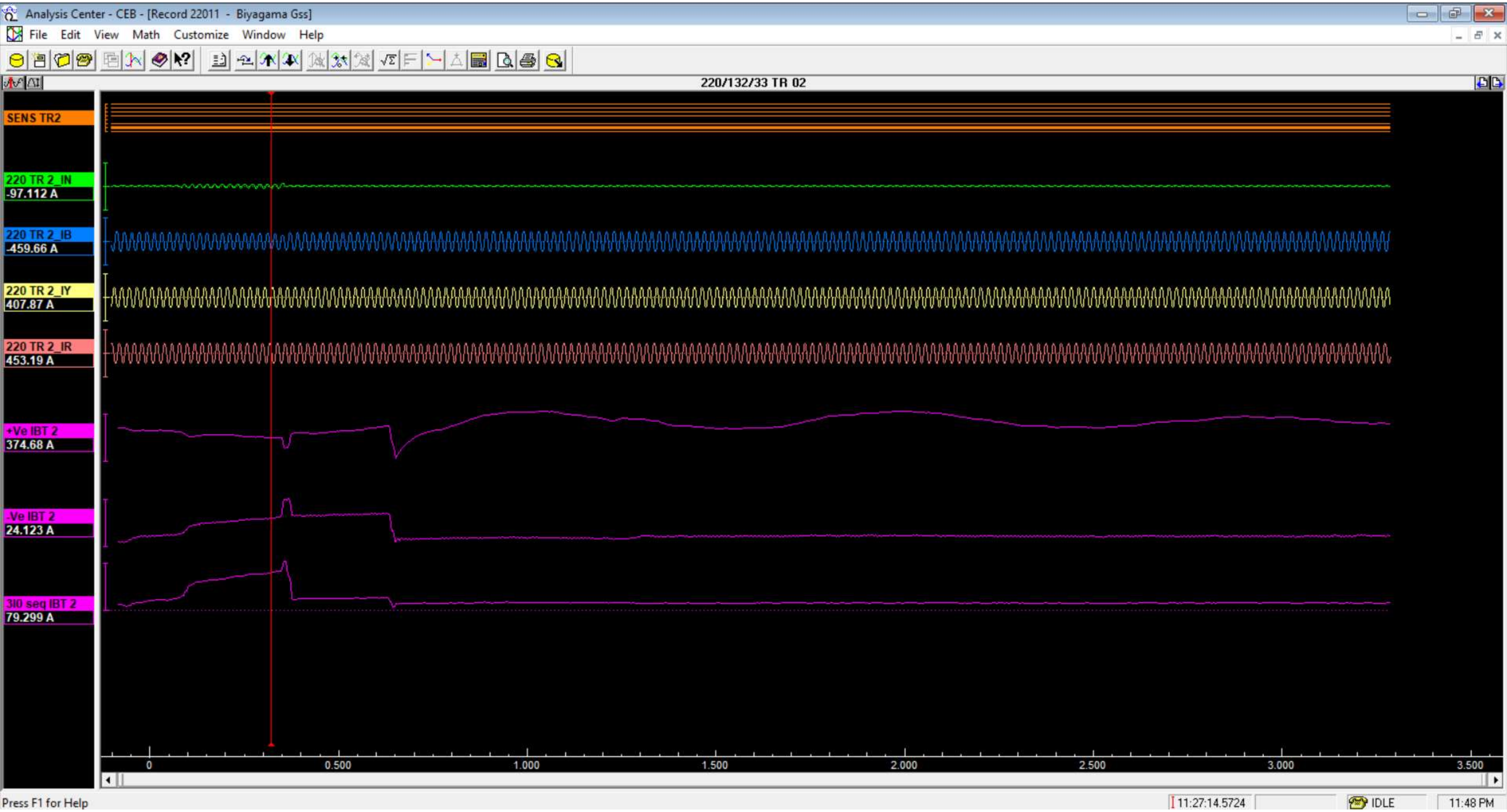
File Edit View Math Customize Window Help
220 KELANITISSA 1
SENS KELANITISSA1
220 KELANITISSA 1 _IN
-77.69 A
220 KELANITISSA 1 _IB
69.058 A
220 KELANITISSA 1 _IY
107.9 A
220 KELANITISSA 1 _IR
-51.793 A
+Ve Kela 1
71.766 A
-Ve Kela 1
11.632 A
3I0 seq Kela 1
49.972 A
0
0.500
1.000
1.500
2.000
2.500
3.000
Press F1 for Help
11:27:14.5724
IDLE
11:52 PM



Analysis Center - CEB - [Record 22011 - Biyagama Gss]
File Edit View Math Customize Window Help
220 KELANITISSA 2
SENS KELANITISSA 2
220 KELANITISSA 2_IN
25.897 A
220 KELANITISSA 2_IB
38.845 A
220 KELANITISSA 2_IY
99.27 A
220 KELANITISSA 2_IR
172.64 A
+Ve Kela 2
71.057 A
-Ve Kela 2
26.325 A
3I0 seq Kela 2
52.701 A
0
0.500
1.000
1.500
2.000
2.500
3.000
Press F1 for Help
11:27:14.5724
IDLE
11:53 PM



Analysis Center - CEB - [Record 22011 - Biyagama Gss]
File Edit View Math Customize Window Help
220/132/33 TR 01
SENS TR1
220 TR 1_IN
-142.43 A
220 TR 1_IB
-215.81 A
220 TR 1_IY
202.86 A
220 TR 1_IR
293.49 A
+Ve IBT 1
201.33 A
-Ve IBT 1
15.625 A
3I0 seq IBT 1
78.997 A
0
0.500
1.000
1.500
2.000
2.500
3.000
3.500
Press F1 for Help
11:27:14.5724
IDLE
11:48 PM



Analysis Center - CEB - [Record 22011 - Biyagama Gss]
File Edit View Math Customize Window Help
220/132/33 TR 02
SENS TR2
220 TR 2_IN
-97.112 A
220 TR 2_IB
-459.66 A
220 TR 2_IY
407.87 A
220 TR 2_IR
453.19 A
+Ve IBT 2
374.68 A
-Ve IBT 2
24.123 A
3I0 seq IBT 2
79.299 A
0
0.500
1.000
1.500
2.000
2.500
3.000
3.500
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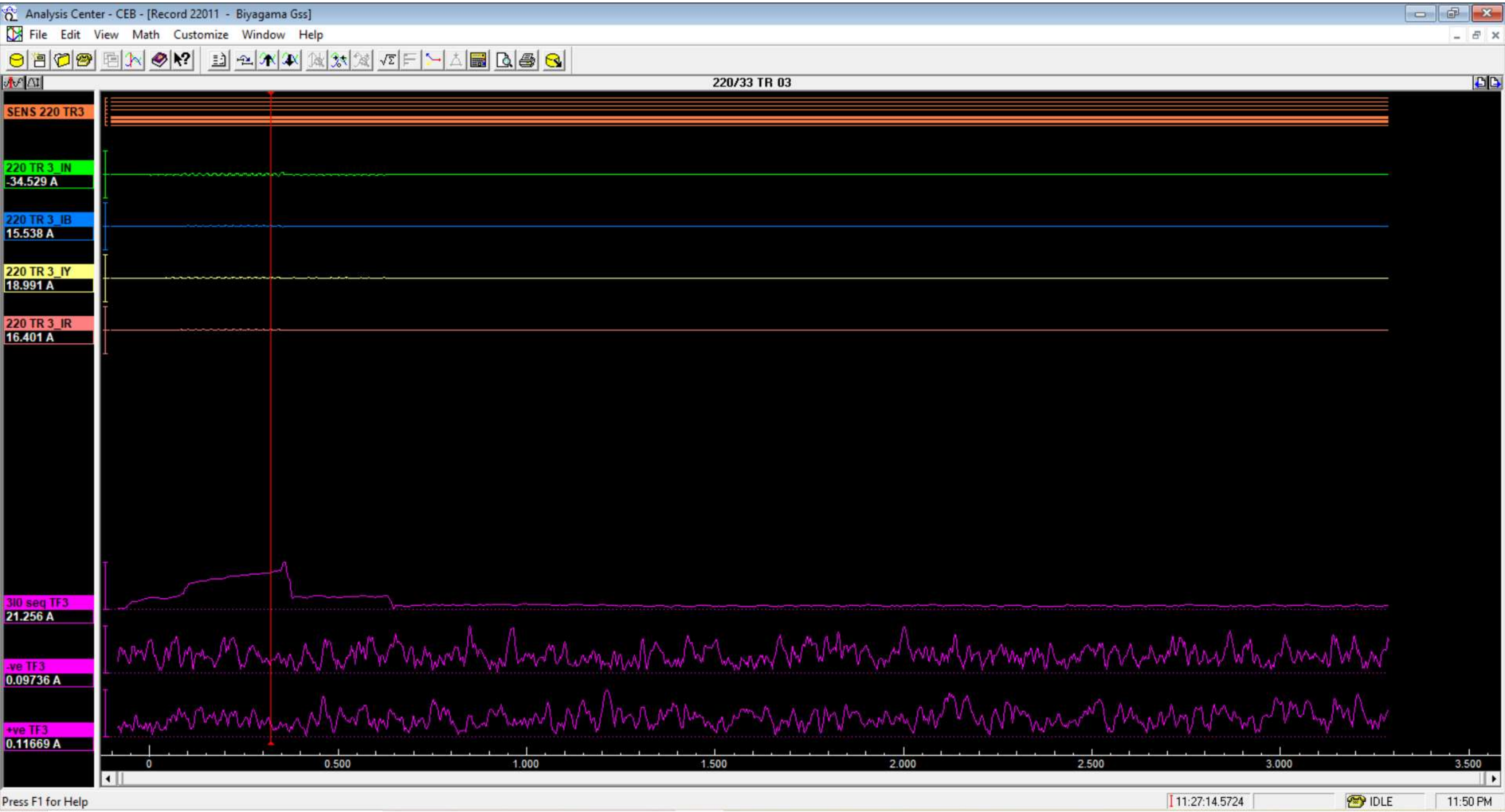
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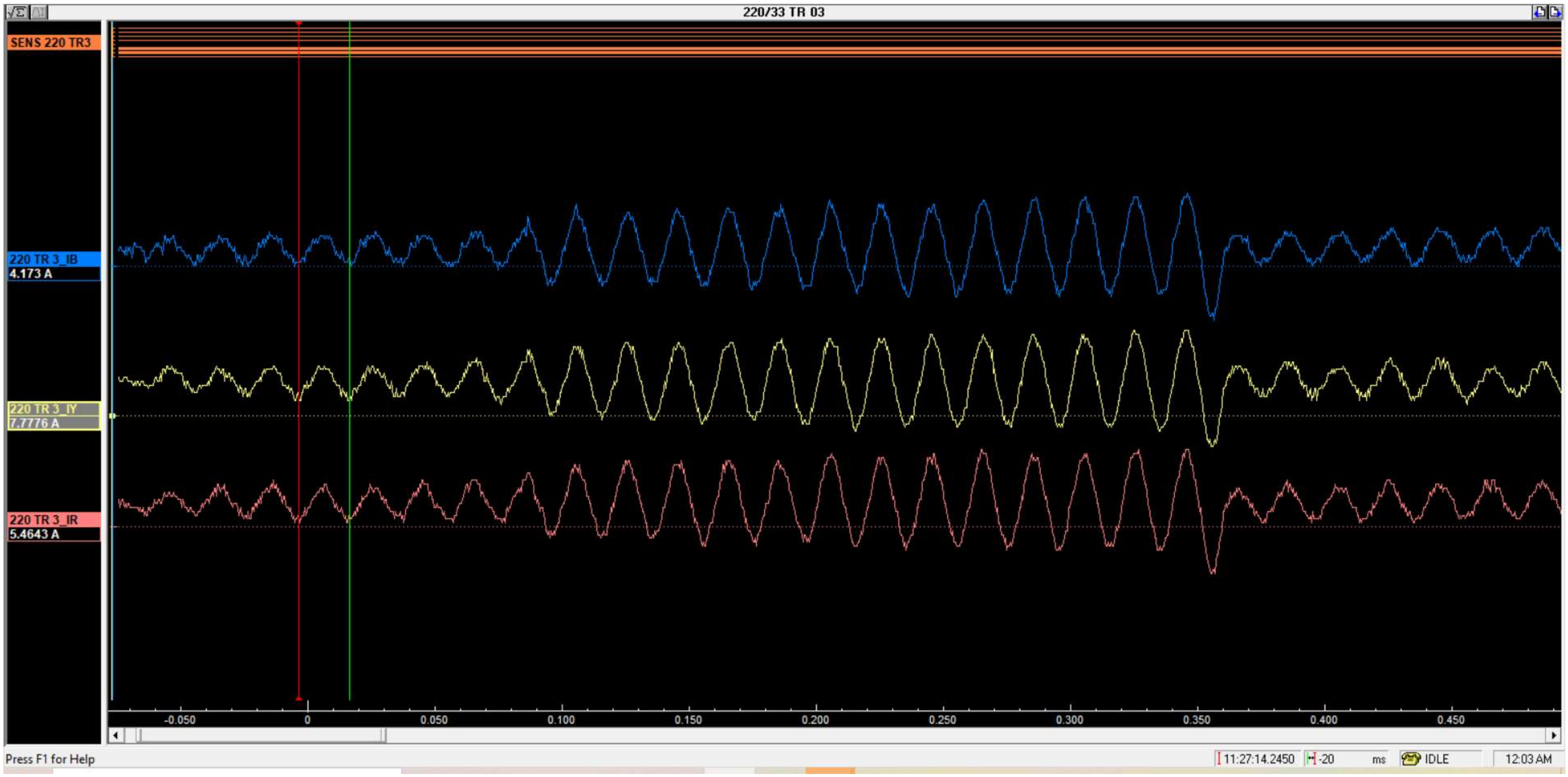
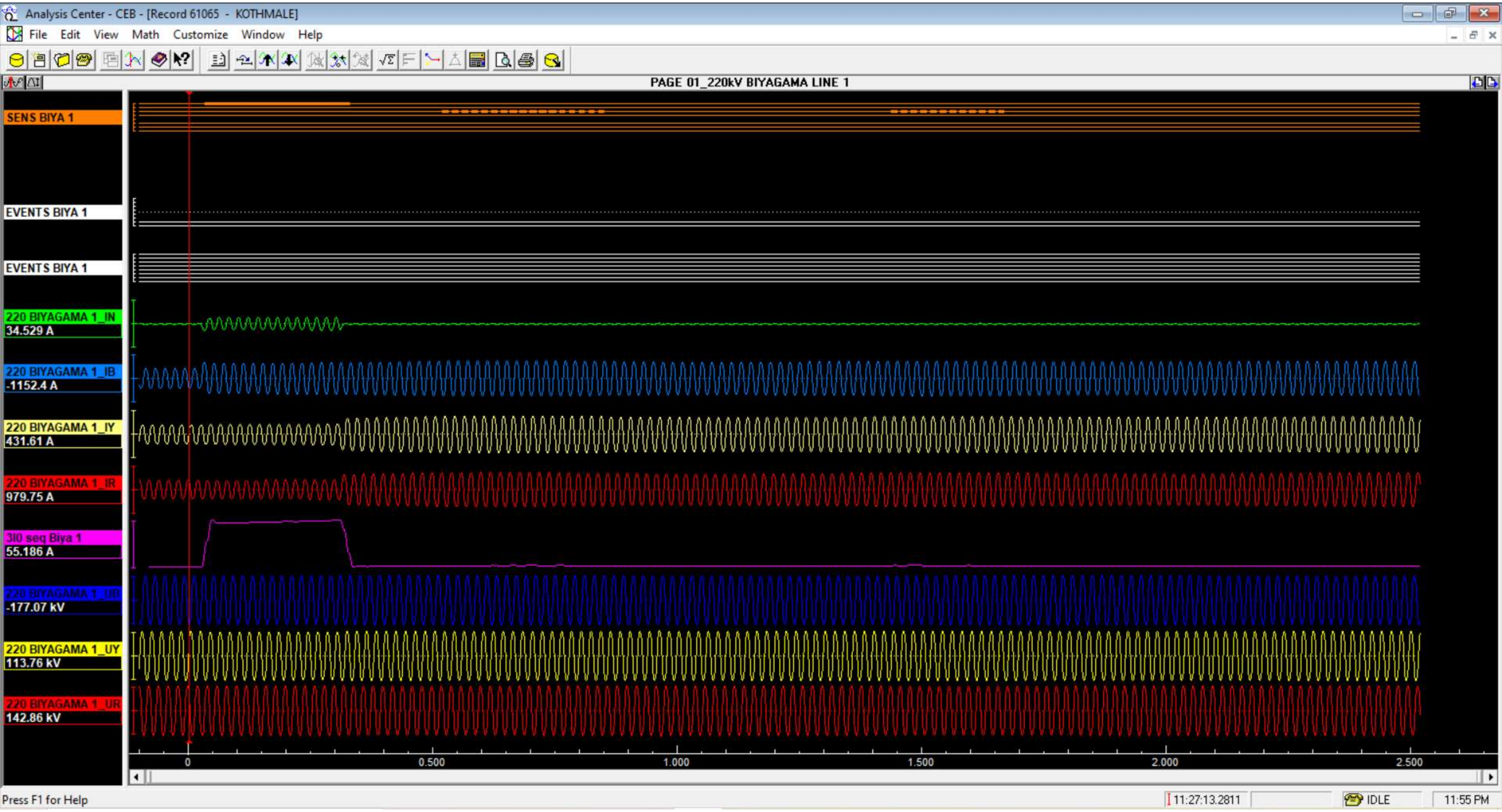
220 TR 3_IB
15.538 A
220 TR 3_IY
18.991 A
220 TR 3_IR
16.401 A
3I0 seq TF3
21.256 A
-ve TF3
0.09736 A
+ve TF3
0.11669 A
0
0.500
1.000
1.500
2.000
2.500
3.000
3.500
Press F1 for Help
11:27:14.5724
IDLE
11:50 PM

R, Y, B Current of 220/33 kV TF 3 at Biyagama GS

The 33 kV CB was in OFF position & 220 kV CB was in closed position during the fault, so the Zero Sequence current flows through the 220 kV neutral of the TF and through all the 220 kV phases during the fault.



Kothmale PS BEN Records



Analysis Center - CEB - [Record 61065 - KOTHMALE]
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PAGE 01_220kV BIYAGAMA LINE 1
SENS BIYA 1
EVENTS BIYA 1
EVENTS BIYA 1
220 BIYAGAMA 1_IN
34.529 A
220 BIYAGAMA 1_IB
-1152.4 A
220 BIYAGAMA 1_IY
431.61 A
220 BIYAGAMA 1_IR
979.75 A
3I0 seq Biya 1
55.186 A
220 BIYAGAMA 1_UB
-177.07 kV
220 BIYAGAMA 1_UY
113.76 kV
220 BIYAGAMA 1_UR
142.86 kV
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1.000
1.500
2.000
2.500
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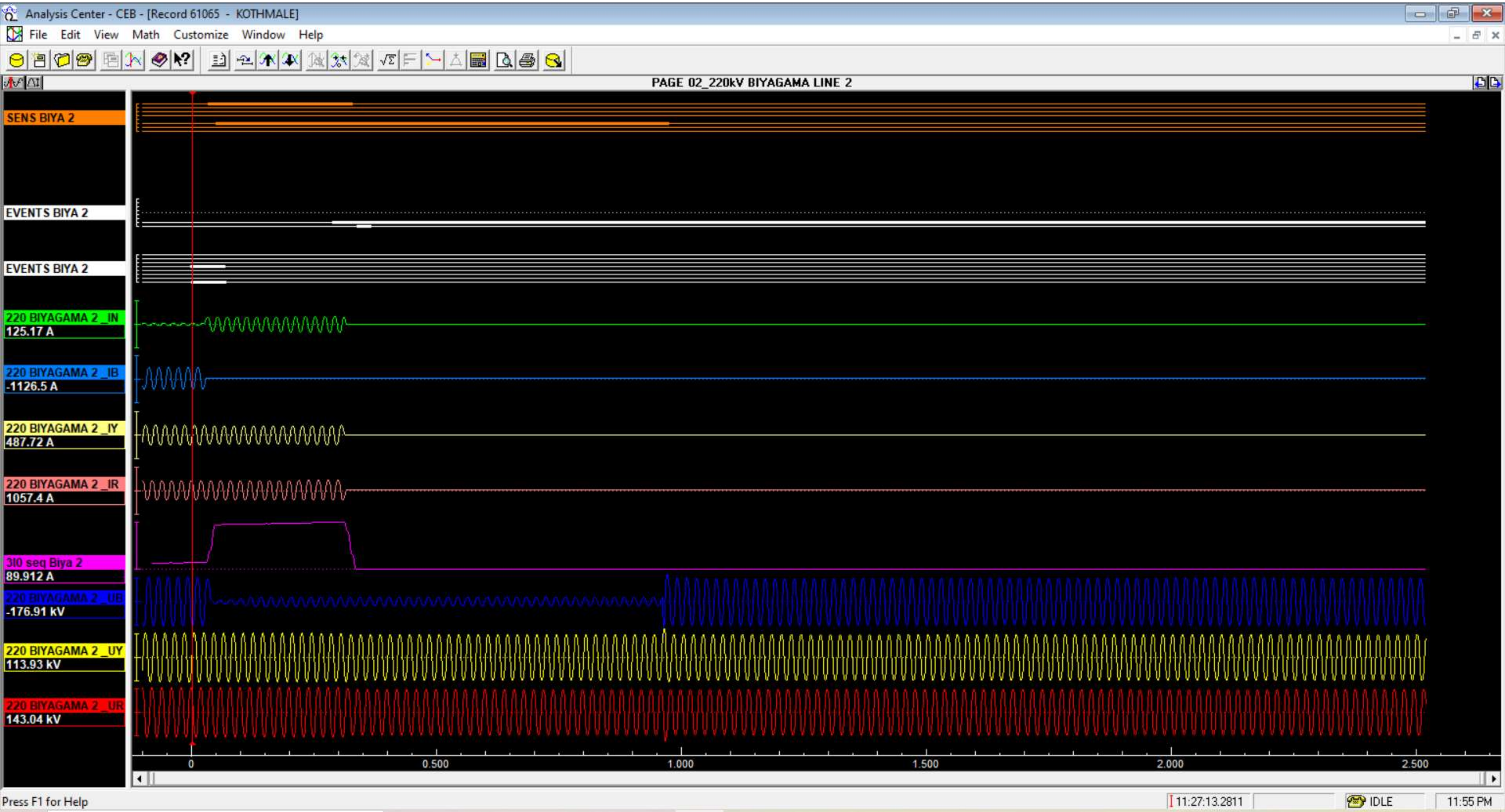
IDLE
11:55 PM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EVENTS BIYA 2
EVENTS BIYA 2
220 BIYAGAMA 2 _IN
125.17 A
220 BIYAGAMA 2 _IB
-1126.5 A
220 BIYAGAMA 2 _IY
487.72 A
220 BIYAGAMA 2 _IR
1057.4 A
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89.912 A
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-176.91 kV
220 BIYAGAMA 2 _UY
113.93 kV
220 BIYAGAMA 2 _UR
143.04 kV
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0.500
1.000
1.500
2.000
2.500
Press F1 for Help
11:27:13.2811
IDLE
11:55 PM

Annex 6.1-3
Additional pictures received from the site of fire

Burnt leaves of near by tree confirming that the fire has been substantial

Annex 6.1-4
Fault distance calculation

Calculation of Distance to the Fault Occurred on 2021-12-03 at 11.27 Hrs in Biyagama Kothmale Line 02

- **Method: Two Ended Negative Sequence Impedance Method**

This concept uses negative sequence quantities of all line terminals for the finding of the location of unbalanced faults. By using negative sequence quantities, it can be negated effect of pre-fault load, fault resistance & zero sequence mutual impedance.

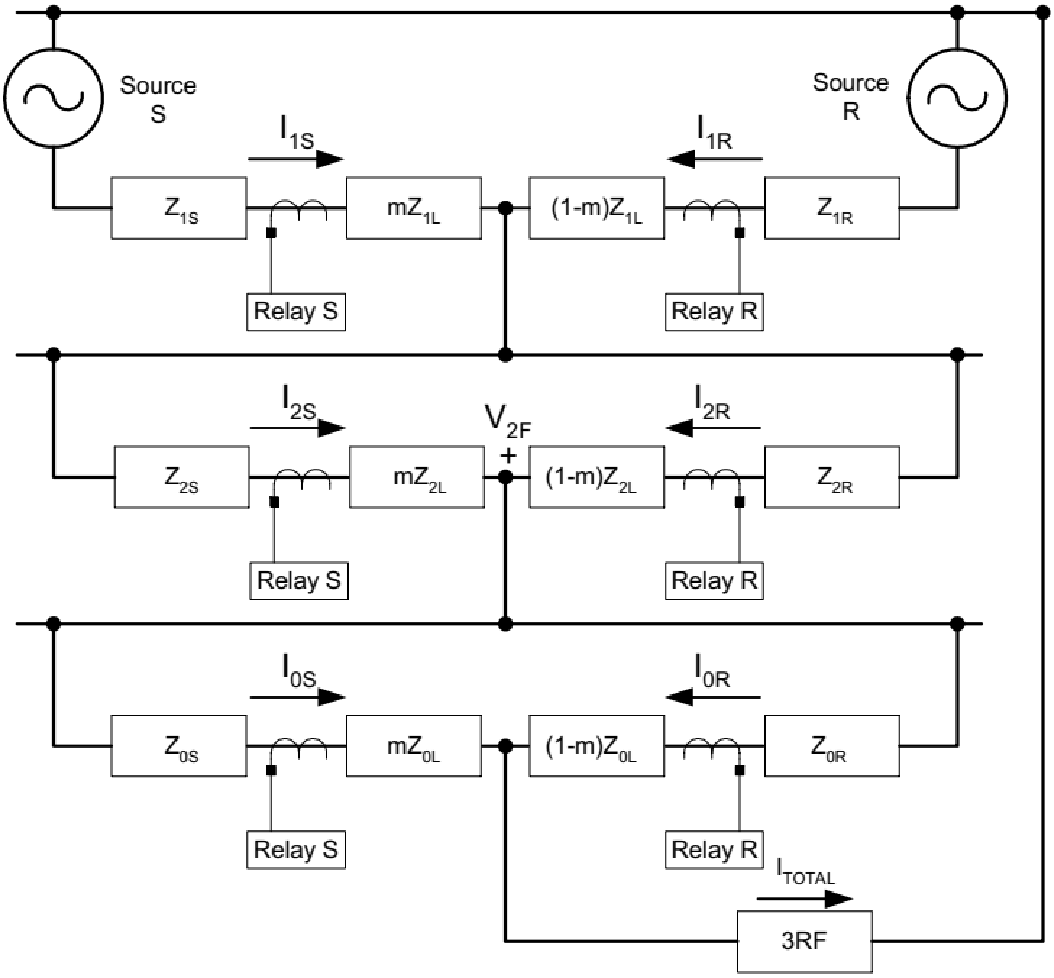

Figure 1: Connection of Sequence Networks for a Single Line to Ground Fault

Using measured negative sequence values available in relays at S & R locations,

$(V_{2F} - V_{2S})/I_{2S} = mZ_{2L}$

$V_{2F} - V_{2S} = I_{2S}*mZ_{2L}$ .... (1)

$(V_{2F} - V_{2R})/I_{2R} = (1-m) Z_{2L}$

$V_{2F} - V_{2R} = I_{2R}*(1-m) Z_{2L}$ .... (2)

V_{2S} = Negative Sequence Voltage Measured by Relay at Terminal S

I_{2S} = Negative Sequence Current Measured by Relay at Terminal S

V_{2R} = Negative Sequence Voltage Measured by Relay at Terminal R

I_{2R} = Negative Sequence Current Measured by Relay at Terminal R

V_{2F} = Negative Sequence Voltage at the Fault Point on the Line

Z_{2L} = Negative Sequence Impedance of the Line

m = Per unit distance to the fault from Terminal S

Equating (1) – (2)

$V_{2R} - V_{2S} = I_{2S}*mZ_{2L} - I_{2R}*(1-m)\ Z_{2L}$

$V_{2R} - V_{2S} = mZ_{2L}*I_{2S} + mZ_{2L}*I_{2R} - I_{2R}*Z_{2L}$

$m = (V_{2R} - V_{2S} + I_{2R}*Z_{2L}) / Z_{2L}*(I_{2S} + I_{2R})$ ………………………………. (3)

- **Correction of Voltage Phase Angle Between Two Buses**

For the accurate estimate of the distance to the fault, correct phase alignment of the values of the two ends shall be done. Using standard power flow equations, voltage angle difference between two ends can be estimated as follows. Line resistance has been neglected & only line reactance has been considered for the estimation due to X>>>>R.

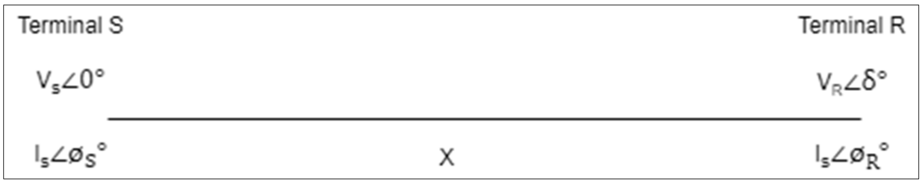

Figure 2: Standard Two Terminal Line Arrangement

$|V_R|.\ |IR|.\cos\phi_R = (|VR|.\ |VS|.\sin\delta)/X$

$\sin\delta = (X.\ \cos\phi_R.\ |I_R|)/|VS|$………………………………… (4)

$|V_S|$ = Magnitude of Terminal S Voltage

$|I_S|$ = Magnitude of Terminal S Current

$|V_R|$ = Magnitude of Terminal R Voltage

$|I_R|$ = Magnitude of Terminal R Current

$\cos\phi_R$ = Terminal R Power Factor

X = Line Reactance

δ = Voltage Angle of Terminal R with respect to Terminal S

The current & voltage values obtained from 7SL87 relay DFR records (point of capture of values are at 30.8 ms before voltage collapse in B Phase) are as below & those values will be used for the estimation of distance to the fault as well. Let's take Terminal **S** as Biyagama GS & Terminal **R** as Kothmale GS.

- **Input Data at Biyagama & Kothmale GSs**

SIGRA V4.60 - [Tables - 2021.12.03_Koth02: 12/3/2021 11:27:13 AM.820]

Cursor 1: 258.6 ms

Measuring Signal	Fundamental / Sub-Harm.	Phase	Extremum	DC	2. Harm. / 1. Int-Harm.	3. Harm. / 2. Int-Harm.	5. Harm. / 4. Int-Harm.
K1:MPI3p1:I A	0.7769 kA	171.3°	-1.0993 kA	0.1%	0.1%	0.1%	0.4%
K1:MPI3p1:I B	0.7904 kA	51.0°	-1.1184 kA	0.4%	0.1%	0.1%	0.5%
K1:MPI3p1:I C	0.3671 kA	-84.2°	0.4975 kA	0.9%	1.1%	3.4%	0.9%
K1:MPI1p1:Ix	52.155 A	118.6°	-73.135 A	1.4%	0.2%	0.4%	0.4%
K1:MPV3p1:V A	120.09 kV	0.0°	169.72 kV	0.1%	0.1%	0.2%	0.7%
K1:MPV3p1:V B	121.47 kV	-119.9°	170.36 kV	0.2%	0.1%	0.1%	0.6%
K1:MPV3p1:V C	120.55 kV	118.8°	-169.33 kV	0.0%	0.2%	0.2%	0.6%
K1:MPV1p1:V B	120.95 kV	-119.8°	169.68 kV	0.1%	0.1%	0.0%	0.7%

Figure 3: Kothmale Line 02 Current & Voltage Values as Recorded in 7SL87 at the Point of Capture in Biyagama GS

SIGRA V4.60 - [Tables - 2021.12.03_Biy 02: 12/3/2021 11:27:14 AM.023]

Cursor 1: 55.5 ms

Measuring Signal	Fundamental / Sub-Harm.	Phase	Extremum	DC	2. Harm. / 1. Int-Harm.	3. Harm. / 2. Int-Harm.	5. Harm. / 4. Int-Harm.
K1:MPI3p1:I A	339.23 A	-13.2°	479.37 A	0.0%	0.0%	0.2%	0.1%
K2:MPI3p2:I A	428.94 A	-13.3°	609.23 A	0.0%	0.1%	0.1%	0.2%
K1:MPI3p1:I B	343.39 A	-133.7°	484.33 A	0.0%	0.2%	0.1%	0.4%
K2:MPI3p2:I B	440.54 A	-133.1°	621.15 A	0.1%	0.2%	0.2%	0.3%
K1:MPI3p1:I C	373.48 A	103.9°	-529.50 A	0.3%	0.1%	0.3%	0.4%
K2:MPI3p2:I C	494.11 A	105.1°	-699.62 A	0.2%	0.1%	0.2%	0.3%
K1:MPI1p1:Ix	56.017 A	-66.7°	82.666 A	0.9%	0.7%	0.5%	0.4%
K1:MPV3p1:V A	126.38 kV	0.0°	179.14 kV	0.2%	0.1%	0.1%	0.9%
K1:MPV3p1:V B	126.28 kV	-120.5°	178.66 kV	0.1%	0.1%	0.2%	1.0%
K1:MPV3p1:V C	125.02 kV	119.1°	-176.59 kV	0.0%	0.2%	0.1%	0.9%
K1:MPV1p1:V B	125.92 kV	-120.2°	177.98 kV	0.1%	0.1%	0.2%	0.9%
K2:MPV1p2:V B	8.9418 V	-22.9°	15.382 V	152.1%	55.8%	44.1%	36.4%
K1:3I0_Main1*	37.000 A	85.3°	-52.733 A	3.1%	1.8%	3.9%	1.5%
K2:3I0_Main1*	57.904 A	102.1°	-85.273 A	2.3%	0.3%	1.3%	1.5%

Figure 4: Biyagama Line 02 Current & Voltage Values as Recorded in 7SL87 at the Point of Capture in Kothmale GS

- **Calculated Phase & Sequential Components related to the terminal S & R are as bellow**

Biyagama End Data(Terminal S)			Kothmale End Data (Terminal R)		
Phase Values			Phase Values		
Phase Quantity	Magnitude(A or V)	Phase Angle (˚)	Phase Quantity	Magnitude(A or V)	Phase Angle (˚)
IL1	776.9	171.3	IL1	768.1697115	-13.2558392
IL2	790.4	51	IL2	783.9194191	-133.3628216
IL3	367.1	-84.2	IL3	867.5433492	104.5834272
UL1	120090	0	UL1	126380	0
UL2	121470	-119.9	UL2	126280	-120.5
UL3	120550	118.8	UL3	125020	119.1
Sequential Components			Sequential Components		
Sequential Quantity	Magnitude(A or V)	Phase Angle (˚)	Sequential Quantity	Magnitude(A or V)	Phase Angle (˚)
I0	144.8589364	122.4922384	I0	31.31910403	95.48889028
I1	641.2522471	168.2534714	I1	806.4185477	-14.06518584
I2	148.8875553	-114.7451511	I2	33.51886621	-160.2327085
U0	500.5178887	12.96264701	U0	516.0142581	16.22246276
U1	120696.9205	-0.365939553	U1	125890.7371	-0.465097763
U2	1275.419212	148.9106338	U2	877.7500029	90.13434852

Figure 5: Phase & Sequential Values Calculated from Figure 3 & Figure 4 Input Data

Biyagama Kothmale Line Parameter Data

Line Impedance (per/km)	0.038+0.306i
Line Length	70.5
Line Impedance	2.679+21.573i
Line Impedance	21.73870672∠82.9210784

Table 1: Line Parameter Data

- **COS ($\emptyset_R$) Calculation**

COS ($\emptyset_R$) = COS (-120.5 – (-133.3628216))

COS ($\emptyset_R$) = 0.956379276……………………………………(5)

Calculation of Voltage Phase Angle Difference between the Substations by Using Healthy Y Phase current & Voltage Values using equation (4) & (5)

Sinδ = (21.573* 0.956379276*783.9194191*)/121470

Sinδ = 0.139222555

δ = Sin^{-1} (0.139222555)

δ = 8.002861391……………………………………(6)

- **Kothmale end Phase & Sequential Values with the compensation of voltage phase angle difference between two buses**

Kothmale End Data (Terminal R)		
Phase Values (with angle correction)		
Phase Quantity	Magnitude(A or V)	Phase Angle (°)
IL1	768.1697115	-5.252977813
IL2	783.9194191	-125.3599602
IL3	867.5433492	112.5862886
UL1	126380	8.002861391
UL2	126280	-112.4971386
UL3	125020	127.1028614
Sequential Components (with angle correction)		
Sequential Quantity	Magnitude(A or V)	Phase Angle (°)
I0	31.31910403	103.4917517
I1	806.4185477	-6.062324453
I2	33.51886621	-152.2298471
U0	516.0142581	24.22532415
U1	125890.7371	7.537763628
U2	877.7500029	98.13720991

Figure 6: Kothmale End Input Data with Compensation of Voltage Phase Angle Difference

- **Estimation of Distance to the Fault**

Calculation of Distance to the Fault from Biyagama End using Figure 5, Figure 6, Table 1 Values

m = **[**(877.7500029∠98.13720991^{0}) – (1275.419212 ∠148.9106338^{0}) + (33.51886621∠-152.2298471) *(21.73870672∠82.9210784)**] / [** (21.73870672∠82.9210784) *((148.8875553∠-114.7451511) + (33.51886621 ∠ -152.2298471)) **]**

m = 0.341871027 ∠17.41606844

Distance to the Fault in Km = 0.341871027*71.5

= 24.10190741 km

Annex 6.1-5

Very High-Resistance Fault on a 525 kV Transmission Line – Case Study

(https://ieeexplore.ieee.org/document/4982523)

Very High-Resistance Fault on a 525 kV Transmission Line – Case Study

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Transener Internacional Ltda.

Vanessa Alves dos Santos Mello Maria
ATE Transmissora de Energia Ltda.

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Schweitzer Engineering Laboratories, Inc.

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Very High-Resistance Fault on a 525 kV Transmission Line – Case Study

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Vanessa Alves dos Santos Mello Maria, *ATE Transmissora de Energia Ltda.*
Fabiano Magrin, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—This paper analyzes a 300 ohm primary ground fault, which is an unusually high value for a 525 kV transmission line in southeastern Brazil. This case study emphasizes the techniques used by the analysts.**

Considering that the fault impedance was larger than those usually observed in single-phase faults on extra-high-voltage (EHV) lines, this paper discusses the probable cause of the fault and mentions an analysis technique to evaluate such faults. The protective relaying community lacks information regarding the causes and values of fault resistances to ground on high-voltage (HV) and EHV transmission lines. The objectives of this paper are to stimulate research and contribute to the collection of very high-resistance fault information.

The analysis techniques are presented using symmetrical components and fault calculations to arrive at fault parameter values that are very close to the ones provided by protective relays. The performance of the line protection is evaluated for the specific fault conditions, with calculation of the observed impedances and currents. The importance of the ground overcurrent directional protection on a pilot directional comparison scheme is shown. Speculation on the widespread use of differential protection for transmission lines should stimulate discussions of line protection philosophies and applications.

The criteria for the resistive reach setting of the quadrilateral ground distance characteristic are presented to show an evolution of past criteria and to open discussion about the setting limits.

The conclusions of this paper highlight the importance of present event report analysis techniques regarding fault calculation software and the need for appropriate settings criteria for the resistive ground distance element threshold. This paper also supports the use of ground directional overcurrent protection with a pilot scheme for HV and EHV transmission line protection, while proposing the widespread use of differential functions for transmission lines, even for the most extensive cases.

I. Introduction

This paper is based on the event report analysis of five faults on a 525 kV single-circuit transmission line located in southeastern Brazil. The 121.4-kilometer transmission line interconnects the SE Assis Terminal to the SE Londrina Terminal in São Paulo and Paraná States, as shown in Fig. 1. Transener Internacional Ltda. is responsible for operating this transmission line.

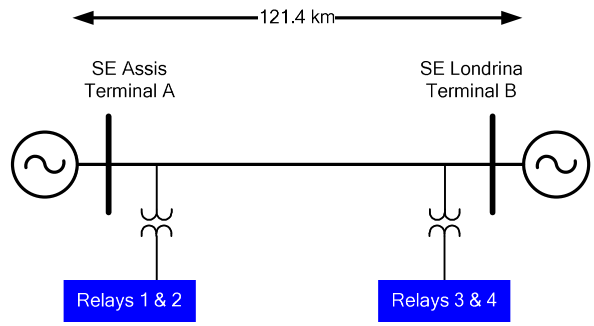

Fig. 1. 525 kV transmission line from SE Assis Terminal A to SE Londrina Terminal B, located in southeastern Brazil

Transener uses a dual main protection system at each terminal. The characteristics of the relays are mho for phase elements and mho and quadrilateral for ground elements. The backup protection uses a DCUB (directional comparison unblocking) scheme with mho Zone 2 phase and ground characteristics and a ground directional overcurrent for high-resistance faults.

The first three faults happened on the same day in July 2006 and two others in August 2006. The line between the cities of Assis and Londrina crosses the Paranapanema River. The line has a positive-sequence impedance of Z1 = 2.50 + j 38.65 ohms primary and a zero-sequence impedance of Z0 = 44.27 + j 170.32 ohms primary.

This paper describes the analysis techniques and the computational tool used to analyze the first fault. For the other faults, the numeric and comparative results are presented, using the same methodology as the first analysis. The nature of the fault, the estimated value of the fault resistance (R_F), and the estimated fault location on the transmission line are presented for each fault. The apparent impedances at each extremity of the transmission line are calculated using the event report data.

The performance of the transmission line protection is evaluated for the observed conditions. From that evaluation, we see the importance of the pilot directional ground overcurrent protection for high-voltage (HV) and extra-high-voltage (EHV) lines. The widespread use of the differential function as the main protection for a transmission line could effectively replace conventional schemes and theories.

II. Analysis of July 2006 Faults

On the same day in July 2006, three faults occurred: the first one at 12:36 p.m., the second at 12:47 p.m., and the third at 12:58 p.m. At the time, the cause of these faults was unknown.

All three faults were high-impedance B-phase-to-ground faults, and all three faults were cleared by ground directional overcurrent elements of the pilot scheme.

A. Analysis of First Fault

1) Nature of the Fault

The first fault was characterized as a high-impedance fault with gradually rising ground current. Several cycles after the start of the fault, the current reached the minimum protection threshold. Fig. 2 displays the ground fault current as seen from Terminal A.

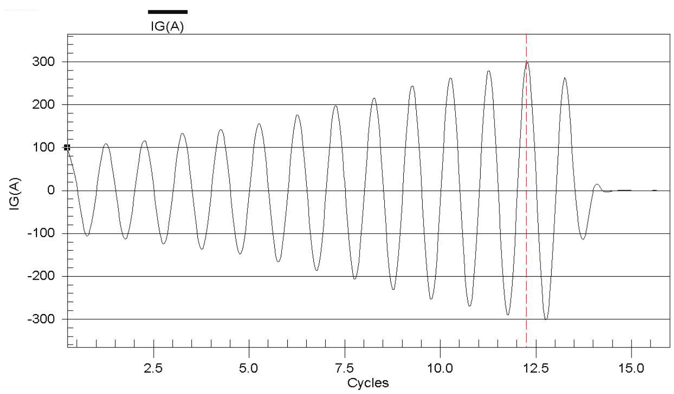

Fig. 2. Ground current at Terminal A

Fig. 3 displays the voltage and current phasors as seen from Terminal A at the moment the relay tripped. There was practically no voltage sag for the faulted phase. With a high-impedance fault (hundreds of ohms), the angular difference between the B-phase voltage and the B-phase current is between –5° and –10°. Fig. 3 shows a predominantly resistive characteristic.

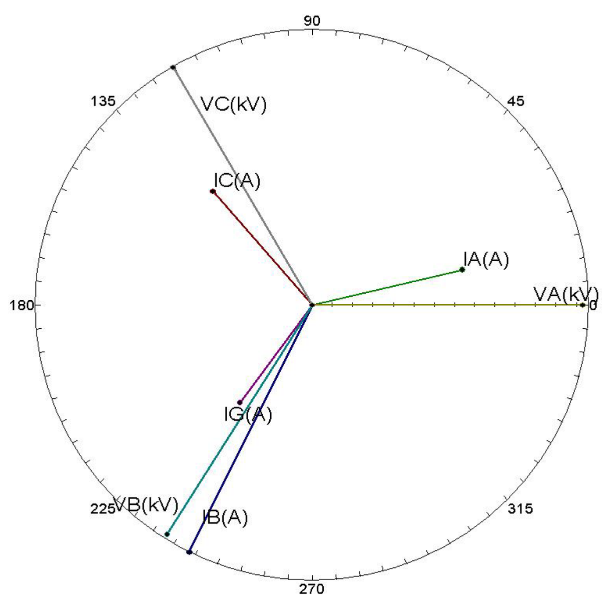

Fig. 3. Voltage and current phasors

When the observed current presents such a resistive angle, the fault is a high-impedance (resistance) type. The I_B phasor is the sum of the prefault load current and the Thèvenin's short-circuit current.

I_{Ground} (Terminal A) = 299.5 A ∠ –4.5° (related to VB)

I_{Ground} (Terminal B) = 266.9 A ∠ –3.3° (related to VB)

2) Fault Current and Thèvenin's Current at Terminal A

The event report shows the total fault current measured by the protective relay. Using the superposition principle, the total current is the result of the prefault load current added to Thèvenin's current.

For the event under analysis, the prefault currents (positive sequence) and voltages are listed in Table I.

TABLE I
TERMINAL A PREFAULT VOLTAGES AND CURRENTS

	Magnitude	Angle	Real	Imaginary
I_{1A} (A)	379.8	236.2	–211.28	–315.61
I_{1B} (A)	379.8	116.2	–167.68	340.78
I_{1C} (A)	379.8	–3.8	378.96	–25.17
V_{1A} (kV)	312.4	225.6	–218.57	–223.20
V_{1B} (kV)	312.4	105.6	–84.01	300.89
V_{1C} (kV)	312.4	–14.4	302.59	–77.69

Table II lists the B-phase fault current and voltage at Terminal A.

TABLE II
TERMINAL A VOLTAGE AND CURRENT AT RELAY TRIP INSTANT

	Magnitude	Angle	Real	Imaginary
I_B (A)	680.8	112.2	–257.23	630.33
V_B (kV)	309.8	110	–105.96	291.12
I_N (A)	299.5	100.10	–52.52	294.86

For the Thèvenin's current calculation, the positive-sequence current of the faulted phase is adjusted to be equal to the measured negative-sequence current, as shown in Table III.

TABLE III
NEGATIVE SEQUENCES USING THÈVENIN'S CURRENT

	Magnitude (A)	Angle	Comments
I_{2A}	109.50	–20.5	
I_{2B}	109.50	99.5	From Event Report
I_{2C}	109.50	219.5	
I_{1A}	109.50	219.5	
I_{1B}	109.50	99.5	Adopted Equal to I2B
I_{1C}	109.50	–20.5	
I_{0A}	99.83	100.1	
I_{0B}	99.83	100.1	From Event Report
I_{0C}	99.83	100.1	

Thèvenin's current is $I_{Bth} = I_{1B} + I_{2B} + I_{0B}$. The fault current is equal to Thèvenin's current added to the prefault current, as shown in Table IV.

TABLE IV
TERMINAL A TOTAL FAULT CURRENT

	Magnitude (A)	Angle
I_F Thev (IB)	318.83	99.69
+		
I Prefault	379.80	116.20
=		
I_F Total	691.44	108.67
From Event Report	680.80	112.20

The calculated current differs by just 1.54 percent from the measured current.

3) Fault Current and Thèvenin's Current at Terminal B

The prefault currents at Terminal B are listed in Table V.

TABLE V
TERMINAL B PREFAULT VOLTAGE AND CURRENTS

	Magnitude	Angle	Real	Imaginary
I_{1A} (A)	370.0	34.7	304.19	210.63
I_{1B} (A)	370.0	274.7	30.32	–368.76
I_{1C} (A)	370.0	154.7	–334.51	158.12
V_{1A} (kV)	310.8	231.2	–194.75	–242.22
V_{1B} (kV)	310.8	111.2	–112.39	289.77
V_{1C} (kV)	310.8	–8.8	307.14	–47.55

Table VI lists the B-phase fault current and voltage from the event report at Terminal B.

TABLE VI
TERMINAL B VOLTAGE AND CURRENT AT RELAY TRIP INSTANT

	Magnitude	Angle	Real	Imaginary
I_B (A)	146.3	257	–32.91	–142.55
V_B (kV)	310.1	112.7	–119.67	286.08
I_N (A)	266.9	110.2	–92.16	250.48

For the Thèvenin's current calculation, the positive-sequence current of the faulted phase is adjusted to be equal to the measured negative-sequence current, as shown in Table VII.

TABLE VII
POSITIVE SEQUENCES USING THÈVENIN'S CURRENT

	Magnitude (A)	Angle	Comments
I_{2A}	79.50	–9.7	
I_{2B}	79.50	110.3	From Event Report
I_{2C}	79.50	230.3	
I_{1A}	79.50	230.3	
I_{1B}	79.50	110.3	Adopted Equal to I2B
I_{1C}	79.50	–9.7	
I_{0A}	88.97	110.2	
I_{0B}	88.97	110.2	From Event Report
I_{0C}	88.97	110.2	

Again, Thèvenin's current is $I_{Bth} = I_{1B} + I_{2B} + I_{0B}$. The fault current is equal to Thèvenin's current added to the prefault current, as shown in Table VIII.

TABLE VIII
TERMINAL B TOTAL FAULT CURRENT

	Magnitude (A)	Angle
I_F Thev (IB)	247.97	110.26
+		
I Prefault	370.00	–85.30
=		
I_F Total	147.04	–112.20
From Event Report	146.30	–103.00

The calculated current differs by just 0.50 percent from the measured current.

4) Fault Resistance and Fault Location

Using a short-circuit calculation program, protection engineers estimated R_F and the fault location. The system data used for the calculation were obtained from the Brazilian National Interconnected System Operator (ONS). Fig. 4 shows the calculated currents with 528 ohms of R_F.

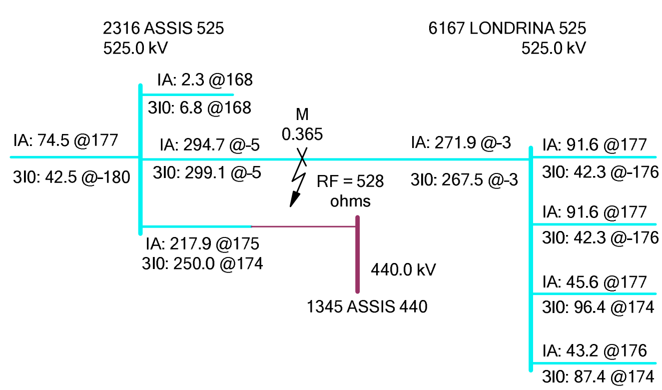

Fig. 4. Fault modeling

Assuming the R_F and fault location as follows, the calculated phase-to-ground currents are quite close to those observed in the real event:

R_F = 528 ohms

Fault location = 0.365 per unit from Terminal A

Table IX compares the real and calculated current values.

TABLE IX
COMPARISON BETWEEN CALCULATED AND MEASURED CURRENTS

	Terminal A		Terminal B	
	Thèvenin (Event Report)	**Calculation Program**	**Thèvenin (Event Report)**	**Calculation Program**
I_B (A)	318.8	294.7	247.97	271.9
I_{Ground} (A)	299.5	299.1	266.90	267.5

The engineers used the zero-sequence network for fault location calculation because it is not influenced by load conditions at the fault instant like the positive-sequence network is. Fig. 5 shows the zero-sequence network, and Table X shows the validation results.

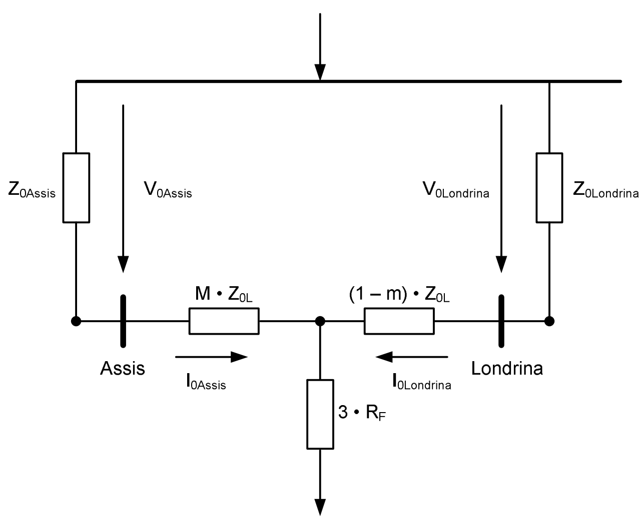

Fig. 5. Zero-sequence network

TABLE X
ZERO-SEQUENCE NETWORK COMPARISON

	Event Report	Calculation Program
V_{0Assis} (V)	6100	6289
I_{0Assis} (A)	299.5	299.1
Z_{0Assis} (Ohms)	61.1	63.0
$V_{0Londrina}$ (V)	2700	2710
$I_{0Londrina}$ (A)	266.9	267.5
$Z_{0Londrina}$ (Ohms)	30.35	30.40

The data used to perform the calculation are accurate. The fault location is estimated as 0.365 per unit from the transmission line. Until this point, the analysts did not know the main cause of the fault; they wanted to confirm that the fault location position was correct.

5) *Protective Relay Impedance Calculation*

Equation (1) shows the expression to calculate the apparent impedance of the phase-to-ground loop (for B-phase):

$$Z_B = \frac{V_B}{I_B + k_0 \bullet I_N} \quad (1)$$

V_B = B-phase voltage

I_B = B-phase current

I_N = residual (ground) current = 3 • I0

k_0 = zero-sequence current compensation factor

a) Terminal A

As mentioned before, apparent impedance can be calculated according to (1); the engineers used the data from the event report to perform the calculation, and the results are shown in Table XI.

TABLE XI
CALCULATED APPARENT IMPEDANCE

	Magnitude	Angle
V_B (kV)	309.80	110.00
I_B (A)	680.80	112.20
I_N (A)	299.50	100.10
k_0	1.189	–13.89
$k_0 \bullet I_N$	356.11	86.21
$I_B + K_0 \bullet I_N$	1012.98	103.34
Z_B Ohms Primary	305.83	6.66

The calculated apparent impedance has R equal to 303.76 ohms and X equal to 35.48 ohms. This impedance value is beyond the reach of the Zone 3 distance element.

In a case of a fault with no load condition, there is only the Thèvenin's current. The calculated apparent impedance is shown in Table XII.

TABLE XII
CALCULATED APPARENT IMPEDANCE WITH NO LOAD

	Magnitude	Angle
V_B (kV)	309.80	110.00
I_B (A)	318.83	99.69
I_N (A)	299.50	100.10
K_0	1.189	–13.89
$k_0 \bullet I_N$	356.11	86.21
$I_B + K_0 \bullet I_N$	670.29	92.58
Z_B Ohms Primary	462.19	17.42

The calculated apparent impedance has R equal to 305.83 ohms, due to load current influence. With no load, it would be 462.19 ohms.

b) Terminal B

We can calculate the apparent impedance using the data from the event report. The result is shown in Table XIII.

TABLE XIII
CALCULATED APPARENT IMPEDANCE

	Magnitude	**Angle**
V_B (kV)	310.10	112.70
I_B (A)	146.30	–103.00
I_N (A)	266.90	110.20
K_0	1.189	–13.89
$k_0 \bullet I_N$	317.34	96.31
$I_B + K_0 \bullet I_N$	185.69	111.41
Z_B Ohms Primary	1670.01	1.29

In this situation, the calculated apparent impedance has R equal to 1,669.59 ohms and X equal to 37.54 ohms. This impedance value is beyond the reach of the distance element.

In a case of a fault with no load condition, there is only the Thèvenin's current. The calculated apparent impedance is shown in Table XIV.

TABLE XIV
CALCULATED APPARENT IMPEDANCE WITH NO LOAD

	Magnitude	**Angle**
V_B (kV)	310.10	112.70
I_B (A)	247.97	110.26
I_N (A)	266.90	110.20
K_0	1.189	–13.89
$k_0 \bullet I_N$	317.34	96.31
$I_B + K_0 \bullet I_N$	561.19	102.43
Z_B Ohms Primary	552.58	10.27

Note again the load influence on the fault.

6) Expression for Phase-to-Ground Impedance

The effect of R_F in a looped line can be seen at [1] and is illustrated in Fig. 6.

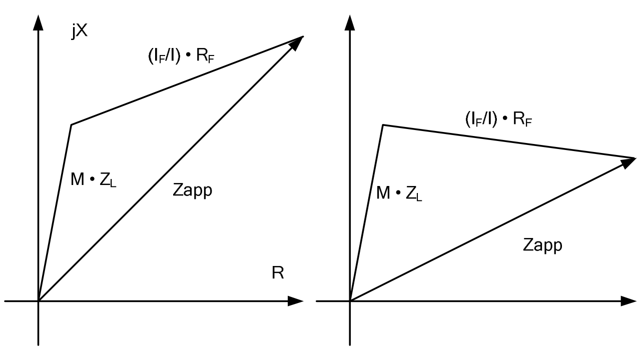

Fig. 6. Fault impedance effect

Zapp = apparent impedance

Z_L = line impedance

m = fault point (per unit from the protection terminal)

$I_F = I_N + I_{N'}$ = total fault current at the short-circuit point

$I_N = 3 \bullet I0$ current at Terminal A

$I_{N'} = 3 \bullet I0$ current at Terminal B

$I = I_A + k_0 I_N$

I_A = phase current for A-phase fault

The I_F/I ratio can cause an increase in the measured R_F as well as a displacement of the measured resistance angle so that the apparent phase-to-ground impedance can assume high values.

The following expression approximates the phase-to-ground impedance for a nonradial transmission line with an A-phase-to-ground fault with R_F:

$$\frac{V_A}{I_A + k_0 \bullet I_N} = Z_A + \left(\frac{I_N + I_{N'}}{I_A + k_0 \bullet I_N} \right) \bullet R_F \tag{2}$$

where:

Z_A = Phase A impedance

$m \bullet Z_L$ = line impedance from relay terminal to fault location

I_N = measured ground current at terminal

$I_{N'}$ = measured ground current at remote terminal

I_A = measured phase current at terminal

R_F = fault resistance

Using event reports to estimate the total current ($I_N + I_{N'}$) is difficult because of system nonhomogeneity (different phase references at the two terminals). However, the arithmetic sum is not exactly the fault current across R_F. To get a common phase reference, we would need to use synchrophasors.

For radial transmission lines, there is no $I_{N'}$ and I_A = In, so the expression becomes:

$$\frac{V_A}{I_A + k_0 \bullet I_N} = Z_A + \frac{R_F}{1 + k_0} \tag{3}$$

7) Impedance Analysis

Tables XV and XVI compare the values of event report data, values provided by the short-circuit calculation program, and estimated impedance values from (3) for Terminals A and B.

TABLE XV
IMPEDANCE COMPARISON TERMINAL A IN OHMS

	Z Event Report	**Z Calculation Program**	**Z Estimated by Expression**
No Load	462.19	466.27	445
With Load	305.83	–	293

TABLE XVI
IMPEDANCE COMPARISON TERMINAL B IN OHMS

	Z Event Report	Z Calculation Program	Z Estimated by Expression
No Load	552.58	514.70	530
With Load	1670.01	–	1591

The short-circuit calculation program was set for a no-load condition (classic short-circuit calculation). Note that the calculated values are quite close to the ones calculated using voltages and currents measured in the event report with no-load effect.

The calculated R_F from (3) shows values of the same order. For that calculation, it is necessary to have the apparent impedance value at the terminal (taken from the event report), knowledge of the ground currents at the two terminals, and the line impedance from the terminal to the fault point. Therefore, the fault point has to be known or well estimated (4).

$$\text{apparent} = Z_A + \left(\frac{I_N + I_{N'}}{I_A + k_0 \bullet I_N} \right) \bullet R_F \qquad (4)$$

For the fault under analysis, the load current caused the relay at Terminal A to measure a lower impedance, whereas the load current caused the relay at Terminal B to measure a higher impedance. This incorrect impedance measurement remained until one of the breakers opened, causing the fault conditions to change. This incorrect impedance measurement highlights the importance of pilot schemes with ground directional overcurrent elements to detect high-resistance faults.

B. Analysis of Second Fault

1) Nature of the Fault

Eleven minutes after the first fault, a new fault was recorded on the same B-phase.

Again, the total fault current had a resistive characteristic. The ground current had the following values:

I_{Ground} (Terminal A) = 457.5 A ∠ –6.8° (related to VB)

I_{Ground} (Terminal B) = 410.0 A ∠ –3.2° (related to VB)

2) Fault Resistance and Fault Location

Using the same techniques, the following results were obtained:

R_F = 342 ohms

Fault location = 0.365 per unit from Terminal A

Table XVII shows the comparison between the calculated apparent impedance data from the event report and the calculated impedance values provided by the short-circuit calculation program.

TABLE XVII
IMPEDANCE COMPARISON IN OHMS

	Terminal A		Terminal B	
	Z Event Report	Z Calculation Program	Z Event Report	Z Calculation Program
No Load	303.62	303	353.85	335
With Load	227.25	–	631.18	–

Again, the calculated values from the short-circuit program are quite close to the calculated values from the event report, considering a no-load effect and an out-of-reach distance function.

C. Analysis of Third Fault

1) Nature of the Fault

About ten minutes after the second fault, there was a third B-phase fault. The ground current had the following values:

I_{Ground} (Terminal A) = 717.2 A ∠ –8.1° (related to VB)

I_{Ground} (Terminal B) = 619.2 A ∠ –6.2° (related to VB)

2) Fault Resistance and Fault Location

Using the same techniques, the following results were obtained:

R_F = 218 ohms

Fault location = 0.352 per unit from Terminal A

Table XVIII shows the comparison between the calculated apparent impedance data from the event report and the calculated impedance values provided by the short-circuit calculation program.

TABLE XVIII
IMPEDANCE COMPARISON IN OHMS

	Terminal A		Terminal B	
	Z Event Report	Z Calculation Program	Z Event Report	Z Calculation Program
No Load	191.53	191.7	230.91	219.8
With Load	159.28	–	321.08	–

D. Main Cause of the Faults

On the day of the faults, the weather conditions were rainy and windy with atmospheric electrical discharges. The possibility of flashover across the insulator to the structure resulting from atmospheric electrical discharge was low, considering the magnitude of the estimated R_F. For flashovers to occur, the R_F must be lower. Even when considering all the ground resistance of structures, the impact to the fault was minimal.

The fault location was calculated to be between 42 and 44 kilometers from Terminal A. At that location, the transmission line crosses over the Paranapanema River. The analysts speculated that the fault could have flashed to the water, assisted by the intense weather conditions.

However, the analysts were still unsure what caused the fault. Because of the high R_F, a tree was ruled out as the cause. Past experience showed typical resistance values of between 30 and 100 ohms primary for faults caused by trees.

E. Analysis of the Protection Performance

The protection performance was correct for all of the faults. The directional ground overcurrent protection on a pilot directional comparison scheme tripped as expected. The directional element's performance and the sensitivity setting for ground faults were satisfactory.

Although the distance elements did not operate, this is considered a correct operation because the fault impedance was outside their zones of operation.

1) Performance of the Negative-Sequence Directional Element

The relay has a negative-sequence element that tests the calculated negative-sequence impedance against forward and reverse thresholds [2].

The transmission line relay settings for the directional control elements at both line terminals are:

Order = Q → negative-sequence polarization

50FP = 0.40 and 50RP = 0.25 → minimum forward and reverse current

Z2F = 1.70 and Z2R = 1.80 → forward and reverse threshold

a2 = 0.10 → minimum I_2/I_1 ratio

Terminal A data for the first short circuit:

PTR = 4565, CTR = 400, PTR/CTR = 4565/400 = 11.41

I_2 = 109.5 A ∠ 99.5° (primary)

I_1 = 476.3 A ∠ 114.5° (primary)

V_2 = 2500 V ∠ –9.7° (primary)

Analysis:

3_{I2} = 3 • 109.5 = 328.5 A (primary) → 0.821 A (secondary)

0.821 > 50FP → okay

I_2/I_1 = 109.2/476.3 = 0.23

0.23 > a2 → okay, negative element active

Line angle Θ = 86.29°

$$Z_2 = \frac{\mathrm{Re}\left[V_2 \bullet (I_2 \bullet 1/\Theta)^*\right]}{|I_2|^2} \tag{5}$$

Z_2 = –39.02/11.41 = –3.42 ohms (secondary)

Z_2 < Z2F (–3.42 < 1.70) → okay, forward fault

The directional element settings were capable of sensing low currents from very high-resistance faults on the transmission line.

2) Phase Discrimination

The relay had correctly discriminated the faulted B-phase at both ends of the line.

3) Performance of the Fault Location Function

The relay has a fault location function. For very high R_F, there was no set condition for an accurate fault location. The displayed values were not reliable. Synchrophasors improve fault location performance in these cases because they have voltages and currents for both terminals at the same instant of time, with accuracy better than five microseconds.

F. Testing the Negative-Sequence Fault Location System

An interesting fault location method is described in [3] that is not affected by prefault load flow, R_F, power system nonhomogeneity, or current infeed from other line terminals.

The algorithm:

$$A \bullet m^2 + B \bullet m + C = 0 \tag{6}$$

$$\begin{aligned} A = |I_{2R}|^2 \bullet \left[\mathrm{Re}(Z_{2L})^2 + \mathrm{Im}(Z_{2L})^2\right] - \\ \left[\mathrm{Re}(I_{2S} \bullet Z_{2L})^2 + \mathrm{Im}(I_{2S} \bullet Z_{2L})^2\right] \end{aligned} \tag{7}$$

$$\begin{aligned} B = -2 \bullet |I_{2R}|^2 \bullet \left[\mathrm{Re}\left(Z_{2R} + Z_{2L}\right) \bullet \mathrm{Re}\left(Z_{2L}\right) + \right. \\ \left. \mathrm{Im}(Z_{2R} + Z_{2L}) \bullet \mathrm{Im}(Z_{2L})\right] - \\ 2 \bullet \left[\mathrm{Re}(I_{2S} \bullet Z_{2S}) \bullet \mathrm{Re}(I_{2S} \bullet Z_{2L}) + \right. \\ \left. \mathrm{Im}(I_{2S} \bullet Z_{2S}) \bullet \mathrm{Im}(I_{2S} \bullet Z_{2L})\right] \end{aligned} \tag{8}$$

$$\begin{aligned} C = |I_{2R}|^2 \bullet \left[\mathrm{Re}(Z_{2R} + Z_{2L})^2 + \mathrm{Im}(Z_{2R} + Z_{2L})^2\right] - \\ \mathrm{Re}(I_{2S} \bullet Z_{2S})^2 - \mathrm{Im}(I_{2S} \bullet Z_{2S})^2 \end{aligned} \tag{9}$$

m = distance (per unit of transmission line)

V_{2S} = sending end negative-sequence voltage

V_{2R} = receiving end negative-sequence voltage

I_{2S} = sending end negative-sequence current

I_{2R} = receiving end negative-sequence current

Z_{2L} = negative-sequence transmission line impedance

Z_{2R} = receiving end negative-sequence source impedance = $-V_{2R}/I_{2R}$

Z_{2S} = sending end negative-sequence source impedance = $-V_{2S}/I_{2S}$

For the first short circuit:

Z_{2L} = 2.50 + j 38.65 ohms primary

V_{2S} = 3600 V ∠ –9.7° (primary)

I_{2S} = 109.5 A ∠ 99.5° (primary)

V_{2R} = 3200 V ∠ 30.8° (primary)

I_{2R} = 79.5 A ∠ 110.3° (primary)

Results:

A = –8505411.08

B = –67490470.78

C = 25864855.38

m_1 = 0.366 from Terminal A

m_2 = –8.30132944

The terms m_1 and m_2 are the two possible solutions for m from (6); the negative value is disregarded.

Note that the negative-sequence fault location algorithm, using data from the two terminals, is quite accurate for very high-resistance faults.

III. New Faults in August 2006

On August 16, 2006, two faults were recorded (at 2:00 p.m. and 2:04 p.m.), with the transmission line opening and reclosing in both cases. At the time, a line maintenance team observed the flashover from the transmission line and the vegetation close to the Paranapanema River, as shown in Fig. 7.

Fig. 7. Fire damage visible at fault location

The first fault was a B-phase-to-ground fault with high impedance (R_F = 350 ohms), and the operation of the ground overcurrent directional comparison scheme was correct. Four minutes after the first occurrence, a second fault occurred at the same phase (R_F = 34 ohms), and the distance protection element tripped the transmission line.

A. *Analysis of First Fault*

1) Nature of the Fault

This fault involved a tree and was characterized by very high resistance. The faulted phase voltage and current and the residual current are displayed in Fig. 8.

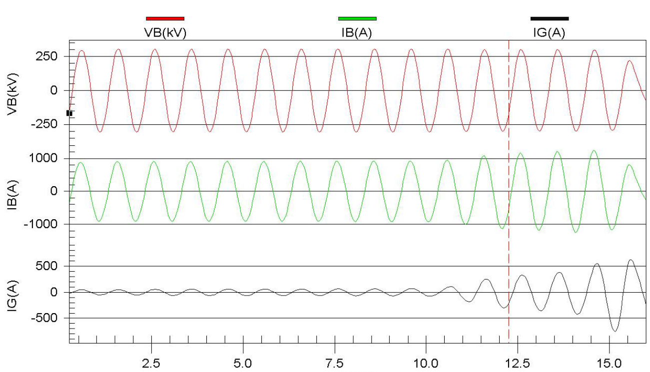

Fig. 8. VB, IB, and IG waveforms

The voltage was essentially maintained during the fault with the following ground currents:

I_{Ground} (Terminal A) = 446.9 A ∠ –10.4° (related to VB)

I_{Ground} (Terminal B) = 400.9 A ∠ –6.3° (related to VB)

2) Fault Resistance and Fault Location

Using the same techniques, the following results were obtained:

R_F = 350 ohms

Fault location = 0.365 per unit from Terminal A

Table XIX shows the comparison between the values of calculated apparent impedance using data from the event report and the calculated impedance value provided by the short-circuit calculation program.

Table XIX
Impedance Comparison in Ohms

	Terminal A		**Terminal B**	
	Z Event Report	**Z Calculation Program**	**Z Event Report**	**Z Calculation Program**
No Load	303.02	310	363.42	343
With Load	170.8	–	1125.39	–

B. *Analysis of Second Fault*

1) Nature of the Fault

It was observed, in this case, that the B-phase-to-ground fault involving a tree was a classic short circuit with high current and voltage sag at faulted phase, as shown in Fig. 9.

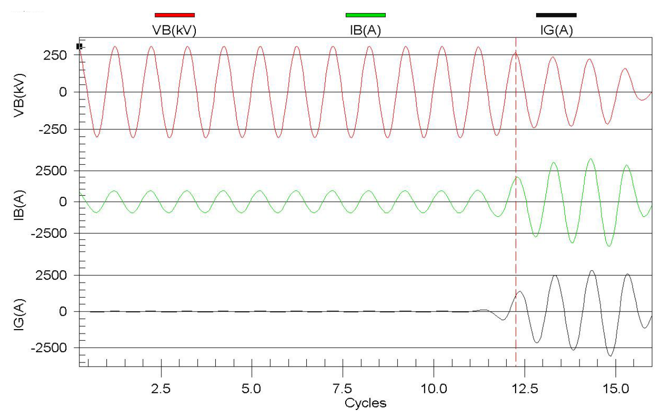

Fig. 9. VB, IB, and IG waveforms show more current and voltage sag at the fault due to the lower impedance fault

The ground currents measured in the event report are:

I_{Ground} (Terminal A) = 2.914 A ∠ –23.3° (related to VB)

I_{Ground} (Terminal B) = 2.569 A ∠ –26.7° (related to VB)

2) Fault Resistance and Fault Location

Using the same techniques as before, the following results were obtained:

R_F = 34 ohms

Location = 0.359 per unit of Terminal A

3) Impedance Calculation

From the event report, we can calculate the apparent impedance, as shown in Table XX.

TABLE XX
RELAY APPARENT IMPEDANCE IN OHMS

Z_B Ohms Primary	Magnitude	Angle
Apparent	32.87	24.60
No Load	35.07	31.25

Fig. 10 shows the calculated impedances, from Table XX, in comparison to the reach of the distance zones. Out of all of the occurrences described in this paper, this event is the only one for which the distance protection function tripped the transmission line.

The fault locator of the relay indicated 47 kilometers for a 44.8-kilometer location.

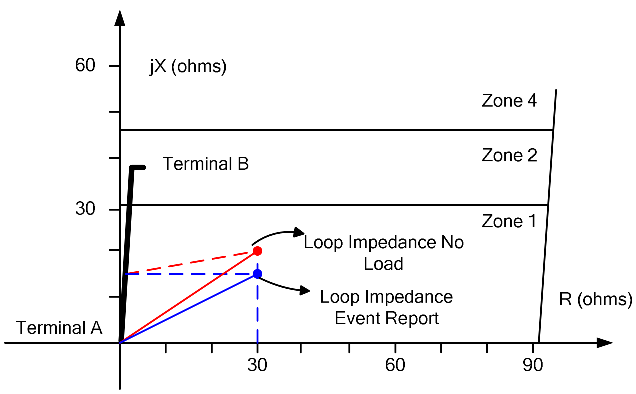

Fig. 10. Distance element and fault point at Terminal A

For Terminal B, the apparent impedances are listed in Table XXI.

TABLE XXI
RELAY APPARENT IMPEDANCE IN OHMS

Z_B Ohms Primary	Magnitude	Angle
Apparent	51.91	40.89
No Load	47.32	33.54

The calculated reactance shows the influence of the load. With load, the apparent impedance is inside Zone 2. Without load, the fault would be in Zone 1 (physically to 64 percent of the transmission line). The fault locator indicated 76.9 kilometers for a 78-kilometer location, as shown in Fig. 11.

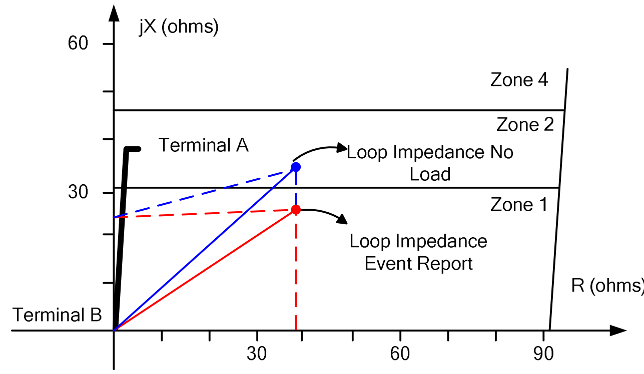

Fig. 11. Distance element and fault point at Terminal B

C. Considerations on the Primary Cause of the Faults

Fig. 7 and the fault locations shown before prove that there was a phase-to-ground fault involving a tree, and the analysts concluded that the July 2006 faults were caused by the same tree. Fault resistances between 528 ohms (first fault of July) and 34 ohms (last fault in August) were observed.

These data prove that there can be a fault-to-ground with very high resistance, even if the fault is through vegetation.

IV. DIRECTIONAL GROUND OVERCURRENT FUNCTION ON PILOT DIRECTIONAL COMPARISON SCHEME

As demonstrated in this paper, the ground directional overcurrent protection function of a directional comparison scheme identified and tripped the feeder on four occasions. It was the only function that detected the high-impedance faults. The two transmission line protection functions in the duplicated scheme meet the established application criteria specified by Brazilian electrical sector authorities. The directional ground overcurrent function used in a pilot scheme has the following advantages:

- It is sensitive enough to detect low-magnitude ground faults due to low currents resulting from high-impedance faults.
- It provides fast tripping of the protected line, considering the time requirements.
- It provides reliable overall protection, depending on the reliability of the communications media between the line terminals.

We cannot expect distance functions to detect all possible transmission line faults, so those functions need complementary ground fault protection.

It is certainly possible to have ground faults with very low currents and extremely high resistance—not suitable for detection even by ground overcurrent relays. Recent studies about these types of protection are mentioned in [1].

V. Differential Function as Main Protection for a Transmission Line

An alternative for line protection is the use of the differential function as the main protection and the distance and/or directional overcurrent functions as backup protection. Differential protection presents the following advantages:

- It is as sensitive to high-impedance fault detection as the ground overcurrent function is, due to new negative-sequence and three-phase-sequence characteristics.
- It is selective.
- The discrimination of the faulted phase is inherent for segregated protection or eventually for protection with a phase discrimination algorithm.
- It does not require voltage information.
- It presents high sensitivity for phase faults.
- It is immune to:
  - Blown potential fuse conditions.
  - Power oscillations through the protected line.
  - Mutual coupling effects.
  - Series unbalance.

One of the few disadvantages of differential protection for a transmission line is the demand for a highly reliable and fast communications link (fiber optic—dielectric or optical ground wire) between the line terminals. This is an economical disadvantage for long lines.

There is a tendency to use differential protection only for short lines (up to 20 kilometers). However, it should be observed that the evolution of technology and the introduction of digital microprocessor-based relays have brought about more resources, different philosophies, and reliable fault detection and decision schemes. Through fiber-optic communication, differential protection can be applied in lines of any length. So, the paradigm associating differential protection only with short lines is no longer true.

VI. Criteria for Resistive Reach Setting of a Quadrilateral Ground Distance Function

A. Suggestion

In the past, Brazilian protection practices tended to use settings for the lateral reach of a quadrilateral characteristic for ground faults with values less than 60 ohms primary. This practice was the result of not having enough information to calculate or even correctly evaluate the value of R_F. During the 1970s and 1980s, values around 20 to 60 ohms primary for R_F were commonly used.

The tendency to consider the occurrence of high-impedance ground faults more probable for medium-voltage systems reinforced this practice. For EHV systems, the probability was considered smaller or even impossible.

With the advent of digital technology, more flexible calculation tools, and the extensive use of event reports, analysts began to observe that ground faults could have larger R_F at any level of voltage.

B. Caution

Protective relay literature, mainly from manufacturers, often shows the criteria to determine the setting limit for resistive reach with line impedance (R + jX) and the Zone 1 setting.

For instance, the appendix in [4] shows that the reactive reach can have an overreach effect depending on its settings, mainly due to the angle error from potential transformers but also due to the system nonhomogeneity, load conditions, and inherent relay errors. For example, a fault at the remote busbar can have the same reactance measured inside the first reactance zone. The error can be compensated through a bias for the polarization angle or through the reduction of the reactive reach for Zone 1 [4].

The resistive reach setting does not affect the reactive reach. In the case of a fault with R_F at the resistive reach setting limit, a reactive reach measurement error of the mentioned angle error can happen [4].

Finally, note that the maximum limit recommended for the resistive reach for ground faults is very important in selecting the pilot protection philosophy used for the distance function. A permissive scheme usually allows higher settings for resistive reach because the Zone 1 tripping will depend on the permission of the remote terminal protection.

VII. Conclusion

A. Events

During all of the events discussed in this paper, the line protection performed correctly, detecting the very high-impedance faults through the directional ground overcurrent functions operating on a directional comparison pilot scheme. The distance functions did not trip (except for the last fault analyzed), and they would not have conditions to trip when fault resistances were very high.

The directional element, based on a principle that calculates negative-sequence impedance and tests the result against thresholds, presented a good directional sensitivity for all the analyzed faults.

The phase discrimination algorithm performed perfectly for the very high-resistance phase-to-ground faults.

The single terminal-based fault location design for regular line protection relays does not perform satisfactorily during very high-resistance faults.

This paper demonstrated that the two- or three-terminal negative-sequence fault location algorithm presented in [3] is quite precise for very high-resistance faults.

B. Analysis Techniques

The influence of the prefault load condition is significant for the impedance measurement made by the distance function. An event report can have enough data for calculating the measured impedance by the distance function at actual load condition, while a classical fault short-circuit program can calculate the fault conditions without the load influence.

Using this calculation software, the resistance of a ground fault can be estimated, or it can be calculated through an expression, since both the extremities fault values and the approximate distance to the fault point are available.

Techniques of fault analysis allow analysts to separate the pure fault current (Thèvenin) and the prefault load current. It is possible to determine the theoretical values of impedance that a distance function would measure if there was no load. It is also possible to compare the calculated conditions by a short-circuit program with what actually happens in a disturbance.

Synchrophasors can improve and speed the event analysis and make it more accurate.

C. Fault Resistance

Fault resistances to ground on the order of hundreds of ohms primary are possible, even in an EHV transmission line. This situation exists more commonly than believed because of the direct association to ground faults through vegetation.

A characteristic of such faults is the occurrence of repetitive ground faults, presenting smaller R_F for each subsequent fault in a shorter interval of time.

D. Resistive Reach Setting Criteria

For the resistive setting of the quadrilateral characteristic of a ground distance function, research has recommended to adopt, on average, a value of at least 80 ohms primary for HV and EHV transmission lines of any voltage level for lines with pilot protection.

Existing recommendations from protective relay manufacturers should be observed to avoid Zone 1 overreaching.

E. Transmission Line Protection

A distance function is never self-sufficient in transmission line protection; proper protection always demands a complementary ground directional overcurrent function and pilot scheme.

Due to distance function limitations, it is always recommended to evaluate the use of a differential function for a non-radial transmission line with distance functions as backup, even for long lines, for any voltage level at which a reliable communications channel is available.

VIII. References

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IX. Further Reading

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X. Biographies

Paulo K. Maezono received his BSEE from the University of São Paulo Polytechnic School of Engineering, Brazil, in 1969. He attended the "Power Technology Course" at Power Technologies Inc. in Schenectady, New York, in 1974. He earned an MSEE degree from the Federal School of Engineering of Itajuba in 1978. From 1972 to 1985, he served as assistant professor at the Mackenzie University School of Engineering in São Paulo. His professional experience from 1970 to 1997 includes electrical engineering work and management at CESP, a utility company of the State of São Paulo. Since 2000, he has been with Virtus as founder and senior consultant in protective relaying and disturbance analysis, with a group of associated consultants. He is a member of IEEE and Cigré.

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