Case-studies on Use of a DFR in an Aluminum Plant

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Abstract

This paper presents three cases where the use of a digital fault recorder (DFR) assisted the owner of an aluminum plant with cogeneration to resolve operational issues. The DFRs were located at different critical stress points in the network. The ability of the DFRs to work together as a centralized system allowed gathering and combining information from the different locations in order to fine-tune the control system to resolve the operating problems.

The paper discusses three cases:

- Loss of grid connectivity from the remote end (due to disturbance elsewhere in the grid) resulted in stability problems in generators due to delayed detection of islanding by the SCADA system
- SCADA system delays due to the combination of transducer's inherent delays and computational time requirements by the SCADA system resulted in too many unwanted tripping actions and consequently loss of production
- An evolving fault in a one of the incoming lines caused the distance relay operation and a cascade effect that shut down generators

The speed of information gathering by the DFRs as compared with SCADA allowed the owner to view, with more details, the evolution of the system conditions that caused their operating problems and simplified the implementation of solutions.

Introduction

Fault records are one of the most important pieces of evidence that event analysis can have during system investigations. They can provide the reasons for premature equipment failure, supply waveforms and the status of equipment behavior, and give necessary information to perform analysis. Proper use and interpretation of records can lead to corrective actions for a given system problem, resulting in improved performance and reliability of any generation and energy distribution system. Oscillography records are also captured by microprocessor relays but such records are limited in sampling rate and record length. Some protection relays use digital filters that do not reflect the real captured waveform.

Digital fault recorders (DFRs) offer specialized, specific, and dedicated microprocessor equipment with far superior sampling rates, record lengths, and unfiltered recording abilities. Operations and maintenance engineers have to make balanced decisions as to what equipment is better to use for analysis, either for troubleshooting purposes or to capture data that can be utilized for preventive maintenance purposes or to improve the performance of the power system. As one would expect, maximized use of recording capabilities leads to better return on investment.

Fault recording has been used for decades now, and it is generally used for two main purposes:

- recording of system events
- monitoring of system protection performance

Using a DFR to collect information at an industrial facility can be very beneficial. The DFR recorder can collect data related to electrical faults, power swings, harmonics, reactive power flow, power factor, sag and swell, and many other power quality issues. In addition, the ability to collect and record time synchronized events can provide the user with information to determine exactly what happened.

Obtaining this information during normal and abnormal conditions can help identify the problems and ultimately provide information needed to analyze and resolve issues. This information can also be used to defend against third party claims of negligence or equipment damage. In addition, the DFR recorder can act like the “black box” used in the airplane industry to verify the operation of other controllers or protective devices. Even though these devices may have their own recording capability to some extent, it is important to validate their quantities using a completely independent source like the DFR recorder.

DFRs are multi-time frame devices, benefitting from more than 20 years of development and in-service experience by the power system industry all over the world. In its present form, the DFR recorder can provide:

1. sequence of events recording
2. fault recording with extensive triggering capabilities
3. recording RMS values of all the power system quantities at a sampling rate of up to 1 RMS value per power cycle
4. trend recording to capture power quantities over extended periods of time
5. harmonic recording
6. software tools to analyze data recorded
7. central station with auto retrieval capability to bring records in after disturbances
8. distributed input quantity collection (in some DFRs) to make installations simpler and more efficient

The remainder of this paper is organized as follows. It discusses the benefits of using DFRs not only as forensic tools to analyse power system faults, but also as a powerful tool to identify possible operational deficiencies that can lead to improvements. The paper describes three cases listed in the introduction and finally it provides conclusions.

Benefits Offered by the DFRs

A DFR located at the main substation’s interconnection with the utility power system can monitor the exchange of electrical quantities between the two systems. This data is critical to monitor power quality, to identify causes when power quality issues do arise, or to identify operational issues during normal operation.

As a digital fault and disturbance recorder, the DFR acts as the eyes and ears of an electrical station. The ultimate advantage of a DFR is to improve system reliability and availability by:

- identification and monitoring of individual elements, as well as the whole system performance, both during normal and abnormal operation
- capture of the complete starting process for large motors, including low inertia motors with a starting time of several seconds. Figure 1 shows a complete starting sequence of a motor with a total record length of 15 s.
- capturing instrumentation information around the monitored element that, together with the electrical quantities, forms a complete electrical, thermal and mechanical picture of its behavior under normal and abnormal operation
- sequential event analysis that mitigates the risk of recurring mal-operations
- verification, evaluation and correction of protection and control systems
- verification of the correct operation of the asset during starting and stopping sequences
- system simulations and meeting of regulatory reporting requirements

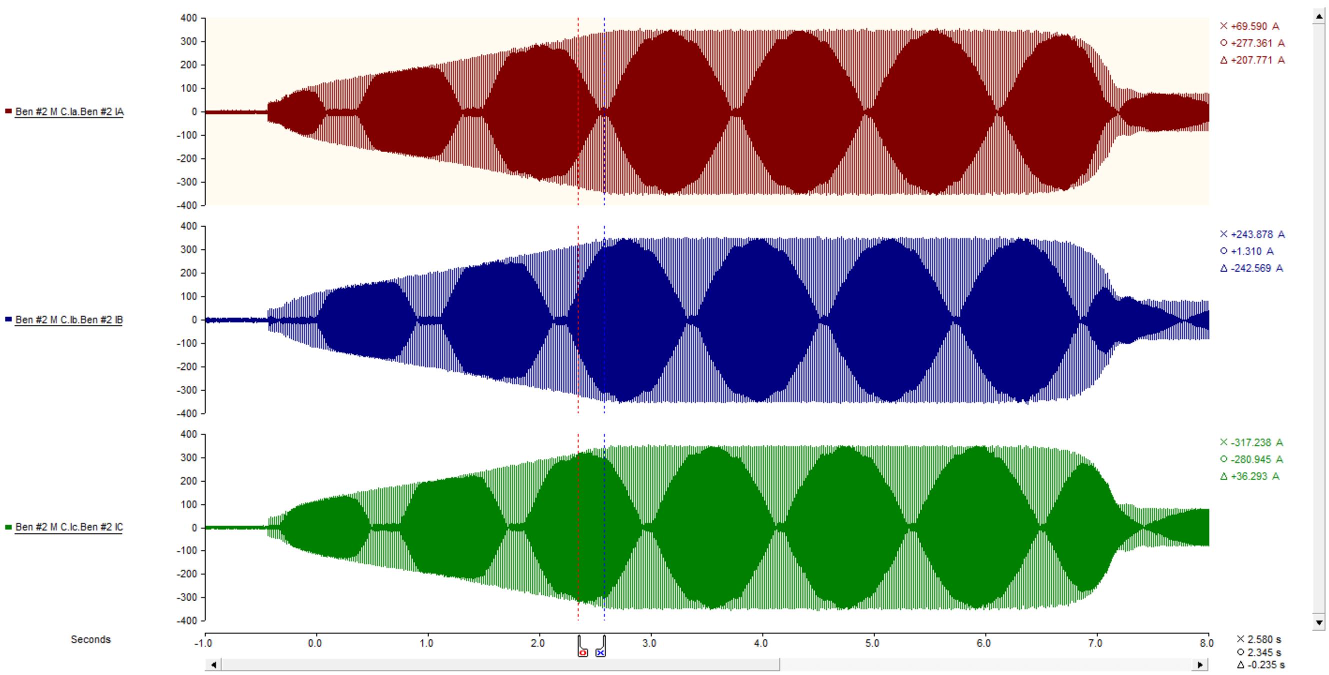

Figure 1 - Starting sequence of a motor

Flexibility is an important characteristic of DFRs to provide access to all required information in an integrated and time synchronized environment. They offer large number of analog channels to capture all data. They also offer calculated (derived) channels to record appropriate data for any further system analysis, and high sampling rates to make accurate transient fault replica.

Table 1 overviews specific benefits of various DFR functions.

Functions	Advantages
DFR	• Troubleshoot and tune the control system • Confirm and improve relay coordination and settings (tuning) • Confirm system and device models • Replay events back for further analysis (COMTRADE files)
DSR	• Troubleshoot and tune the control system • Understand out-of-step tripping for controlled separation • Verify power swing damping to improve stability • Detect sub-harmonic oscillations in series compensated lines • Performance monitoring of generators, transformers, etc.
SER	• Verify operation of breakers/disconnecting switches and their sequence of operations • Improve time coordination • Understand the event (reconstruction) and verify their occurrence (time) and accuracy
LTR	• Monitor seasonal variations of the load (daily, monthly) • Capture harmonics trends • Model system components through statistical analysis • Capture slow phenomena of power system
CDR	• Understand long term power system behavior • Provide redundancy for data storage • Capture events without setting triggers • Provide filtering of data to be stored in the central location • Store in memory PMU data by means of CDR
PQR	• Specify a single harmonic to monitor on any voltage or current channel • Monitor THD on any of these same channels • Estimate THD index • Understand voltage sag and swell conditions • Analyze and tune filter performance
PMU	• Monitor synchro-phasors (magnitude & phase angle) in real time • Control power system in real time • Limit cascading effects of disturbances with wide area visibility • Warn early of deteriorating power system conditions • Improve transmission reliability planning & validate models

Table 1 - Advantages of DFR functions

Multi-Function Power System Monitoring and Recording

Besides monitoring, DFRs can be set to record data simultaneously in 4 time domains: high speed transient fault (seconds), low speed dynamic swing (minutes), continuous data and trend (10 second to 1 hour intervals), based on configurable triggering conditions set independently (for the first two domains) in either measured or calculated channels; and it can be set to provide real time metering.

Table 2 shows each time domain and applicable actions.

Functions	Application	Actions	Human Actions
10 - 15 years	Power System Planning	Grid Management (Power Plants, Substations, Transmission and Distribution Assessment)	Yes
6 months - 1 Year	Maintenance Scheduling	Operation Management (Power Plants, Substations, Transmission and Distribution Assessment)	Yes
24 hours - 1 week	Unit Commitment	Daily / Weekly Generation Scheduling	Yes
10 – 30 minutes	Economic Dispatch	Short-term Generation Management / Scheduling	Yes
Few minutes	Power Swings / System Stability	AGC (Automatic Generation Control) / Contingency Analysis	Yes
100 ms – 10 s	Power System Dynamics	Dynamic Stability / Load Flow Management / Harmonic Analysis / Governor, Exciter Response	No
µs – 100 ms	Power System Transients	Fault / Switching / Lightning / Harmonic Management (Protection Relays, Control and Automation Devices)	No

Table 2 - Time domains in power system analysis

A DFR integrates multiple functionalities required in different time domains in a single box.

Most DFRs provide simultaneous features such as a Sequence of Events Recorder (SER), Digital Fault Recorder (DFR), recording of RMS values, trend recordings, Continuous Disturbance Recorder (CDR) and Power Quality Recording (PQR), and some DFRs also offer continually streaming synchro-phasors (PMU).

Recording channels include analog inputs, external inputs, virtual inputs or calculated (derived) channels. When fitted with IEC 61850, those channels are also capable of subscribing or publishing GOOSE messages.

Distributed Recording

In some applications, DFR recorders can operate in what is known as cooperative mode, to capture a greater number of channels and to monitor a wider area (creates a distributed recording system). The recorders are connected through an Ethernet LAN to be accessed as one single cooperative group. This mode being IP-based, presents limitations on distance. This mode of operation enables automatically synchronized cross-triggering when one of the group's recorders is triggered, with automatic retrieval and consolidation of all the individual records into a single group record.

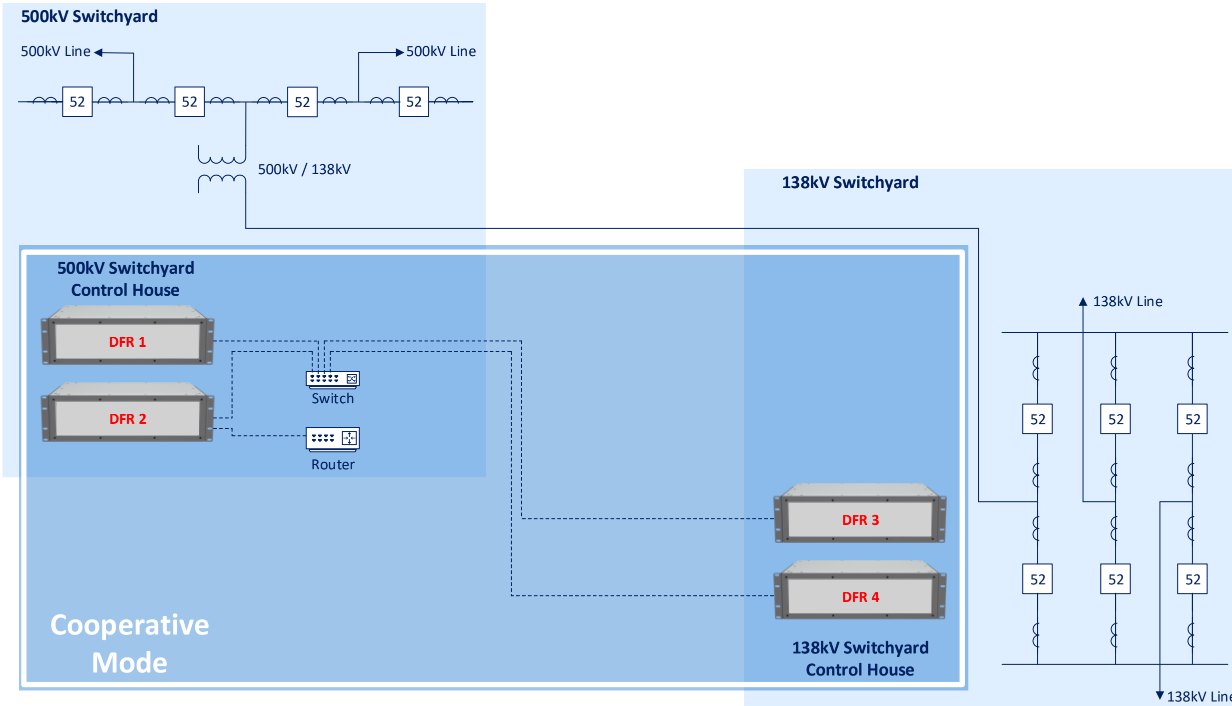

Figure 2 - Distributed recording system (cooperative mode)

Comparing DFR Recording with Relay Recording

Recording via the DFR provides many advantages over protection relay recording:

- **Quantity of records and memory size**
  Quantity of records is very limited in relays (about 40 records); however, a DFR can store over 1000 records in flash memory. A typical relay's memory size is limited, but a DFR's can be extended.
- **Analog and digital input channels**
  A typical relay may have 12 analog inputs and about 30 digital inputs/outputs. A DFR in cooperative mode features 144 analog inputs and 288 digital inputs/outputs.
- **Multi-function and multi-time frame capabilities**
  CDR, LTR, PQR and PMU functionalities are usually missing in a typical relay. A relay may not be able to act as a multi-time frame device.

As described above, stand-alone recorders are needed in electrical stations; relays alone cannot meet the full range of necessary power system monitoring and recording requirements.

DFR Applications

DFRs can be installed at any voltage level in generation, transmission and energy distribution sectors. Each function can meet some specific requirements in terms of monitoring, recording and control of station operations locally or in wide area applications. Table 3 shows an applications overview of functionalities.

Functions	Applications
Fault Recorder and Sequence of Event Report	• Transient stability analysis • Short-circuit level calculations • Harmonic analysis • Inputs to contingency analysis • Operation assessment (protective relays, control and automation devices) • Analysis of fast transient faults (short-circuits, lightning, strikes, switchgear surges, voltage spikes) • Analysis of events in the range of milliseconds and seconds
RMS Value Recording and Sequence of Event Report	• Dynamic stability analysis • Power swing analysis • Sub-synchronous harmonic analysis • Load flow analysis (short term generation planning) • Governor, exciter response time • Analysis of slow time-varying events in the range of seconds and minutes (weak power systems, interties, generation spinning reserve)
Trending, CDR and Sequence of Event Report	• Power system planning • Seasonal trend recordings and analysis • Daily / weekly / monthly generation scheduling • Maintenance scheduling (power plants and substations) • Analysis of long term or very slow-time-varying events • Data management at station level
PMU	• Smart Grid applications using synchro-phasors • Real time Wide Area Monitoring and Control (WAMS / WACS) • Supervision of wide area conditions to avoid system collapse in cascading disturbances • Supervision of transmission line active and reactive power exchange to improve reliability

Table 3 - Applications of DFR functionalities

Many elements of the power system should be included in system monitoring.

Co-Generation Plants

The power island and electrical balance of a plant can be monitored by DFR, including its generator AC current and voltage, AVR control system, field DC current and voltage (excitation system), governor control system, generator circuit breaker (GCB), bus voltage, step-up transformer AC current and voltage, HV CB, auxiliary transformer AC current and voltage, temperature, vibration, mechanical conditions and other parameters.

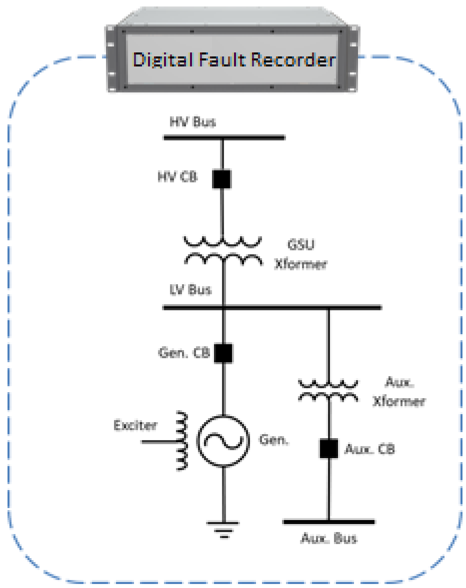

Figure 3 - DFR monitoring a typical generation station

One of the applications in the generation sector is frequency response in a “loss of generation” phenomenon. Level or “rate of change” in frequency can easily trigger swing recording. Figure 23 shows frequency response in a 1600MW generator trip. The record shows a 0.048Hz drop in 1.17 seconds.

Figure 4   DFR recording frequency response in a loss of generation phenomenon

Another application is power swing monitoring, in which a “rate of change” (in watts) triggers a power swing record indicating “loss of generation”. Figure 24 shows one such power swing record from a hydro power plant.

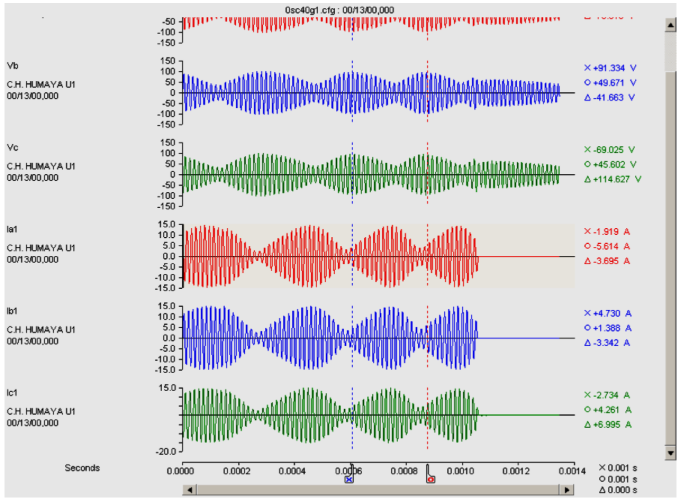

Figure 5 - DFR capturing power swings

Power Transformers

Power transformers are one of the most important assets, requiring careful management. DFR offers real-time monitoring as well as trend record data storage. Monitoring components include load, ambient temperature, top-oil temperature, hot-spot temperature, OLTC tank temperature, and loss-of-life through fault current, moisture and gas content.

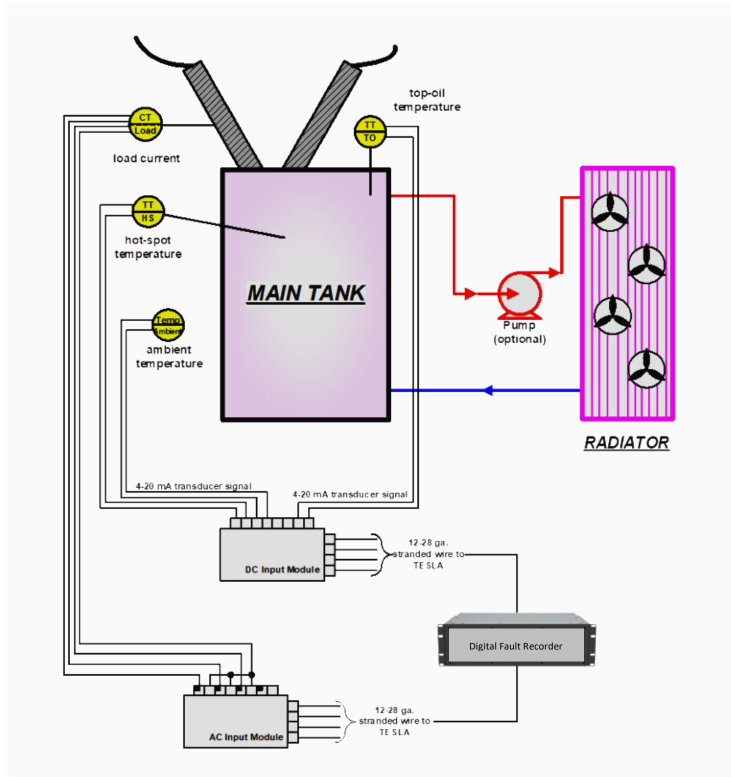

Figure 6 - DFR monitoring power transformer

Other electrical parameters can be recorded for further analysis. Figure 26 shows voltage and current records in a transformer over-excitation (V/Hz) disturbance.

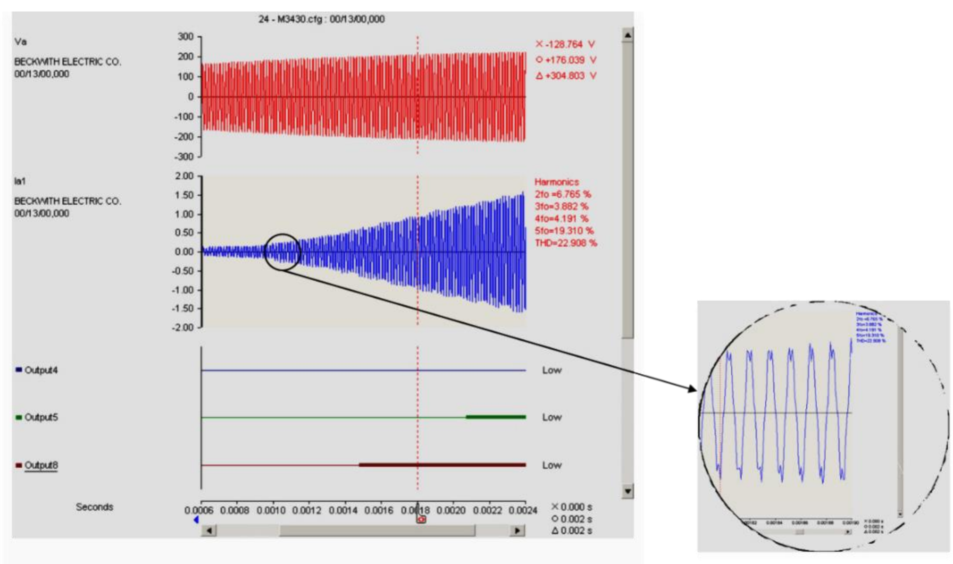

Figure 7 - Voltage and current records in a transformer over-excitation (V/Hz) disturbance

Hindalco Industries Limited – Production and Generation Power Plants

Figure 8 - Location of the Plants

Hindalco's Renukoot Aluminum Plant and Renusagar Co-generation Power Plant are located in the northern state of Uttar Pradesh in India. The plants are approximately 40 kilometers from each other.

Renukoot Aluminum Plant was commissioned in 1962 with one potline and a smelter of 20,000 tons per annum (tpa) capacity.

Figure 9 - Hindalco's Renukoot aluminum plant

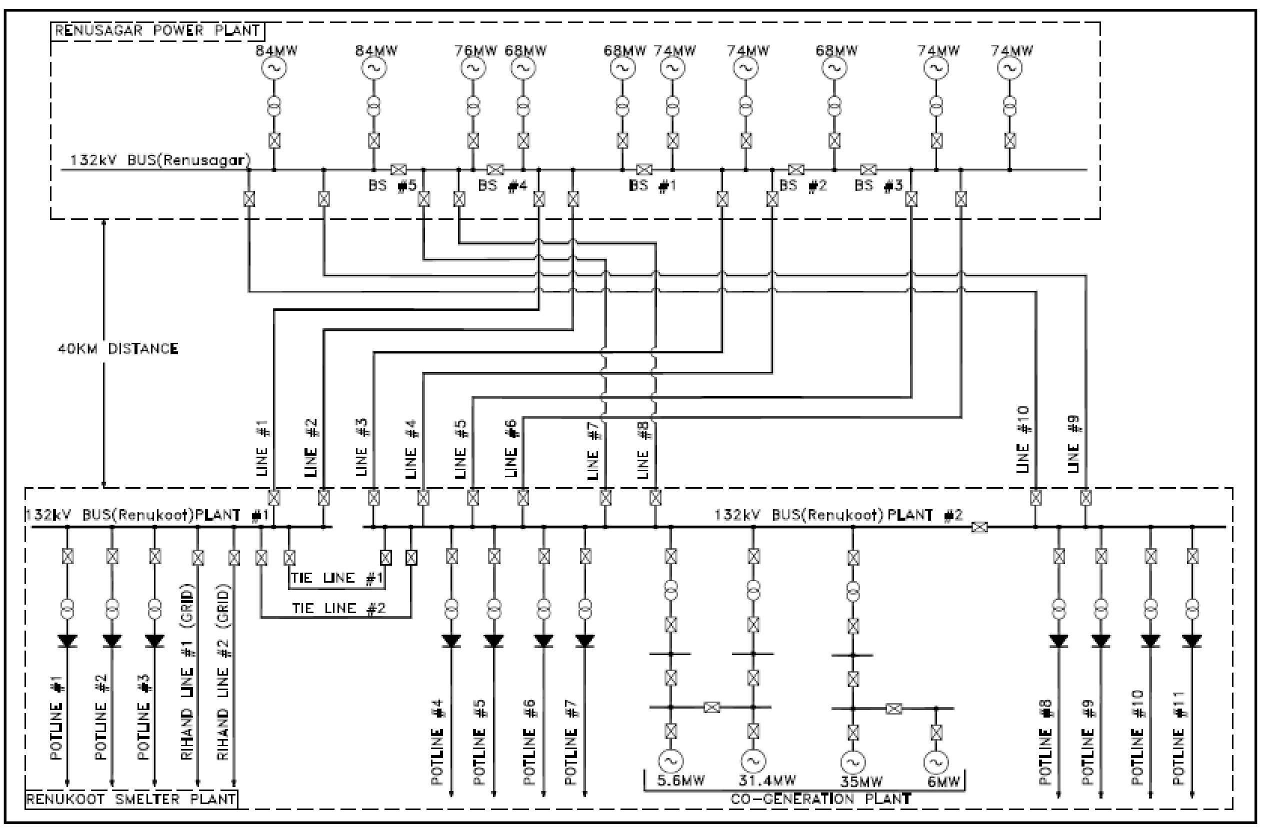

Figure 10 - SLD of Hindalco: Renukoot (smelter) and Renusagar (co-generation plant)

Today Hindalco's Renukoot integrated facility houses a 700,000 tpa alumina refinery and a 345,000 tpa aluminum smelter along with facilities for production of semi-fabricated products.

Renusagar Power Plant was established in 1967 by Hindalco as co-generation power plant for Renukoot and today generates a total of around 750 MW and transmits this power to Renukoot Aluminum Plant over 10 x 132kV transmission lines.

The following sections will describe three cases where the use of a DFR assisted the owner of Hindalco Industries Limited to resolve operational issues at their Renukoot Aluminum Plant and also at their Renusagar Co-Generation Plant. The DFRs were located at different critical stress points in the network. The ability of the DFRs to work together as a centralized system allowed gathering and combining information from the different locations that was used to fine-tune their control system to resolve the operating problems.

Case No. 1

Background

Hindalco is connected to Uttar Pradesh State Grid through two 132kV lines that operate in a synchronized state.

Hindalco can import power from the grid as needed for normal operation or export power in case of excess generation.

Hindalco installed power system recorders (DFRs) in both the co-generation plant and the smelter plant, which are 40km apart.

All the DFR recorders at different critical stress points in the network are configured to work together as a distributed system (also known as cooperative mode), collecting and combining records into one.

Hindalco has a SCADA-based scheme to detect islanding from the grid switching to frequency control mode in case of an islanding condition.

In the case of tripping of the Hindalco side breaker due to grid disturbances, the islanding condition is detected in the SCADA system by external inputs that monitor the breaker status. However, in the case of breaker tripping from the grid (remote) end, the SCADA system detects the islanding condition through logic based on zero power flow with some time delay.

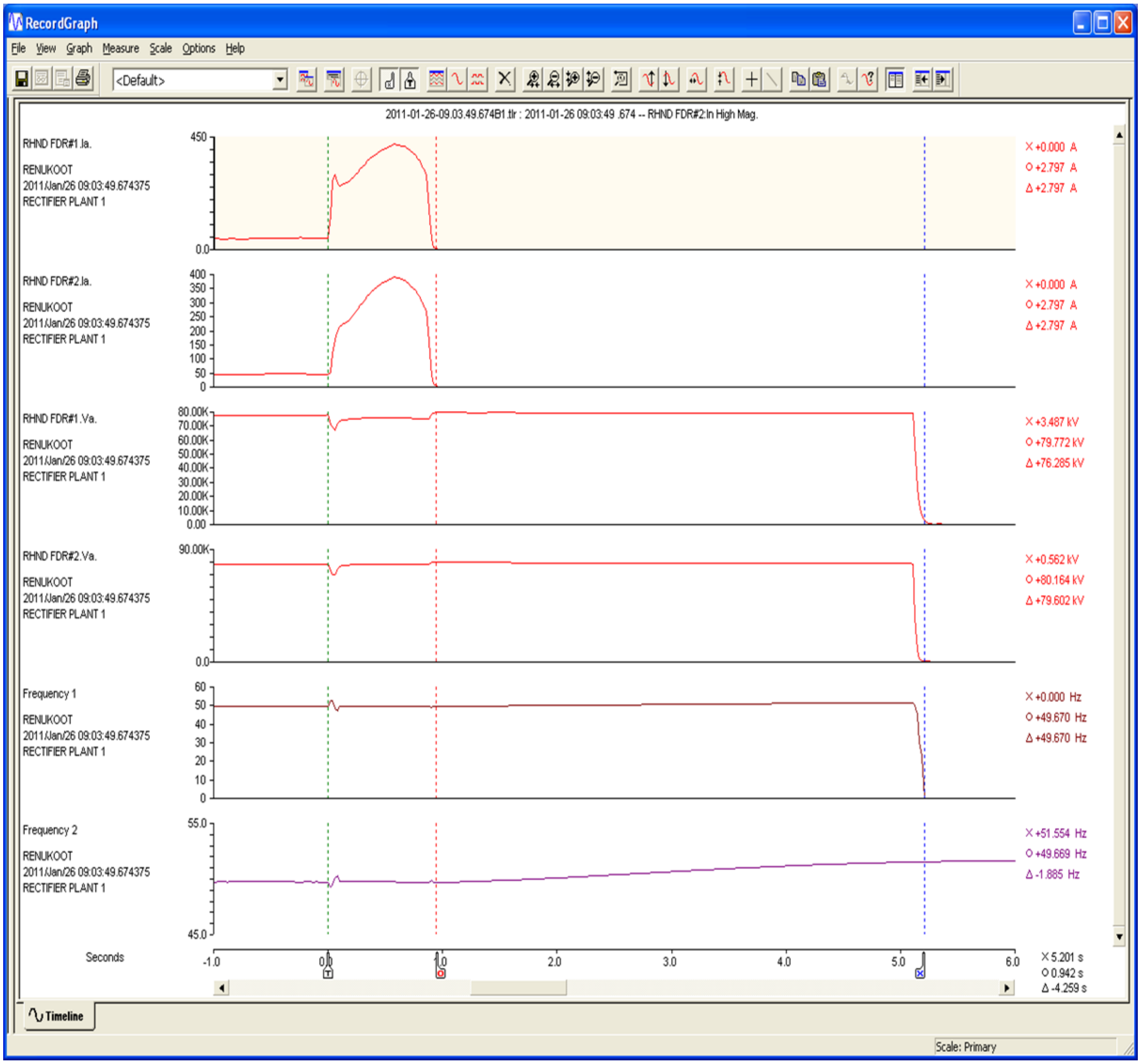

Figure 11 – Frequency, current and voltage RMS graphs

Analysis

In Figure 11, an abrupt rise in current flow can be seen between Hindalco and the state grid due to a grid disturbance, resulting in tripping of a breaker from the grid at the remote end. In addition, it can be noticed from the voltage profile on the two grid lines (as recorded from the Hindalco's side), the SCADA system was not able to identify the disturbance and switch-over to island (frequency-control) mode. Due to a delay in islanding detection of 5 seconds, the frequency of the Hindalco network was not controlled and continued to rise to 51.5 Hz.

Problem Observed by Means of DFR Data

The loss of grid connectivity from the remote end due to disturbance elsewhere in the grid, resulted in stability problems in the Hindalco generators.

The SCADA system's delayed detection of the resulting islanding condition through a logic-based scheme led to frequency hunting of the machines at Hindalco.

A faster SCADA system switching over to islanding mode, would have caused the frequency of Hindalco's smelter and generating plants to have been stabilized faster through frequency control mode via the SCADA system.

Solution

Hindalco installed a controller at the remote grid station and extended fiber connectivity to Hindalco's plant to transfer the remote breaker status signals to the SCADA system.

With this input confirming the grid islanding from the remote end, an over-ride action could be identified by the SCADA system, eliminating the 5-7 second time delay, switching to islanding (frequency-control) mode instantly.

This ensured safe operation of all the machines and avoiding over frequency problems in the Hindalco network.

Case No. 2

Background

Power oscillation between Hindalco and the state grid exceeded the set limits of import conditions in the SCADA system.

Due to this, the SCADA system, in accordance to their load shedding scheme, would have tripped two of their potlines in order to stabilize the plant.

While the condition was still stabilizing, within next 2 seconds, the SCADA system-initiated tripping of an additional potline, making this three potlines out of service. This led to excess power availability in Hindalco, resulting in tripping of a generator.

In summary, unnecessary cascade of trippings on a typical power swing condition resulted in loss of production due to insufficient generating capacity.

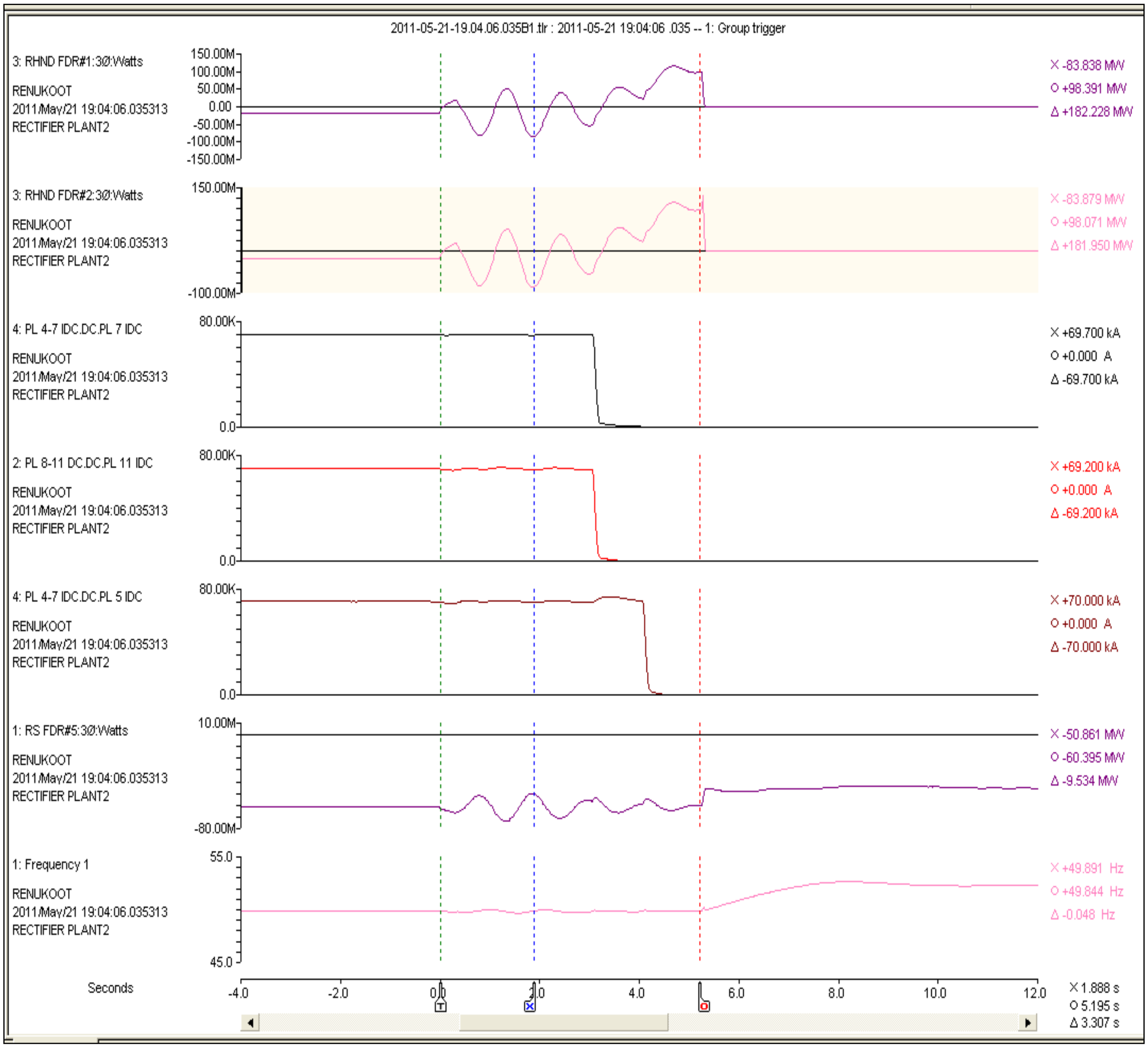

Figure 12 – Frequency, current and voltage RMS graphs

Analysis

In Figure 12, a typical power swing can be noticed between the Hindalco system and the power grid.

As expected, and per design, the SCADA system sheds two smelter potlines to prevent grid power exchange violation. Since the condition did not normalize by this normal operating action, the SCADA system shed a third smelter potline in the next 2 seconds to prevent continuing with a power exchange violation, which was not considered normal. The disconnection of the third potline rendered an unbalance between generation and loading, which caused the SCADA system to trip one machine due to high grid export.

Problem Observed by Means of DFR Data

SCADA delays, which are due to a combination of a transducer's inherent delays and the computational time requirement of the SCADA system itself, were resulting in too many unwanted tripping actions, and consequently in loss of production.

DFR recorders installed at strategic locations in Hindalco gave ample information of the actual response of various equipment (generators, grid feeders, inter-connecting tie-lines, co-generation plant, etc).

Through DFR records, it was discovered that tripping of the third potline was an incorrect action by the SCADA system and in turn led to tripping of a generator, as a consequence of its initial incorrect action.

Without the DFR data, the SCADA system's actions might have seemed correct and problems would have gone undetected.

Solution

Hindalco optimized the performance of the SCADA system by introducing additional logics and soft timers.

This has helped the SCADA system to distinguish between power swing and grid energy exchange violation, and to handle power swing more appropriately.

These optimizations have saved Hindalco from many unwanted potline tripping.

The stability of the smelter plant operation has enhanced many fold, resulting in better productivity.

Case No. 3

Background

On Renusagar tie-line #6 (one of the 10 transmission lines between the Renusagar Power Plant and the Renukoot Smelter Plant), a C-phase to Ground (C-G) fault happened, which developed into a 3-phase fault.

The distance relay operated on both the Renukoot and Renusagar sides of this line and issued a trip to their respective circuit breakers.

But strangely, Hindalco Renusagar experienced an unusual cascade of tripping events after what could be considered a normal case of line fault.

Breaker BS #2 (associated to unit#5 connected to an adjacent bus section) tripped and subsequently BS #3, unit #6 and unit #7 (connected to the same bus section) also tripped on back-up protections. This cascade of unusual tripping events led to further investigation using DFR records.

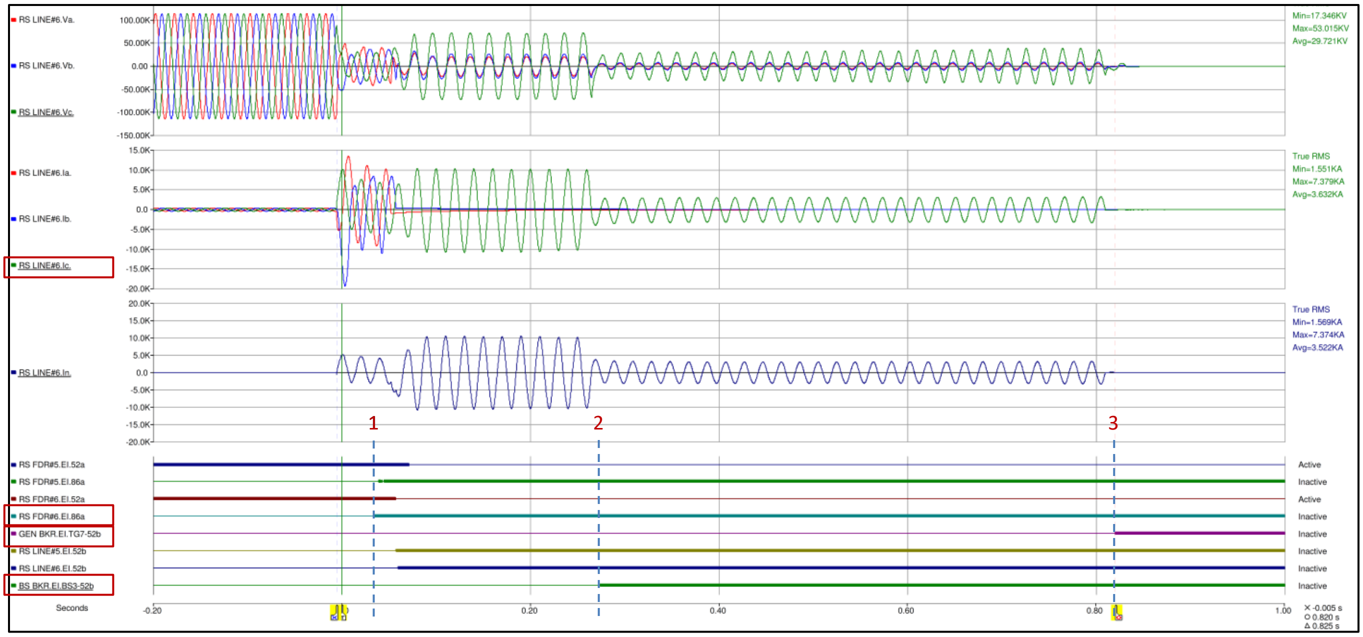

Figure 13 – Oscillography records captured by the DFR

Analysis

As described in Figure 13, 50 – 60 ms after fault inception, breaker RS#6 (indicated by dotted line 1) trips, which can be seen due to the corresponding status change as seen by the DFR. At this point, one would have expected that the currents in all three phases drops to zero, however, the current of phase C remains, as well as the neutral current which is calculated by the DFR. In an attempt to control this unhealthy operating condition, breaker BS #3 trips 278 ms (indicated by dotted line 2) after fault inception, however, this breaker operation did not resolve the problem. It took the operation of breaker TG#7 821(indicated by dotted line 3) ms after fault inception to finally bring the current to zero.

Problem Observed by Means of DFR Data

With the DFR system, all the analog and digital signals of different elements (that is tie-line, bus sectionalizer (BS) and generators) were captured in one single record file, which facilitated the event analysis.

Through waveform records, as shown in Figure 13, a distance relay on the Renusagar side operated its circuit breaker successfully.

However, fault current and voltage were still present in phase C of RS Line#6. The reason for this was that the contact for pole C of a gang-operated breaker didn't open (or got jammed or stuck).

Fault feeding continued in phase C for around 821 ms from the inception of the fault and also caused unwanted tripping of BS#2 and unit#5 on the adjacent bus section.

Solution

Breaker failure protection was introduced on bus-sections by Hindalco Renusagar, the faulty circuit breaker was replaced and breaker maintenance schedules were revised to improve the reliability of circuit breakers.

Back-up relay settings were optimized for better relay coordination for selective tripping, and to avoid tripping of adjacent bus-section elements.

Conclusions

DFRs are powerful tools that can be applied to industrial applications to capture information operation during normal or abnormal conditions. Obtaining this information enables owners to analyze problems and verify the proper operation of the plant, leading to better efficiency, less maintenance and higher returns.

Biographies

René Midence (IEEE M’2007, IEEE SM’2009) For over 30 years, Mr. Midence has been involved in the design and commissioning of power substations and power plants including Protection and Control, SCADA, Substation Automation and Substation LAN systems. His well-rounded experience covers the fields of consulting and engineering, construction and commissioning, manufacturing, strategic marketing, technical support and training.

In the manufacturing business, he has worked in the design and testing of medium and high voltage substations as well as metalclad switchgear, protection and control panels. During his more than 15 years of experience in manufacturing, he has contributed to the development and market introduction of new protection and control microprocessor-based relays, Ethernet switches and routers.

Mr. Midence is a Senior Member of the IEEE, have active participation in the development of IEEE standards, member of the IEEE Power Systems Relaying and Control Committee (PSRCC), member of the International Electrotechnical Commission (IEC) TC57 WG10.

Mr. Midence graduated in 1983 from the University of Honduras with the degree of Bachelor of Applied Science in Electrical and Industrial Engineering. He joined ERLPhase Power Technologies in 2010 and currently holds the position of Director of Technical Services. He is a professional engineer registered in the Province of Ontario.

Mr. Premnath graduated in 1982 in Electrical and Electronics Engineering from Madras University. He has extensive experience in design, commissioning, operation and maintenance, business and strategic roles. In the last 35 years he has worked in multiple roles handling projects from substation and railway electrification to power plants. He has first-hand experience with the major challenges facing industries such as aluminum smelters with a predominant DC load and the influence of harmonics on controllers like excitation systems and protection systems. He has strong knowledge about how analytical tool like DFRs can be useful to operations and maintenance engineers. In his current role with Easun Reyrolle for the last 16 years, he is responsible for business promotion and geographical responsibility for protection and automation systems.

Anderson Oliveira (IEEE M'2012) has over 15 years of experience in power generation, transmission and distribution systems. Working for utilities, consulting and currently for a manufacturer, he has been involved in the application, design, commissioning and maintenance of protection and control, SCADA, substation automation and substation equipment for power plants and substations.

Mr. Oliveira is a member of the IEEE and has participated in the development of IEEE standards as a member of the IEEE Power Systems Relaying and Control Committee (PSRCC). He is also a professional engineer registered in the Province of Ontario.

Mr. Oliveira graduated in 2002 from the University of Pernambuco in Brazil with the degree of Bachelor of Applied Science in Electrical Engineering and got his Master of Engineering degree in Electric Power Engineering from the University of Waterloo in 2017. He joined ERLPhase Power Technologies in 2013 and currently holds the position of Technical Services Engineer.