Fault Analysis of the Gautrain 2×25 kV AC Traction Power Supply System using Disturbance Fault Records and On-site Testing

N. M. Moyo, Ramesh C. Bansal, *Senior Member, IEEE*, Raj Naidoo, *Senior Member, IEEE*

Abstract—**A typical 2×25 kV traction power supply system consists of both primary and secondary equipment housed in control rooms, and the traction overhead wiring (OHW) that runs between the substations. Substation secondary equipment consists of the protection and control intelligence electronic devices (IEDs) known as relays. Each section of the OHW between the substations is protected by a set of two relays at both ends of a line for impedance protection and their backup relays. At substations facing the sections at the end of line where there is no other substation on the other end, usually overcurrent and earth fault protection is used. At the substations, there are disturbance fault recorders installed or relays equipped with a capability to record and store disturbance fault records (DFRs). Analysis of these fault records makes a significant contribution in the efficient running of a traction system of the Gautrain. A combination of analysis of the faults that occur in the OHW as recorded and stored in the relays, as well as the performance of the IEDs and the protection settings using on-site tests are a subject of this paper.**

***Index Terms*— Power system protection, current transformers, substation protection, overhead wiring, disturbance fault records (DFRs), fault analysis, traction power supplies, catenary, feeder, ground, autotransformer, on-site tests.**

I. Introduction

Traction power supply systems are prone to electrical faults or electrical disturbances during operation. In traction power supplies and in electrical power systems in general, any electrical fault must be cleared quickly and selectively using substation relays thereby, isolating the affected sections before there is damage to equipment [1]. In traction systems, just like in power utility companies, the end use of power systems disturbance recorded data can be a challenge [2]. Analysis and a clear understanding of the different types of faults that occur in the traction system contributes in reducing down time during power system faults [1]-[2].

Analysis of the disturbance records is essential in the understanding of the predominant fault types and how they occur so that the protection systems can be improved or optimized to be suitable for a particular traction system [3]. On the other hand, performance tests are essential in understanding how the relays perform during such predominant faults in terms of conformance, reliability, and dependability. Lee *et al.* [4] studied the performance of protection relays using real time digital simulators for a power distribution system with the intention to assist power system planners and operators to solve problems that occur in such systems. Kezunovic *et al.* [5] also demonstrated the importance of relay tests when doing studies on the performance of distance relays using digital simulators.

For the purposes of this study, specialized test equipment was connected to relay panels and test blocks connected to current transformers (CTs) and voltage transformers (VTs) at the substations at both ends of existing OHW line sections and different types of faults were simulated. The tests are done relative to measured impedances, system parameters and applied protection settings for the line sections under evaluation [6]. The results obtained from these tests including fault types and operating performances are analyzed. In addition, comparisons for trip and operating times for the same fault types are done for relays at the local and remote substations. The main aim for this activity is to check if there are any faulty relays, incorrect relay operations, malfunctioning of inter-trip communications and incorrect protection settings or any other relay performance and conformance shortcomings [4]-[5]. An incorrect relay operation detected at one substation during DFR analysis can be used to make improvements in other substations and for improvements in the protection design philosophies of new traction projects.

Both DFR analysis and on-site tests assist in making sure that the relays are operating correctly and performing according to the protection design philosophy. The behavior of the protection systems, the protection settings applied and its shortcomings can be understood during disturbance analysis [7]. Another method that can contribute to a safe restoration of service much quicker is the analysis of the disturbances or faults using additional tools such as digital signal processing (DSP) [8]-[9], which are not discussed further in this paper.

N.M. Moyo is with Bombela Maintenance (Pty) LTD and part time with the Department of Electrical, Electronic and Computer Engineering, University of Pretoria (email: ndaedzo.moyo@bombardiersa.co.za).

Ramesh C. Bansal is with the Department of Electrical Engineering, University of Sharjah, Sharjah, United Arab Emirates (email: rcbansal@ieee.org).

R. Naidoo is the Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria, South Africa (email: raj.naidoo@up.ac.za).

The results of the analysis demonstrated in this paper can be utilized by a variety of departments in a diverse traction project environment. It helps the engineering design, operation and maintenance teams. The System Operator (SO) at the Operation Control Centre (OCC) may be informed by the data analyst or engineer on whether the fault is persistent or not, its location and how the section of the line may be isolated or sectionalized so that trains can continue with minimum interruption to service. Design engineers may use the analyzed information to confirm correct operation, review the protection settings and make improvements to enhance the traction power system performance. Maintenance teams may use the information to understand the type of the fault, whether the fault has cleared or not and the location of the fault.

Furthermore, railway traction systems have needs and requirements that change during their lifecycles, for example, a possible addition of new trains or change of traffic headway. In addition, IEDs go through an obsolescence phase during the lifecycle of a traction system [10]. Applied protection settings and decision-making on suitability of the relays and their characteristics during project expansions or replacement of obsolete relays can also be improved using results obtained using this methodology. Hence, the importance of this study which may identify the shortfalls of the current traction power protection system and provides solutions or prompts a re-design or re-evaluation of the protection philosophy.

The rest of the paper is organized as follows: Section II presents the General Background, section III describes the Gautrain Rapid Rail System as a case study, and section IV describes the Fault Reporting and Analysis Process. Section V provides the Traction Power Systems Protection Testing Methodology. Section VI presents the Test Results and Comparison with Protection Settings. Section VII provides the Discussion and Analysis of Results, and section VIII provides the Conclusion.

II. General Background

In the Gautrain power supply protection system, the DFRs are imbedded in the IEDs, although standalone DFRs with dedicated fault locators can be found in other systems. Saha *et al.* [1] distinguishes between the protective relays and the fault locators in terms of requirements. Relays require faster on-line and instant communication in order to clear the fault speedily, whereas fault locators are for analysis of the faults after they have cleared, although, both require specialized analysis when the data is received [1].

Supervisory Control and Data Acquisition (SCADA) systems are used for analysis in conjunction with the disturbance records. SCADA is used for overall system management including remote control of the system and data acquisition, as well as monitoring system performance and condition [11]. DFRs continuously monitor the power system but the disturbance recordings are only triggered to record the pre-fault, during fault and post-fault data whenever a fault occurs [12].

The disturbance records contain such information as types of fault, current and voltage magnitudes, fault duration, and in some cases fault location [5], [12]-[13]. In order for distance protection relays to operate accurately, they need accurate system parameters, suitable philosophies and accurate relay settings that are applicable to the type of power system being protected [6], [14]-[15]. Other authors explain why it is complicated to identify the fault location of a 2×25 kV traction system due to its non-linear impedance value when measured as a function of distance [15]-[17]. From the Gautrain experience, identifying the section and zone where the fault has occurred with the current DFRs/IEDs is not a problem, however, it is complicated to identify the actual distance to fault from the substations, and hence, further analysis of the DFRs is required.

There may be shortfalls in the system that can be improved from DFR analysis in terms of effective protection and fault analysis, such as; accurate distance to fault location, time synchronization with (SCADA) and Train Data Systems (TDS) which is important in ascertaining the exact time the fault has occurred and the position of the train. This is very important especially in traction networks were timeous fault analysis and clearance, is of paramount importance with a possibility of passengers being stranded in the trains during faults. Time synchronization is normally achieved by connecting the IEDs to the network time server which makes sure that all the IEDs record DFRs at the same time for ease of correlation and analysis of sequence of events. However, the relays that have been discussed in this paper use an internal clock and not connected to the network time server; hence, their time is not synchronized. In this case, the analysis of the DFRs is done in conjunction with the SCADA information because the SCADA system is synchronized to the network time server. The SCADA system is also set up to monitor the signals generated by the IEDs during faults and for control purposes.

Some power utilities have developed their own substation based expert systems [18], however, in the Gautrain traction system, DFRs downloaded from IEDs in the substations and SCADA are used.

The first stage of testing the behaviour of the protection devices is functional tests conducted in the laboratory before getting installed on-site. These tests are done to prove that they meet the specifications, and the relays are not defective before they can be shipped to the customer [19]. Site integration tests that involve on-site performance tests have an advantage that real site conditions are used, including soil resistivity, system configuration and the actual fibre optic communication channel. Furthermore, tests described in this paper ensure that defects that may have occurred due to equipment degradation or aging over time are identified and corrected before a fault or relay mal-operation occurs. In addition, the interface and wiring between the IEDs and the primary plant such as CTs and VTs is complete on site as compared to the laboratory. Examples of analysis that resulted in changes being made after testing and DFR analysis are given in section VII.

III. CASE STUDY: GAUTRAIN RAPID RAIL SYSTEM

A. Overview

In this paper, the Gautrain rapid rail system in South Africa which uses APSs with feeder and catenary conductors in a 2×25 kV configuration is used as a reference or case study.

Traction lines differ from high voltage or medium voltage transmission lines in their configuration and equipment or components that make up the OHW, the types of feeding transformers used in the substations and protection systems. For example, the traction system has the earth return circuit, neutral sections, section insulators, crossovers, weight tensioning devices, feeder wires, and contact/catenary wire combination interconnected through wire droppers hanging between the catenary and contact wire [6], [20]-[23]. There are also differences in impedances, train pantograph/OHW interaction and different power systems protection philosophies [6]. The autotransformer feeding system described in other systems [21], [24] contains sectioning post and parallel post locations. Fig. 1 is a simplified APS traction system configuration.

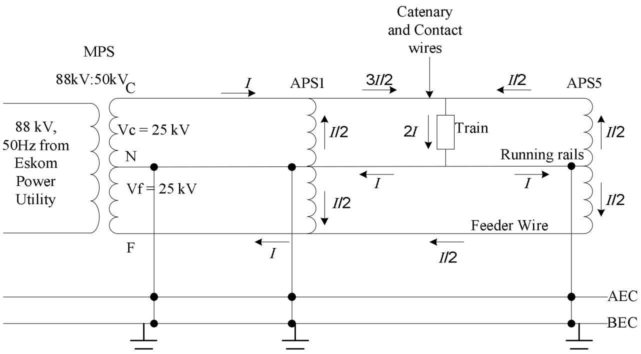

Fig. 1. Simplified Configuration of Gautrain System showing the MPS and the APSs in the South.

B. Traction power system protection

The power system protection can be divided mainly into substation equipment protection, and OHW protection. In this paper, the focus is online impedance or distance protection which is used for OHW protection because the OHW part of the traction system is more susceptible to power system faults. The impedance protection relays are configured to measure voltage and current signals and use them to calculate the loop impedance for fault detection [25]. Izykowski *et al* [25] discussed how fault loop impedance measurement is conducted for transmission lines. The same principle is applicable to traction systems, whereby the loop is formed between the catenary, feeder, and grounded circuits. The equivalent model of a traction system can be constructed using equivalent self-impedances and mutual-impedances of the system [26]-[27]. Distance protection relays or IEDs are installed in substations at both ends of OHW line section which can either be an MPS or APS [28].

Lee *et al* [26] proposed that the OHW system could be reduced into an equivalent model which represents feeder, catenary and contact wire conductors group, and return or grounded circuits. The running rails, AEC and BEC in Fig. 1 are generally grouped together as the current return or grounded circuit [29]. The rails, the AEC and the BEC and other conductors that are at earth potential provide the path of the return currents and fault currents [30]. The types of faults that are found in a traction power supply systeminclude; catenary-to-earth (C-E Fault), feeder-to-earth fault (F-E Fault), feeder-to-catenary-to-earth fault (F-C-E Fault), feeder-to-catenary fault (F-C Fault), earth fault, and overcurrent fault [31]-[32].

When the abovementioned faults occur, both the feeder and catenary circuits are disconnected using double pole circuit breakers that receive trip signals or commands issued by distance protection relays installed on both ends of the line section [20]. When measured by relays at one end of the line, the fault loop impedances can be expressed using the equations below [15], [19], [20], [25], [31], [33]. The feeder-to-catenary fault impedance Z_{CF} can be expressed as follows:

$$Z_{CF} = \frac{V_C - V_F}{I_C - I_F} \quad (1)$$

The feeder-to-ground fault impedance Z_{FG} can be expressed as follows:

$$Z_{FG} = \frac{V_F}{I_F + K_0 I_N} \quad (2)$$

The catenary-to-ground fault impedance Z_{CG} can be expressed as follows:

$$Z_{CG} = \frac{V_C}{I_C + K_0 I_N} \quad (3)$$

$$I_N = I_C + I_F \quad (4)$$

In equations (1) to (4), V_C is the catenary voltage, V_F is the feeder voltage, I_C is the catenary current, I_F is the feeder current, I_N is the neutral or current flowing in the return circuit and K_0 is the zero sequence compensation factor which is defined as [31], [33]:

$$K_0 = \frac{Z_0 - Z_1}{2Z_1} \quad (5)$$

Where Z_0 is the zero-sequence impedance of the faulted feeder and Z_1 is the positive sequence of the faulted feeder. Due to the nature of APS traction systems which consist of parallel tracks and autotransformers that are interconnected to OHW of both tracks, it is also possible to experience sympathetic trips [34]-[35]. This is when faults that occur in one circuit are detected and trip in the adjacent or parallel circuit [34]-[35]. These kinds of trips have been observed during this research and they compromise selectivity. The zones of protection applicable to all line sections are shown in Fig. 2 using the MPS and APS1 as examples. Some researchers refer to fault location in terms of these zones [16] as compared to the actual distance to fault in kilometres.

In the Gautrain, each relay is set to 85 % of the line section impedance between the substations for the zone 1 reach. This helps to prevent overreaching due to relay, current transformer (CT) and voltage transformer (VT) errors. Zone 2 is set at 120 % and zone 3 is for back-up ad it is set at 200 % of the protected line of an end section for forward zones and 50 % of zone 1 reach for reverse zones.

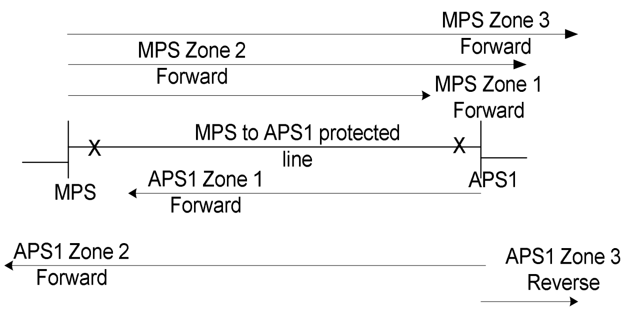

Fig. 2. Zones of protection.

Zone 1 and zone 2 are both set to be in the forward direction with zone 1 set to trip instantaneously and zone 2 set with a time delay. Zone 3 which acts as back-up to cover the entire network is set to be bi-directional with a time delay. The auto-reclose (ARC) cycle is used to check if it is a permanent fault or if the fault has cleared in which case the circuit breaker would close and remains closed. If the fault is not cleared, the circuit breaker would open again and remain opened and locked out. The relays are also set for only one ARC cycle in which the circuit breaker operates in an Open-Close-Open-Lockout sequence.

The communication for permissive trip signals between the relays at the substations that are situated on both ends of the OHW line section is achieved through fibre optic cables that are installed along the track between the adjacent substations [5], [10]. In addition to this, the relays are connected to the SCADA framework through MODBUS IP.

Quadrilateral relays are used for the distance protection of such systems described in this paper. Other relay characteristics can be used for traction systems such as the polar and polygon distance characteristics [19]. The quadrilateral characteristics give much more resistance coverage under fault conditions, especially high resistance faults [20], [30], [36]. Maximum relay reach is set to avoid load encroachment and the regenerative braking zone which might initiate incorrect trip signals [19].

The quadrilateral relay characteristics for the Gautrain traction line is shown in Fig. 3. In the diagram, the protected line section, and the zones of protection are defined as zone 1, zone 2 and zone 3 forward or reverse [19], [37]-[38]. Zone 3 forward or zone 3 reverse are applied in accordance with the requirements of a given line section at a particular substation. The train load areas during normal operation and during regenerative braking are also shown in the diagram [19], [38].

In traction systems, two independent measuring loops are defined for each zone, namely, the phase-to-phase loops and the phase-to-earth loops. The zero-sequence compensation factor, defined by equation 5, contributes to the accuracy of the reactive reach regardless of the fault loop. For each zone, the reactive reach for each type of fault is defined as well as the resistive reach for both the phase-to-phase and phase-to earth faults are shown in Fig. 3 [39].

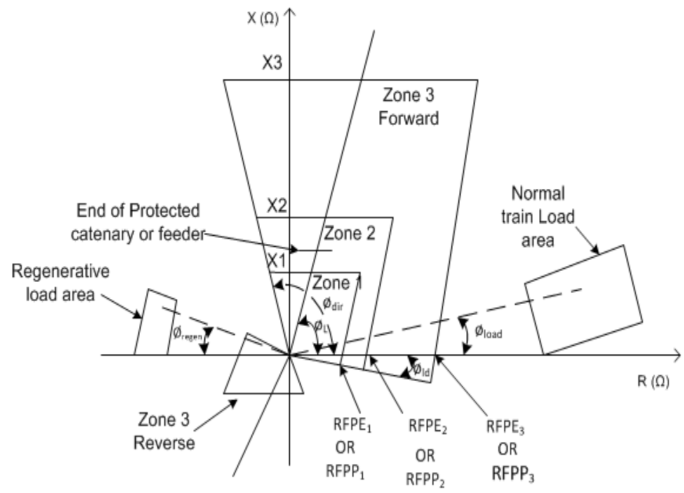

Fig. 3. Quadrilateral distance relay characteristics.

Circles that are originally used in the Mho offset characteristics can also be used to define the boundaries of the quadrilateral characteristics [40], [41]. In general, the distance relay is set to operate when it measures an impedance Z_R that is lower than the set impedance Z_{set} or the impedance of the protected line [42].

$$Z_R < Z_{set} \tag{6}$$

The relation for defining the impedance circles is given by a comparison of squared amplitudes for current and voltages [39]:

$$U^2/Z_{set} < Z_{set} \text{ x } I^2 \tag{7}$$

The straight-line functions in the reactive and resistive zones are defined as follows [39]:

$$S = U \times I^* < (R_{set} + jX_{set}) \times I^2 \tag{8}$$

The impedance of the protected line is [43]:

$$Z_L = R_L + jX_L \tag{9}$$

and its angle is:

$$ø_L = \tan^{-1}[X_L/R_L] \tag{10}$$

The load impedance can be expressed as [44]:

$$Z_{load} = U^2/P_{load} \tag{11}$$

and the load angle is expressed as:

$$ø_{load} = \tan^{-1}[P_{reactive}/P_{real}] \tag{12}$$

The angle for load delimitation or directional angle $ø_{ld}$ is set as a default angle of 15° according to guidelines [39], [45]. The angle for directional delimitation $ø_{dir}$, also known as the negative restrain angle (NRA), is also set to a default angle of

115° according to guidelines [40], [45]. The maximum zone reaches defined in the quadrilateral characteristics are calculated as follows [43], [45]:

$$RFPE_1 \leq \min(4.5 \times X_1, 0.8 \times R_{load}) \quad (13)$$
$$RFPP_1 \leq \min(3 \times X_1, 1.6 \times R_{load}) \quad (14)$$
$$RFPE_2 \leq \min(4.5 \times X_2, 0.8 \times R_{load}) \quad (15)$$
$$RFPP_2 \leq \min(3 \times X_2, 1.6 \times R_{load}) \quad (16)$$
$$RFPE_3 \leq \min(4.5 \text{ x } X_3, 0.8 \times R_{load}) \quad (17)$$
$$RFPP_3 \leq \min(3 \times X_3, 1.6 \times R_{load}) \quad (18)$$

IV. Fault Reporting and Analysis Process

When a fault occurs, the trip signal, the fault response in terms of tripping times and commands, voltage and current magnitudes are all recorded by either the TDS in the train, SCADA database or the DFRs imbedded in the relays or a combination of the three depending on the type of fault and where it occurs. The TDS will not necessarily report at the same time as SCADA because TDS depends on whether there is a train in the faulted section or not. Just like in substations, data received by TDS will trigger a disturbance which will result in the train isolating its power circuit, thereby lowering the pantograph. Relays and SCADA communicate to each other and to the OCC through a serial port, allowing the data to be shared among the engineering maintenance teams, the power supply utility company and the system operator [11].

Data collected from the SCADA, TDS and DFRs is then analyzed by an Engineer who in turn compiles a report and saves the report and DFRs in the Failure Reporting Analysis Corrective Action System (FRACAS) database for future reference and further analysis. It is the responsibility of the Engineer to create the FRACAS database. A similar approach as applicable to communication systems of a smart grid which allows for remote data acquisitions for analysis and data exchange is discussed in [11].

The same concept is applicable for traction systems with modern IEDs and advanced communication networks. The FRACAS library can also be augmented by the tests and the fault analysis conducted using the tests described in this paper. Kezunovic and Ren [46] who used an ATP model as well as MATLAB simulations for conformance and compliance test studies for a power transmission system described how such tests can be used to build a library with different test cases together with real disturbance events that occur in a power system.

V. Traction Power Systems Protection On-Site Testing Methodology

A test kit which consists of the Omicron CPC 100 primary injection equipment, the Omicron CP CU1 coupling unit and variable frequency test kit was set-up at the traction substations and used for on-site tests at all the substations in the system. In this study, Omicron CPC 100 primary injection equipment was used to simulate the faults by connecting it to an existing traction system. Installed relays with test blocks, as well as installed primary plant equipment such as CTs and VTs, and OHW were used for the tests. Different types of faults as discussed in section III were simulated and triggered using the setup. The faults generate disturbance reports and records that get stored in substation IEDs [34], [47]. In this study, the two dual main relays that back each other are of the exact type from the same manufacturer and the settings are the same in both relays, hence they are both referred to as dual main relays. Table I shows the total number of relays at each substation and their designation.

Table I
Position of Local and Remote Relays at the Substations

	Local-MPS	Remote-APS1	Remote- APS2
PA South	LM1	RM1	-
	LM2	RM2	-
PB South	LM1	RM1	-
	LM2	RM2	-
PA North	LM1		RM1
	LM2		RM2
PB-North	LM1		RM1
	LM2		RM2

The relays can either be referred to as either local or remote relays depending on the fault injection point. So, a relay referred to as local can also become remote during a different test and vice versa. Local relays refer to the relays at the test substation and remote relays are relays at the substation at the end of the line section as shown Fig. 4. Table 1 must be read in conjunction with Fig. 4. The following designations are assigned to the relays:

- LM1 and LM2- Local Main 1 and Local Main 2 relays, respectively.
- RM1 and RM2-Remote Main 1 and Remote main 2 relays, respectively.
- Lines PA and PB are the names of the OHW traction lines between the MPS and APS1.

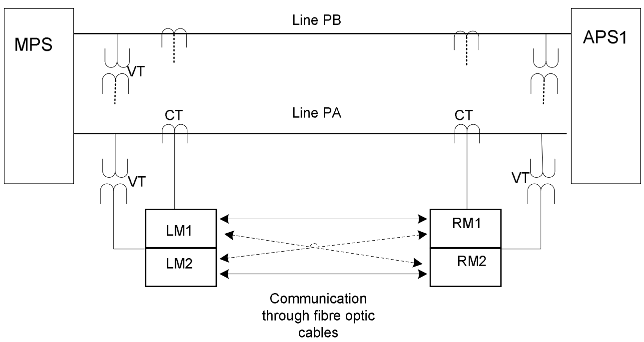

Fig. 4. Distance protection relay setup for the Gautrain.

The setup is the same in all substations, with each line such as line PA and line PB in Fig. 4 being protected by a set of relays housed in substations at both line ends. The relays were pre-set with protection settings as they have been implemented for the protection of the lines in accordance with the protection philosophy applied in the traction system and as described in Section III of this paper. Fig. 5 shows the impedance points of the applied catenary-to-feeder faults in the quadrilateral plane of the relays with zone 1 and zone 2 in forward direction and zone 3 in reverse. The faults were pre-set in the Omicron software and the faults were triggered automatically and in succession. The trip times were then measured and compared with the design protection settings trip times.

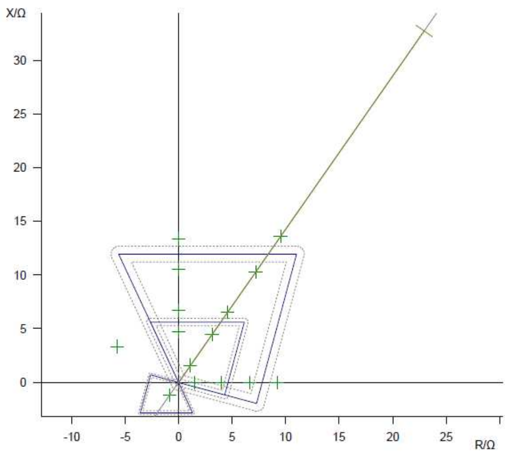

Fig. 5. APS1 LM1 and MPS LM2 Relay quadrilateral setup for catenary-to-feeder fault tests on line PA.

The set-up is for the PA line with APS1 LM1 as the local relay and the MPS as a remote relay. The protection zones of Fig. 5 are explained in the quadrilateral relay characteristics in Fig. 3. In this set-up, a 2 kA fault current was injected at the APS1 and faults with several impedances were then simulated. Although the fault currents were injected on the secondary side of the instrument transformers, the values referred to the primary side are used in this paper.

VI. Test Results and Comparison with Protection Settings

A. *On-site protection test results*

Tables 2 and 3 show the results of the relay tripping time when faults of given impedance values were injected into the relays. In the tables, $T_{settings}$(s) is the expected tripping time when a fault occurs in a given zone per the relay settings, $T_{act\text{-}test}$(s) is the actual tripping time as measured during the tests, and T_{dev} (ms) is the deviation time between $T_{settings}$(s) and $T_{act\text{-}test}$(s). Table II shows the results for the catenary-to-earth faults as seen by the LM1 relay at the MPS for the PA line. Table 3 shows the results of the catenary-to-feeder faults injected at APS1 with APS1 LM1 and MPS RM2 for line PA.

Figures 6 to 8 show the comparison between the tripping times as per settings and the actual tripping times during tests. The results in Figures 6 and 7 are based on Tables II and III above. In Fig. 6, comparisons are made between the protection settings trip times and the actual test trip times for the PA line for all the three zones. Fig. 7 is a comparison of the results showing MPS LM1 zone 3 in forward direction and APS1 RM1 Zone 3 in reverse direction. The overcurrent protection function was also tested, and the results are shown in Fig. 8 for the catenary-to-earth fault.

Table II

MPS-APS1 PA LINE MAIN 1 CATENARY-TO-EARTH FAULT- 2kA FAULT INJECTED AT MPS

Protection Zone	**|Z| Ω**	**Angle (…°)**	**$T_{settings}$ (s)**	**$T_{act\text{-}test}$ (s)**	**T_{dev} (ms)**
1	3.148	55.00	0.00	0.042	42.40
2	3.936	20.00	0.30	0.348	47.50
2	6.925	10.00	0.30	0.348	48.00
2	7.269	90.00	0.30	0.361	60.60
2	8.733	55.00	0.30	0.352	52.00
2	10.000	10.00	0.30	1.048	48.00
2	10.000	90.00	0.30	0.353	53.30
3	13.990	90.00	1.00	1.054	54.00
3	16.660	55.00	1.00	1.046	46.00
3	26.040	55.00	1.00	1.044	44.00

Table III

APS1-MPS- PA LINE MAIN 1 CATENARY-TO-FEEDER FAULT- 2kA FAULT INJECTED AT APS1

Protection Zone	**|Z| Ω**	**Angle (…°)**	**$T_{settings}$ (s)**	**$T_{act\text{-}test}$ (s)**	**T_{dev} (ms)**
1	1.501	0.00	0.00	0.426	42.60
1	1.939	55.00	0.00	0.521	52.10
1	4.000	0.00	0.00	0.605	60.50
1	4.725	90.00	0.00	0.607	60.70
1	5.475	55.00	0.00	0.546	54.60
2	6.632	0.00	0.30	0.357	56.70
2	6.730	90.00	0.30	0.354	53.80
2	8.000	55.00	0.30	0.355	54.70
2	10.500	90.00	0.30	0.358	58.00
2	12.550	55.00	0.30	0.360	60.40
3	1.464	-125.00	1.00	1.062	62.00

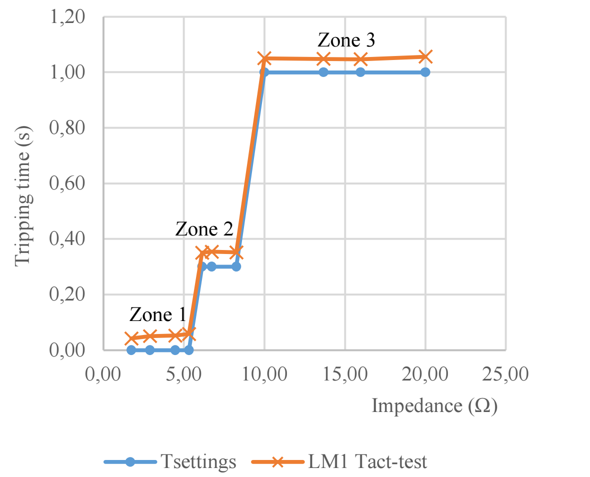

Fig. 6. A comparison between trip times according to the protection settings and test trip times for the PA line with MPS LM1 and APS1 RM1.

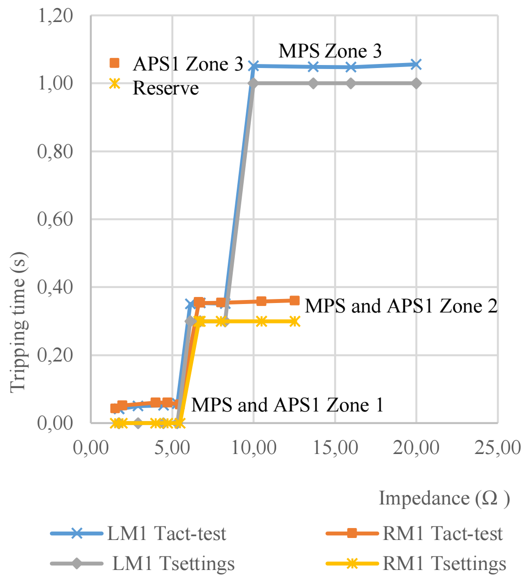

Fig. 7. A comparison of local and remote relays results with MPS local and APS1 remote with zone 3 at the MPS in forward direction and Zone 3 in APS1 in reverse direction.

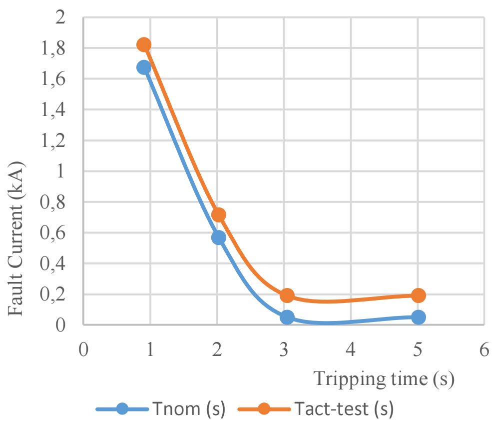

Fig. 8. Overcurrent trip times for catenary-to-earth faults.

B. DFR results

Fig. 9 (a) and (b) are samples of DFRs for a fault that occurred in the traction system as discussed in example 1 of section VII. In the DFR graphs, the horizontal axis is time in ms. The graphs show the fault type, tripping times, zones of protection the magnitudes of the pre-fault, during fault and post-fault voltages and currents and sequence of events.

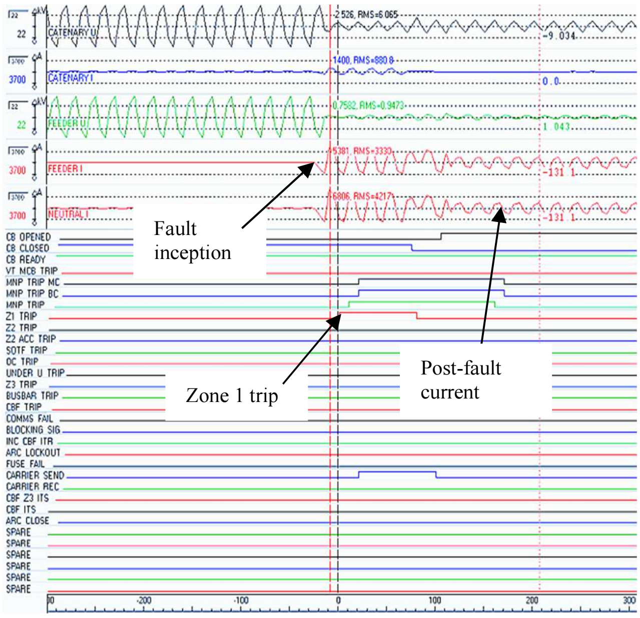

Fig. 9 (a). Feeder-to-Earth fault at APS4 with incorrect relay tripping.

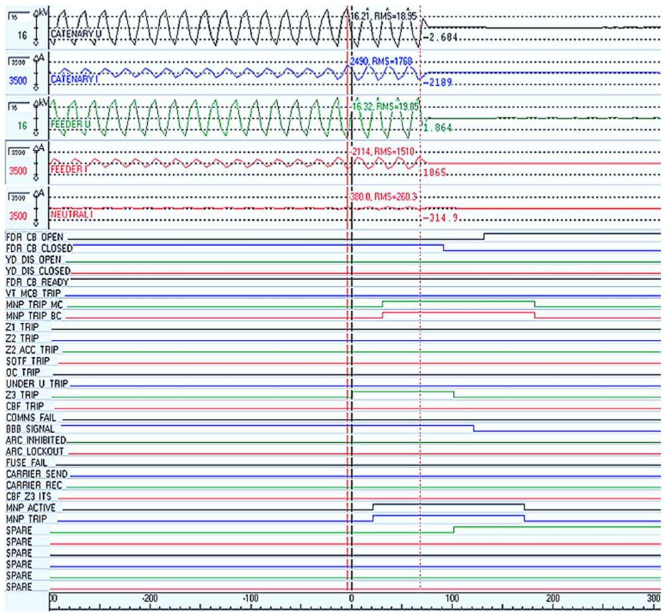

Fig. 9 (b). Zone 3 trip at the MPS due to a fault near APS4 as recorded in Fig. 9 (a).

VII. Discussion and Analysis of Results

A. On-site protection tests

The tripping times as per settings and the actual tripping times according to the on-site tests are compared. In this set of graphs in Fig. 7, the MPS zone 3 is in forward direction and the APS1 zone 3 is in reverse direction. From the results, it can be concluded that LM1 and RM2 or the LM2 and RM1 themselves are interoperable and compatible in terms of their performance. For overcurrent tests shown in Fig. 8, the deviation for catenary-to-earth faults is very high up to 280.8 % as compared to that of feeder-to-catenary that is very low at about 3 %. Further practical analysis is given using examples in subsection C below.

B. Disturbance Fault Records

A common feature in all the DFRs is that the faulted phases will have higher current values and the healthy phase will have a small resultant current flowing through it. This is useful information for maintenance teams that are involved in patrolling the line to check for the root cause of a fault on the correct conductor. Fig. 9 (a) shows a feeder-to-earth fault recorded at APS4. The fault and analysis are described in example 1 below.

Overall, the DFRs show higher tripping times of up to 100 ms as compared to the on-site tests that have a deviation of up to 62 ms across all zones and the protection settings times which are supposed to be instantaneous for zone 1 trips.

Researchers [4] who use a real time digital simulator (RTDS) observed that the overcurrent relay did not trip for some single-line-to- ground faults for up to 200 ms. Authors [46] that use digital simulators using the Alternative Transient Program (ATP program) found that the operating times for some relays were much longer in zone 1.

Other types of faults recorded and stored in the FRACAS database generated for this study include high resistance faults, insulated cable failures, overcurrent faults that occurred due to faults internal to the train instead of the OHW and train pantograph hook-ups. Faults due to birds, grass fires, neutral section pollution and reduced clearance between feeder and catenary or earth wire were also recorded during the study. It has been observed during the course of this study that, high resistance faults can result in catenary or feeder wire breakages if the fault is not cleared speedily although the quadrilateral characteristics described are chosen to take these into consideration.

C. Examples of analysis using a combination of both on-site protection tests and DFR

Example 1 fault description: In early 2019, circuit breakers MPS-J7, MPS-J8 and APS4-J2 had a line protection trip. The line protection trip affected both the A and B lines between MPS and APS4. The DFRs for this fault is shown in Fig. 9 (a) and (b) recorded at the MPS and APS4, respectively.

Fault Analysis: The disturbance records at the MPS and APS 2, 3 and 4 were analysed to understand how the fault occurred. History of other faults that have occurred prior to this fault were checked to establish if there was a pattern or a repeat of similar faults. Trains that were in locations where the fault occurred were also checked for pantograph damage. Line patrols were also conducted to check for possible causes such as under-clearance, foreign objects thrown over the OHW or bird flashovers. Investigation of relay and communication malfunctions at both APS 3 and APS 4 was conducted.

DFR Analysis: According to disturbance fault records from the substations, the fault occurred within zone 1 of APS 4. Relay APS4-J2 shows that the fault was between the feeder and earth wire with fault currents of 5831 A on the feeder, 6806 A on the neutral and 1400 A on the catenary. On the graphs, it shows a carrier-send signal at the APS4-J2 relay, but there was no zone accelerated trip initiated and there was no carrier-receive signal. At APS 3, there was no fault recorded.

From the graphs, it can be observed that the post-fault current recorded at APS 4 was there for a long period because the fault had not cleared on the APS 3 side. This was an incorrect operation of the relays and on further investigations that included a site visit to the substations, communication failure alarms were found at both APS 3 and 4 relays.

At the MPS which is 40.34 km away from APS4, the substation that recorded the zone 1 fault, and with two other APSs in-between, relays MPS-J7, MPS-J8 both tripped on zone 3 as shown in Fig. 9 (b). A zone 3 element at the MPS is set as a back-up protection to cover the entire network impedance so that it trips when all other impedance protection fails. Fault currents of 2114 A on the feeder, 2490 A on the catenary and 380 A on the neutral were recorded. So, the reason why the MPS relays tripped for a zone 3 was due to the communication failure at APS 2, APS 3 and APS 4.

The analysis of TDS records did not show any train faults such as pantograph damage. Line patrols were conducted to check for under-clearance and any foreign objects, and no abnormalities were found.

Relay Testing and Results: In this example, from the analysis of DFRS at APS4, it was immediately clear that there were a few possible failures that needed to be investigated namely; a relay malfunction resulting in the relay zone 2-accelerated function failure at APS4, a relay malfunction resulting in the relay failing to communicate function at APS4, a total relay failure at the remote end at APS3, or an optic fibre communication failure between APS3 and APS4.

Analysis of the DFRs at APS4 also gave very important information about the type of fault, which was between the feeder and catenary, as well as the fault current magnitude. An on-site relay performance test as described in the paper was then conducted.

On-site relay performance: The first test was conducted with APS4 as the local relay location (LM1) and APS3 as the remote location (RM1). In this case, a feeder-to-catenary fault was simulated within zone 1 of APS4. The relay at APS4 tripped for the fault but there was no inter-tripping signal received at APS3.

The same test was conducted with APS3 as the local relay and the APS4 relay as the remote relay. Again, there was also no inter-tripping between the two substations. Both relays showed that their zone 2-accelerated trip was not being initiated during the tests and either relay did not have a carrier receive signal. As both relays showed a similar problem, the fibre optic cable that provides inter-tripping and communication between APS 3 and APS 4 was tested from patch panel to patch panel and it was found that there was a break at 6100 m from APS4 side and 698 m from APS3 side on the A-line. This is the reason why there was no protection trip at APS3.

***Example 2 fault description*:** In February 2020, a protection trip occurred between the MPS and APS2.

Fault Analysis: The disturbance records at the MPS and APS 2 were analysed to understand how the fault occurred. It was found that the line tripped on zone 1 and buszone fault recorded at APS 2, and no fault was found during line patrols. Also, further analysis showed that the other two lines facing out of APS2 towards APS3 tripped for a fault in the section between APS 2 and MPS, indicating a failure to achieve selectivity in the substation.

Protections settings description: The distance protection relays at APS2 incomers from MPS substation are set as follows; Zone 1 – Forward, Zone 2 – Forward, Zone 3 –

Reverse, Buszone set with Zone 3 start and not a busbar block through a delay timer set.

DFR Analysis and on-site Testing: DFR analysis was conducted as described above and it was concluded that the relay had tripped incorrectly. The relays at MPS and APS2 were tested in accordance with the on-site testing methodology described in this paper. It was found that for a fault that is close to APS2 between MPS and APS2 substation the relays pick it up correctly. The relays tripped incorrectly for buszone fault as the relay for a forward fault picks it incorrectly in zone 3 which in this case is set in reverse. Also, the delay timer was set to zero which makes it trip instantaneously on buszone due to incorrect zone 3 start signal. For a buszone trip, the fault should be in reverse and not block from relays on APS2 and APS3 line with delay ON timer set. During the tests, relays at MPS and relays between APS2 and APS3 tripped correctly. As a result, the buszone trip delay ON time setting was changed from 0 s to 50 ms to allow delayed buszone trip. Also, the relay logics were corrected to avoid the buszone signal initiating on a zone 1 fault. This is an example whereby the tests and analysis helped to improve the protection settings.

VIII. CONCLUSION

In this paper a new analysis method using a combination of DFR analysis and relay testing technologies is presented. In this study, the impact to traction systems of relay tripping speeds, reliability, selectivity, conformity and dependability is also tested. A test setup and test scenarios specific to the Gautrain 2×25 kV railway traction power supply system is used. DFRs obtained from traction substations can be used together with train records for further analysis and quick identification of the root cause of the fault. The examples given in the discussions and analysis of results demonstrate how a combination of the two methods can be used to find faults and to solve problems with an in-depth analysis whenever relays trip incorrectly. Protection settings and relay logics were also revised as a result. In the future, during expansion projects or during replacement of obsolete relays, similar tests can be conducted to be able to select the relays that are more dependable and with faster trip times and that will also help in making decisions about the protection philosophy. The use of digital signal processing software (DSP) may be proposed or used for further analysis. The use of DFRs to explore distance to fault locations can be investigated further.

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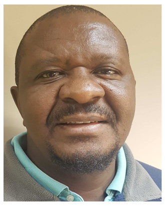

Ndaedzo Moyo received his BSc Engineering degree (Electrical) and his MSc Engineering (Power and Energy Systems) from the University of Kwa-Zulu Natal in year 2000 and 2003 respectively. While at the University of Kwa-Zulu Natal, he specialised on HVDC Research. He worked in the Electrical Transmission Division of Eskom from 2003 to 2006. He has been working for Bombela Maintenance, a division of Bombardier Transportation in the Gautrain project in South Africa from 2007 to present day. He specialises in HVDC and traction power supply systems. He has presented in 8 conferences and published 4 journal articles, two of which are local journals. He is currently studying towards a PhD in Electrical Engineering at the University of Pretoria.

(SM'03) Professor Ramesh Bansal has more than 25 years of diversified experience of research, scholarship of teaching and learning, accreditation, industrial, and academic leadership in several countries. Currently he is a Professor in the Department of Electrical Engineering at University of Sharjah. Previously he was Professor and Group Head (Power) in the ECE Department at University of Pretoria (UP), South Africa. Prior to his appointment at UP, he was employed by the University of Queensland, Australia; University of the South Pacific, Fiji; BITS Pilani, India; and Civil Construction Wing, All India Radio.

Prof. Bansal has significant experience of collaborating with industry and Government organizations. He has made significant contribution to the development and delivery of BS and ME programmes for Utilities. He has extensive experience in the design and delivery of CPD programmes for professional engineers. He has carried out research and consultancy and attracted significant funding from Industry and Government Organisations.

Prof. Bansal has published over 300 journal articles, presented papers at conferences, books and chapters in books. He has Google citations of over 9000 and h-index of 44. He has supervised 20 PhD, 4 Post Doctorates and currently supervising several PhD students. His diversified research interests are in the areas of Renewable Energy (Wind, PV, DG, Micro Grid) and Smart Grid. Professor Bansal is an editor of several highly regarded journals, IET-RPG and IEEE Systems Journals. He is a Fellow and Chartered Engineer IET-UK, Fellow Engineers Australia, Fellow Institution of Engineers (India), Fellow SAIEE, and Senior Member of IEEE-USA.

Prof. Raj Naidoo has more than 20 years of teaching, research, and industrial experience. He received his Ph.D. in electrical engineering from the University of Cape Town, South Africa, in 2008. He is currently an associate Professor in the Department of Electrical, Electronic, and Computer Engineering at the University of Pretoria, South Africa. He was previously the CEO and founder of Enermatics Energy and a board member at Stellenbosch Wind Energy Technologies. He has worked and consulted to several blue-chip companies. He is a currently a director at EWYZE. He has published many research articles in various journals and conferences and has diversified research interests in the areas of the smart grid, renewable energy, and power systems.