Analysis of 138kV Tree Fault in Jamaican Public Service Company System

Russell W. Patterson, P.E.
Consultant
Relayman Protection Services, LLC
Chattanooga, TN

Hortnel Johnson
P&C Engineer
Jamaican Public Service Co.
Kingston, Jamaica

Marvin Watson
P&C Engineer
Jamaican Public Service Co.
Kingston, Jamaica

presented to the

12th Annual Fault and
Disturbance Analysis Conference
Atlanta, GA

April 20-21, 2009

Abstract

A high-resistance tree fault occurred on a 138kV line in the Jamaican Public Service power system. A lack of adequate resistive coverage by the protection system allowed the fault to persist until it developed into a multi-phase fault and was detected and cleared by the protection. The first stage of system under frequency load shedding (UFLS) operated during the initial fault. Subsequently, the line was test closed and the high-resistance ground fault re-occurred and persisted adding 100+ MW of load to the JPS system resulting in UFLS stage 2 operations after which it developed into a less resistive fault and was detected by the protection and cleared. Several issues with the protection system have been discovered through the event analysis and are detailed.

Introduction

On June 20, 2008 a 138kV phase conductor sagged into a tree on the Tredegar to Old Harbour 138kV line in the JPS system. Due to inadequate ground fault resistive coverage the fault could not be detected until it developed into a phase-phase fault. This event was analyzed by review of the event reports captured by digital relays and by detailed analysis of the actual event report oscillography in CAPE (Computer Aided Protection Engineering software by Electrocon).

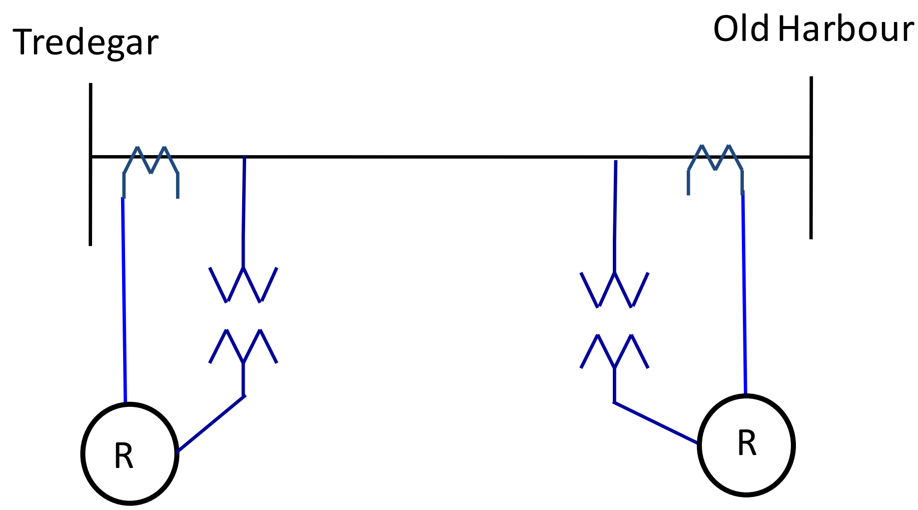

Figure 1. Tredegar – Old Harbour 138kV line.

The pilot scheme of choice used in the JPS 138kV system is the permissive overreaching transfer trip scheme (POTT) via microwave radio using modern digital relays. The pilot ground protection being provided with ground mho and ground quadrilateral. The plot shown in Figure 2 was created in CAPE and the locus of a 5-ohm ground fault is plotted as the fault is moved down the line.

Note that the ground protection on the line consisted of a microprocessor relay in a POTT scheme with three zones of ground mho and quadrilateral (the quadrilateral elements weren't set to provide significant resistive coverage), a second microprocessor relay in a step-distance backup, and an electromechanical inverse-time backup ground overcurrent. The remote terminal is equipped similarly.

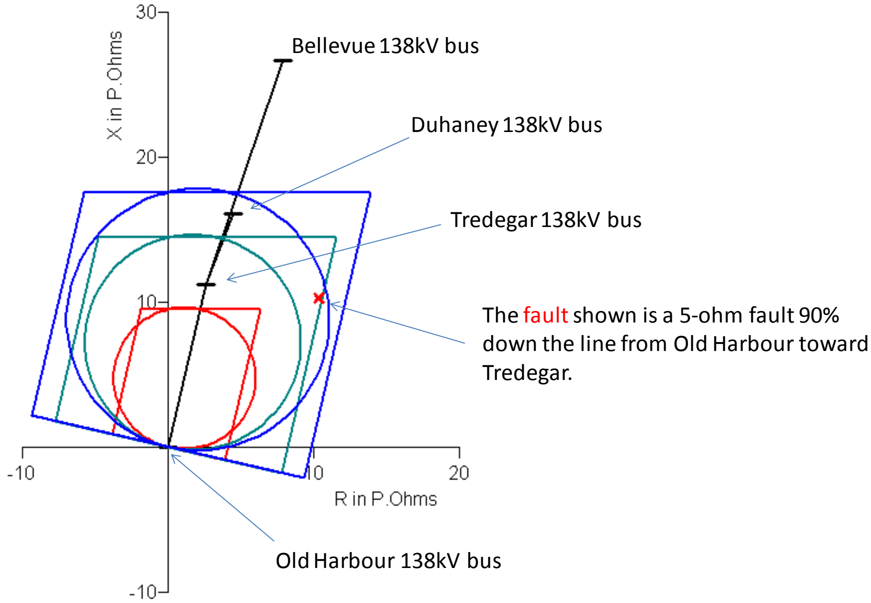

Figure 2a. Old Harbour Substation – Tredegar 138kV line primary ground fault protection.

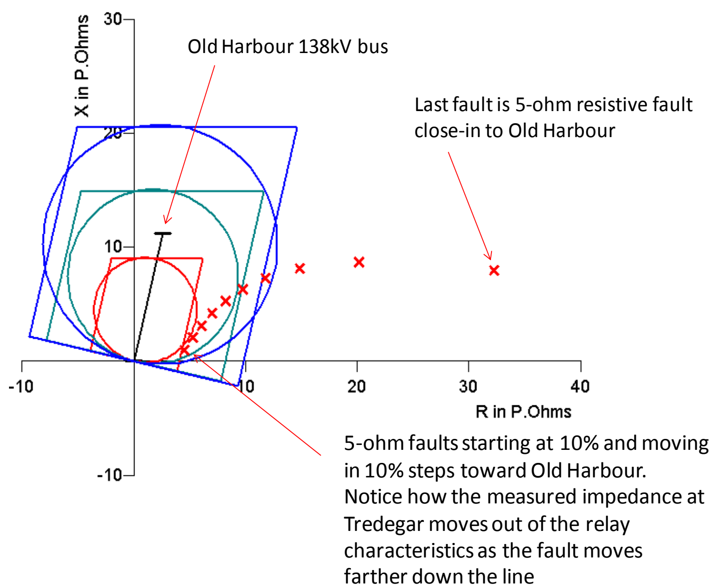

Figure 2b. Tredegar Substation – Old Harbour 138kV line primary ground fault protection.

The subsequent analysis of the event reports from the digital relays uncovered several problems with the protective settings allowing quick improvements and underscoring the importance of event analysis. Four of the event reports are reviewed in the following pages and what they reveal to the analysis engineer.

The normal spinning reserve at JPS is 29MW and the available reserve at the time of the fault on June 20th was 41MW. The generation online at the time of the fault was approximately 586MW. The JPS UFLS schedule is 49.2Hz, 48.9Hz, 48.5Hz, and 48.1Hz all using 7.5 cycle delays (on 50Hz basis).

Sequence of Events Overview

Initial Fault

1. High-resistance fault occurs.
2. Stage 1 UFLS (49.2Hz, 7.5 cycle delay) operates.
3. Fault evolves to phase-phase and is cleared.

Test Closing At Tredegar

1. Test Close.
2. 14 seconds later breaker opened (no relay records).

Test Closing At Old Harbour

1. Test Close and resistive fault reoccurs.
2. Stage 2 UFLS (48.9Hz, 7.5 cycle delay) operates.
3. Fault develops solid enough for protection to clear.

Shot 1 (12:04:09)

The microprocessor relay event report dated 6/20/2008 12:04:09 from Old Harbour on the Tredegar 138kV line is shown in Figure 3 with the fault initially a high-resistance ground fault. It then becomes less resistive (note A-phase current increase with corresponding increase in residual) but is still not detected by the ground protection elements. The negative sequence directional element (32QF) does assert forward just prior to cycle 5. The directional element is supervised by a negative sequence overcurrent element (50QF set on 120A primary 3I2) and it is unable to assert earlier in the event due to the fact that only 50A primary of 3I2 is flowing for this very high resistance fault. The 3I2 increases enough around cycle 5 to assert this 50QF supervisor allowing the 32QF to assert. During this time the stage 1 UFLS operates to drop approximately 41MW.

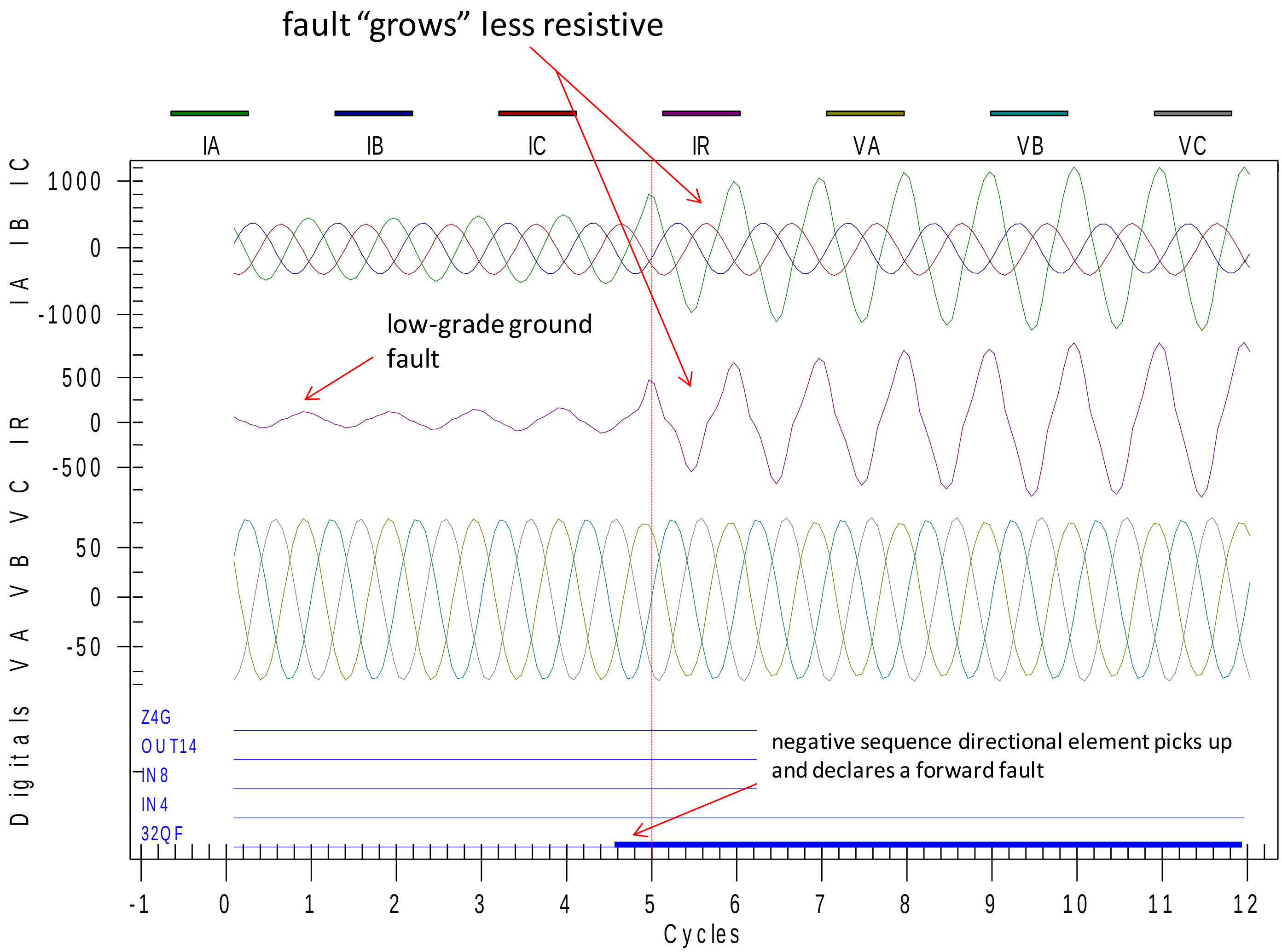

Figure 3. Old Harbour relay event report for initial high-resistance ground fault.

The impedance measured by the relay for a ground fault is determined by the faulted phase voltage, faulted phase current, and the residual current multiplied by the zero-sequence current compensation factor, k0.

The impedance measured by the relay's A-phase ground mho distance loop is calculated as below.

$$Z_{AG} = \frac{V_A}{I_A + k0 \cdot I_R}$$

The zero sequence compensation (complex quantity) for this relay is calculated as below.

$$k_0 = \frac{Z_0 - Z_1}{3Z_1}$$

These equations will be used along with phasor data from the relay event report to evaluate the impedance seen by the relay's ground distance elements. The phasor data from the event calculated at cycle 9 is shown below in Table 1. The voltages are in primary kV and the currents are in primary amperes.

Channel	Mag	Angle	Scale	Show	Ref
IR	856.4	344.1	1	0	0
IA	1183.5	341.4	1	0	0
IB	348.0	222.3	1	0	0
IC	379.7	96.4	1	0	0
VA	80.6	0.0	1	0	1
VB	79.3	244.1	1	0	0
VC	82.5	123.6	1	0	0

Table 1. Phasor event data from cycle 9.

Using the ground distance equation and the captured event data the following measured impedance can be calculated. Compare this calculated value with the relay characteristic shown in Figure 2a.

$$Z_{AG} = \frac{(80.6\angle 0^\circ \text{ kV})}{[1{,}183\angle 341^\circ + (0.76\angle 1.53^\circ)(856\angle 344^\circ)]}$$

$$Z_{AG} = 44\angle 17^\circ \Omega \text{ (primary)}$$

This event report was exported from the relay vendor's analysis software into COMTRADE format and read directly into CAPE. CAPE has the capability of reading a COMTRADE file and calculating the sample-by-sample phasor data and supplying the resulting voltages and currents to the detailed CAPE model of the particular relay so that the response of the ground distance element could be evaluated. The resulting plot is shown in Figure 4. Note that the detailed CAPE model accommodates the dynamic characteristics of the particular relay (expansion etc.) but for plotting purposes in this paper only the static characteristic is shown.

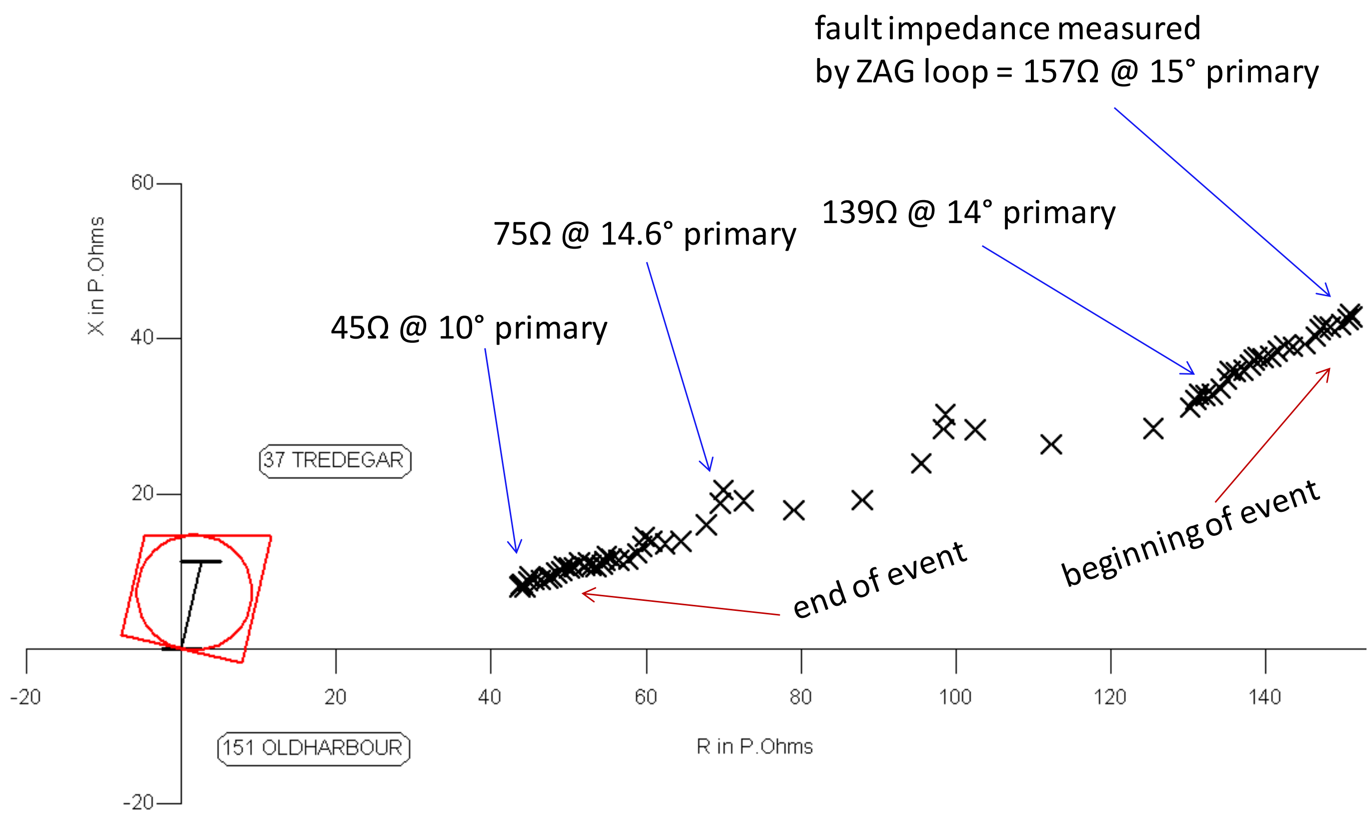

Figure 4. Shot 1 imported into CAPE and plotted against relay zone 2 ground characteristic.

At the beginning of the event (far right) the ZAG impedance measured by the relay (zone 2 ground mho and quadrilateral characteristic plotted) is around 157Ω @ 15°. The impedance locus migrates down and to the left until the end of the event report (across 12 cycles) where it is around 45Ω @ 10°. About midway between the beginning and end of the event the 32QF asserts properly assigning the fault direction as forward. However, due to the insensitivity to fault resistance of the ground protection the relay does not make a trip decision.

Shot 2 (12:04:10)

The relay event report dated 6/20/2008 12:04:10 from Old Harbour on the Tredegar 138kV line is shown in Figure 5. This is a continuation of the event that began in Figure 3. The fault has evolved into a phase-phase fault and can be detected by the phase distance protection. Both ends of the 138kV line detect the fault (as evidenced by the receipt of a permissive signal from Tredegar on input IN4) and trip in pilot time to clear the line.

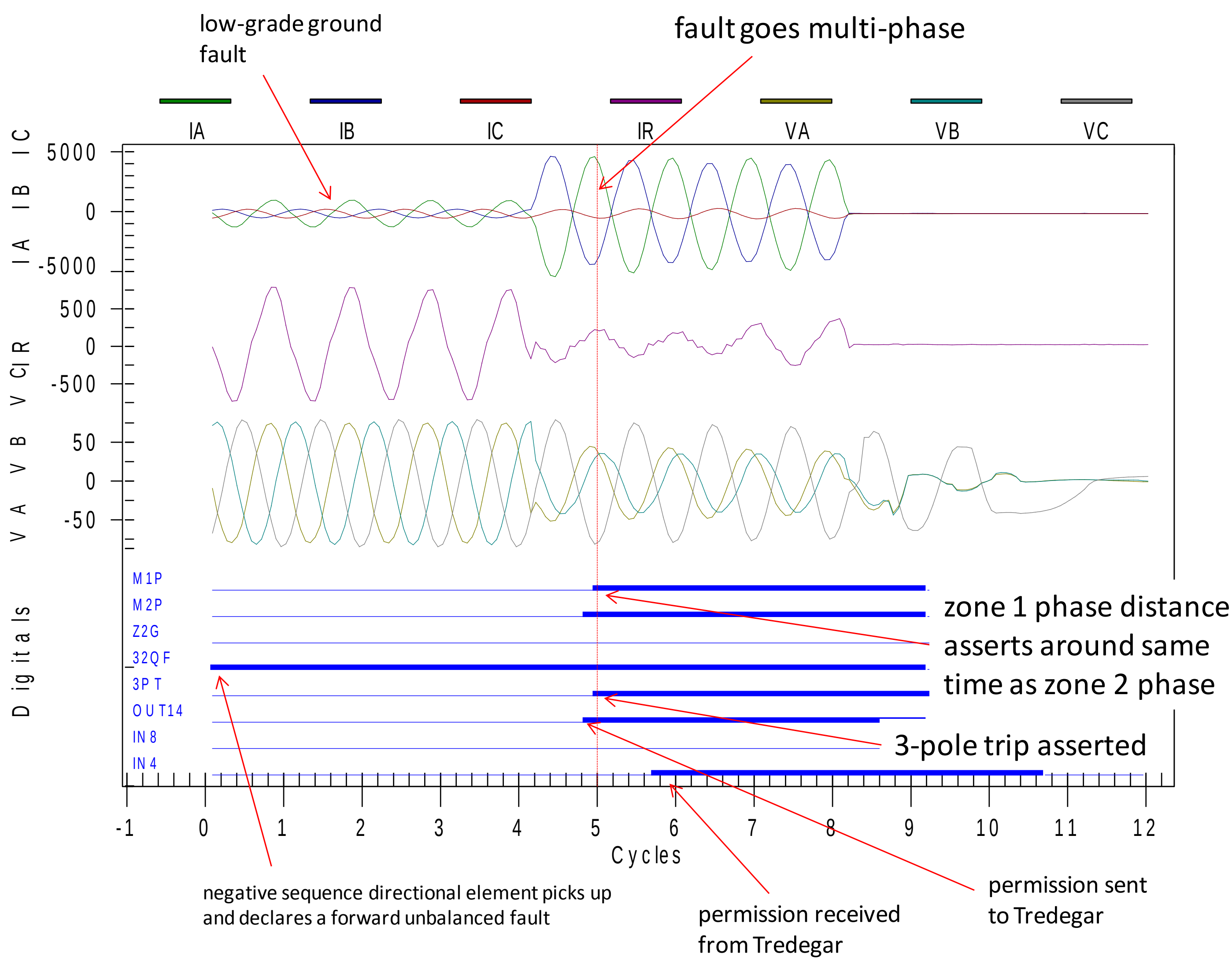

Figure 5. <u>Old Harbour relay event report showing high-resistance fault go phase-phase</u>.

This event report was also exported, converted to COMTRADE, and read directly into CAPE so that the response of the phase distance element could be evaluated. The impedance traverses right to left and downward crossing into the zone 2 phase distance characteristic first and then into the zone 1 phase distance characteristic.

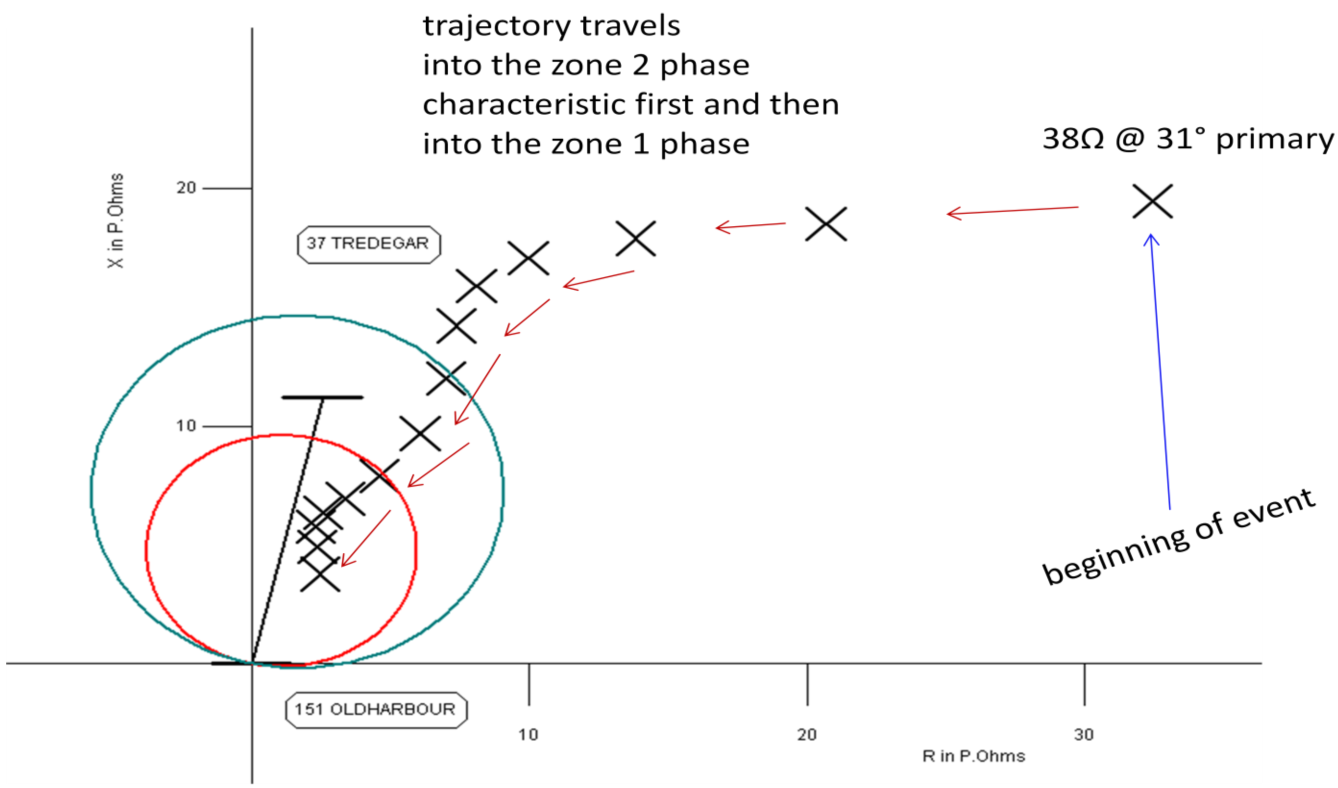

Figure 6. <u>Shot 2 imported into CAPE and plotted on zone 1 and 2 phase distance characteristic</u>.

Shot 3 (12:05:31)

The relay event report dated 6/20/2008 12:05:31 from Old Harbour on the Tredegar 138kV line is shown below. Prior to this event the Tredegar end had been closed and inexplicably opened 14 seconds later. No event oscillography exists for that event and per SOE information no UFLS operated. For this event shown below, the line is initially dead and then is test closed by the operator. The fault reoccurs and subsequently the stage 2 UFLS operates (dropping approximately 43MW) before the fault can be cleared.

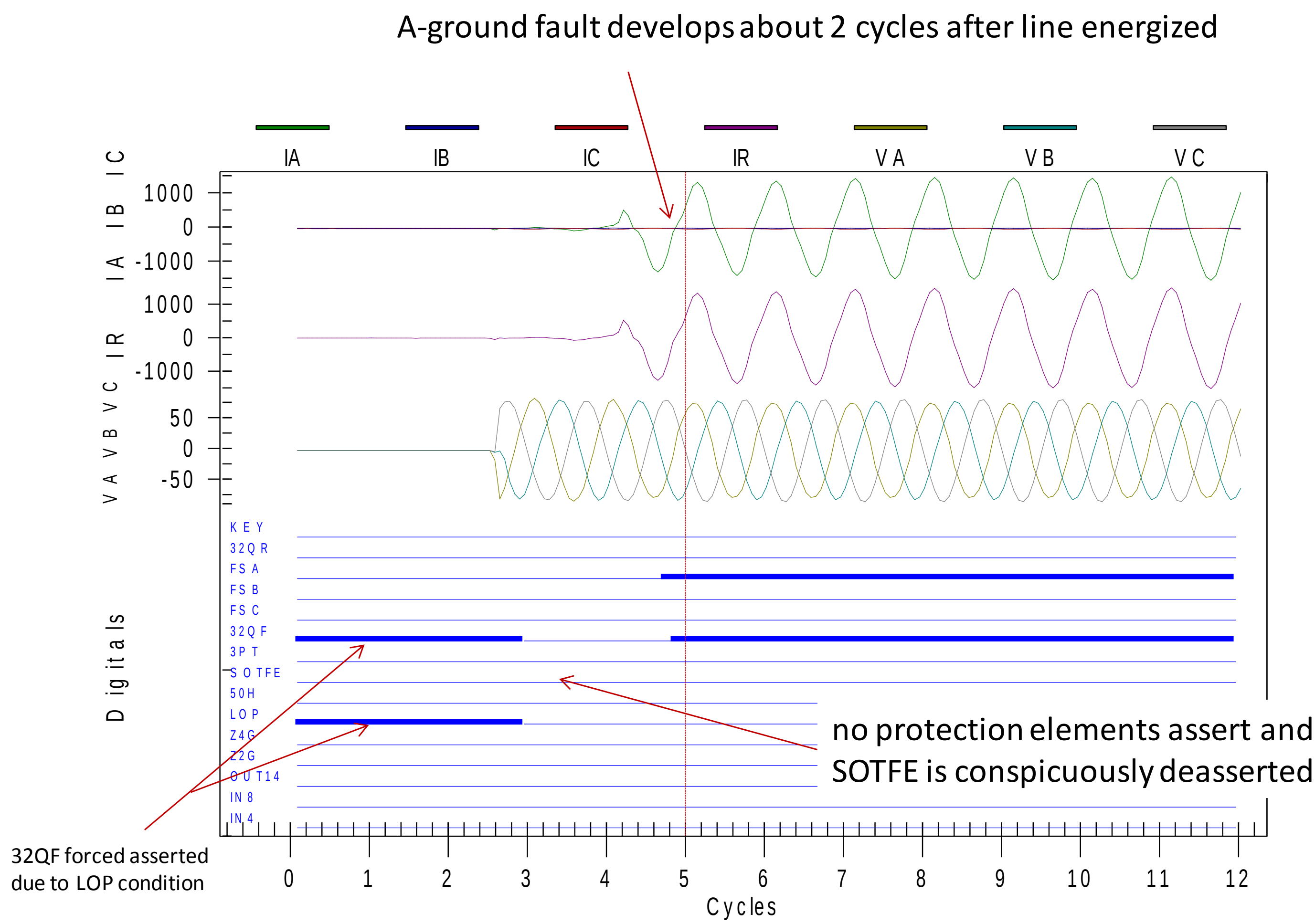

Figure 7. Old Harbour relay event report showing fault recurring shortly after test close.

Upon testing the line the fault reoccurs and again is not detected by the insensitive ground protection elements.

Another important problem is noticeable as well, the absence of switch onto fault enable (SOTFE). This logic is used with line-side potentials to ensure that the relay can trip upon closing into a fault. The relay wasn't set to provide SOTF protection. Switch onto fault protection (also known as CIFT, Close into Fault Trip) is needed when line side potential devices are used to provide voltages to protective relays.

The relay event record shows the following phasor data at cycle 9 while the fault was still "steady-state" in the resistive A-ground fault.

Channel	Mag	Angle	Scale	Show	Ref
IR	1388.5	351.4	1	0	0
IA	1394.4	349.2	1	1	0
IB	36.1	74.0	1	1	0
IC	18.0	117.0	1	1	0
VA	79.1	0.0	1	1	1
VB	77.7	249.2	1	1	0
VC	83.4	127.4	1	1	0

Table 2. Phasor event data from cycle 9.

This results in the following primary impedance measured by the A-phase ground distance loop.

ZAG = [79.1kV@0° ÷ (1394A@349° + (0.76@1.53°)(1388@351°)] = 32Ω @ 9.5°

The result again is failure to detect this resistive fault.

Using the phasor data (with the understanding that the remote end is open) we can calculate the following.

$$MVA_{Aphase} = V_A \cdot I_A^*$$

$$MVA_{Aphase} = (79.1\angle 0^\circ) \cdot (1{,}394\angle -349^\circ)$$

$$MVA_{Aphase} = 110\angle 11^\circ \text{ MVA}$$

$$MW_{Aphase} = 108 \text{ MW}$$

This would explain the under frequency load shedding that occurred since 108MW is a significant percentage of the total JPS generation capacity.

A stability study would need to be performed to show the actual machine dynamics but this is a simple rough hand calculation that shows that the real loading on the system has increased substantially due to the resistive fault.

Figure 8 and 9 shows the instantaneous power calculation graphically.

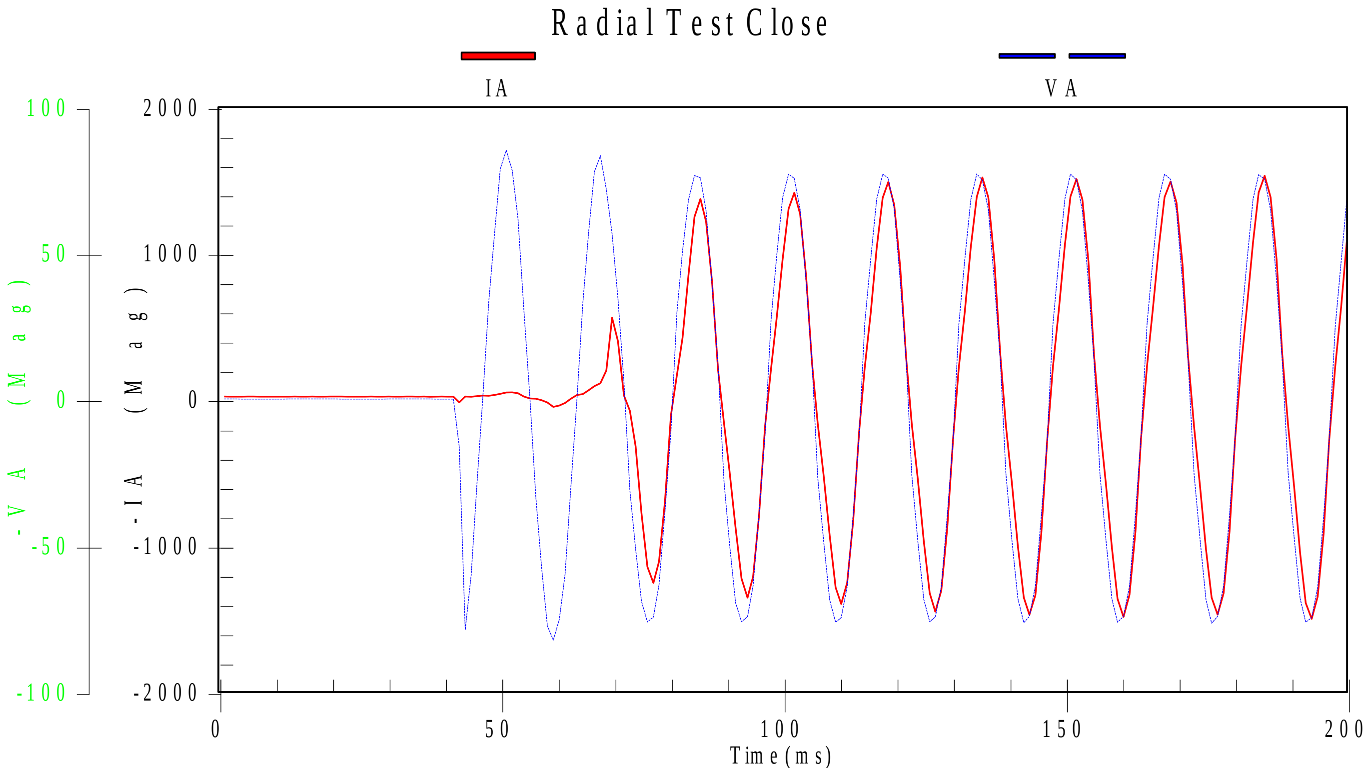

Figure 8. Voltage and Current for radial resistive ground fault during test close.

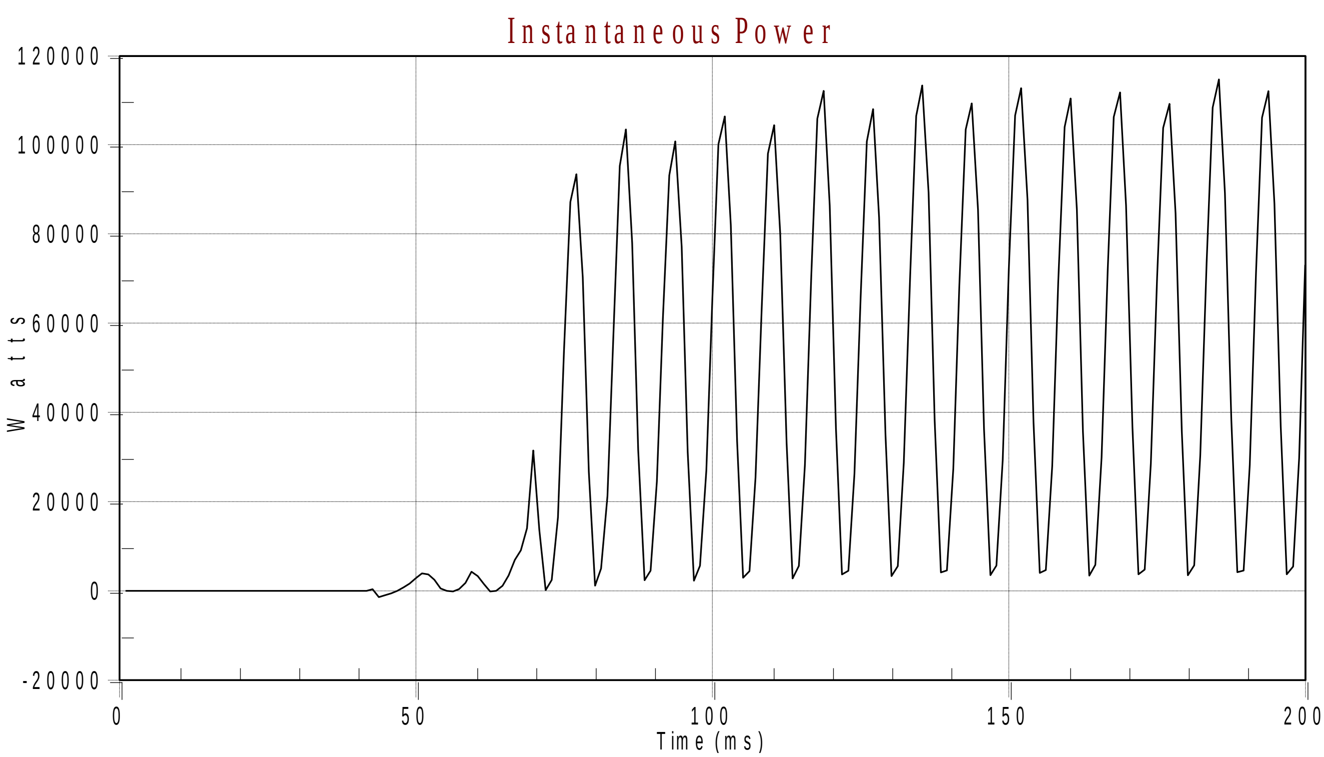

Figure 9. Instantaneous VA x IA for radial resistive ground fault during test close.

Shot 4

The relay event report dated 6/20/2008 12:05:33 from Old Harbour on the Tredegar 138kV line is shown below. This appears to be the continuation of the test close event and indicates that this subsequent fault was apparently on for a couple seconds or longer (based on time stamps).

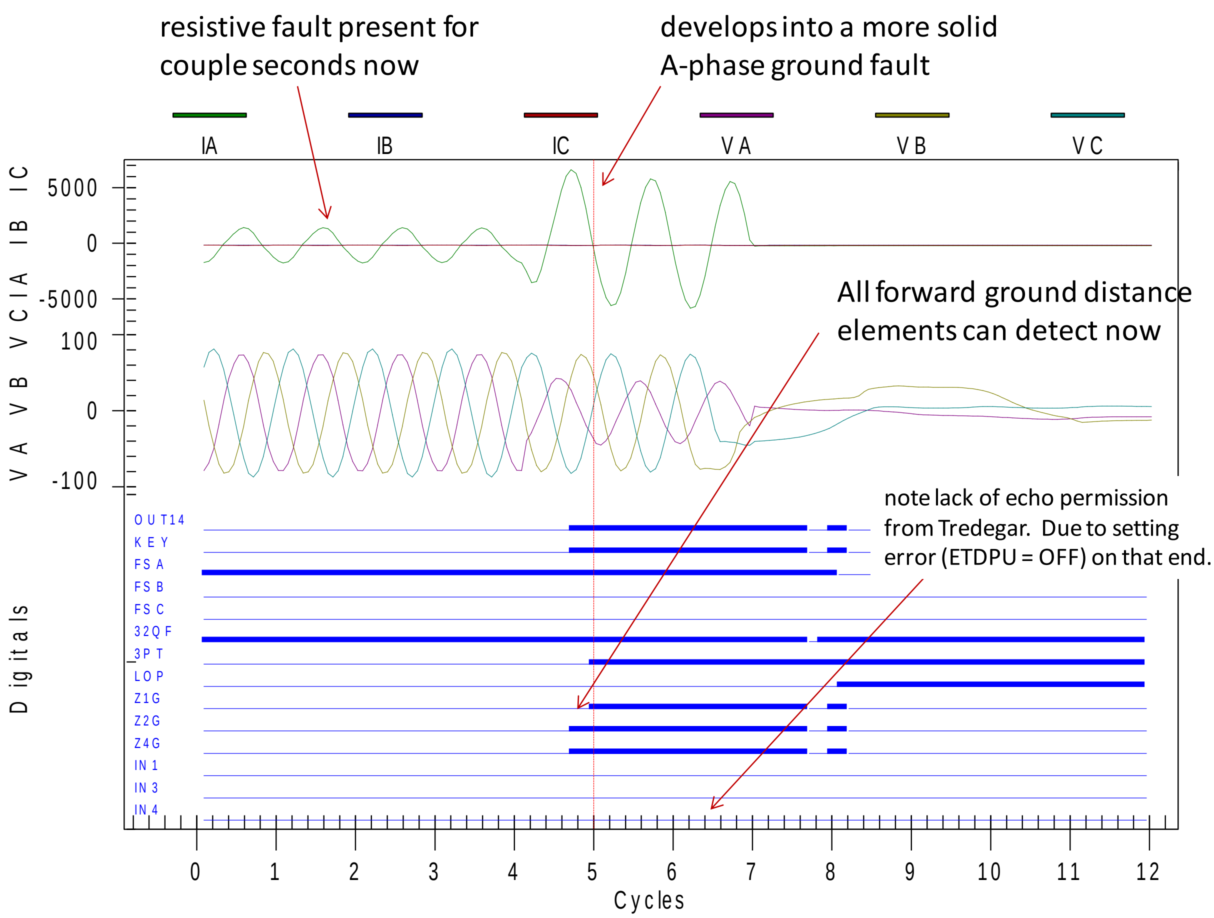

Figure 10. Relay event report showing continuation of test close event.

When the fault evolves into a more solid phase-ground fault the forward ground distance elements can detect it and operate.

Note that the A-finger (IN1) is not asserted in any shot. Note that permission is not echoed from Tredegar after it is sent from Old Harbour (KEY). Echo trip logic was disabled in the settings. This logic is used to allow fast clearing of line-end faults if the remote breaker is open. A critical line such as Old Harbour-Tredegar should never be test closed without high-speed protection available for the entire line length.

Improvements

Based on the detailed analysis described above JPS was able to make immediate improvements in their 138kV protection system.

- Addition of sensitive directional residual overcurrent elements to the POTT logic to allow excellent resistive fault coverage.

- Enabling of switch onto fault protection to facilitate high-speed clearing of the line when radial test close occurs. Since the line has negligible charging and no tap load a very sensitively set overcurrent level can be used with appropriate line voltage supervision.

- Enabling of the echo trip logic portion of the POTT scheme logic so remote end faults can be cleared in pilot time when the remote breaker is open. Note that most digital relays require a breaker status (52A) input be wired for this logic.

Summary

The analysis of this event is straight forward and underscores the improvements that can be made to the security and dependability of protection systems simply from doing analysis. This detailed analysis was also made possible by the event recording capabilities of modern digital relays as well as the analysis capabilities of well developed engineering tools such as CAPE.

Bibliography

1. "Analysis of Event Reports", Jeff Roberts and Edmund 0. Schweitzer, III, 16th Annual Western Protective Relay Conference, Spokane, Washington, October 24 -26, 1989.

2. "Analyze Relay Fault Data To Improve Service Reliability", Roy Moxley, Schweitzer Engineering Laboratories, http://www.selinc.com/techpprs/6157.pdf.

3. "Understanding And Analyzing Event Report Information", David Costello, Schweitzer Engineering Laboratories, http://www.selinc.com/techpprs/6110.pdf.

Software

CAPE – Computer Aided Protection Engineering, www.electrocon.com

TOP – The Output Processor by Electrotek Concepts®, http://www.pqsoft.com/TOP/index.htm.

Biographical Sketches

Russell W. Patterson is a consultant in power system protection and control with 17 years in the industry. Prior to entering full time consulting he was manager of System Protection & Analysis for the Tennessee Valley Authority (TVA) in Chattanooga, Tennessee. As manager of System Protection & Analysis he was responsible for the setting calculations for all protective relays in the TVA transmission system and at hydro, fossil and nuclear generating plants. Prior to managing System Protection & Analysis his roles included manager of Advanced Power Applications group, manager of Power Quality, and a Specialist in System Protection & Analysis. Russell is an adjunct instructor in electrical engineering at the University of Tennessee at Chattanooga. He is a member of the IEEE Power System Relaying Committee (PSRC) and is vice-chairman of the Line Protection Subcommittee and a member of the Rotating Machinery Subcommittee. Mr. Patterson earned the B.S.E.E. from the Mississippi State University in 1991. Russell is a registered professional engineer in the state of Tennessee, a Senior Member of IEEE, member of NSPE, NCEES registered, and a member of CIGRE´. Russell can be e-mailed at rwpatterson@ieee.org and his webpage is http://relayman.org.

Hortnel Johnson is a Protection and Control Engineer at Jamaica Public Service Company (JPS) since November 2006. He graduated with a BSc Degree in Electrical Engineering from ISMM University in the Republic of Cuba, and prior to that an Asc. Degree in Industrial Systems Operations and Maintenance from the Caribbean Maritime Institute. His responsibility as a Protection Engineer at JPS includes, protective relay settings calculation and fault analysis.

Marvin B. Watson received his BENG in Electrical Engineering at the University of Technology, Jamaica in 2001 where he majored in Electrical Power. After completion of his first degree, he joined Jamaica Public Service in 2001 as an Assistance Control Engineer in which he served in that capacity for three years. He was later transferred to the Protection and Control Department in 2004 as an Application Engineer with primary responsibilities for relay settings calculation and fault analysis. Mr. Watson is member of the IEEE Power and Energy Society (PES) and is a member of the Engineering Management Society.