Analysis of the behavior of one digital distance relay under islanding condition with ATP

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***Abstract*—Due to a fault in one 150 kV radial transmission network, an isolated network with passive loads and induction motors is developed. As a result of this event, one digital distance relay gave an incorrect three-pole-trip signal to a circuit breaker being the three-phase auto-reclosing function blocked. As a consequence, there was an interruption of the supply. This paper focuses on the most important aspects of the issues: a) the relay principle and ATP (Alternative Transients Program) modeling b) the evaluation of the digital distance relay performance during the sequence of events aforementioned c) the conclusions resulting from the simulations in order to find out an explanation for the incorrect tripping of the relay, and therefore, give a solution to the problem.**

***Keywords*: digital distance relays, ATP modeling, ground and phase distance functions, islanding.**

I. Introduction

FIG.1 shows the one-line single diagram of one radial transmission network in the 150 kV voltage level of Uruguay.

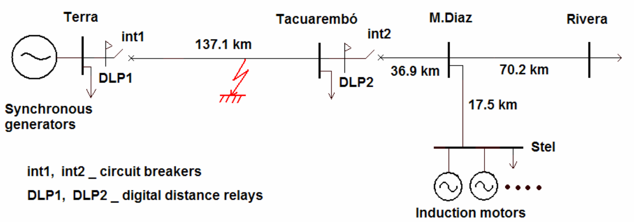

Fig. 1. Radial transmission system

Many times the following sequence of events took place: a) a single phase-to-ground fault happened in the transmission line Terra-Tacuarembó b) digital distance relay DLP1 gave a three-pole-trip signal to circuit breaker int1. Three-phase auto-reclosing is allowed c) digital distance relay DLP2 gave a three-pole-trip signal to circuit breaker int2 during the dead time associated with the auto-reclosing scheme of circuit breaker int1. A phase distance function of Zone 1 gave this order. At the same time, the three-phase auto-reclosing is blocked d) when circuit breaker int1 reclosed circuit breaker int2 was still open. Therefore, there was an interruption of the supply. As a result of these events, some oscillography data were stored by relays DLP. In conclusion, and from a preliminary analysis of these recordings, the tripping action of relay DLP2 was incorrect.

In order to avoid the interruption of the supply, the responses of the phase and ground distance functions facing the electromagnetic transients in the transmission line Tacuarembó-Rivera, which were caused by the opening of circuit breaker int1, were studied in the time domain. Consequently, the radial network of Fig. 1 was represented with the ATP program as well as the phase and ground distance functions of Zone 1 relay DLP2 and the corresponding phase angle comparators were implemented in routine TACS of ATP using device Type 69.

II. Digital Distance Relay [1][2][3]

Manufactured by General Electric, the DLP (Digital Line Protection System) is a digital distance relay which has the following functions: 21/50/51/67N/79/97.

This relay is a microprocessor-based digital relay system that uses wave-form sampling of the current and voltage inputs, together with appropriate algorithms, to provide transmission line protection and fault location. Other functions are: overcurrent backup, reclosing, out-of-step blocking, alarms and oscillography.

The DLP incorporates four zones of distance protection to implement six different protection schemes: Step Distance, Zone 1 Extension, Permissive Overreach Transfer Trip, Permissive Underreach Transfer Trip, Blocking and Hybrid. For relays DLP1 and DLP2 Zone 1 Extension scheme was chosen which does not utilize a communication channel. It provides high-speed tripping at each terminal for 100% of the protected line section. This is accomplished by letting the Zone 2 overreaching function trip without any intentional time delay for the initial fault occurrence. The opening of the circuit breaker, due to a single phase-to-ground fault, starts the associated automatic-reclose function, and restores Zone 1 reach to 80% of the protected line section. This condition stays in effect until the recloser resets. The reclosing function is set to provide one reclose attempt, the reclose time delay is equal to 500 ms. For Zone 1 of protection six individual measuring functions are present, three variable-mho phase distance functions and three variable-mho ground distance functions.

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III. ATP Modeling of the Radial System [4-8]

In order to analyze the behavior of the DLP2 distance functions during the sequence of events presented in item I, the radial network of Fig.1 was simulated with the ATP program. The transmission line Terra-Tacuarembó is transposed and each transposition section was simulated using K.C. Lee model. The untransposed transmission line Tacuarembó-Rivera was simulated with the same model. Induction motors are connected at Stel bus bar; however, their real data was not available. The wave shapes of currents and voltages recorded by the DLP2 relay were simulated from a qualitative point of view, utilizing typical data of induction motors and the U.M. module of ATP.

IV. ATP Modeling of the DLP2 Distance Relay

The phase and ground distance functions of Zone 1 relay DLP2 and the corresponding phase angle comparators were implemented in routine TACS of ATP using device Type 69. The ATP model is composed of different modules schematically shown in Fig. 2. The input signals of the model are: size of the time step, simulation time, line to ground voltages and phase currents at Tacuarembó bus bar. This model generates three output files: REPORT1 which indicates if a fault happened or not and the fault type, FD which shows the time variation of the Fault Detector output, ANGULO which shows the time variation of the Phase Angle Comparator outputs.

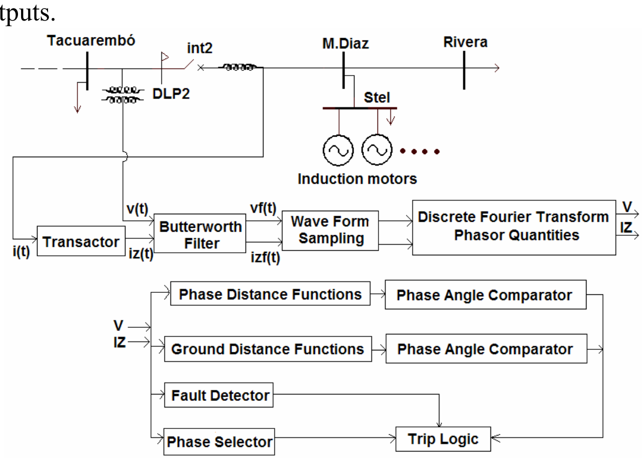

Fig. 2. Modules of ATP model

A. Transactor

Protective relays must filter their inputs to reject unwanted quantities and retain signal quantities of interest. Because distance relay measure impedance, and because impedance is defined at a given frequency, distance relay filters must save only the fundamental frequency. When the resistance-inductance behavior of the power system dominates, the voltages and currents are, as usual, sinusoids with exponentially decaying DC offsets. The offsets can severely affect the currents, but seldom seriously affect the voltages. A "software transactor" algorithm is used to remove any DC offset that may be present in the currents.

The general equation for a fault current which includes DC offsets is:

$$i(t) = I * \sin(\omega t + \alpha - \theta) - I * \sin(\alpha - \theta) * e^{-t/T} \qquad (1)$$

Where: I peak value of current, $\omega = 2\pi f$, α angle on voltage wave at which fault occurs, $\theta = \arctan(\omega L/R)$ impedance angle of power system, T= L/R. An impedance, $R2 + j\omega L2$, is considered to be a replica of the power system impedance if:

$$\frac{L}{R} = \frac{L2}{R2} \qquad (2)$$

The voltage across this replica impedance is:

$$v(t) = i(t) * R2 + \frac{d}{dt} i(t) * L2 \qquad (3)$$

Equations (1), (2) and (3) lead to:

$$iz(t) = v(t) = [(R2)^2 + (\omega L2)^2]^{1/2} I * \sin(\omega t + \alpha) \qquad (4)$$

From (4) is observed that the voltage across a replica impedance does not contain any DC offset and it is phase shifted θ degrees leading compared to the current. Equation (3) was implemented in routine TACS using device Type 69 and the trapezoidal rule of integration. The replica impedance is equal to 80% of the positive sequence impedance of the transmission line Tacuarembó-Rivera, which is the reach setting of Zone 1. Fig.3 shows input signal i(t) and output signal iz(t) of the transactor, in the time domain.

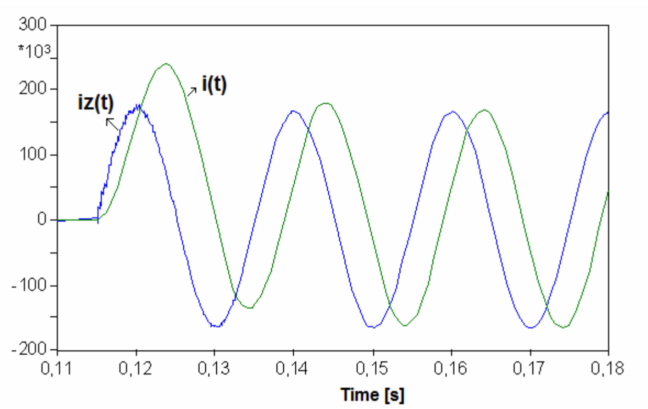

Fig. 3. Transactor signals

B. Butterworth Filter [9]

The DLP relays sample current and voltage 16 times per cycle, operate at nominal 50 Hz system frequency, so that the sampling frequency is 800 Hz. If the sampling frequency were lower than the Nyquist frequency, there would be overlap in the shifted replicas of the Fourier Transform input signal, called aliasing. This can be prevented by passing the input signal through an analog low-pass filter prior to sampling. This filter must have a cut-off frequency equal to or less than 400 Hz. The anti-aliasing low-pass filter is a three-pole Butterworth design with a gain of -25 db at 400 Hz. The filter transfer function in Laplace domain is:

$$H(S) = \frac{1}{2*10^{-8} S^3 + 1.47*10^{-5} S^2 + 5.42*10^{-3} S + 1} \qquad (5)$$

Equation (5) was implemented in routine TACS using S-blocks option.

C. Discrete Fourier Transform (DFT)

The DFT is used to estimate the fundamental frequency (50Hz) components, in this case a full-cycle algorithm was chosen. The algorithm implemented has a data window of 16 samples, that is, as a new sample becomes available, the oldest of the 16 sample values is discarded and the new sample value is included in the calculation. The recursive form of the full-cycle algorithm was implemented in routine TACS through device Type 69 option.

D. DLP Distance Functions

In this section, the most important aspects of the DLP distance functions are presented.

1) Operating principle

The DLP relay uses variable mho characteristic, as shown in Fig.4a, being ZR the reach of Zone 1. A classical mho unit is developed by measuring the phase angle between two voltage signals in the relay, called an operating signal and a polarizing signal. Because of this, it is convenient to work with a voltage diagram in order to describe how they are derived. It may be obtained from the R-X diagram of Fig.4a by multiplying all the points by the fault current in the relay, as shown in Fig.4b. Since the fault current will change as the system conditions and fault location change, the voltage diagram will contract or expand. However, the voltage phasors will have the same phase angle and magnitude relationships as the impedance vectors on the R-X diagram.

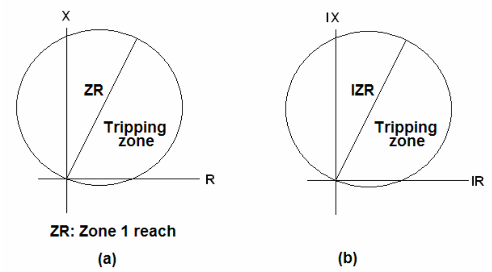

Fig. 4. Impedance and voltage diagrams

Consider that a fault is applied in the line Tacuarembó-Rivera as shown in Fig. 5. Let ZF be the impedance from DLP2 relay location to the fault, and I and V be the current and voltage supplied to the relay. Therefore, voltage V is I*ZF and current I is transformed into a voltage I*ZR by the action of the transactor.

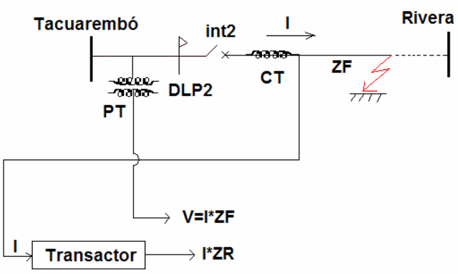

Fig. 5. Voltage and current supplied to DLP2 relay

The voltage phasors V and I*ZR could be drawn on the voltage diagram, considering three relative positions for V in relation to the mho circle: a) on it, b) inside it and c) outside it. Fig. 6 shows case a).

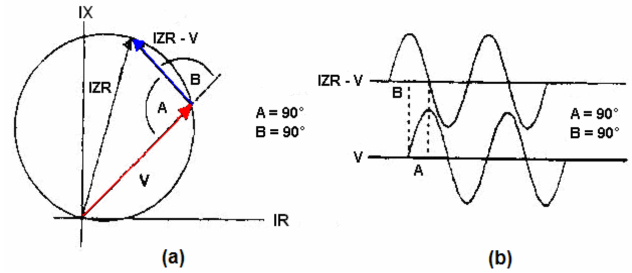

Fig. 6. Case a)

Since I*ZR is the diameter of the circle, both angles A and B are equal to 90º. Two sides of the triangle are formed by the phasors V and I*ZR, the third side is the phasor difference of these signals, I*ZR-V which is known as the operating signal. The phasor V is known as the polarizing signal. Sine wave signals representing V and I*ZR-V are shown in Fig. 6b corresponding to the phasors of Fig. 6a. Angle A measures the coincidence between the operating and polarizing waveforms. Coincidence occurs when both signals have the same instantaneous polarity.

Fig. 7 shows case b). In this case, the fault is moved closer to the DLP2 relay, that is, inside its zone of protection. For this condition, angle A is greater than 90º while angle B is less than 90º. Fig.8 shows case c). In this case, the fault is moved farther from the DLP2 relay, that is, outside its zone of protection.

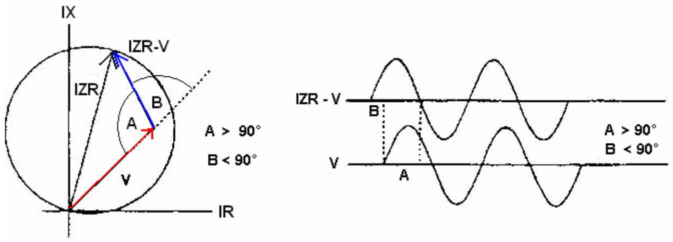

Fig. 7. Case b)

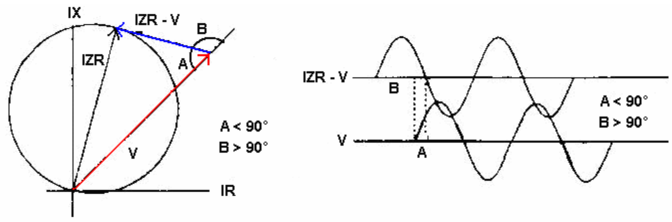

Fig. 8. Case c)

For this condition, angle A is less than 90º while angle B is greater than 90º. From Figs. 6 to 8 it can be concluded that when a fault is within the mho function's zone of protection angle A is greater than or equal to 90º.

2) Phase Angle Comparator

Phase Angle Comparator is used to measure the phase angle between the operating and polarizing signals. This is a software module that measures the coincidence between operating and polarizing waveforms and checks if angle A is greater than or equal to 90º. In the affirmative case it produces a logic output directed to the trip logic. An algorithm to measure the coincidence was developed and implemented in routine TACS through device Type 69 option, by the authors.

3) Memory action

The polarizing signal is the faulted phase voltage. This presents a problem when a fault is applied near the relay location, since the faulted phase voltage goes to zero magnitude. To overcome this situation, a "remembered" voltage, based on the prefault voltage, is used as a polarizing signal for a long enough time (80ms) to allow the distance functions to operate.

4) Phase and Ground Distance functions

In this section, the phasor inputs to the phase angle comparator for each distance function are presented. For each zone of distance protection there are six separate distance functions: three phase distance functions, one per phase pair (AB, BC, CA) and three ground distance functions, one per phase (A,B,C).

Phase distance-variable mho:

$$(\dot{I}_J-\dot{I}_K)*|Z_{1L}|_{<\varphi 1}-(\dot{V}_J-\dot{V}_K) \quad (6)$$

$$(\dot{V}_J-\dot{V}_K)_{1M} \quad (7)$$

$$(\dot{I}_J-\dot{I}_K)*|Z_{1L}|_{<\varphi 1} \quad (8)$$

AB: J=A and K=B

BC: J=B and K=C

CA: J=C and K=A

$\dot{I}_A,\dot{I}_B,\dot{I}_C,\dot{V}_A,\dot{V}_B,\dot{V}_C$ - phase currents and phase to ground voltages at relay

$|Z_{1L}|_{<\varphi 1}$ - 80% positive-sequence impedance of the line

$(\quad)_{1M}$ - memory prefault value of $(\quad)$

Ground distance-variable mho:

$$(\dot{I}_J-\dot{I}_0)*|Z_{1L}|_{<\varphi 1}+\dot{I}_0*K_0*|Z_{1L}|_{<\varphi 0}-\dot{V}_J \quad (9)$$

$$(\dot{V}_J)_{1M} \quad (10)$$

$$(\dot{I}_J)_2*|Z_{1L}|_{<\varphi 1} \quad (11)$$

$$\dot{I}_0*|Z_{1L}|_{<\varphi 1} \quad (12)$$

AG: J=A

BG: J=B

CG: J=C

$|Z_{1L}|_{<\varphi 0}$ – 80% zero sequence impedance of the line

The manufacturer setting assumed that the magnitude of the sequence impedances are identical and differ in phase angle only.

$\dot{I}_0$ – zero-sequence current at relay

$(\quad)_2$ - negative-sequence component of $(\quad)$

K_0 - Zone 1 zero-sequence compensation factor, defined as

$$K_0=0.95*\left|\frac{\dot{Z}_{0L}}{\dot{Z}_{1L}}\right| \quad (13)$$

$\dot{Z}_{1L}, \dot{Z}_{0L}$ - positive and zero sequence impedances of the line

The coincidence between all of the input signals, defined by Eq.(6-8) for each phase distance or Eq.(9-12) for each ground distance, is measured. The phasors defined by Eq.(6-13) were calculated using the DFT and implemented in routine TACS through device Type 69 option.

V. SHUNT FAULT CASE STUDIES

In order to evaluate the performance of the DLP2 relay, the responses of the phase and ground distance functions facing different shunt faults were simulated with ATP. The case studies were carried out taking into account: i) faulty phases ii) instants of time of fault application iii) fault locations iv) sequences of phase opening of the circuit breaker int1. Two different situations were considered: induction motors in service and out of service. From the set of cases, some examples are presented. In these examples, the time variation of angle A is shown after the Fault Detector has detected a fault.

A. Faults in Tacuarembó-Rivera line

A double lineA-to-lineB fault was applied at the M.Diaz bus bar, within the DLP2 Zone 1 reach. Fig.9 and Fig.10 show the time variation of angle A for each DLP2 Zone 1 distance function. From these figures it could be observed that angle A of the AB phase distance function is greater than 90º and the rest of the angles are less than 90º, showing that the operating principle is correct.

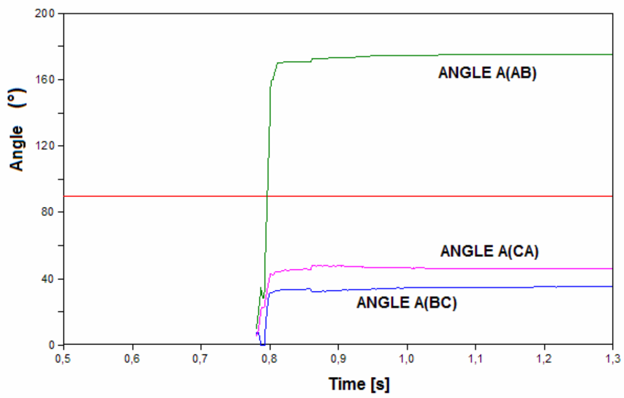

Fig. 9. Angle A for each DLP2 phase distance function

A single phaseA-to-ground fault was applied at the M.Diaz bus bar, within the DLP2 Zone 1 reach, and the same conclusion is valid. The same type of faults were applied at the Rivera bus bar, outside the DLP2 Zone 1 reach, resulting angle A for each DLP2 Zone 1 distance function less than 90º, showing a correct performance. For all the simulated cases there was not a misoperation of the relay.

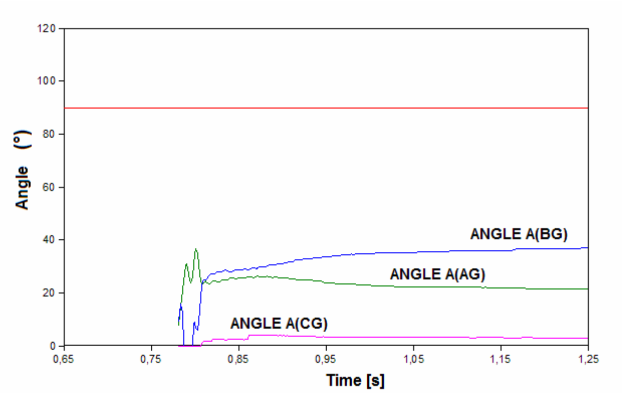

Fig. 10. Angle A for each DLP2 ground distance function

B. Faults in Terra-Tacuarembó line

The following sequence of events was simulated with ATP: a) a single phaseC-to-ground fault was applied at 45 km from Terra in the Terra-Tacuarembó line. b) opening of the circuit breaker int1 60 ms after. The sequence of phase opening was CBA. c) circuit breaker int2 remained closed.

1) Induction motors in service

Fig. 11 and Fig.12 show the time variation of the line to ground voltages and the phase currents at Tacuarembó bus bar, after the opening of circuit breaker int1.

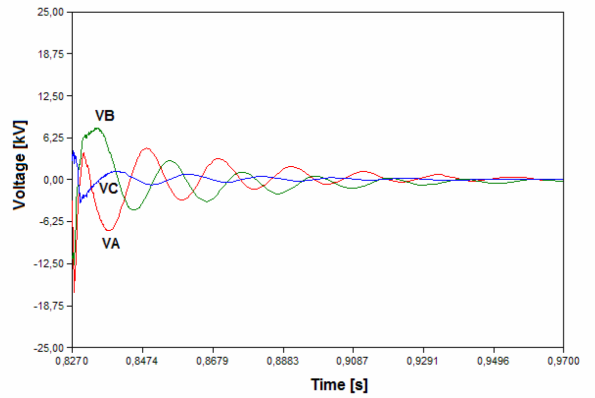

Fig. 11. Line to ground voltages at Tacuarembó bus bar

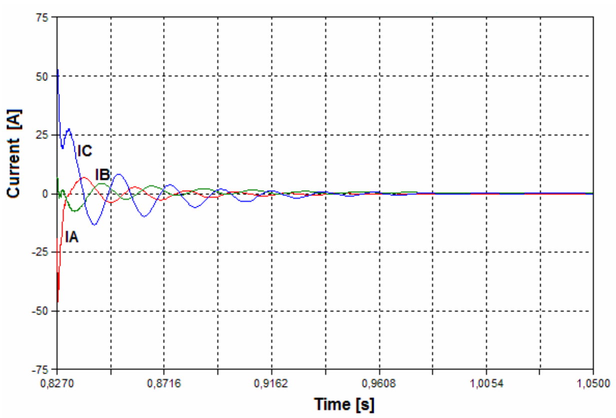

Fig. 12. Phase currents at Tacuarembó bus bar

As a result of the opening of circuit breaker int1, an isolated network is developed, on which induction motors became asynchronous generators. Thus the frequency is no longer 50 Hz and the current and voltage wave shapes are exponentially decaying sinusoidal functions. The A angles of the distance functions were calculated, in the time domain, taking into account two consecutive intervals of time: a) T1 time elapsed from the application of the fault to the opening of circuit breaker int1 b) T2 time elapsed from the opening of circuit breaker int1 until the memory action is over. Fig.13 and Fig.14 show the time variation of angle A for each DLP2 Zone 1 distance function.

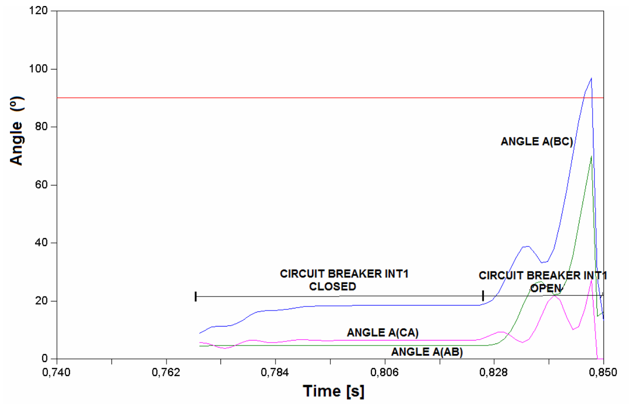

Fig. 13. Angle A for each DLP2 phase distance function

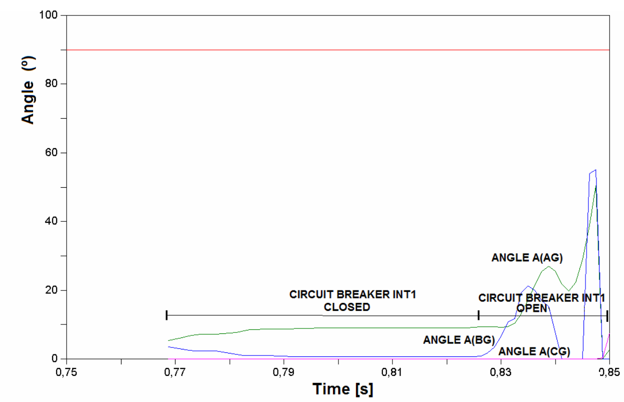

Fig. 14. Angle A for each DLP2 ground distance function

From these figures, it could be observed that: a) during T1 period angle A of the all distance functions is less than 90º, showing a correct performance in the backward direction. b) during T2 period angle A of the BC phase distance function is greater than 90º, indicating an incorrect performance of the algorithm. The DLP2 relay will give a trip signal to circuit breaker int2, causing an interruption of the supply.

2) Induction motors out of service

Fig.15 shows the time variation of the phase currents at Tacuarembó bus bar, after the opening of circuit breaker int1. Without induction motors, the current and voltage wave shapes are only exponentially decaying. Fig.16 shows the time variation of angle A for each DLP2 Zone 1 phase distance function. From this figure it could be observed that during T2 period angle A of the CA phase distance function is greater than 90º, indicating an incorrect performance of the algorithm.

Consequently, there will be an interruption of the supply.

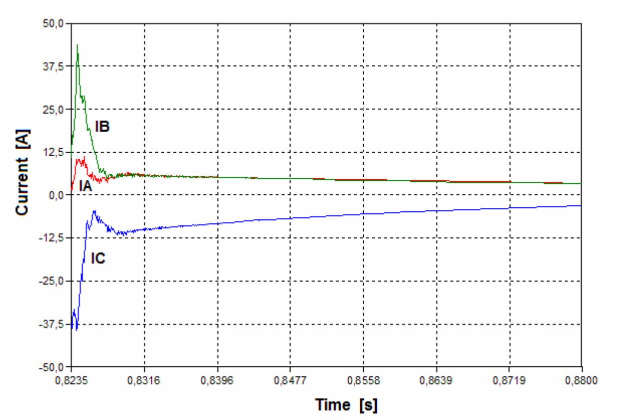

Fig. 15. Phase currents at Tacuarembó bus bar

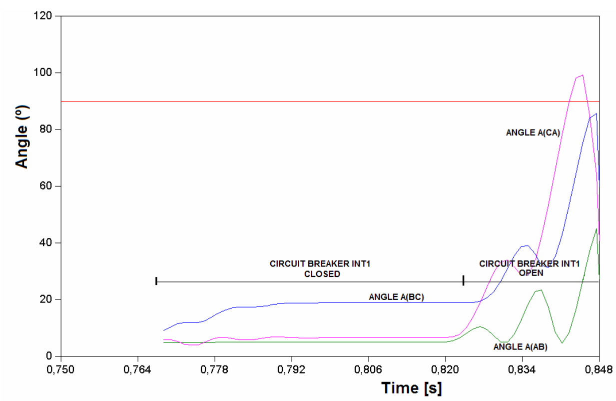

Fig. 16. Angle A for each DLP2 phase distance function

VI. Conclusions

For faults in the forward direction the performance of the DLP2 relay was correct.

In the time domain, for faults in the backward direction the behavior of all DLP2 ground distance functions of Zone 1 was correct.

During T1 period, all angles A of the DLP2 phase distance functions of Zone 1 were less than 90º, showing a correct behavior.

During T2 period, some angle A values of the phase distance functions resulted greater than 90º, therefore, relay DLP2 will give a trip signal to circuit breaker int2, which in turn will lead to an undesirable interruption of the supply.

As a result of the opening of circuit breaker int1, an isolated network is developed, on which induction motors became asynchronous generators. Thus, the frequency is no longer 50 Hz and the current and voltage wave shapes are exponentially decaying sinusoidal functions.

Without induction motors, the current and voltage wave shapes are only exponentially decaying.

The DLP relays sample current and voltage 16 times per cycle, and there is no way to change it when the frequency of the network varies.

The algorithms of the phase and ground distance functions use a recursive Discrete Fourier Transform to create phasor quantities from the sampled values of current and voltage assuming sinusoidal variations in the time domain.

These operational characteristics of relay DLP2 are not satisfied under islanding conditions, so some distance functions are expected to respond erroneously.

In order to solve the problem detected, the following ideas are under consideration: i) not to block the three-phase auto-reclosing of circuit breaker int2 ii) to block int2 opening after int1 has opened iii) to change the type of system protection.

The Type-69 TACS device is a new subroutine in which the user can define his own model in Fortran or C language. It allowed to successfully model the complex algorithms of the DLP relay shown here.

VII. References

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