Advanced Phase Selection for Severe Line Protection Requirements

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ABSTRACT

This paper describes a new phase selector that operates reliably during many unfavorable conditions, such as high fault resistance, high load flow, power swing, Current Transformer (CT) saturation, converter-based generation, weak infeed. The phase selector is based on the angular relationship between the sequence current components and sequence voltage components. The use of voltages and currents is dynamically selected. Some complimentary methods are added for phase selection during power swings. Matlab Simulink® simulations are performed to check the operation of the mentioned phase selector and to demonstrate its reliability. Oscillographic records from real faults are also analyzed.

Keywords: Phase-Selector, sequence-components, converter-based generation, weak infeed, power swings

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1. INTRODUCTION

Phase-selectors are core units in the line protection, as the identification of the type of fault is required for single pole tripping given by non-phase segregated units (such as neutral, negative sequence or positive-sequence differential or directional overcurrent), for the release of the corresponding fault loop in distance protection or in one-ended fault location, for signaling, etc.

Phase selectors must be reliable and fast but there are many factors that can make them fail in the fault type identification, such as fault resistance, load flow, system non-homogeneity, presence of power swings, Current Transformer (CT) saturation, weak infeed, dominant zero-sequence current contribution, converter-based generation, etc.

This paper describes the most common phase selection methods used. It focuses on the current sequence component phase selector, used in ZIV relays, explaining all the conditions that have been considered. It then explains the problems encountered by this phase selector and the improvements that were added, like complementing it with use of voltage sequence components. Results from Matlab Simulink® simulations and from oscilos coming from real faults are shown.

2. TYPES OF PHASE SELECTORS

There are several types of phase selectors, however, the most used ones are based on: impedance measurement, superimposed currents and sequence currents. This paper will describe the three mentioned methods and will focus on the sequence components one.

2.1 Impedance phase selectors

Phase selectors based on the impedance measurement have been implemented for many years by using impedance starters. These impedance starters are non-directional zones that surround all the tripping zones. The six units of the starter zone (AG, BG, CG, AB, BC, CA) are continuously measured. The faulted phase is selected based on the units that activate. For certain faults, the units related to the healthy phases can also operate. This makes impedance phase selection quite challenging. Some examples are included below [1].

- Phase distance elements can operate for a close-in reverse phase-to-phase-to-ground fault (AB unit can operate with BCG fault)
- Phase distance elements may operate for a phase-to-phase-to-ground fault with heavy loading (CA unit can operate with BCG fault)
- Phase distance elements can operate for a close-in phase-to-ground fault (CA unit can operate with AG fault)
- Ground distance elements can operate for a close-in reverse phase-to-ground fault (CG unit can operate with AG fault)
- Phase distance elements can operate for a close-in reverse phase-to-phase fault (BC unit can operate with CA fault)

During a phase-phase-ground fault the phase-phase unit will operate but it will also operate the leading phase ground unit [2].

The impedance phase selectors must use appropriate resistive and reactive reach settings, directionality, etc to avoid wrong operation.

2.2 Superimposed phase selectors

Reference [3] describes a phase selector based on the comparison between the incremental phase-phase currents.

When there is an AG fault ΔIab and ΔIca will be approximately equal and higher than ΔIbc.

When there is a BC(G) fault ΔIbc will be higher than ΔIab and ΔIca.

When the fault is ABC ΔIab, ΔIbc, ΔIca will be approximately equal.

This phase selector has the advantages of being very fast and not requiring any settings. However, the relationship between the incremental phase-phase currents is obtained from the relationship between the sequence currents [3]. Therefore, if the last relationship fails, this type of phase selector will also fail. As it will be seen in the next point, the sequence component current phase selector has limitations during certain conditions, such as weak-infeed, converter-based generation, and CT saturation. The same limitations will apply to the current superimposed based selector.

2.3 Sequence components phase selectors

ZIV relays have been using a current sequence component phase selector for many years. This phase selector normally uses the angle between the negative-sequence current and the pure fault positive-sequence current (pre-fault current subtracted). In certain conditions the angle between the negative-sequence and zero-sequence currents is used. The implemented angular sectors are shown in Figure 1, Figure 2 and Figure 3 [4] :

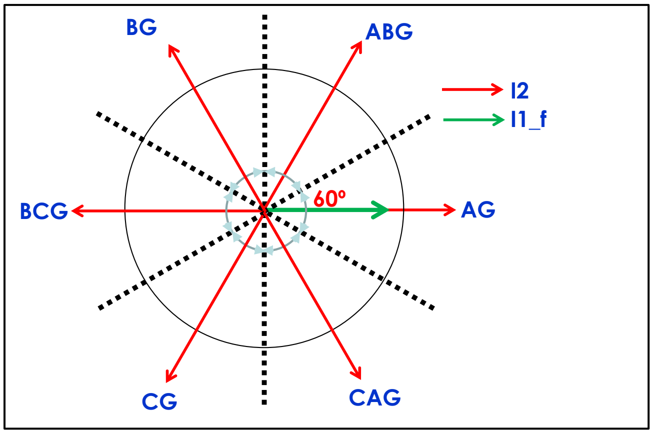

Figure 1. Sectors for the angle between negative-sequence and pure fault positive-sequence currents for ground faults

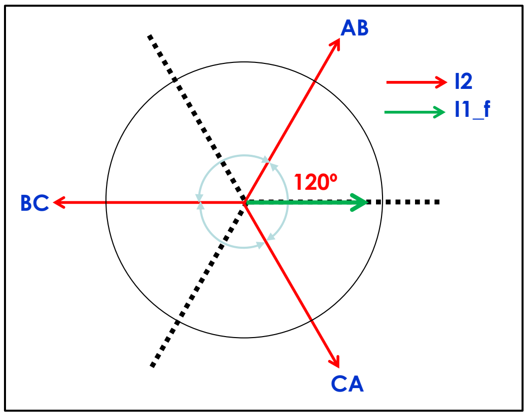

Figure 2. Sectors for the angle between negative-sequence and pure fault positive-sequence currents for phase-phase faults

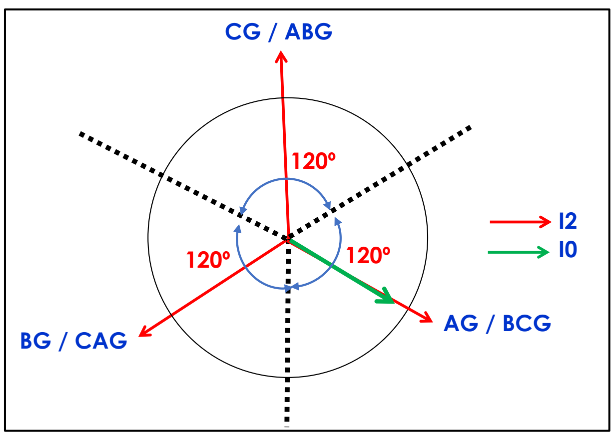

Figure 3. Sectors for the angle between negative-sequence and zero-sequence currents for ground faults.

The deduction of the phase relation between the sequence currents is obtained from the sequence networks for the different fault types shown in Figure 4,Figure 5 and Figure 6 . It also considers that, in systems including synchronous generators, the pure fault positive-sequence source impedance is similar to the line impedance. This makes the pure fault positive-sequence current seen by the relay (I1fp=I1-I1p, where I1p is the pre-fault current) almost in phase with the total positive-sequence fault current (IF1). The same happens with the negative-sequence and zero-sequence currents seen by the relay with regard to the corresponding sequence currents in the fault point. Therefore, it is concluded that the angular relationships between the sequence currents at the fault point are similar to the ones of the sequence currents at the relay point.

Single-phase to ground faults:

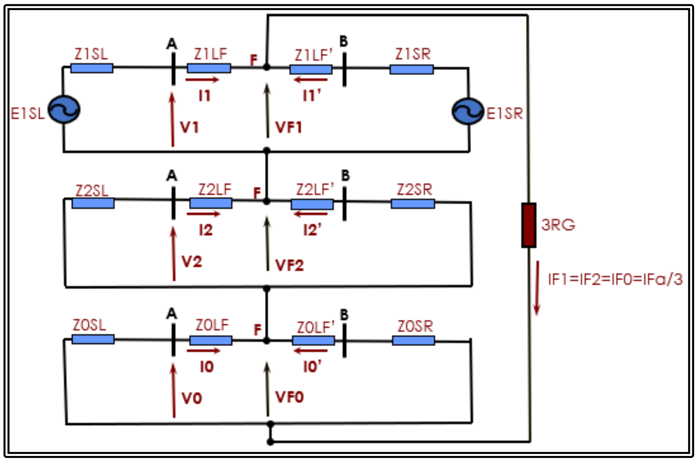

Figure 4. Sequence networks connection for an AG fault.

As IF1=IF2=IF0, the following angular relationships are obtained:

AG fault: IF1A=IF2A=IF0A

BG fault: IF1B=IF2B=IF0B, therefore the angle between IF2A and IF1A will be 120º and the angle between IF2A and IF0A will be -120º

CG fault: IF1C=IF2C=IF0C, therefore the angle between IF2A and IF1A will be -120º and the angle between IF2A and IF0A will be 120º

Phase-phase-ground faults

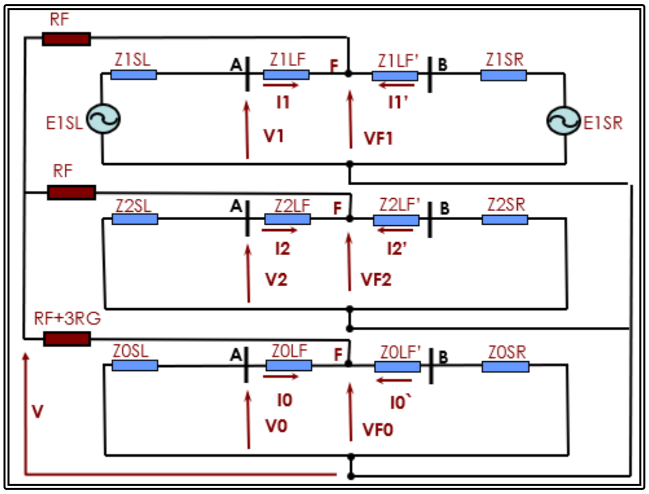

Figure 5. Sequence networks connection for a BCG fault.

$$\frac{IF2}{IF1} = -\frac{\mathrm{RF} + 3\mathrm{RG} + \mathrm{Z0par}}{2\mathrm{RF} + 3\mathrm{RG} + \mathrm{Z0par} + \mathrm{Z2par}}$$

Where Z0par and Z2par are the parallel equivalent of the corresponding sequence impedances

$$\frac{IF2}{IF0} = \frac{\mathrm{Z0par+RF+3RG}}{\mathrm{Z2par+RF}} \quad (1)$$

IF2 and IF1 will be approximately -180º for a BCG fault. In case of phase-phase-ground faults the angle between them will not be practically influenced by RF (phase resistance) and RG (ground resistance). However, the angle between IF2 and IF0 will be very influenced by both fault resistances. Assuming that the angle between Z0par and Z2par is the same, if RG=100 and RF=0, the angle will reach -89º, that is why the angle sectors are rotated 30º clock-wise as shown in Figure 3.

The following angular relationships are obtained:

BCG fault: neglecting the fault resistance the angle between IF2A and IF1A will be 180º and the angle between IF2A and IF0A will be 0º

CAG fault: neglecting the fault resistance the angle between IF2B and IF1B will be 180º and the angle between IF2B and IF0B will be 0º, therefore the angle between IF2A and IF1A will be -60º and the angle between IF2A and IF0A will be -120º

ABG fault: neglecting the fault resistance the angle between IF2C and IF1C will be 180º and the angle between IF2C and IF0C will be 0º, therefore the angle between IF2A and IF1A will be 60º and the angle between IF2A and IF0A will be 120º

For a phase-phase fault

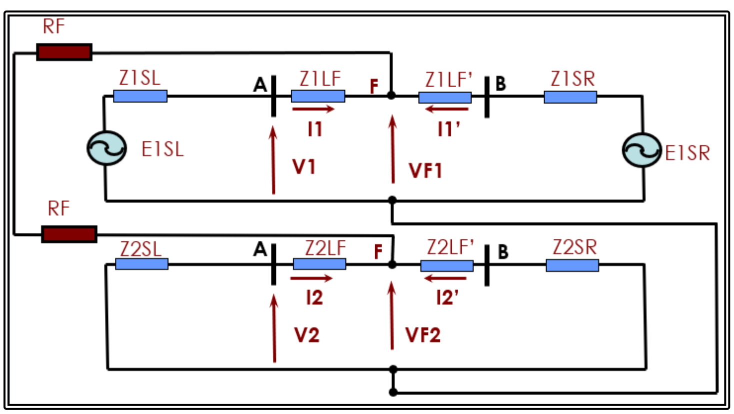

Figure 6. Sequence networks connection for an BC fault.

IF1=-IF2, therefore the angle between IF2A and IF1A will be 180º for a BC fault, 60º for an AB fault and -60º for a CA fault.

2.3.1 Use of the angle between negative and zero sequence currents.

In certain conditions the phase selector uses the angle between I2 and I0 as the pre-fault current is not reliable:

2.3.1.1 Remote Breaker Open Condition

When the remote breaker opens there is no load, so the pre-fault current is no longer valid. The opening of the remote breaker is detected because in the healthy phases there is a current decrease or a capacitive current flow.

For ground faults, the distinction between phase-phase-ground faults and single-phase-ground faults is based on the detection of the healthy phases with the method mentioned before.

When phase-phase faults occur, all the distance units are released (AB, BC, CA units).The type of fault is detected based on the distance units that operate.

2.3.1.2 Close Onto Fault Condition

As there is no pre-fault current, the calculation of the positive-sequence pure fault current cannot be done.

If the fault does not involve ground (no zero-sequence current) all the distance units (AB, BC, CA) are released. The type of fault is detected based on the distance units that operate.

The distinction between phase-phase-ground faults and single-phase-ground faults is based on the distance characteristics that pick-up (AG vs BCG; BG vs CAG; CG vs ABG).

2.3.1.3 Power Swing Condition

As the angle between the sources is changing, the load current is also changing, therefore the stored pre-fault current is not valid anymore.

Phase to phase faults

If the fault does not involve ground, the type of fault will be detected based on the units (AB, BC, CA) that have the lower change of impedance. During bolted faults, after the transient period (the filter window lenght used), the faulted unit impedance practically stops moving. During resistive faults the faulted unit impedance continues moving, but with a lower rate of change than the impedance of the healthy units. This detection can be done with two methods:

Method 1:

ZIV line relays detect a power swing with two zones, called external and medium zones [4]. A power swing is detected if the measured impedance remains in the band defined by the two zones a time longer than the power swing detection time. Normally the resistive limit of the medium zone is set equal to the resistive limit of the most external tripping zone, that is normally zone 3. The resistive limit of the external zone is set 30% larger than the resistive limit of the medium zone.

Two additional zones can be used to define three bands inside the medium zone. Zones 7 and 8 (ZLF includes 8 zones [4]) can be set to 33% and 66% of the medium zone resistive reach, respectively.

As the zones 3, 7 and 8 AB, BC and CA units activation is continuously calculated, band 1, 2 and 3 AB, BC and CA units activation can also be calculated:

- Band 1=(zone 7)
- Band 2=NOT(zone 7)*zone 8
- Band 3=NOT(zone 7)*NOT(zone 8)*zone 3

Figure 7 shows zones 7, 8 and 3 and medium and external zones.

The type of fault can be obtained based on the band units that pick-up for a time longer than twice the power swing detection time (as the impedance can cross the band from right to left when it enters and then from left to right when it exits, it can remain in each band twice the power swing detection time). Because during resistive faults the fault impedance remains moving, not only the permanence of the impedance in the three bands is considered, but also its permanence in the 3 zones: zone 7, 8 and 3. The time set for each zone to detect a fault is:

Z7: twice the power swing detection time
Z8: four times the power swing detection time
Z3: six times the power swing detection time

The times mentioned before are set considering that if the impedance reaches the negative resistive axis in the R-X diagram, it will exit the medium zone through the left resistive limit, as the power swing will be unstable.

The phase selection will be faster if a dynamic power swing detection time is used, that is if the time that the impedance remained between the external and medium zones for each power swing cycle is used. This avoids always considering the maximum power swing detection time which corresponds to the slower power swing.

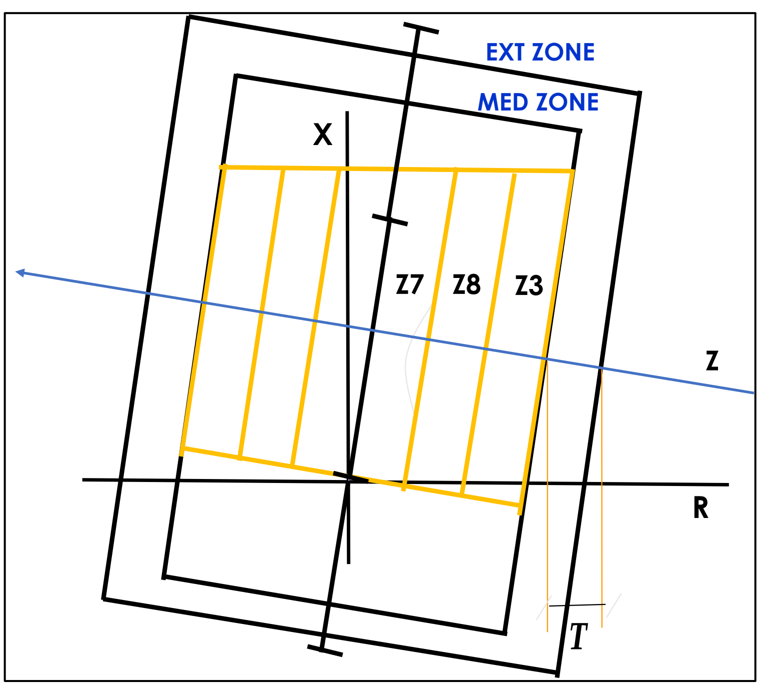

Figure 7. Power swing detection zones (external and medium) and additional zones to define bands 1, 2 and 3 for phase selection.

Method 2:

The change of the resistive component of the three impedance units (AB, BC and CA) is compared during a certain period. This is done one-cycle after the presence of negative-sequence current is detected. This time is introduced to allow the fault impedance to stabilize. The resistance is used because it is the impedance component that moves the most during a power swing (the trajectory of the impedance is perpendicular to the transfer impedance) and the real parts of the impedances are calculated in ZIV distance relays for the load encroachment function. In [5] the resistive component is used to detect power swing.

Phase-phase-ground faults

The distinction between phase-phase-ground faults and single-phase-grounds faults can be done based on the ratio I0/I2. This ratio is closed to 1 for a single-phase to ground fault and lower than 0.8 for phase-phase-ground faults (in formula (1) the higher value is obtained considering RG=0 and RP a high value; in this case a value of 0.78 is obtained; but normally RG is much higher than RP. This results in very low values of I0/I2)

The distinction can also be done with methods 1 and 2 but comparing AG and BCG impedances or BG and CAG or CG and ABG ones.

Figure 8 and Figure 9 show the impedance of the AG and BCG units, respectively, during an AG fault that occurs during a power swing. The AG impedance practically stops moving after the transient condition but the BC impedance continuous moving. The movement was calculated during 3.5 cycles. In this case Re(ZAG) accumulated a total movement of 1.93 ohms while Re(ZBC) accumulated a total movement of 22.31 ohms.

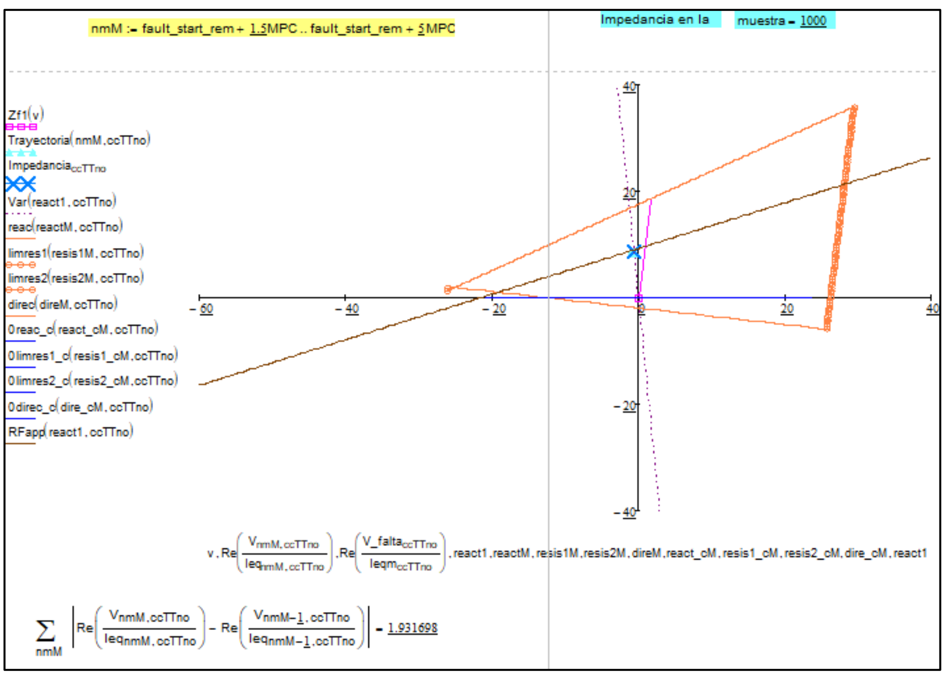

Figure 8. AG impedance and accumulated AG resistive change during 3.5 cycles for an AG fault occurring during a power swing

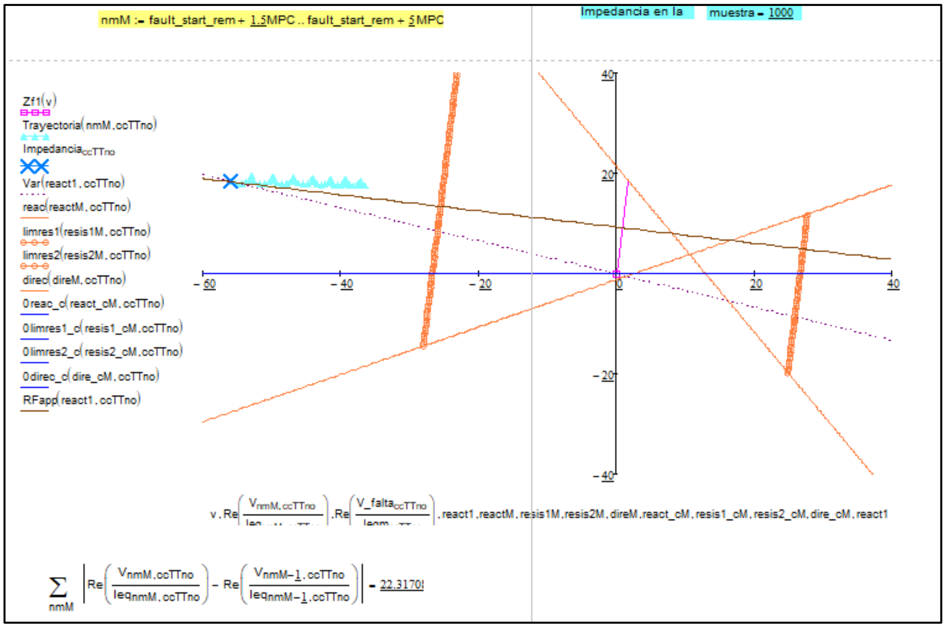

Figure 9. BCG impedance and accumulated BCG resistive change during 3.5 cycles for an AG fault occurring during a power swing

2.3.1.4 One Pole Open Condition

Both I0 and I2 currents are affected by the unbalance generated during the open pole condition in the same way so there is no need to remove the pre-fault I0 and I2 currents.

For ground faults, the distinction between phase-phase-ground faults and single-phase-ground faults is based on the open phase detection (the fault cannot involve the open phase).

If the fault does not involve ground (no change in the zero-sequence current) the fault is considered phase-phase and the closed phases are selected.

Faults occurring during power swing with the open pole condition are detected based on zero-sequence current or negative-sequence current change. The phase selection works the same way as if there was no power swing: if the fault involves ground the difference between phase-phase-ground faults and single-phase-ground faults is based on the open phase detection. If the fault does not involve ground the phase-phase fault related to the closed phases is activated.

2.3.2 Limitations of the sequence current based selector.

The sequence current phase selector described before has limitations during certain conditions:

2.3.2.1 Week Infeed

During weak infeed conditions, the phase selector cannot use sequence currents, at least positive and negative-sequence currents (the existence of delta-wye transformers can supply important zero-sequence current), as the currents can be very small.

The solution that was implemented in ZIV relays was based on undervoltage units. The limitation of this method is the definition of the undervoltage pick-up value.

2.3.2.2 CT Saturation

CT saturation generates phase and magnitude errors in the measured current [6].This affects the phase selector based on currents.

2.3.2.3 Converter Based Generation

2.3.2.3.1 Type 4 Wind Generator photovoltaic

The superposition principle, usually used to decomposed current in fault and pre-fault components, can still be applied for inverter bases resources if we replace a current source by a voltage source with a series impedance. Nevertheless, I1 limitation by the control system generates positive sequence pure fault impedance angles higher than 90º, increasing the non-homogeneity of the pure fault positive sequence circuit. This makes the angle between pure fault positive-sequence and negative-sequence currents differ from the expected [7].

Furthermore, Type 4 wind generators, depending on the applicable Grid Code might not be required to inject negative sequence current.

2.3.2.3.2 Type 3 Wind Generator

In the case of a Type 3 or Double Feed Induction Generator (DFIG), during unbalanced conditions, when the crowbar activates, the DFIG operates as an induction machine but with a higher rotor resistance due to the crowbar one. The positive and negative-sequence networks are shown in the below Figure 10 and Figure 11 ,where Rr is the sum of the rotor and crowbar resistances.

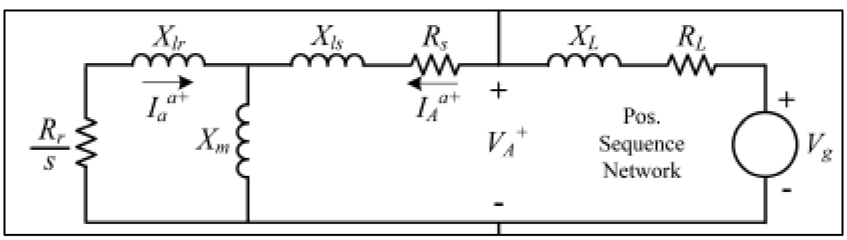

Figure 10. Positive-sequence network of an induction machine [8].

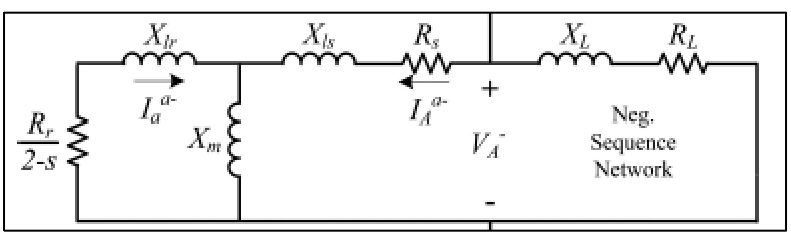

Figure 11. Negative-sequence network of an induction machine [8].

This makes positive-sequence and negative-sequence impedances very different. They depend on the slip. The pure fault positive-sequence impedance and negative-sequence ones are also very different. Angles obtained in simulation are the following:

Table 1 Type 3 Pure Fault Positive and Negative Sequence Source Impedance Angles

ZS1fp	ZS2
165º	68º
169º	69º
130º	66º

When the crowbar does not operate, the angles of the pure fault positive and negative-sequence impedances depend on the control. In this case similar results as with the type 4 generator are obtained.

There are also type 3 control strategies that suppress I2 during asymmetrical faults, aiming to balance stator current, in order to ensure balanced heating on the three-phase stator winding, as mentioned in [9].

The angle between I2 e I0 could also be higher than the limit because, due to the slip, ZS2 can have an angle much lower than Z0S. But Z0S is normally closed to 90º, as it is the zero-sequence impedance of the transformer that connects the wind park.

The ratio I0/I2 to distinguish AG and BCG faults during power swings is no longer valid because the I2 and I0 distribution with converter-based generation is completely changed. Therefore I0/I2>threshold for single-phase-ground faults and I0/I2<threshold for phase-phase-ground faults is not fulfilled.

2.4 Voltage Based Phase Selection Algorithm

Reference [7] described a phase selection algorithm based on the angular relationship of the voltage sequence components. The following angles were considered:

$$\varphi_{V21} = \varphi_{V2} - \varphi_{V1}$$

$$\varphi_{V20} = \varphi_{V2} - \varphi_{V0}$$

where:

φ_{V21}: Angle difference between negative and positive sequence voltage components.
φ_{V20}: Angle difference between negative and zero sequence voltage components.

The formulas used to obtain the angular relationships are the following:

Single-phase-ground fault

$$\frac{\mathrm{VF2}}{\mathrm{VF0}} = \frac{\mathrm{Z2par}}{\mathrm{Z0par}}$$

$$\frac{\mathrm{VF2}}{\mathrm{VF1}} = -\frac{\mathrm{Z2par}}{3RG + \mathrm{Z2par} + \mathrm{Z0par}}$$

Phase-phase-ground fault

$$\frac{VF2}{VF1} = \frac{(\mathrm{RF} + 3\mathrm{RG} + \mathrm{Z0par}) * \mathrm{Z2par}}{(2\mathrm{RF} + 3\mathrm{RG} + \mathrm{Z0par} + \mathrm{Z2par})(\mathrm{RF} + \frac{(\mathrm{RF} + \mathrm{Z2par}) * (\mathrm{RF} + 3\mathrm{RG} + \mathrm{Z0par})}{(\mathrm{RF} + \mathrm{Z2par}) + (\mathrm{RF} + 3\mathrm{RG} + \mathrm{Z0par})})}$$

$$\frac{VF2}{VF0} = \frac{\mathrm{Z0par} + \mathrm{RF} + 3\mathrm{RG}}{\mathrm{Z2par} + \mathrm{RF}} * \frac{\mathrm{Z2par}}{\mathrm{Z20par}}$$

Phase-phase fault

VF1=VF2+IF1*2*RF

Regarding the angle φ_{V21}, both the ground and phase resistances (RG and RF) introduce a counterclockwise shift, always lower than 90º (i.e. if RG is changed from 0 to 100 ohms, the angle φ_{V21} changes for an AG fault from 180º to 267º; if RF is changed from 0 to 100 ohms, the angle φ_{V21} changes for a BCG fault from 0º to 88º). That is why the angular sectors are rotated 30º counterclockwise.

Concerning the angle φ_{V20}, it is only RG which introduces a clockwise rotation, also lower than 90º (i.e. if RG changes from 0 to100 ohms the angle φ_{V21} changes for a BCG fault from 0º to -88º). That is why the angular sectors are rotated 30º clockwise.

The angular sectors used are shown in Figure 12 and Figure 13.

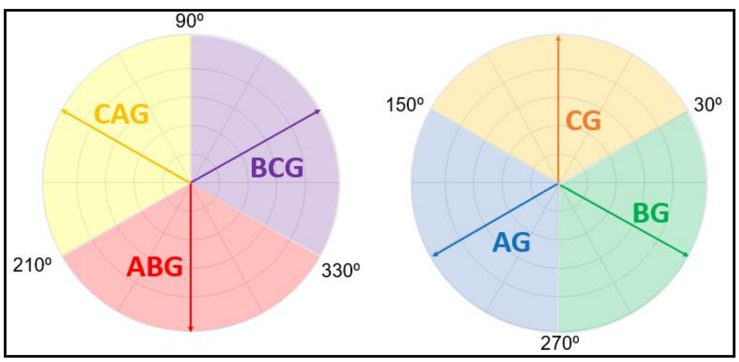

Figure 12 φV21 Angular zones for faulted phase selector.

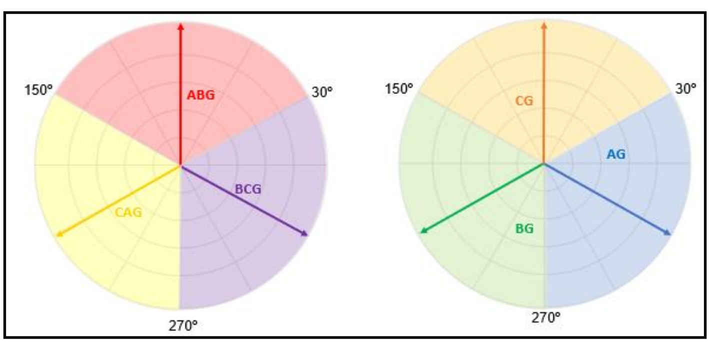

Figure 13 φV20 Angular relationships for faulted phase selection.

Once φ_{V21} and φ_{V20} are calculated. The following logic is applied to determine fault type:

AG: 150º≤ φ_{V21}<270º & 270º≤φ_{V20} <30º

BG: 270º ≤ φ_{V21}<30º & 150º≤φ_{V20} <270º

CG: 30º ≤ φ_{V21}<150º & 30º≤φ_{V20} <150º

ABG: 210º≤ φ_{V21}<330º & 30º≤φ_{V20} <150º

BCG: 330º≤ φ_{V21}<90º & 270º≤φ_{V20} <30º

CAG: 90º≤ φ_{V21}<210º & 150º≤φ_{V20} <270º

To improve the reliability on the proposed faulted phase selector, if none of the angular relationship combinations are met, the activation of distance AG, BG, CG or ABG, CAG or BCG units in conjunction with φ_{V20} are used to determine the faulted phase, differentiating single- or two-phase faults. Zero sequence voltage component is used to discriminate ground faults.

Reference [7] described the improvements in the operation of distance units in the presence of converter-based generation. This allows the correct activation of the distance units for distinguishing phase-phase-ground faults from single-phase-ground ones.

With converter-based generation or weak infeed, due to the limited positive-sequence current, the positive-sequence voltage measured by the relay will be practically in phase with the positive-sequence voltage at the fault point. Note that with converter-based generation the use of pure fault positive-sequence voltage will not be reliable. This is demonstrated in the following point.

2.4.1 Use of pure fault positive-sequence voltage

The pure fault sequence networks for AG, BCG and BC faults are shown in Figure 14, Figure 15 and Figure 16.

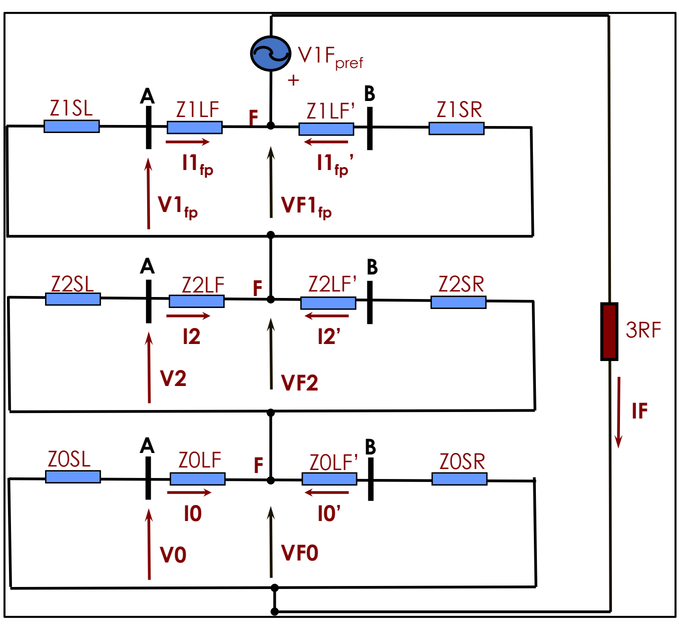

Figure 14. Pure fault Sequence networks connection for an AG fault.

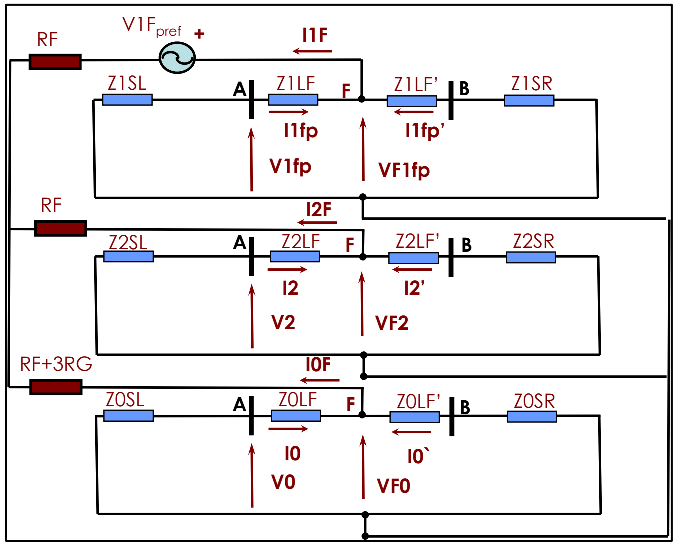

Figure 15. Pure fault Sequence networks connection for an BCG fault.

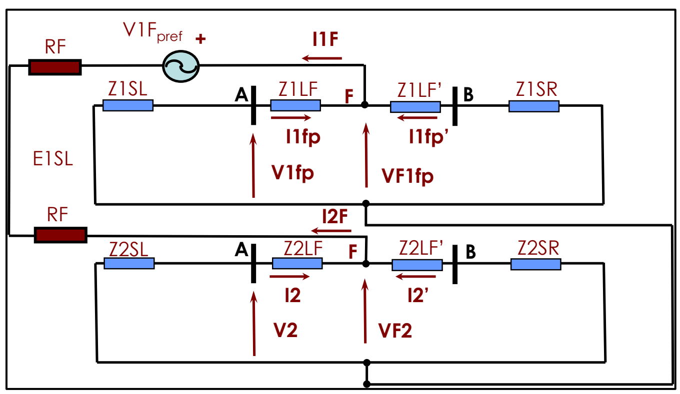

Figure 16. Pure fault Sequence networks connection for an BC fault.

In all these circuits the following equations are fulfilled:

VF1fp=IF1*Z1fp_par (2)
VF2=IF2*Z2par (3)

Where Z1fp_par is the equivalent parallel impedance of the positive-sequence pure fault network.

Therefore:

$$\frac{VF2}{VF1fp} = \frac{\mathrm{IF2}}{IF1} * \frac{Z2par}{Z1fp\_par} \quad (4)$$

Based on equation (4), if Z1fp_par has the same angle of Z2par, the angular relationship between VF2 and VF1fp is the same as the one between IF2 and IF1, so 0º for an AG fault, 180º for a BCG fault and 180º for a BC fault. Therefore, the angular sectors shown in Figure 1 and Figure 2 would also apply for the voltages.

When converter-based generation is included, Z1fp_par and Z2par do not have the same angle, so this method is not reliable.

2.4.2 Use of current and voltage sequence components

The phase selector based on sequence currents operates correctly when conventional generation is used but it fails with converter-based generation, weak infeed and CT saturation. When any of these conditions are detected the phase selector uses the sequence voltages:

- **Converter-based generation**: this condition is detected by measuring the angles and magnitudes of the pure fault positive-sequence and negative-sequence source impedances. The mentioned impedances are measured with the following formulas:

$$\mathrm{Z1SL} = \frac{-(V1 - V1prefault)}{(I1 - I1prefault)}$$

$$\mathrm{Z2SL} = \frac{-V2}{I2}$$

If these angles and modules are different from the ones that correspond to conventional generation (if the angles are too high or too low and their difference is above a threshold or if their magnitude ratio is above a threshold) the phase selector based on sequence voltages is enabled. In this case, it uses the positive-sequence voltage without removing the pre-fault voltage.

As during reverse faults the angles of Z1SL and Z2SL will be shifted by more than 90º, a directional supervision is used to validate the conditions of the mentioned angles being too high or too low. The directional supervision is based on a positive-sequence directional unit, which behaves correctly for type 4 wind generator [7]. A negative-sequence directional unit is used when crowbar activation in type 3 generator is detected. This detection is done with the I2/I1 ratio (as it was mentioned in point 2.3.2.3.2, if the crowbar operates, the type 3 generator behaves as an induction machine and the negative-sequence impedance is much lower than the positive-sequence one; this leads to negative-sequence currents higher than the positive-sequence ones).

Note that, even if the directional units fail, there are other conditions to detect that the generation is a converter-based one, such as the angle and magnitude difference between Z1SL and Z2SL

- Weak infeed: this condition is detected if the positive or negative-sequence currents are below a threshold. In this condition the phase selector based on voltages is enabled. It uses the positive-sequence voltage without removing the pre-fault voltage. Note that during zero-sequence infeed the voltage phase selector will work properly.

- CT saturation: it is detected by means of a CT saturation detector [6]. Due to the limited short-circuit current of converter-based generation, CT saturation normally happens with conventional generation. In this case the phase selector can use the pure fault positive-sequence voltage removing the pre-fault voltage

Even if the local source impedances correspond to conventional synchronous generation, if the remote source is a converter-based one, due to the non-homogeneity of the pure fault positive-sequence network, the phase selector based on the angle between pure fault positive-sequence and negative-sequence currents can fail to detect phase-phase-ground faults. Therefore, for ground faults, the phase selector based on the angle between negative and zero-sequence currents is used. Type 3 generators can create non-homogeneity in the negative-sequence network, mainly when the crowbar is activated. In this case, as seen in Figure 10 and Figure 11., the negative-sequence source impedance of the DFIG can have a low angle due to the high crowbar resistance. Nevertheless, as the angular sectors used by this phase selector have 120º (the angular sectors in the phase selector based on the angle between the negative and positive-sequence currents have 60º), the trend to maloperate is much lower. No wrong operation was detected on the grid side during the simulations performed.

Note that if the converter-based generation does not supply negative-sequence current, the negative-sequence current provided by the conventional generation will be equal to the negative-sequence current in the fault point, so the phase selector will work correctly.

The distinction between phase-phase-ground and single-phase-ground faults can be done with the angle between the pure fault positive-sequence and negative-sequence currents as the margin to distinguish both types of faults is 180º (see Figure 1) and the error generated does not make this differentiation fail. The operation of the distance units mentioned in point 2.3.1 can also be used.

For phase-phase faults, as the angular sectors have also 120º, the trend to maloperate due to the non-homogeneity of the pure fault positive-sequence network is also much lower. No wrong operation was detected on the grid side during the simulations performed.

During power swings, the pure fault positive-sequence source impedance cannot be calculated as the pre-fault current is not reliable. However, as it was mentioned in point 2.3.1.3 the phase selector cannot be based on the angle between I2 and I1fp. It can neither be based on the angle between V1 and V2, because of the phase shift that V1 experiences during the power swing. Therefore, it will just be based on the angle between I2 and I0 or the angle between V2 and V0. The selection of currents or voltages is based on the ratio I2/I1 (to detect type 3 generator with crowbar activation), on the magnitude of I2 (to detect the injection of I2 current) and on the angle of Z2S (to detect abnormal angles).

If the angle between V2 and V0 is used, the distinction between single-phase-ground or phase-phase-ground is done with the methods 1 or 2 mentioned in point 2.3.1.3

If the voltage based phase selector was selected and a remote breaker open or pole open is detected, it will use the angle between V2 and V0. The differentiation between single-phase-ground and phase-phase-ground faults will use the same methods mentioned in points 2.3.1.1 and 2.3.1.4

During close onto fault, the positive-sequence pure fault source impedance cannot be calculated either, as there is no prefault current. In this case, the use of the angle between I2 and I0 or the angle between V2 and V0 uses the same method as for power swings.

3. Tests with simulations

The described phase selector was tested using Matlab Simulink® simulation of a Type 3 and 4 wind generators. Faults on a 120kV were simulated using different fault locations, generated power, and fault resistance. In Table 2 the results for Type 4 generation with faults at 50% of the line, with different fault resistance and fault type, are shown.

Angles that make the phase selector work properly are highlighted in green. The ones causing a malfunction are shown in red. In yellow are the ones that fall into the right angular zone but does not stabilize.

Note that the Type 4 model is adapted to comply with Low Voltage Ride Through (LVRT) requirements. That is why the phase selector based on the angle between negative and zero-sequence currents operates correctly. This will not happen in the presence of legacy WTs not complying with the most actual grid codes

The difference between the impedances Z1Sfp and Z2S can be noticed. This difference will enable the voltage sequence component phase selector, as a converter-based generation is detected.

Table 2 Results for Type 4 Generation

RF/RG (Ω)	Type of fault	Ang(Z1Sfp)	Ang(Z2S)	Ang(I2)-ang(I1)	Ang(I2)-ang(I0)	Ang(V2)-ang(V1)	Ang(V2)-ang(V0)
0	AG	121º	93º	28º	-9º	180º	-3º
0	AB	122º	84º	92º	N/A	240º	N/A
0	ABG	102º	80º	83º	127º	240º	120º
10	AG	131º	86º	37º	-3º	189º	2º
10	AB	129º	85º	97º	N/A	247º	N/A
10	ABG	126º	87º	72º	87º	240º	87º
50	BG	160º	86º	170º	228º	-20º	238º
50	CG	158º	86º	289º	108º	98º	118º
50	BCG	142º	88º	190º	290º	0º	290º
50	CAG	141º	88º	300º	170º	120º	168º

In Table 3 the results for Type 3 generation for a fault at 50% of the line are shown. Table 4 shows the results when crowbar activates in type 3 generator.

Table 3 Results for Type 3 Generation

RF/RG (Ω)	Type of fault	ang(Z1Sfp)	Ang(Z2S)	Ang(I2)-ang(I1)	Ang(I2)-ang(I0)	Ang(V2)-ang(V1)	Ang(V2)-ang(V0)
0	AG	158º	88º	59º	-4º	180º	-4º
0	AB	166º	83º	133º	N/A	240º	N/A
0	ABG	132º	83º	102º	119º	240º	115º
50	AG	165º	92º	64º	-8º	218º	-3º
50	BG	162º	91º	183º	234º	-23º	237º
50	CG	162º	91º	183º	234º	-23º	237º
50	ABG	164º	86º	98º	49º	240º	49º
50	BCG	164º	86º	220º	-40º	0º	288º
50	CAG	164º	86º	338º	170º	120º	168º

Table 4 Results for Type 3 Generation with crowbar activation

RF/RG (Ω)	Type of fault	Ang(Z1Sfp)	Ang(Z2S)	Ang(I2)-ang(I1)	Ang(I2)-ang(I0)	Ang(V2)-ang(V1)	Ang(V2)-ang(V0)
0	AG	165º	68º	116º	12º	178º	-8º
0	AB	169º	69º	170º	N/A	240º	N/A
0	ABG	130º	66º	167º	142º	240º	120º

4. Test with Oscillographic records from real faults.

The previously described theory was put to test with two oscillographic records from real scenarios where fault currents were feed by converter-based generation.

4.1 Case A

For a CA fault on a 132kV line, the contribution of a wind park with a mix of Type 3 and Type 4 wind turbines is shown:

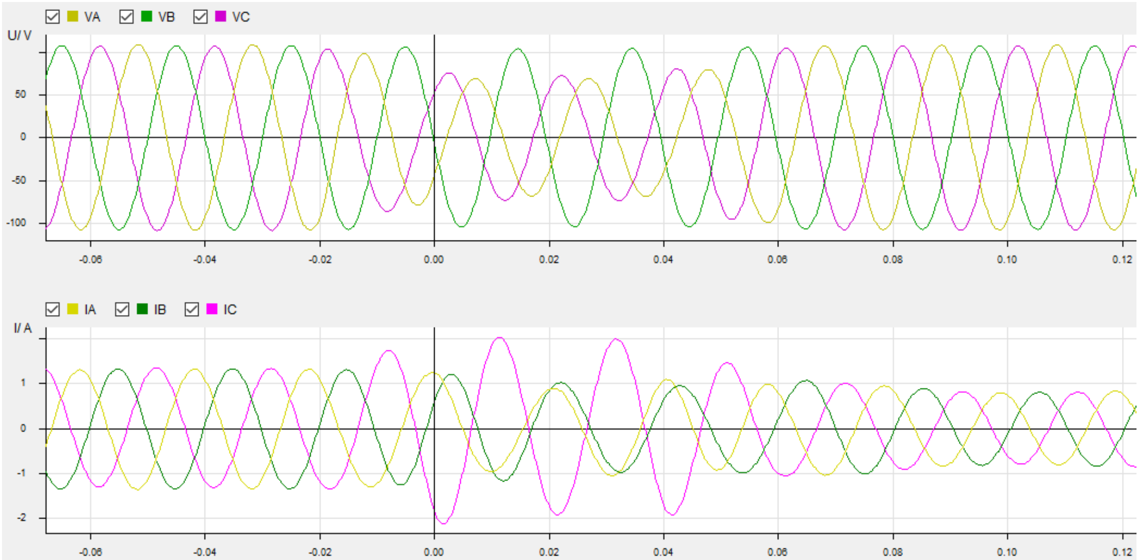

Figure 17 Case A Voltage and current fault patterns.

In which an CA fault can be recognized by the under-voltages in A and C phases, but for which the current pattern does not correspond to an CA fault.

From sequence components point of view, current component angular comparison does not lie on a stable area, indicating AB fault during some time, while as seen in Figure 18, voltage comparison lies on the CA area and asserts CA fault as shown in Figure 19.

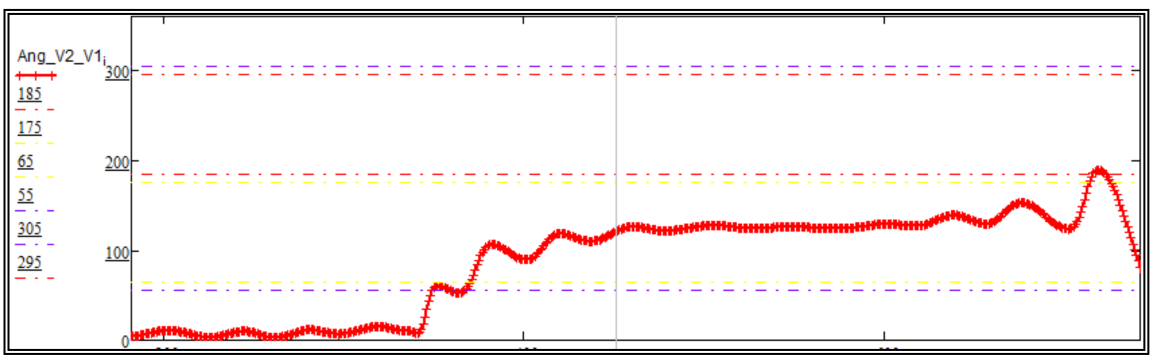

Figure 18 V2/V1 angular relationship for case analysis.

The angle of the pure fault positive-sequence source impedance is around 150º.

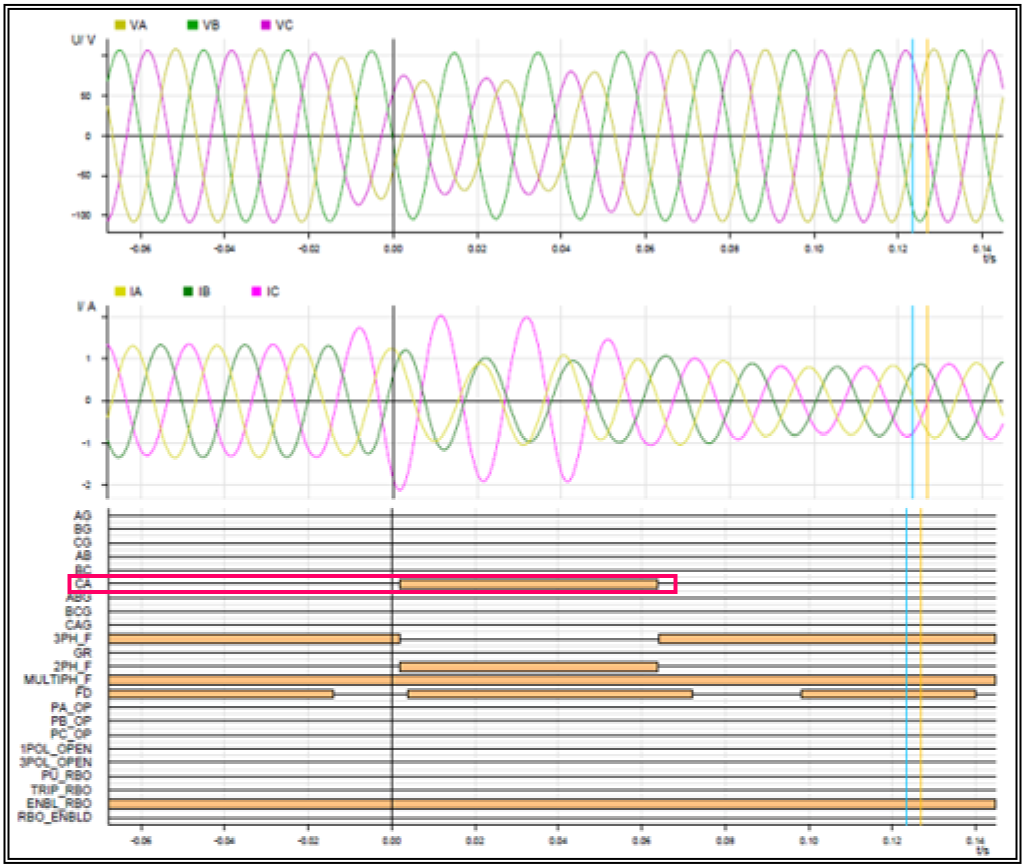

Figure 19 CA fault recognition.

4.2 Case B

A second case from a 66kV Line is tested for the faulted phase selector. For the fault shown in Figure 20. The voltage pattern corresponds to a BG fault; however, the current pattern does not correspond to this type of fault. CG and ABG faults are detected by the current-sequence component phase selectors.

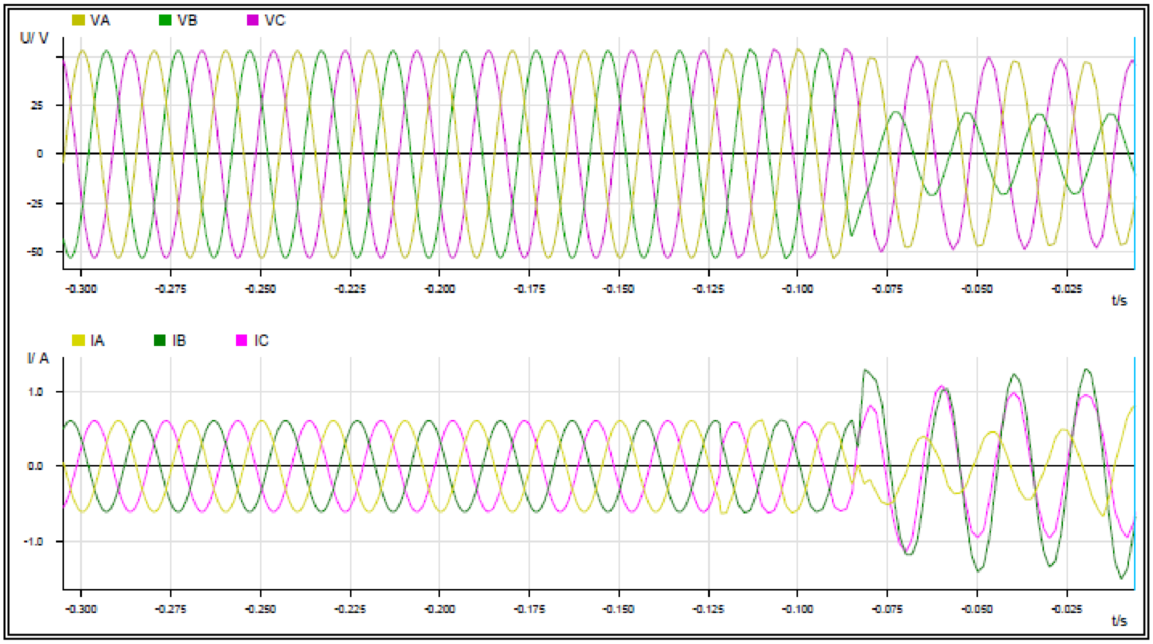

Figure 20 Case B.

The voltage based phase selector correctly selects BG fault, as shown in Figure 21.

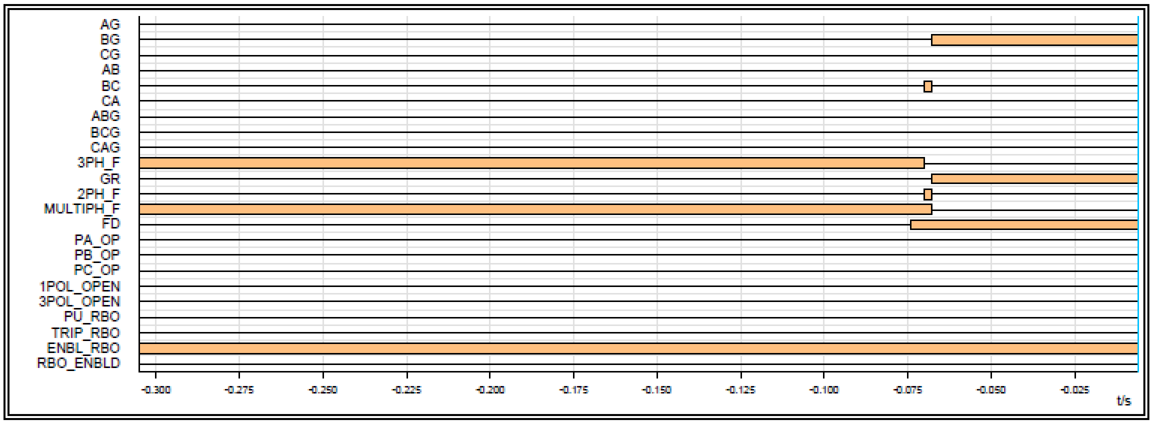

Figure 21 BG Fault recognition.

The angle of the pure fault positive-sequence source impedance is around 130º.

4.3 Case C

A third case from a 132 kV Line is tested for the faulted phase selector. For the fault shown in Figure 22. the voltage pattern corresponds to an AB fault; however, the current pattern corresponds a three-phase fault. The phase selector based on voltages, as it is seen in Figure 23, it determines AB fault. The pure fault positive-sequence source impedance has an angle of around 150º.

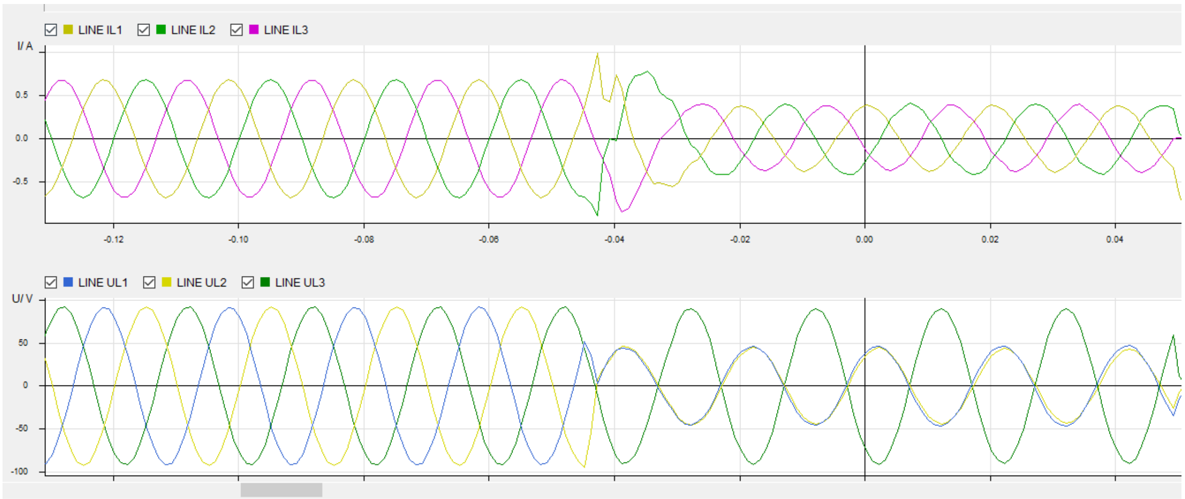

Figure 22 AB Fault

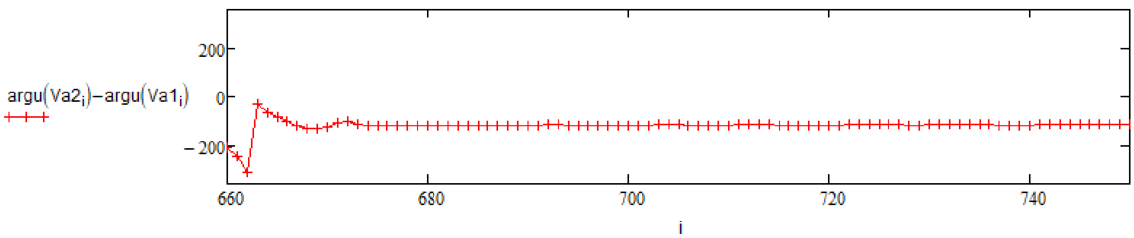

Figure 23 Voltage phase selector output (angle between V2 and V1)

5. CONCLUSIONS

This paper has described the algorithm of the phase selector based on current sequence components and the special conditions that were considered to maintain its reliability, such us remote breaker opening, close onto fault, power swing, pole-open, etc. Although the mentioned phase selector is reliable in most of the conditions, it fails with converter-based generation, weak infeed or CT saturation. These conditions are detected with the measurement of the source impedances, the values of the positive and negative-sequence currents and a saturation detector, respectively. Once detected, a new phase selection algorithm based on sequence voltage components is enabled. The new algorithm was tested with Matlab Simulink simulation and with oscillographic records obtained from real faults. A good reliability is obtained in all the cases.

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BIOGRAPHICAL DATA

Roberto Cimadevilla graduated in Electrical Engineering from the Superior Engineering College of Gijón, Spain in 2001. He did his final year project at the University of Dundee, Scotland, and obtained a master´s degree in “Analysis, simulation and management of electrical power systems” at the University of País Vasco, Spain. He started his professional career in the protection maintenance area of Red Eléctrica de España (Spanish TSO). Roberto joined ZIV in 2003, where he actively participated in the development of several protection and control devices, including distance, transformer differential, line differential and feeder relays. Roberto has held several positions of technical and management responsibility inside ZIV. He is currently the Manager of the Application Engineering Department. Roberto has written more than 30 papers, he is an IEEE member and has participated in several CIGRE working groups.

Alberto Castañón was born in Tixtla, México in 1990. Graduated and Electromechanical Engineer by the Monterrey Institute of Superior Technological Studies in 2014. Between 2014 and 2019 worked as an Electrical Engineer for General Electric in the Gas Turbine Division. In 2009 he studies a Masters about Renewable Energy Integration on the Electrical Grid by the University of País Vasco, Spain, writing its final thesis by ZIV, which he joined as an application engineer up to now, working mainly on distance protections on renewable energy impact on protection engineering.