Air-core dry-type shunt reactor protection based on an alternative current alpha plane

Maria Leonor Silva de Almeida1 | Larissa Marques Peres2 | Guilherme Gomes dos Santos1

1 School of Mechanical Electrical & Computer Engineering, Federal University of Goiás, Goiás, Brazil
2 Federal Institute of Education, Science and Technology of Goiás, Goiás, Brazil

Correspondence
Maria Leonor Silva de Almeida, Federal Institute of Education, Science and Technology of Goiás, Goiás Brazil.
Email: marialeonor@ufg.br

Abstract
This paper proposes an alternative current alpha plane protection for shunt reactors, which is able to identify internal faults, including turn-to-turn faults. The proposed algorithm is based only on zero sequence and neutral currents, eliminating the need for voltage measurements. Furthermore, the proposed algorithm is based on an alternative current alpha plane, where the restraint characteristic is defined simply as its left half-plane, in such a way that minimal settings are required. In order to evaluate the performance of the proposed algorithm, the Alternative Transients Program was used to simulate different internal faults into an air-core dry-type shunt reactor connected to a 230 kV/60 Hz transmission line. The proposed algorithm performance was compared with the restricted earth fault function. From the obtained results, it is demonstrated that the proposed protection properly operates in turn-to-ground and turn-to-turn faults with operation times shorter than one power cycle, even for 1% of short-circuited turns. On the other hand, restricted earth fault function failed to operate in some of these cases. The proposed algorithm ensured the integrity of the air-core dry-type shunt reactors in all evaluated scenarios, correctly restraining in all simulated external faults (including cases with current transformer saturation). Thus, the proposed algorithm is considered a reliable and promising alternative for shunt reactors protection.

1 | INTRODUCTION

Capacitive coupling between phases and ground consists in one of the most relevant characteristics of medium and long-length high-voltage transmission lines. It results in capacitive parasite current which flows from the line to the ground and between phases. When this capacitive current is greater than the inductive loading current, as in the case of light-load line operation conditions, an excess of capacitive reactive power is verified in the line. Hence, due to the Ferranti effect, overvoltages occur throughout the system [1]. In order to absorb the excess of capacitive reactive power, shunt reactors are usually installed in the transmission line terminals [2]. These equipments contribute to line voltage control, leading the system to operate within acceptable voltage margins [3].

Protection functions are essential to quickly and correctly detect shunt reactor internal faults. In this context, according to the literature, traditional protective relays typically apply: phase differential protection, phase and ground overcurrent functions, phase under- or overvoltage protection, directional zero sequence function, distance protection, restricted earth fault (REF) function, negative sequence overcurrent function and split-phase protection [2, 4–7]. Besides, the protection provided by electrical measuring relays is normally complemented by mechanical devices, such as gas detection relay (i.e. Buchholz relay), sudden pressure relay and winding temperature contact thermometer [5–7].

The appropriate choice of protection functions depends on the reactor construction characteristics. Indeed, the equipment topology and parameters are key aspects that determine its behaviour during internal faults, which can be classified as phase-to-phase, turn-to-ground and turn-to-turn faults [4]. Phase-to-phase and turn-to-ground faults are usually identified without great difficulties by using the aforementioned traditional protective functions. Meanwhile, turn-to-turn faults result only in slight changes in voltages and currents, which are of the
same order as those variations tolerated during nominal operating condition. Therefore, the correct identification of this kind of fault is a challenging task for the commonly employed protection functions [5]. As a result, some authors propose specific schemes for detecting turn-to-turn faults [3, 4, 8–12].

In [3], the authors consider functions based on unbalanced parameters caused by turn-to-turn faults for the protection of high-voltage magnetically controlled shunt reactor (MCSR). Thus, for each MCSR winding type, different functions are used, such as zero-sequence directional overcurrent protection, negative-sequence directional overcurrent protection and unbalanced protection. In [4], a method based on zero-sequence current is presented, which depends on an extra logic to distinguish between internal and external faults. Such extra logic is called zero sequence impedance based directional element and it is based on the ratio between zero sequence voltage and current at the reactor terminals. Considering that the reactor inductance may change during internal faults, in [8], a protection scheme based on the energy associated with equivalent inductance of reactor is presented. To do so, inductance parameters and electrical values are considered and the operating protection criterion is adjusted according to the value of energy loss function associated with inductance.

In [9], the authors claim that negative sequence current is greater than zero sequence current during turn-to-turn faults. Based on that, a negative sequence power directional relay is developed, in which the input parameters are the negative sequence current measured at high-voltage reactor terminal and negative sequence voltage, which must be measured at the bus side to ensure correct operations. In contrast, the method proposed in [10] is self-adaptive in relation to the potential transformer (PT) location, corresponding to an inter-turn fault protection based on unbalanced parameter, which compares the per-phase equivalent inductance parameters of the reactor. For this implementation, time-domain quantities as well as voltage across the reactor and phase current measurements taken from both reactor terminals are used.

The method presented in [11] depends on negative sequence elements, as it calculates the difference between normalised negative sequence terminal voltage and normalised negative sequence reactor current. According to the authors, this method can identify the faulted phase without requiring information on the reactor impedance value and current measured at neutral current transformer (CT). In [12], two different methods to identify inter-turn faults in air-core dry-type shunt reactors are described. The first logic is used when two or more reactor banks are connected on the same bus. According to the first logic, an internal fault is identified if the difference between zero sequence currents from each reactor banks is greater than a preset threshold. The second logic is applied for single reactors connected to the bus. Furthermore, the second logic is based on zero sequence current and voltage measured at bus, and also assesses the relationship between zero and negative sequence current to identify the faulted phase in reactor.

Among the solutions provided by vendors for shunt reactors protection, the high impedance differential (HID) module from General Electric Company is firstly addressed here. This module provides high impedance differential protection for internal faults through joint operation of resistors, voltage limiters and high-speed overcurrent relay. Furthermore, HID module must be used in single-phase model for reactor winding protection [13]. Another available solution in the market is the SEL-387 relay, from Schweitzer Engineering Laboratorios (SEL) [14]. This relay uses a current differential element with percentage restraint, overcurrent element, directional element and REF function to provide sensitive detection of internal ground faults.

Finally, there is the RET670 relay from ABB [15], which uses a low impedance REF function to detect internal faults involving earth. In this device, a sensitive negative sequence current scheme is used to detect turn-to-turn faults, focusing on low level faults that are not detected by traditional differential protection schemes, until they evolve into more severe faults. It is noteworthy that the negative sequence current function operation depends on an extra logic, which is an internal/external fault discriminator. Due to operating time delays applied for the sake of security, the response time of negative sequence current function is of about 30 ms for very low level turn-to-turn faults.

Although the logic described in [3, 4, 8–12] perform well, their implementation depend on the measured voltage values at the reactor terminals. Such requirement limits their use only in shunt reactors equipped with PTs or in cases when the voltage measured at the reactor connection point is available, either in the line or at the bus side. Furthermore, the manuals described in [13, 14], from HID module and SEL-387 relay, respectively, did not mention specific solutions for turn-to-turn faults identification. On the other hand, according to [15], the sensitive negative sequence current based turn-to-turn fault protection of the RET670 relay can identify turn-to-turn faults. However, in faults with few turns involved, its operation can occur in up to 30 ms, which is an acceptable operation time, but whose reduction would be beneficial for the shunt reactor integrity.

In [12], the benefits associated with dry-type shunt reactors is further described. Since they have no oil or iron core, they are environment friendly, modular in design, cheap and simple in construction and installation. Moreover, as these reactors have linear electrical properties and no issues regarding inrush current, their protection, design, and implementation are simpler than those of oil-filled equipment [4]. Furthermore, due to technological developments in material and design techniques, air-core dry-type reactors have been used in transmission systems up to and including 345 kV [16], as illustrated in [17].

Based on the above context and on the advantages arising from the use of air-core dry-type shunt reactors, this paper presents a current differential protection, which was adapted from the algorithm described in [18]. The proposed solution is based only on the zero sequence current (calculated through the currents measured at reactor phase terminals) and the current obtained from the neutral terminal, that is, the need for PTs is eliminated. In addition, the proposed algorithm is based on an alternative current alpha plane, where the restraint characteristic is defined simply as the left half-plane, in such way that minimal settings are required.

The proposed algorithm performance evaluation was carried out through simulations in Alternative Transients Program (ATP), whereby a wide variety of turn-to-ground and
turn-to-turn faults were applied into an air-core dry-type shunt reactor connected to a 230 kV/60 Hz transmission line 380 km long. Since the proposed algorithm is based on zero sequence current and neutral current, it was compared to the REF function, which is based on similar measurements, being traditionally used in reactors protection \([5, 19]\). From the results, it is shown that the proposed function presented a better performance than the traditional REF protection, revealing that it is a promising alternative to be used in numerical reactors relaying.

2 | PROPOSED ALGORITHM

The proposed algorithm is an adaptation of the one presented in \([18]\), which corresponds to an incremental complex power differential protection for transmission lines. In this adaptation, zero sequence and neutral current are used instead of the complex power at line terminals. First, phase currents are used to compute zero sequence current, and along with neutral current, they are compared to a pick-up threshold. If any of these currents are greater than the threshold, a complex term given by the ratio between zero sequence and neutral currents is calculated. If the complex term moves out from the restraint region, the protection scheme operates, issuing a trip signal to the shunt reactor circuit breakers. The flowchart diagram of the proposed algorithm is illustrated in Figure 1 and each module is described next.

2.1 | Samples normalisation

Since the current transformation ratios (CTR) of CTs may differ, a samples normalisation module is used to normalise the measured currents. Using the reactor nominal current as base current, the CTs phase currents \((i_A, i_B, i_C)\) and neutral current \((i_N)\) are divided by \(TAP_e\) (defined in Equation (1)), resulting in the correspondent per unit currents \(i_A, i_B, i_C\) and \(i_N\):

\[
TAP_e = \frac{S_{REACTOR}}{\sqrt{3} \cdot V_{L,L} \cdot CTR_e},
\]

where \(S_{REACTOR}\) is the three-phase apparent power of the reactor, \(V_{L,L}\) is the reactor line-to-line rated voltage, \(e\) is an index that indicates the winding for which the \(TAP_e\) is being calculated (phases A, B, C or the neutral) and \(CTR_e\) is the current transformation ratio of the CT connected to \(e\).

2.2 | Phasor estimation

In the Phasor estimation module, the algorithm described in \([20]\) is applied, as it presents an excellent decaying DC component removal. The time domain currents \(i_A, i_B, i_C\) and \(i_N\) are used to calculate their frequency domain currents \(\hat{i}_A, \hat{i}_B, \hat{i}_C\) and \(\hat{i}_N\), respectively.

2.3 | Zero sequence calculation

Based on the frequency domain currents \(\hat{i}_A, \hat{i}_B, \hat{i}_C\), the zero sequence calculation module calculates the corresponding zero sequence current \(\hat{I}_0\) (near supply side), as shown in Equation (2), where \(k\) represents the \(k\)th sampling instant:

\[
\hat{I}_0(k) = \frac{\hat{i}_A(k) + \hat{i}_B(k) + \hat{i}_C(k)}{3}.
\]

2.4 | Fault type detection

The reactor construction characteristics consist in an important factor to determine the fault current behaviour. As the dry-type air-core reactors are manufactured in single-phase format and then connected, the air acts as an insulating material. Therefore, there is a safe spacing between the phases, resulting in a better isolation between them, such that the phase-to-phase faults are not a concern. If the insulation between the phase and ground is made out of air, the probability of turn-to-ground faults is very low. However, the probability grows if the insulation between phase and ground is a conducting medium, so that turn-to-ground faults should be analysed. Finally, the turn-to-turn faults should also be evaluated, since they can take place at any dry-type air-core reactor and they are hardly detected by the protection schemes \([4]\).

In the proposed algorithm, a fault type detection module is used to identify if the reactor is experiencing a turn-to-turn fault. To illustrate how this module works, the behaviour of zero and neutral currents is presented in Figure 2, where SCP is the system connection point, for four different operation conditions: a) normal condition, b) external grounded fault, c) turn-to-ground fault and d) turn-to-turn-fault.

FIGURE 1  Flowchart diagram of the proposed algorithm
Under nominal conditions, both zero and neutral currents are approximately equal to zero (if the system is balanced), as shown in Figure 2(a). For an external grounded fault, as illustrated in Figure 2(b), the zero sequence current flows out of the phase terminals, while the neutral current flows into the neutral terminal. In a turn-to-ground fault condition, the zero current flows into the phase terminals and neutral current flows into the neutral terminal, as presented in Figure 2(c). In a turn-to-turn fault condition, zero current flows into the phase terminals and neutral current flows out of the neutral terminal, as shown in Figure 2(d).

In view of these operating situations, we can conclude that \( \hat{I}_N \) only flows out of the neutral terminal during turn-to-turn faults conditions. Hence, to identify this type of fault, the neutral current angle is the only variable that needs to be considered. To further consolidate our conclusion, several simulations were carried out in ATP, considering different types of external faults, turn-to-ground and turn-to-turn faults. In all the simulations, the angle of \( \hat{I}_N \) was evaluated and confirmed that, only for turn-to-turn faults, \( \hat{I}_N \) remains in first or second quadrant (considering the CTs polarities as presented in Figure 2). Therefore, the neutral current is the input of fault type detection module and only if \( \theta_N \) is in the first or second quadrant, the variable \( FID \) is set to \(-1\). Otherwise, \( FID \) is set to \(1\).

Still referencing Figure 2, \( n_f \) is defined as the total percentage of turns per phase. For turn-to-ground faults, the winding is divided into two sub-winding: one with \( n_f \) percentage of turns, counted from the bush to the fault point, and other with \( n_g \) percentage of turns, such that \( n_g = n_T - n_f \), as represented in Figure 2(c). Thus, \( n_f \) is directly involved in the fault, while no current flows through \( n_g \), as it is deflected to the ground connection. In turn-to-turn faults, represented in Figure 2(d), the winding is divided into three parts: \( n_f \), \( n_h \) and \( n_g \), being the last one the segment in fault condition, which is defined as \( n_g = n_T - n_f - n_h \) [21].

### 2.5 Alternative current alpha plane

The alternative current alpha plane is the most important module of the proposed algorithm, as it is the one responsible for determining whether a trip command must be sent to the circuit breakers. For this purpose, \( \hat{I}_0 \), \( \hat{I}_N \) and \( FID \) are used to determine a complex ratio called \( \Gamma \) (Equation (3)), if at least one of \( \hat{I}_0 \) or \( \hat{I}_N \) has magnitude greater than a pick-up threshold \( I_{pkR} \). Otherwise, \( \Gamma \) is fixed in \((-1,0):  

\[
\Gamma(k) = \begin{cases} 
\frac{\hat{I}_0(k)}{\hat{I}_N(k)} \cdot FID & \text{if } (|\hat{I}_0(k)| \text{ OR } |\hat{I}_N(k)|) > I_{pkR} \\
-1, & \text{otherwise.}
\end{cases}
\]

The \( \Gamma \) behaviour is interpreted based on the alternative current alpha plane, shown in Figure 3, where the \( x \)-axis and \( y \)-axis correspond to real and imaginary parts of \( \Gamma \), respectively. The stability point is set on \((-1,0)\) and the restraint characteristic is simply defined as the left half-plane. Furthermore, to avoid misoperation during transient periods, the proposed algorithm only issues a trip signal if consecutive samples are detected in the right half-plane during a half cycle. In Figure 3, the \( \Gamma \) behaviour for internal and external faults are illustrated, considering \( N \) as the number of samples per cycle.

To better understand \( \Gamma \), its behaviour for the conditions presented in Figure 2 can be evaluated. For nominal conditions (Figure 2(a)), the magnitudes of \( \hat{I}_0 \) and \( \hat{I}_N \) are approximately equal to zero and, therefore, they are smaller than \( I_{pkR} \), making \( \Gamma \) equal to \(-1\). It is noteworthy that the pick-up value is
determined empirically, considering the simulations carried out involving external faults, turn-to-ground faults, and turn-to-turn faults with different characteristics. Henceforth, $I_{pk87R}$ value is defined to ensure a correct operation for all analysed cases.

In case of external grounded faults, the phase currents flow out from the reactor, while the neutral current flows into the reactor, as shown in Figure 2(b). As the angle displacement between $I_0$ and $I_N$ is approximately $180^\circ$ and the variable $FID$ is equal to 1, $\Gamma$ lies on the second or the third quadrants of the alternative current alpha plane, defined as the restraint region.

For any turn-to-alpha faults, phase and neutral currents flow into the reactor, as shown in Figure 2(c). As $I_0$ and $I_N$ are in phase and the variable $FID$ is equal to 1, $\Gamma$ lies on the first or the fourth quadrants of the alternative current alpha plane, defined as the operating region.

For turn-to-turn faults, the phase currents flow into the reactor, while the neutral current flows out of the reactor, as shown in Figure 2(d). As $I_0$ and $I_N$ are lagged by $180^\circ$ and the variable $FID$ is equal $–1$, $\Gamma$ lies on the first or fourth quadrants, which are within the operating region.

3 PROPOSED ALGORITHM PERFORMANCE EVALUATION

The proposed algorithm (named 87R function) performance is evaluated through the analysis of $\Gamma$ considering a wide variety of fault conditions modeled and simulated in the ATP software. An electric power system was modeled, composed by a 230 kV/60 Hz line 380 km long with 50% shunt compensation by means of dry-type air-core shunt reactors. These reactors are installed at only one line terminal, with rated power equal to 10.25 Mvar. Different cases of faults external and internal to the reactor were applied, considering turn-to-ground and turn-to-turn faults, varying the value of leakage factor and also the amount of turns involved.

As input signals, the 87R function uses phase currents measured at the reactor terminals (near the supply side) and at neutral terminal, through C400 CTs, modeled as reported in [22]. In addition, CTR for phase CTs and neutral CT were set to 1200/5 and 200/5, respectively. Moreover, the output signals were resampled at 16 samples per cycle ($N = 16$) and $I_{pk87R}$ was chosen empirically as 0.01 pu.

To enable a comparative evaluation, the proposed algorithm performance was compared with the performance of the traditional REF function, which is a traditionally used reactor protection schemes. According to [5], although multi-functional numerical protection relays are used for reactor protection, typically old protection schemes are still specified and applied with just a few protection functions. Among them, the REF protection, called 87N in [5], is normally used as reactor unit protection. Each manufacturer implements the REF element in a different way, varying the calculation method of the operating and restriction currents, and even the type of function: differential or directional [19]. In its differential form, the REF function can be implemented by comparing the neutral current at the reactor neutral point with the zero sequence current calculated from the currents measured at the reactor bushings [5].

For a comparative evaluation, the REF function was implemented using the operating current $I_{op}$ and restriction current $I_{res}$, as defined in (4) and (5), respectively [19]. The constant $k_R$ adjusts the sensitivity of the REF protection and was set to 2:

$$I_{op}(k) = [\hat{I}_N(k)],$$

$$I_{res}(k) = k_R \cdot [\hat{I}_N(k) - 3 \cdot \hat{I}_0(k)] - [\hat{I}_N(k) + 3 \cdot \hat{I}_0(k)].$$

The fault is identified and the trip is issued if $I_{op}$ satisfy both conditions described in (6), where $I_{pk}$ is the minimum operating current, set to 0.1, which corresponds to a typical setting [4]:

$$I_{op}(k) > I_{res}(k) \text{ and } I_{op}(k) > I_{pk}(k).$$

3.1 Results presentation

The first case study consists of the reactor energisation case (that occurs in 100 ms) until normal steady-state regime. These results are presented in Figure 4, which shows the interval between 80 and 300 ms. It can be seen in Figure 4(a), where it is demonstrated that $\Gamma$ remains at stability point during reactor energisation. This behaviour is explained because, despite the inrush current, the unbalance between the phases is not big enough to make $\hat{I}_0 \text{ or } \hat{I}_N$ greater than $I_{pk87R}$. A short time after the energisation, the shunt reactor enters in a steady-state condition and $\Gamma$ remains at $(-1,0)$. In nominal conditions, as the reactor operates under rated conditions, its supply is balanced and, therefore, spurious zero sequence and neutral currents are smaller than $I_{pk87R}$. Similarly, as $\hat{I}_0 \text{ and } \hat{I}_N$ are negligible during the reactor energisation until normal steady-state regime, REF function does not operate, being $I_{op} < I_{pk}$, as shown in Figure 4(b).

In order to evaluate the proposed algorithm during abnormal operating conditions, turn-to-ground and turn-to-turn faults were simulated. All of the faults were applied to one of the
TABLE 1 Features of the evaluated turn-to-ground faults

| Case | \( \alpha_{fg} \) | \( n_f \) (%) | \( n_g \) (%) | \( R_f \) (\( \Omega \)) |
|------|-----------------|--------------|--------------|----------------|
| 1    | 0.25            | 1            | 99           | 0              |
| 2    | 1.00            | 1            | 99           | 0              |
| 3    | 0.25            | 50           | 50           | 0              |
| 4    | 1.00            | 50           | 50           | 0              |
| 5    | 0.25            | 99           | 1            | 0              |
| 6    | 1.00            | 99           | 1            | 0              |
| 7    | 1.00            | 1            | 99           | 100            |
| 8    | 0.75            | 99           | 1            | 100            |

TABLE 2 Features of the evaluated turn-to-turn faults

| Case | \( \alpha_{fg} \) | \( \alpha_{gh} \) | \( \alpha_{fh} \) | \( n_f \) (%) | \( n_g \) (%) | \( n_h \) (%) |
|------|-----------------|-----------------|-----------------|--------------|--------------|--------------|
| 9    | 0.25            | 0.25            | 0.25            | 1            | 1            | 98            |
| 10   | 0.80            | 0.80            | 0.80            | 1            | 1            | 98            |
| 11   | 0.25            | 0.25            | 0.25            | 98           | 1            | 1             |
| 12   | 0.80            | 0.80            | 0.80            | 98           | 1            | 1             |
| 13   | 0.25            | 0.25            | 0.25            | 98           | 1            | 1             |
| 14   | 1.00            | 1.00            | 1.00            | 1            | 98           | 1             |
| 15   | 0.50            | 0.75            | 0.25            | 1            | 25           | 74            |
| 16   | 0.25            | 0.50            | 0.75            | 49           | 50           | 1             |

Phases at 100 ms, such that the performance of 87\( R \) and REF function are observed between 80 and 120 ms. The different cases of internal faults were obtained by varying the amount of turns involved and the value of leakage factor. The leakage factor (\( \alpha \)) is a constant and it can assume values from 0 (zero) to 1 (one). It represents how much of the fault current disperses during a fault. The smaller the value of the leakage factor (close to zero), the lower the flux leakage and, consequently, the greater fault currents are. On the other hand, the higher the \( \alpha \) value (close to one), the greater is the flux leakage and, consequently, the lower the fault currents are. The leakage factor depends on the constructive aspects of the reactor and the percentage of turns involved. In this way, in turn-to-ground faults, it is defined as \( \alpha_{fg} \); in turn-to-turn faults, it is defined as \( \alpha_{gh} \), \( \alpha_{fg} \) and \( \alpha_{fh} \) [21].

Moreover, for the turn-to-ground faults, the fault resistance (\( R_f \)) that may take place between the winding and the ground was evaluated. The parameters of the turn-to-ground and turn-to-turn applied faults are presented in Tables 1 and 2, respectively. The number of turns involved in the fault is described in Figures 2(c) and (d). For all the cases described in Tables 1 and 2, the behaviour of the proposed algorithm and the REF function are compared and presented next.

Based on Table 1, cases 1 and 2 correspond to turn-to-ground faults applied close to the phase terminals, with 99% of turns in fault (\( n_g = 99\% \)). These cases are different only by the values of the leakage factor: for Case 1, \( \alpha_{fg} = 0.25 \), while for Case 2, \( \alpha_{fg} = 1.00 \). These values of leakage factor were chosen in order to evaluate extreme conditions of this index, which result in the largest and smallest fault currents.

The results for Cases 1 and 2 are shown in Figure 5. From Figures 5(a) and (c), it is verified that \( \Gamma \) values enter into the operation characteristic, issuing a trip signal in 9 ms after the fault application (operating time) for Case 1 and 10 ms for Case 2. From Figures 5(b) and (d), it can be seen that, after the fault application, \( I_{op} \) exceeds \( I_{res} \) and \( I_{pk} \), issuing a trip signal in 5.21 ms after the fault incidence for Cases 1 and 2. Thus, the proposed algorithm and REF function work correctly, regardless the leakage factor value for turn-to-ground faults near phase terminals.

In Cases 3 and 4, turn-to-ground faults were simulated with 50% of short-circuited turns. The difference between these cases is that for Case 3 the \( \alpha_{fg} \) is equal to 0.25, while for Case 4 the leakage factor is equal to 1.00. The results for Cases 3 and 4 are presented in Figure 6. From Figures 6(a) and (c), it is verified that \( \Gamma \) moves into the operation region, resulting in a tripping time of 10 ms for both Cases 3 and 4. From Figures 6(b) and (d), it can be seen that, after fault application, \( I_{op} \) is greater than \( I_{res} \) and \( I_{pk} \), resulting in trip issuance in times equal to 5.21 ms and 10.42 ms for Cases 3 and 4, respectively.

Turn-to-ground faults applied near the neutral terminal with 1% of short-circuited turns (\( n_g = 1\% \)) were evaluated in Cases 5 and 6, considering \( \alpha_{fg} = 0.25 \) and \( \alpha_{fg} = 1.00 \), respectively. Since these faults are applied near the neutral terminal, they result in very small fault currents. Therefore, it is more difficult for protection schemes to identify them. The results for Cases 5 and 6 are shown in Figure 7. From Figures 7(a) and (c), it is verified that \( \Gamma \) moves into the right half-plane, resulting in a trip...
signal with operation time of 10 ms in both cases. From Figures 7(b) and (d), it is shown that REF function also operates correctly with operation time of 4.17 and 10.42 ms in Cases 5 and 6, respectively. It is important to point out that the fault simulated in Case 6 corresponds to a critical case for protective operation, since the number of turns involved is minimal ($\eta_g = 1\%$) and the leakage factor is high.

Cases 7 and 8 correspond to turn-to-ground faults with high fault resistance ($R_f = 100\Omega$). For Case 7, there are 99% of turns in fault and $\alpha_{gf} = 1.00$. For Case 8, there are 1% of turns in fault and $\alpha_{gf} = 0.75$. The results for Cases 7 and 8 are shown in Figure 8. From Figures 8(a) and (c), it is verified that $\Gamma$ moves to the operation characteristic, resulting in trip with operation time of 10 ms for both Cases 7 and 8. It is emphasised that Case 8 is as critical as Case 6: the fault is applied close to the neutral side, the turns involved is minimal ($\eta_g = 1\%$) and it has high leakage factor ($\alpha_{gf} = 0.75$). Furthermore, the fault has high fault resistance ($R_f = 100\Omega$), which further restricts the fault current. Despite these conditions, the $87R$ function operates correctly, issuing a trip signal in less than one cycle. On the other hand, REF protection does not operate, as shown in Figures 8(b) and (d), since $I_{res}$ is greater than $I_{op}$. 

Turn-to-turn faults applied near the neutral terminal with 1% of turns in fault ($\eta_g = 1\%$) were evaluated in Cases 11 and 12, that are distinguished by the set of leakage factors used: for Case 11, all leakage factor are equal to 0.25, while for Case 12, they are equal to 0.80. Besides turn-to-turn faults are applied near the neutral terminal, which results in small currents. The results for Cases 11 and 12 are shown in Figure 10. From Figures 10(a) and (c), it is verified that $\Gamma$ moves towards the right half-plane, leading to a trip with operation time of 10 ms for Case 11 and 14 ms for Case 12. It is important to emphasise that Case 12 corresponds to a turn-to-turn fault applied close to the neutral terminal with minimal turns involved ($\eta_g = 1\%$) and with a high leakage factor (equal to 0.80). Even though these characteristics result in a very small fault current, the proposed protection scheme properly operates with operation time smaller than one power cycle. In contrast, REF protection does not operate, as shown in Figures 10(b) and (d), since $I_{res}$ is greater than $I_{op}$.

In Cases 13 and 14, turn-to-turn faults were simulated with 98% of turns in fault ($\eta_g = 98\%$). The difference between both scenarios is: for Case 13, all leakage factor are equal to 0.25,
while for Case 14, they are equal to 1.00. The results for Cases 13 and 14 are shown in Figure 11. From Figures 11(a) and (c), it is verified that the complex index moves to the operation region, such that proposed protection operates 9 ms after the fault inception in Cases 13 and 14. Since these cases involve many turns in the fault (almost the entire winding), high fault currents are verified, even in Case 13, in which a high leakage factor is considered. Thus, the protection operates with shorter operating time. On the other hand, REF protection does not operate, as shown in Figures 11(b) and (d), because $\hat{I}_0$ and $\hat{I}_N$ are shifted by 180°. As a result, $I_{\text{res}}$ is reinforced, being greater than $I_{\text{op}}$, even if the high fault currents are verified.

In order to evaluate the $87R$ function under different scenarios of turn-to-turn faults, Cases 15 and 16 are analysed in Figure 12. From Figures 12(a) and (c), it is verified that the complex index moves to right half-plane, resulting in a trip in 10 ms after the fault application for Cases 15 and 16. It is therefore verified that the proposed protection operates properly, regardless if the turns in fault are close to the phase or the neutral terminal. In contrast, REF protection does not operate, as shown in Figures 12(b) and (d), since $I_{\text{op}} < I_{\text{res}}$.

Two different bolted single-phase-to-ground fault with CT saturation were also considered to evaluate the $87R$ performance. First, an AG fault was applied just behind the CTA (close to the supply side), corresponding to an external fault, which results in Figure 13(a). Then, the fault was applied just beyond the CTA, corresponding to an internal fault, whose results are presented in Figure 13(b).

From Figure 13(a), it can be seen that $\Gamma$ remains within the restriction region for external fault, despite the oscillations due to distortions caused by CT saturation. On the other hand, according to Figure 13(b), when the fault is applied internally to the reactor, $\Gamma$ moves to the right half-plane, resulting in the protection operation 10 ms after the fault inception. It is noteworthy to mention that the $87R$ function correctly operated, properly distinguishing external and internal faults, even in the presence CT saturation.

The proposed protection is also sensitive to external faults in the substation, close to the point at which the shunt reactor is connected. Since the reactors are connected at the line terminal, faults at the busbar can erroneously induce the operation of the reactor protection. To evaluate the proposed protection performance in such situation, a three-phase external fault and a single-phase-to-ground external fault were applied at 100 ms, being the $\Gamma$ behaviour analysed from 80 to 120 ms. These results are show in Figure 13.

For the three-phase external fault case, it is seen in Figure 14(a) that $\Gamma$ remained at the stability point (-1.0), since in such symmetrical fault scenario the system remains balanced. As a result, $\hat{I}_0$ and $\hat{I}_N$ do not exceed $I_{\text{pk}}$. For the single-phase-to-ground external fault, it can be noticed in Figure 14(b) that the complex index moves out from (-1,0) due to the flow of zero sequence and neutral currents, but $\Gamma$ remains in the left half-plane, not resulting in the protection operation. Considering these cases, the protection properly restrained, even in critical situations of external faults.

Based on the obtained results, discussions are presented here. It was verified that the $87R$ function presented a correct operation for all tested turn-to-ground and turn-to-turn faults, with operation times smaller than one power cycle. This performance
depends neither on the amount of turns involved in the fault nor on the value of the leakage factor, even high values of leakage factors are considered, which result in lower fault currents. There-withal, the proposed algorithm performs well also for faults applied near the neutral terminal, which results in small fault currents. For turn-to-ground faults, the proposed algorithm presented a promising performance, even in the existence of high resistance faults between the winding and the ground connection. One can also see that $87R$ function provided a sub-cycle operating time for all of the cases evaluated.

This ability of the proposed algorithm to identify both turn-to-ground and turn-to-turn faults corresponds to an advantage over the other protections found in the literature. This is justified because, in most of the existing solutions, turn-to-ground and turn-to-turn faults are identified by different logics, which increases the complexity of the protection scheme implemented for the shunt reactors. Moreover, turn-to-turn faults are usually identified by mechanical relays that complement the operation of electrical measuring relays. However, mechanical relays have a significantly longer operating time, what can physically damage the reactor in cases of severe faults. In contrast, $87R$ function operates correctly and quickly for both turn-to-ground and turn-to-turn faults.

3.2 Discussions

Comparing the performance of $87R$ and REF protection, for turn-to-ground faults with high resistance fault, REF protection did not identify the fault. This is explained by the fact that high $R_f$ value limits the fault current, such that $I_{op}$ is smaller than $I_{pk}$, not satisfying Equation (6). In contrast, the proposed algorithm operates for these fault conditions due to its intrinsic logic, which allows a smaller pick-up value ($I_{pk}$). In addition, as $87R$ function also considers the current direction in its formulations, even if fault resistance value is high, both zero sequence and neutral currents flows into the reactor terminals, as indicated in Figure 2(c). Therefore, $87R$ function identifies turn-to-ground faults.

For turn-to-turn faults, REF function also resulted in misoperations. For these cases, as indicated in Figure 2(d), $\hat{I}_0$ flows into the phase terminals and $\hat{I}_N$ flows out of the neutral terminal. Thus, $I_{res}$, calculated according to Equation (5), is reinforced, making it greater than the $I_{sp}$, not satisfying (6). Thus, the REF function does not operate for turn-to-turn faults, while the proposed algorithm identifies that $\theta_N$ values lead FTD to be set to $-1$. Consequently, the correct identification of turn-to-turn faults is accomplished.

It is important to mention that the proposed algorithm stands out from the others described in the literature, due to its restraint characteristic being simply defined by the left half-plane of the alpha plane, in such way that minimal settings are required. Moreover, unlike some described functions in the literature, $87R$ function does not depend on voltage measurements. This is advantageous because, besides simplifying the protection scheme, it can be used with shunt reactors in which voltage measurements are not available.
4 | CONCLUSION

A reactor differential protection based on an alternative current alpha plane is presented here. In order to evaluate the performance of the proposed algorithm, the ATP software was used to simulate different faults internal and external to an air-core dry-type shunt reactor, which is connected to a 230 kV/60 Hz transmission line. Based on the results, it was verified that the proposed protection is able to identify both turn-to-ground and turn-to-turn faults, with operation times smaller than one cycle, regardless of the amount of turns involved. The value of the leakage factor and the value of fault resistance have also shown to be not critical for the proposed algorithm, which in turn has demonstrated to be also reliable in external fault cases, even under CT saturation conditions.

From the comparative analysis between the proposed algorithm and the traditional REF function, it can be seen that the $87R$ function operates for all of the analyzed cases, while the REF function failed to operate for all studied turn-to-turn faults. Moreover, compared to other protections schemes, the developed protection has the advantage of being independent of voltage measurements, being simpler that other formulations and requiring very few settings.

Based on the presented analysis, the benefits associated with the proposed algorithm can be clearly seen, such that $87R$ function might be used as an alternative promising solution in numerical relays for air-core dry-type shunt reactors protection.

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