On Applying an Enhanced Generalized Alpha Plane to Shunt Reactor Protection

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Abstract—Shunt reactors are used for long and high voltage transmission lines operation. Therefore, it is necessary to use a protection logic to identify turn-to-ground and turn-to-turn faults with few turns involved or high leakage factor value. In this context, the present work evaluates the use of differential functions based on Alternative Current Alpha Plane and on Enhanced Generalized Alpha Plane for dry-type air-core shunt reactors protection. These algorithms are independent of voltage measurement and are implemented considering the reactor's zero-sequence current and neutral current. Based on simulations implemented in the Alternative Transient Program software, different turn-to-ground and turn-to-turn faults were investigated by varying the number of short-circuited turns, the leakage factor value, and fault resistance value. The obtained results reveal that the joint use of these functions guarantees a more secure identification of internal faults in shunt reactors, even when dealing with low current faults.

Index Terms—Differential protection, alpha plane, turn-to-ground faults, turn-to-turn faults and shunt reactors.

I. INTRODUCTION

During light loading conditions of long and high voltage transmission lines, the charging current can be greater than the load current, such that an excess of reactive power, which is associated with the Ferrant Effect, is verified in the line [1]. Consequently, overvoltages in the transmission line are observed, which can damage the electrical equipment insulation. Therefore, it is necessary to avoid these overvoltages by using shunt reactors. When connected to lines, reactors absorb excess capacitive reactive power during low load operation, controlling the voltage at appropriate levels [2].

Given the importance of shunt reactors for operating transmission lines at adequate voltage levels, the application of shunt reactors protection schemes is important to rapidly identify abnormal operating conditions, such as internal faults. Among the protection functions usually employed in shunt reactors, the differential function (87R) is widespread [3]. At first, one can understand its application for shunt reactor is similar to power transformer. This application requires current transformers (CTs) for measuring currents entering and leaving each phase. These measured currents are compared, thereby the differential function protection identifies an internal fault.

The restricted earth fault (REF) function also corresponds to a commonly implemented differential function for shunt reactors, and in this application only four CTs are required: three on the bushing terminals and one on the neutral terminal [4]. In this case, phase currents are used to define the zero sequence current, which is compared to the neutral current.

The 87R protection function can identify phase-to-phase and phase-to-ground faults, and REF function can operate for high turn-to-ground magnitude faults [5]. However, neither the 87R nor the REF logic can detect turn-to-ground faults in shunt reactors whenever it takes a few turns or occurs close to the neutral point. In the case of turn-to-turn faults, the drawback for 87R and REF algorithm is even aggravated since they may result in minimal variations in phase and neutral currents reactor [6]. Hence, even after the fault, the operating conditions of the reactor barely vary, which compromises the identification of these faults through the analysis of the voltages and currents of the reactor.

According to [7], the use of gas detection relay (i.e. Buchholz relay) to identify faults with few turns involved is common. However, the identification of these faults through mechanical parameters can be slow, compromising the reactor integrity. Additionally, in reference [7], only three solutions are used by present industrial practice for identification of faults with few turns involved. Considering the absence of different solutions in industry to fast identification this abnormal condition operation, several types of research have been developed to propose a protection solution for shunt reactors that can identify both turn-to-ground and turn-to-turn faults.

According [6], distance relays can be used to detect turn-to-turn faults, as, during this type of fault, the reactor experiences a significant reduction in its 60 Hz impedance. Through finite element models, the characteristics of the magnetic field distribution of shunt reactor are evaluated, and based on that protection algorithm to detect turn-to-turn fault was reported in [8]. To overcome the problems associated with REF function, in [9] is proposed a new REF function, which is composed of a biased differential element, a current polarized directional element, a negative sequence voltage polarized element, and an adaptive second harmonic blocking element. To identify turn-to-turn faults in shunt reactors, in [10] a protection function based on the unbalanced parameters detection is proposed, in which the measurement and the comparison of per phase
inductance parameters are calculated.

In [11] an algorithm is proposed that can detect the turn-to-turn fault in shunt reactors through the difference between normalized negative sequence terminal voltage and normalized negative sequence reactor current phasors. In [12] a zero-sequence voltage polarized directional element is proposed, which is used along with a supervision overcurrent element, that distinguishes internal and external faults. Based on the current through the reactor neutral, two methods for turn-to-turn fault detection are proposed in [13]: one can be used with two reactors connect to a bus, and another one that can be applied with a single reactor in service.

As shown in [6] - [13], the described logics are able to identify turn-to-turn faults. However, all the presented functions depend on the voltage measurement. As a result, they require voltage transformers (VTs), making their application unfeasible when voltage measurement is not available. Furthermore, the logic present in [10] also depends on the employment of six CTs, which makes installation more expensive. Finally, it is noteworthy that none of these studies evaluates the influence of the leakage factor of the reactor on the performance of the evaluated protection function.

It was reported in [7] a differential function for dry-type air-core shunt reactors, based on Alternative Current Alpha Plane. The zero-sequence current (calculated on the phase side of the reactor) and the neutral current of the star-connected reactor were used to calculate a complex ratio, plotted on the alpha plane used. Furthermore, the performance of the proposed function was compared with REF function for different turn-to-ground and turn-to-turn faults. The results show that the proposed function operates for all turn-to-ground and turn-to-turn faults, while REF function did not operate for turn-to-turn faults. Despite the advantages associated with the use of the proposed logic, instead of other protection functions reported in the literature, the results presented by [7] show that the complex ratio used can result in low values, in the order of $10^{-3}$, for some cases of turn-to-ground and turn-to-turn faults, which can compromise its correct performance.

Aiming to investigate a differential protection function capable of satisfactorily identifying turn-to-ground and turn-to-turn faults for any shunt reactor, the present work evaluates the use of the differential function based on an Enhanced Generalized Alpha Plane proposed in [14]. The investigation of this function is justified because according to the results presented in [14], the proposed logic operates correctly for transmission lines, buses, and transformers, and in the latter equipment, turn-to-ground and turn-to-turn faults were evaluated. In addition, the considered logic guarantees security by not operating for external faults, which is feasible through the enhanced characteristic used that ensures greater reliability in operation without compromising its sensitivity. As the results presented are promising, the possibility of success in applying this logic to reactors was identified.

In the meantime, the application of logic proposed by [7] and [14] for the protection of a dry-type air-core shunt reactor is assessed in this paper. Therefore, the Alternative Transient Program (ATP) software was used to model an electric power system composed of a 500 kV/60 Hz line 400 km long with 60% shunt compensation through dry-type air-core shunt reactors. The application of protection functions were evaluated when the shunt reactor was submitted to transients caused by maneuvers in the modeled power system. In addition, the performance of protection functions was also evaluated when the reactor was subjected to different internal faults.

## II. THE EVALUATED PROTECTION FUNCTIONS

Both logics analyzed in this work are based on the alpha plane, in which the abscissa axis corresponds to the real part of the calculated complex ratio, while the ordinate axis corresponds to the imaginary part of the calculated complex ratio. The mathematical procedure to define the complex ratio depends on the logic used. Thus, in the logic proposed by [7], an Alternative Current Alpha Plane is used, such that this logic will be called $87_{ACAP}$, and its complex ratio will be defined as $\Gamma_{ACAP}$. In the logic proposed by [14], an Enhanced Generalized Alpha Plane is used, such that this logic will be named as $87_{EGAP}$, and its complex ratio will be defined as $\Gamma_{EGAP}$. The similarities and differences between the $87_{ACAP}$ and $87_{EGAP}$ functions are described next.

For the evaluated functions, the zero sequence and neutral current are used. Thus, the phase currents $\hat{I}_A$, $\hat{I}_B$ and $\hat{I}_C$ are measured respectively by the CT$_A$, CT$_B$ and CT$_C$ current transformers, indicated in the solidly grounded reactor circuit, shown in Fig. 1, where SCP is the system connection point. The phase currents are used to compute zero sequence current ($\hat{I}_0$), as indicated in (1), where $k$ represents the $k$-th sampling instant. The zero sequence current is analyzed along with the neutral current ($\hat{I}_N$), which is measured by CT$_N$.

$$\hat{I}_0(k) = \frac{\hat{I}_A(k) + \hat{I}_B(k) + \hat{I}_C(k)}{3} \quad (1)$$

![Shunt Reactor Circuit](image)
Considering the behavior of $\hat{I}_0$ and $\hat{I}_N$ during normal operating conditions and during external and internal faults (both turn-to-ground and turn-to-turn faults), it is verified that $\hat{I}_N$ only flows out of the neutral terminal during turn-to-turn faults conditions [7]. Hence, to identify this type of fault, the neutral current angle ($\theta_N$) is the only variable that needs to be considered, as only for turn-to-turn faults, $\theta_N$ remains in first or second quadrant, considering the CTs polarities as presented in Fig. 1. Therefore, in the two evaluated functions only if $\theta_N$ is in the first or second quadrant, the variable Faulted Type Detection (FTD) is set to -1. Otherwise, FTD is set to 1.

Based on the $87_{ACAP}$ differential function proposed by [7], $\hat{I}_0$, $\hat{I}_N$ and FTD variable are used to determine a complex ratio called $\Gamma_{ACAP}$, calculated as Eq. (2), if at least one of $\hat{I}_0$ or $\hat{I}_N$ has magnitude greater than a pick-up threshold ($I_{pk87ACAP}$). Otherwise, $\Gamma_{ACAP}$ is fixed in (-1,0).

$$\Gamma_{ACAP}(k) = \frac{\hat{I}_0(k)}{\hat{I}_N(k)} \cdot FTD$$

Based on the $87_{EGAP}$ differential function proposed by [14], $\hat{I}_0$, $\hat{I}_N$ are used to calculate the differential current ($\hat{I}_{dif}$) and the restraint current ($I_{res}$), as shown in Eqs. (3) and (4), respectively.

$$\hat{I}_{dif}(k) = 3\hat{I}_0(k) + \hat{I}_N(k)$$

$$I_{res}(k) = |3\hat{I}_0(k)| + |\hat{I}_N(k)|$$

Based on $\hat{I}_{dif}$ and $I_{res}$, the currents $\hat{I}_M$ and $\hat{I}_L$ are determined as described in Eqs. (5) and (6), respectively. It is noteworthy that $\eta_1$ and $\eta_2$ are adjustment factors, which are calculated as shown in Eqs. (7) and (8), respectively, where $\Gamma_F$ is the adjusted value for real coordinate of center in alpha plane; and $k_\Delta$ is the radius of the circular fault settlement region, that corresponds to the operation region of $87_{EGAP}$.

$$\hat{I}_M(k) = \frac{1}{\eta_1 + \eta_2} (\eta_1 \hat{I}_{dif}(k) + I_{res}(k))$$

$$\hat{I}_L(k) = \frac{1}{\eta_1 + \eta_2} (\eta_1 \hat{I}_{dif}(k) - I_{res}(k))$$

$$\eta_1 = \frac{1}{k_\Delta} (1 + \Gamma_F)$$

$$\eta_2 = \Gamma_F \cdot \eta_1$$

So, the FTD variable and the calculated currents $\hat{I}_M$ and $\hat{I}_L$ are used to determine a complex ratio called $\Gamma_{EGAP}$, as shown in Eq. (9), if at least one of $\hat{I}_{dif}$ or $I_{res}$ has magnitude greater than a pick-up threshold ($I_{pk87EGAP}$). Otherwise, $\Gamma_{EGAP}$ is fixed in (-1,0).

$$\Gamma_{EGAP}(k) = \frac{\hat{I}_M(k)}{\hat{I}_L(k)} \cdot FTD$$

Furthermore, despite the fact that both functions described are based on the alpha plane, it should be noted that the operating characteristics used are different. For the $87_{ACAP}$ logic, illustrated in Fig. 2(a), the restraint characteristic corresponds to the left half alpha plane, and the operating characteristic (indicated in gray) corresponds to the right half alpha plane. For the $87_{EGAP}$ algorithm, illustrated in Fig. 2(b), the restraint characteristic corresponds to the entire region outside the operating characteristic, which corresponds to the circular fault settlement region, filled in gray.

### III. PRESENTATION AND DISCUSSION OF RESULTS

The performances are evaluated through the analysis of $\Gamma$ considering a wide variety of fault conditions and maneuver, which were simulated in the ATP software. So, an electric power system was modeled, composed by a 500 kV/60 Hz line 400 km long with 60 % shunt compensation by means of dry-type air-core shunt reactors. These reactors are installed at both line ends and each of them has the inductive impedance of 1331 $\Omega$.

Through the used reactor model, it is possible to simulate both turn-to-ground and turn-to-turn faults. Therefore, the faulted phase winding must be modeled as a sequence of three subwindings coupled together in series; $n_f$, $n_g$ and $n_h$ [15]. In turn-to-turn faults, three subwindings are required, such that $n_h = n_f - n_g$. On the other hand, to simulate the turn-to-ground fault, only two subwindings are used, such that the $n_h$ subwinding is implemented with small values (approximately zero ohm), so that the phase impedance is distributed predominantly in the two remaining subwindings and $n_f = n_T - n_g$.

In this reactor model, the fault current is influenced by the leakage factor, which is a constant that varies from 0 (zero) to 1 (one) and measures how much the short-circuit current is dispersed during a fault. The leakage factor depends on the constructive aspects of the reactor and the percentage of turns involved. Thus, the leakage factor $\alpha_{fg}$ is calculated for the turn-ground faults, and measures the coupling between $n_f$, $n_g$. And for turn-to-turn faults, the three leakage factors $\alpha_{fg}$, $\alpha_{gh}$ and $\alpha_{fh}$ are calculated and measure the coupling between the three subwindings. It is noteworthy that these three leakage factors will be considered equal and labeled $\alpha_{lt}$ for the simulations of turn-to-turn faults.

The simulations performed were firstly implemented through some maneuvers cases, in order to evaluate the performance of $87_{ACAP}$ and $87_{EGAP}$ functions while transients occur in the system, such that these analyses are evaluated
during time. After this, the parametric sensitivity analysis were also simulated, in which the behavior of $\Gamma_{ACAP}$ and $\Gamma_{EGAP}$ functions during the fault steady-state regime are evaluated.

A. Transient Analysis

For the assessment of the influence of transients on the evaluated functions, the performance of $\Gamma_{ACAP}$ and $\Gamma_{EGAP}$ functions is initially presented for a case of a single-phase-to-ground external fault, applied immediately before the CT $A$ (indicated in Fig. 1) and, therefore, outside the differential protection zone. It is noteworthy that the fault was applied in 100 ms and the behavior of $\Gamma_{ACAP}$ and $\Gamma_{EGAP}$ between 80 ms and 130 ms are shown in Fig. 3. It is verified that none of the functions operate, which contributes to prove the secure of both algorithms.

External faults that lead to CT saturation can also result in maloperations of protection [5]. Therefore, the occurrence of an external single-phase-to-ground fault in phase A at 100 ms was simulated, which culminated in the saturation of the CT of phase A. The behavior of $\Gamma_{ACAP}$ and $\Gamma_{EGAP}$ between 80 ms and 130 ms are shown in Fig. 4, in which it is verified that, even with the CT saturation, $\Gamma_{ACAP}$ and $\Gamma_{EGAP}$ functions remained in the restraint regions, avoiding the protection from sending a trip command for this critical external fault.

The protection functions performances were also evaluated during the transmission line energization. The energization maneuver was implemented considering the closing of the remote terminal breakers in 100 ms, such that Figs. 5(a) and 5(b) illustrate the $\Gamma_{ACAP}$ and $\Gamma_{EGAP}$ functions behavior, respectively, between 80 ms and 130 ms. And the total energization of the line took place with the closing of the local terminal in 500 ms, such that Figs. 5(c) and 5(d) illustrate the $\Gamma_{ACAP}$ and $\Gamma_{EGAP}$ functions behavior, respectively, between 480 ms and 530 ms. From these results, it is noted that none of the functions misoperate, even with transients caused by line energization.

From all the results of the transient analyses, it is observed that the evaluated functions operate properly, even if transients occur in the electrical system.

B. Parametric Sensitivity Analysis

In order to assess the influence of the dispersion factor and the number of turns involved in the evaluated differential functions, different cases of turn-to-ground and turn-to-turn faults were obtained, varying the value of leakage factor and also the amount of turns involved, as indicated in Table I. For $\Gamma_{ACAP}$ function, the pickup current was considered as $I_{pk87ACAP} = 0.1 \text{ pu}$. For $\Gamma_{EGAP}$ function, the pickup current was considered as $I_{pk87EGAP} = 0.1 \text{ pu}$ and, for the sake of security, the parameters were set as: $\Gamma_F = 2.0$, $k_Delta = 0.4$ and $\Psi = 5$ [14]. It is noteworthy that, to obtain a fairer comparative evaluation, for both $\Gamma_{ACAP}$ and $\Gamma_{EGAP}$ functions, the complex ratio $\Gamma$ was calculated if at least one of $I_{df}$ or $I_{res}$ has magnitude larger than the pick-up threshold ($I_{pk87EGAP}$). Otherwise, $\Gamma$ is fixed in (-1.0).

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 [16]. 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 ($N = 16$).

Based on turn-to-ground faults simulations, wich encompass Cases 1, 2 and 3 (with $R_f = 0\Omega$) and Cases 4, 5 and 6

![Fig. 3.](image1.png)

![Fig. 4.](image2.png)

![Fig. 5.](image3.png)
TABLE I
FEATURES OF THE EVALUATED FAULTS.

<table>
<thead>
<tr>
<th>Case</th>
<th>Type of Fault</th>
<th>Leakage Factor</th>
<th>Subwinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turn-to-ground and $R_f = 0 \Omega$</td>
<td>$\alpha_{fg} = 0.25$</td>
<td>$n_g : 1$ to $99%$</td>
</tr>
<tr>
<td>2</td>
<td>Turn-to-ground and $R_f = 0 \Omega$</td>
<td>$\alpha_{fg} = 0.50$</td>
<td>$n_g : 1$ to $99%$</td>
</tr>
<tr>
<td>3</td>
<td>Turn-to-ground and $R_f = 0 \Omega$</td>
<td>$\alpha_{fg} = 0.75$</td>
<td>$n_g : 1$ to $99%$</td>
</tr>
<tr>
<td>4</td>
<td>Turn-to-ground and $R_f = 100 \Omega$</td>
<td>$\alpha_{fg} = 0.25$</td>
<td>$n_g : 1$ to $99%$</td>
</tr>
<tr>
<td>5</td>
<td>Turn-to-ground and $R_f = 100 \Omega$</td>
<td>$\alpha_{fg} = 0.50$</td>
<td>$n_g : 1$ to $99%$</td>
</tr>
<tr>
<td>6</td>
<td>Turn-to-ground and $R_f = 100 \Omega$</td>
<td>$\alpha_{fg} = 0.75$</td>
<td>$n_g : 1$ to $99%$</td>
</tr>
<tr>
<td>7</td>
<td>Turn-to-turn</td>
<td>$\alpha_{tt} = 0.25$</td>
<td>$n_f : 1%$ $n_g : 1$ to $98%$</td>
</tr>
<tr>
<td>8</td>
<td>Turn-to-turn</td>
<td>$\alpha_{tt} = 0.50$</td>
<td>$n_f : 1%$ $n_g : 1$ to $98%$</td>
</tr>
<tr>
<td>9</td>
<td>Turn-to-turn</td>
<td>$\alpha_{tt} = 1.00$</td>
<td>$n_f : 1%$ $n_g : 1$ to $98%$</td>
</tr>
</tbody>
</table>

(with $R_f = 1000 \Omega$), it is verified from Figs. 6, 7, 8, 9, 10 and 11 that both $\Gamma_{ACAP}$ and $\Gamma_{EGAP}$ functions identify the fault for all the tested cases, regardless of the number of turns involved, the leakage factor value and fault resistance values. It stands out both functions operated even in cases where fault current has a low value, as in situations with few turns involved of Case 3 (with high leakage factor value). The challenge of identifying the simulated faults in case 6 is also highlighted, as in addition to having high leakage factor value, these faults also have a fault resistance of $1000 \Omega$, which further reduces the fault current value, making it difficult for protection operation.

Despite operating correctly, it can be seen from Figures 6(a), 7(a), 8(a), 9(a), 10(a) and 11(a) that $\Gamma_{ACAP}$ greatly varied its value according to the number of turns involved, and for a few turns, the real part of $\Gamma$ presented magnitude in the order of $10^{-3}$, making the complex ratio to be very close to the restriction region. On the other hand, the $\Gamma_{EGAP}$ showed a more stable behavior, remaining on the inner circle of operation region, regardless of the number of turns involved and leakage factor value, as indicated in Figs. 6(b), 7(b), 8(b), 9(b), 10(b) and 11(b).

In Figs. 12, 13 and 14 the performance of the evaluated...
functions for turn-to-turn fault simulations, corresponding to Cases 7, 8 and 9, are presented. It can be seen that $\Gamma_{ACAP}$ moves to the operating region (half-right alpha plane) and exhibits stable behavior, regardless of the number of turns involved and the leakage factor value, as illustrated in Figs 12(a), 13(a), 14(a). It is noteworthy that $\Gamma_{ACAP}$ function can identify the fault, even in cases whose fault current has a low value, as in situations with few turns involved of Case 9 (with high leakage factor value).

However, the performance of the $\Gamma_{EGAP}$ function is restricted depending on the fault analyzed. It is verified from Fig. 12(b), that for Case 7, $\Gamma_{EGAP}$ lies inside operating region only for faults with less than 85% of turns evolved. From case 8, whose result is shown in Fig. 13(b), it is noted that $\Gamma_{EGAP}$ moves to the interior of the operating region only for faults with less than 89% of turns evolved. And for Case 9, $\Gamma_{EGAP}$ moves into the operating region only for faults with less than 90% of turns evolved, as indicated in Fig. 14(b).

Comparing the results obtained from the two analyzed logic, it is verified that for turn-to-ground faults, the $\Gamma_{EGAP}$ function presents a more stable behavior, remaining on the inner circle of operation region, regardless of the number of turns involved, leakage factor value and fault resistance value. On the other hand, for turn-to-turn faults, the $\Gamma_{ACAP}$ function exhibits a more stable behavior, with little variation of the $\Gamma'$ complex ratio, regardless of the number of turns involved and the leakage factor value. These results show that the joint use of these two functions guarantees a more stable and safe behavior for the protection of shunt reactors. It is noteworthy that the combined use of these two functions is possible since both depend on the same measurements: the phase currents (to calculate the zero sequence current) and the neutral current.

**IV. CONCLUSION**

Based on the analyzes described, it is verified that both functions can identify turn-to-ground and turn-to-turn faults in the dry-type air-core shunt reactor, even when dealing with low current faults. It should note that these disturbances with low current can occur when there are few short-circuited turns, when the leakage factor value is high and when the fault resistance value is high. If these three conditions coincide, the fault current will be even lower. Still, according to the results presented, the evaluated protection functions could identify the fault correctly.

Furthermore, it can see that for turn-to-ground faults, the $\Gamma_{EGAP}$ function presents a more stable behavior, remaining on the inner circle of the operation region. Nonetheless, for turn-to-turn faults, the $\Gamma_{ACAP}$ function exhibits a more stable behavior, with a slight variation of the $\Gamma'$ complex ratio. Since both evaluated functions depend only on the zero sequence currents (calculated based on the phase currents) and the
neutral current, it is concluded that the joint use of these two functions guarantees more secure identification of both turn-to-ground faults and turn-to-turn faults in a shunt reactor.

It is noteworthy that using these two logic is independent of voltage measurement, making their use feasible, even if the system does not have VTs installed near the reactor.

REFERENCES


