Assessment of the Main Phasor-Based Power Transformer Differential Protection Elements

R. P. Medeiros, F. B. Costa, *Member*, *IEEE*, and M. A. D. Almeida

***Abstract*—With the advance of the digital technology, the basic principles of the power transformer differential protection have been implemented in logical schemes in the modern numerical differential relays. Moreover, the power transformer differential protection also incorporated the usage of additional protection functions, such as harmonic restraint, harmonic blocking, and negative-sequence current differential elements, improving the discrimination between internal faults and other events. This paper aims to present an analysis about the operation of the main phasor-based differential protection functions during the occurrence of relevant disturbances involving a power transformer modeled in ATP software. By means of the analyze of the differential currents obtained in the different records, the behavior of the several protection functions and the importance of each one were highlighted in order to ensure a robust, reliable and fast protection.**

***Index Terms*—Power transformer, differential protection, harmonic restraint, harmonic blocking, negative-sequence.**

I. Introduction

Power transformers are essential components in many energy conversion systems, allowing the widespread usage of the AC current energy systems, due to the possibility of the voltage levels adjustment between the generation, transmission and distribution systems [1].

As other components operating in the electrical system, power transformers are submitted to the adverse effects of the electrical transients constantly. When these devices have some failure, its repair demands an expensive financial cost because its high commercial value and the possible fines applied due to the temporary unavailability of energy [2]. According to [3], about 10% of faults in electrical systems occur in power transformers, in which 70% are caused by short-circuits in their windings and switches taps, which justifies the research for faster and more reliable protection schemes than the conventional one.

Among the protective functions applied in transformers, differential function has been widely used as primary protection for power transformers with rated power greater than 10 MVA [4], providing reliable discrimination between internal and external faults or nominal load conditions. Furthermore, the technological advancement became possible the implementation of the differential protection principles in microprocessed numerical relays, which proved to be faster and more reliable than the old electromechanical relays [5].

This work was supported by CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico).

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In general, differential relays compare the currents flowing through of the protected transformer terminals, so that in an internal fault condition, the equipment is disconnected from the electrical system. However, some operating conditions, such as transformer energization maneuvers can cause significant inrush currents. In order to prevent relay misoperation in these cases, the correct discrimination between a fault current and an inrush current is required [6].

In order to overcome this problem, modern relays have employed some phasor-based differential protection methods, whose operating principle is associated to the restraint and blocking of specific harmonic components. For instance, in transformer energization, the 2nd order harmonic component of the differential current is usually higher that in a typical fault current [7]. However, according to [2], most of the commercial numerical relays has not been able to protect power transformers for faults that happen in less than 15% of their windings, i.e., those faults involving few turns (incipient internal faults). In these cases, a negative-sequence differential element with high sensitivity has been used as a backup protection [8].

This paper presents an analysis about the operation of the main phasor-based power transformer differential protection functions (harmonic blocking, harmonic restraint, and negative-sequence) during the occurrence of relevant disturbances involving a power transformer modeled in ATP software, such as an external fault, external fault clearance, current transformer (CT) saturation due to an external fault, transformer energization in the presence or absence of a fault, and internal faults. By means of the analyze of the differential currents obtained in the different records, the behavior of the several protection functions and the importance of each one were highlighted in order to ensure a robust, reliable and fast protection.

II. Power Transformer Differential Protection Elements

The traditional phase differential protection is commonly applied in power transformers with rated above 10 MVA [4]. However, it has been used in association with some additional protections addressed in this section.

A. Traditional Phase Differential Protection

The traditional phase differential protection scheme is based on the comparison between an operating current (I_{op}) an restraining current (I_{res}) in a differential characteristic curve (Fig. 1). The former is usually computed as follows [8]:

$$I_{op} = |\widehat{I}_H + \widehat{I}_X|, \tag{1}$$

whereas I_{res} can be computed as follows [8]:

$$I_{res} = k(|\widehat{I}_H| + |\widehat{I}_X|), \tag{2}$$

where $\widehat{I}_H$ and $\widehat{I}_X$ correspond to the secondary phasor currents flowing through the CTs connected to the high and low voltage power transformer windings, respectively, and the constant k presents typical values equal to 0.5 or 1.0. Therefore, the relay operates if the operating point (I_{res}, I_{op}) is located in the operating region, as follows:

$$I_{op} > I_{puT}, \tag{3}$$

$$I_{op} > SLPI_{res}, \tag{4}$$

where I_{op} is the operating current; I_{res} is the restraining current; I_{puT} is the minimum current adjustment; and SLP is the slope of the characteristic curve of the differential relay.

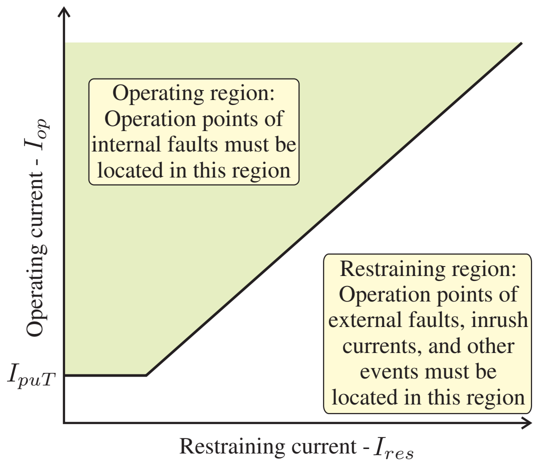

Fig. 1. Characteristic curve in a power transformer differential protection scheme.

B. Harmonic Blocking Differential Element

According to [9], the implementation of a harmonic blocking differential element takes into account a logic which blocks the differential relay when the ratio between a specific harmonic content and the fundamental component of the differential current reaches a pre-adjusted threshold. In this method, the differential element incorporates the concept of the traditional phase function defined in (3) and (4) and uses the magnitude of the harmonic components of 2nd and 4th order of the differential current in order to prevent the relay misoperation during inrush conditions and external faults with CT saturation. Therefore, if (3) and (4) are true, the relay will trip if (5) and (6) are also true, as follows:

$$K_2 I_2 < I_{op}, \tag{5}$$

$$K_4 I_4 < I_{op}, \tag{6}$$

$$K_N = \frac{100}{PCT_N}, \tag{7}$$

where I_2 and I_4 correspond to the magnitudes of the harmonic components of 2nd and 4th order of the differential current, respectively; k_2 and K_4 are constants; K_N is the constant associated to the magnitude of the nth order harmonic; and PCT_N is the percentage adjustment for the nth harmonic. When (5) or (6) are not met, it is expected that the harmonic content of the differential current is high enough, which blocks the relay operation.

The differential element also uses the magnitude of the fifth harmonic component of the differential current in order to block relay operation in power transformer overexcitation conditions. Therefore, the differential element is blocked when:

$$K_5 I_5 > I_{op}, \tag{8}$$

where I_5 is the magnitude of the harmonic component of 5th order of the differential current and K_5 is a constant.

C. Harmonic Restraint Differential Element

According to [9], the harmonic restraint differential element incorporates the concept of the traditional phase function and uses the harmonic components of 2nd and 4th order of the differential current to supply an additional restraint to the differential element, so as not to operate during inrush conditions and external faults with CT saturation, without sacrifice its reliability for internal faults with CT saturation. The harmonic restraint differential element operates if (3) and the following condition are met:

$$I_{op} > SLPI_{comp}, \tag{9}$$

in which I_{comp} is computed as follows:

$$I_{comp} > I_{res} + \frac{1}{SLP}(K_2 I_2 + K_4 I_4). \tag{10}$$

D. Negative-Sequence Differential Element

The operating principle of the negative-sequence current differential element (87Q) is similar to the traditional phase differential element. The operating (I_{opQ}) and the restraining (I_{resQ}) negative-sequence differential currents are computed from the negative-sequence phasor currents ($\widehat{I}_{HQ}$ and $\widehat{I}_{XQ}$) flowing by the CTs, as follows [9]:

$$I_{opQ} = |\widehat{I}_{HQ} + \widehat{I}_{XQ}|, \tag{11}$$

$$I_{resQ} = |\widehat{I}_{HQ}| + |\widehat{I}_{XQ}|. \tag{12}$$

The output of the 87Q element is activated if the differential element of common harmonic blocking is not enabled and if the following two conditions are met:

$$I_{opQ} > I_{puQ}, \tag{13}$$

$$I_{opQ} > SLP2 I_{resQ}, \tag{14}$$

where I_{puQ} and $SLP2$ correspond, respectively, to the minimum setting for the operation and the slope value for the characteristic curve of the negative-sequence current differential element.

III. Evaluation of Power Transformer Disturbances

In this paper, the performance of the harmonic blocking, harmonic restraint, and negative-sequence current differential elements was assessed for different disturbances related to the transformer of the power system detailed in [10]. The secondary current signals of the current transformers were extracted by means of a routine created within the MODELS language in the ATP software [10], at a sampling rate of $f_s = 960$ Hz, and filtered through a third-order Butterworth anti-aliasing low-pass filter, with cutoff frequency at $f_c = 0.9fs/2$. The CT secondary current phasor estimation through the full-cycle Fourier filter, as well as the implementation of the differential protection functions, were performed in an ATP external routine.

For the performance evaluation of the protection functions, in Figs. 2-9 are depicted the instantaneous currents measured in the secondary circuit of the CTs and the rms value obtained by the phasor estimation process for operating and restraining differential currents (phase and negative-sequence), as well as the rms value for the second, fourth, and fifth harmonic components of the operating current, in some typical events related to the power transformer protection. The protection functions were adjusted such that $K_2 = K_4 = \frac{100}{15}$, $K_5 = \frac{100}{35}$, $PCT_2 = PCT_4 = 15\%$, $PCT_5 = 35\%$, $I_{puT} = 1.0$ pu, $I_{puQ} = 0.1$ pu, $SLP = 0.5$, and $SLP2 = 0.8$.

A. External fault

In external faults to the transformer differential protection zone, differential relays must be designed to remain in blocking during normal system operation [11]. Fig. 2 depicts the currents signals related to a phase-to-ground fault in the high voltage bus, near to the power transformer.

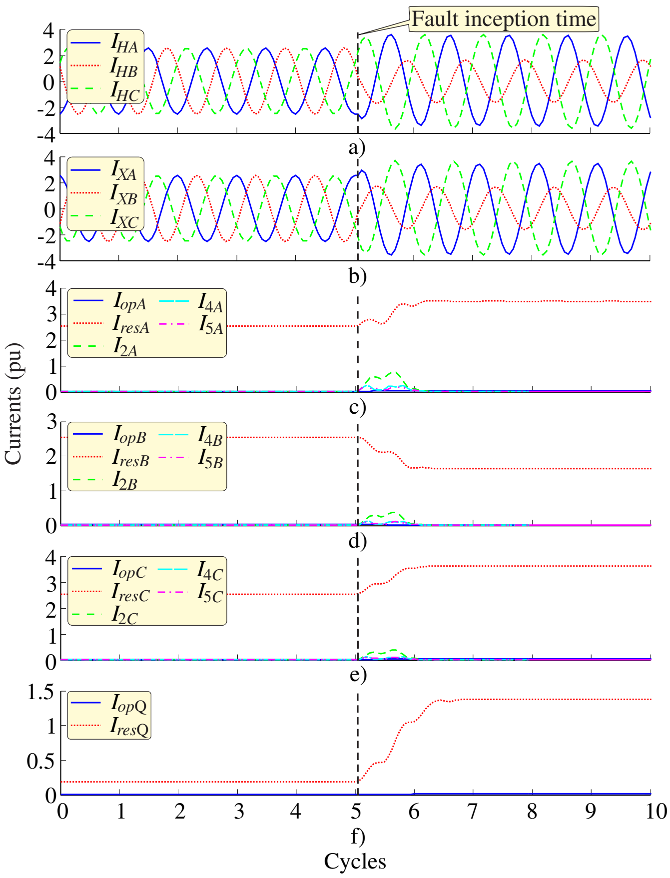

Fig. 2. Currents due to an external fault to the power transformer: a) Currents at the high-voltage side; b) Currents at the low-voltage side; c) Differential currents at phase A; d) Differential currents at phase B; e) Differential currents at phase C; f) Negative-sequence differential currents.

According to Fig. 2 and in the absence of the CT saturation, the external fault would not be wrongly detected as an internal fault, since the traditional phase differential unit was not sensitized (restraining currents always much greater than the operating currents). Moreover, the harmonic-based and the negative-sequence additional functions were not influenced during this event occurrence.

B. External Fault Clearance

Besides the power transformer energization, inrush currents may also arise during external fault clearance, causing the conventional differential relay to operate incorrectly [12]. Fig. 3 depicts the current signals related to a phase-to-ground fault in the high voltage bus, near to the transformer, followed by its clearance.

From the fault clearing time (Fig. 3), the operating current fell below the setting value for the operation of the differential relay, which would not compromise the efficiency of the analyzed differential elements, and the event would not be detected as an internal fault. However, the possible appearance of significant inrush currents during this event could lead to a relay misoperation, if it were not taken into account the implementation of the harmonic blocking unit.

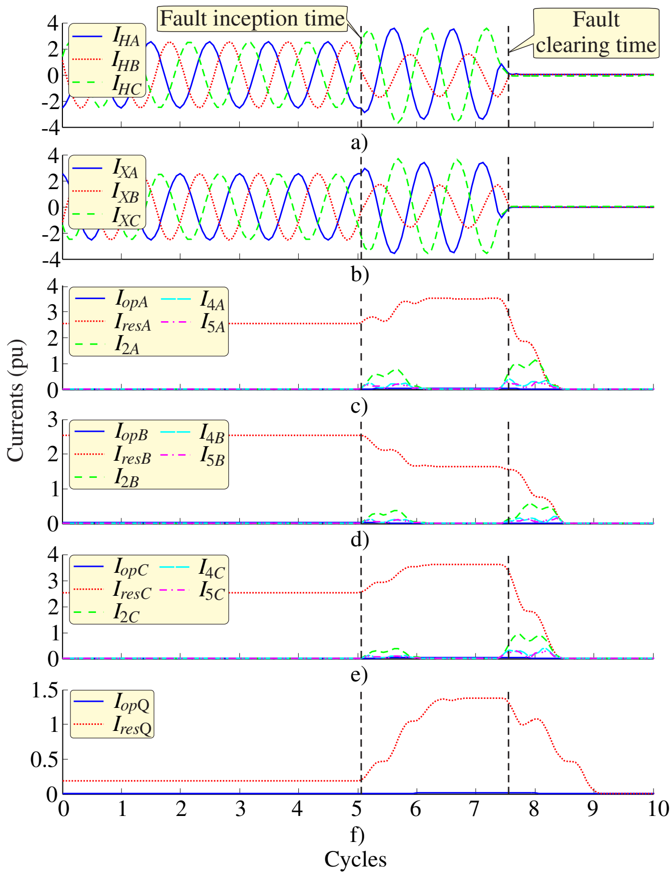

Fig. 3. Currents due to an external fault followed by its clearance: a) Currents at the high-voltage side; b) Currents at the low-voltage side; c) Differential currents at phase A; d) Differential currents at phase B; e) Differential currents at phase C; f) Negative-sequence differential currents.

C. CT Saturation

In the presence of CT saturation, a major concern in the transformer protective engineering is the possible operation failure of the differential relay for external faults, in which differential currents greater than the set values for the relay operation can be obtained. In these cases, the relay tends to operate improperly, and external faults are detected as internal faults from the beginning of the saturation [13]. Fig. 4 depicts the currents signals related to a phase-to-phase external fault near to the power transformer with CT saturation.

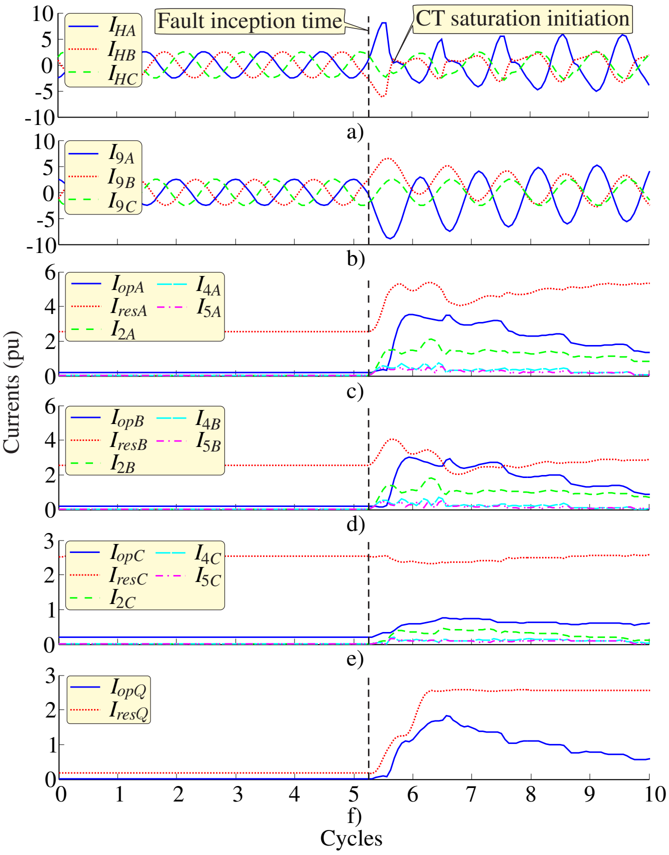

Fig. 4. Currents due to a external fault with CT saturation: a) Currents at the high-voltage side; b) Currents at the low-voltage side; c) Differential currents at phase A; d) Differential currents at phase B; e) Differential currents at phase C; f) Negative-sequence differential currents.

According to Fig. 4(a), about half-cycle after the onset of the fault, the secondary currents of the CT connected to the power transformer secondary winding were distorted due to CT saturation. During the saturation, the increase of the operating currents in phases A and B [Fig. 4] would cause problems to the phase differential function, leading to a relay misoperation. However, the harmonic blocking and harmonic restraint elements ensured safety to the protection scheme. The negative-sequence unit would not aware in this case.

D. Transformer Energization

During transformer energization, transformer differential relays are prone to unwanted operation in the presence of inrush currents [14]. Fig. 5 depicts the currents signals related to a transformer energization performed by closing the high-voltage circuit breaker with the secondary terminal opened.

According to Fig. 5, $I_{op} > I_{res}$ in all phases, which could generate a wrong trip command, if the phase function were used alone. However, due to the high-second harmonic content, the operation of the differential relay was blocked by the harmonic blocking function. In addition, due to the strong additional restraint caused by the inclusion of the harmonic components of 2nd and 4th order, the harmonic restraint differential element did not provide trip for this event. Fig. 6 depicts the behavior of the quantities in (5) and (9), during the occurrence of this event. For simplicity of the analysis, these equations were normalized by the operating current. Since the operating and restraining currents are equal during the energization, the negative-sequence element could be sensitized. However, the harmonic blocking inhibited the operation of 87Q element, which ensured security for the protection scheme.

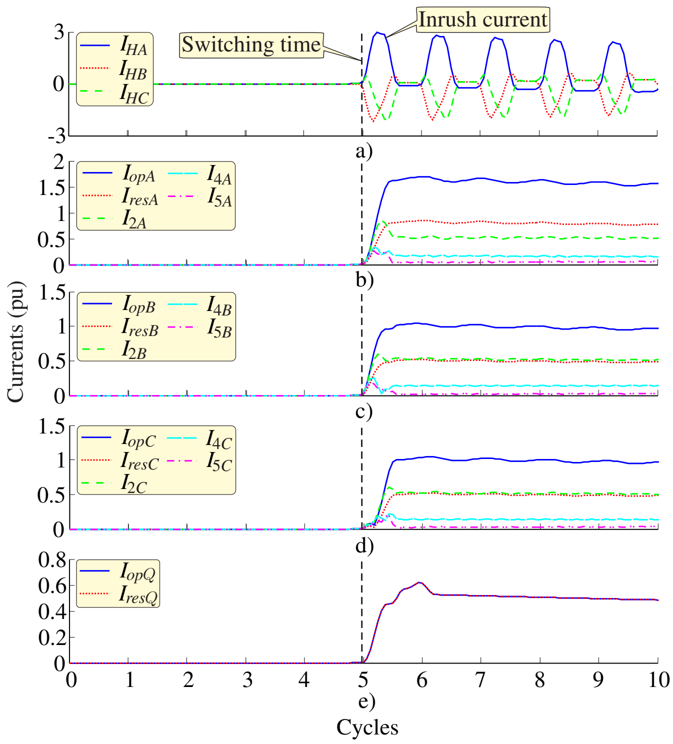

Fig. 5. Currents due to a power transformer energization: a) Currents at the high-voltage side; b) Currents at the low-voltage side; c) Differential currents at phase A; d) Differential currents at phase B; e) Differential currents at phase C; f) Negative-sequence differential currents.

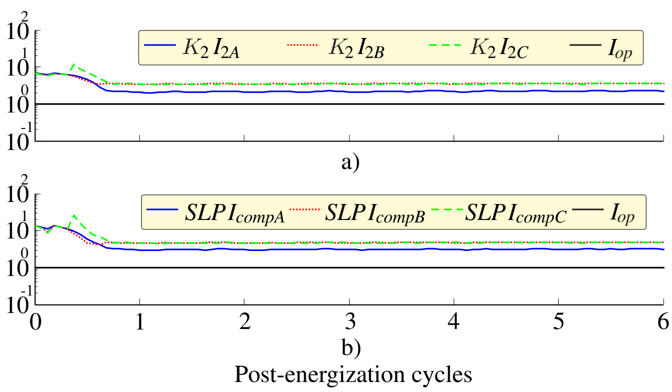

Fig. 6. Behavior of the harmonic restraint and second harmonic blocking functions, in all phases, during power transformer energization.

E. Transformer Energization with Internal Fault

In transformer substations, the accumulation of water from rainfall within the enclosure of a transformer can cause a fault during its energizing [15]. Energizing a transformer with a fault within its differential protection zone has been a challenge to the protective engineering, since the appearance of the harmonic content relating to the inrush currents can block the operation of the relay, which can cause damage to the power transformer [9]. Fig. 7 depicts the currents related to a situation in which the power transformer is switched-on in the presence of a fault involving the phases B and C.

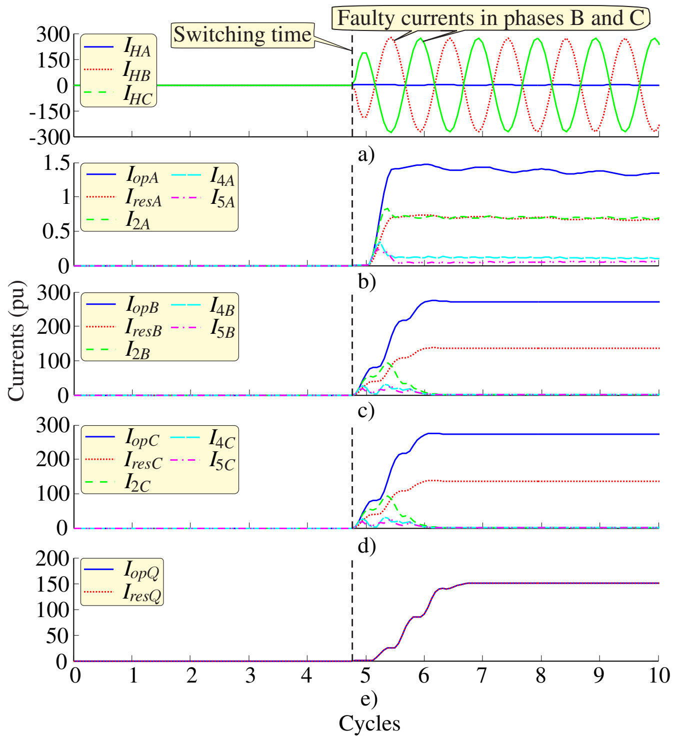

Fig. 7. Currents due to a power transformer energization with internal fault: a) Currents at the high-voltage side; b) Currents at the low-voltage side; c) Differential currents at phase A; d) Differential currents at phase B; e) Differential currents at phase C; f) Negative-sequence differential currents.

According to Fig. 7, the high-second harmonic content verified in phase A of the differential current was able to block the differential element in all phases. However, the fault could be appropriately discriminated from the inrush current by analyzing the behavior of the currents in B and C faulty phases and by considering the operation of the harmonic restraint and negative-sequence differential elements.

F. Internal Fault

The occurrence of faults in transformer bushings is directly associated with the loss of their dielectric properties and can be a result of problems with sealing elements or even the aging of insulation [16]. Fig. 8 depicts the currents related to an internal fault in the transformer bushing.

According to Fig. 8, all the analyzed differential elements could detect the internal fault in the transformer bushing, since the operating currents were greater than the restraining ones and almost no harmonic content was verified in the differential currents.

G. Incipient Internal Fault

According to [9], the phase differential element is usually able to detect the most internal faults in transformers, except

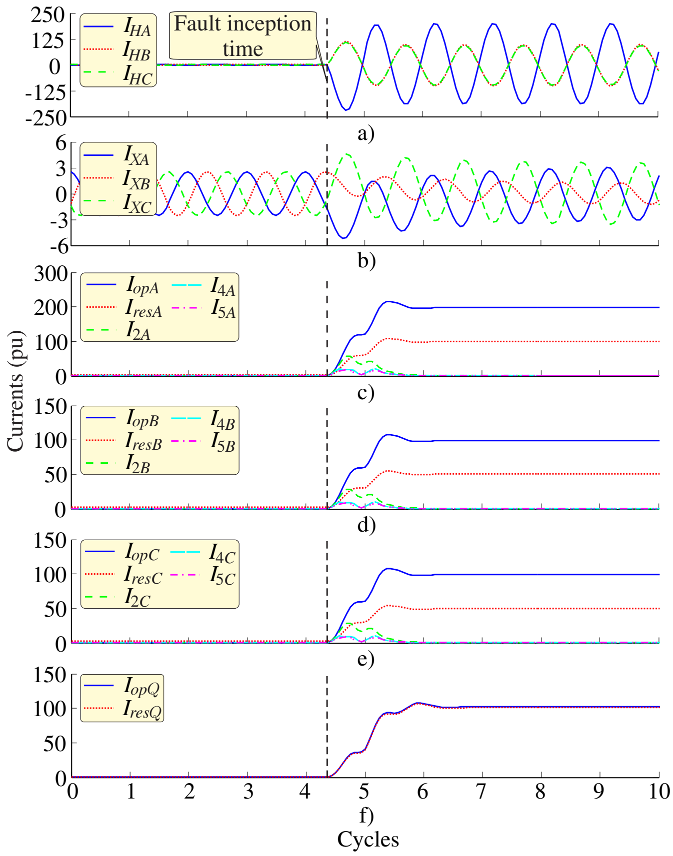

Fig. 8. Currents due to a fault in the transformer bushing: a) Currents at the high-voltage side; b) Currents at the low-voltage side; c) Differential currents at phase A; d) Differential currents at phase B; e) Differential currents at phase C; f) Negative-sequence differential currents.

some cases of turn-to-turn faults in a same winding and phase-to-ground faults close to the transformer neutral, in which the fault current can be confused with the transformer load current, which may compromise the operation of the protection scheme. However, these types of faults (incipient faults) are asymmetrical and cause negative-sequence currents circulating in the system, which can be detected through the use of a negative-sequence current differential element [17]. Fig. 9 depicts the currents signals for a turn-to-turn fault involving only 2% of the wye winding.

According to Fig. 9, the increase in the operating current was minimal in all phases so that the traditional differential element could not detect the fault. However, the negative-sequence operating current was quite sensitized, which would make possible the detection of the event, highlighting the importance of usage of the negative-sequence differential element with high sensitivity in association to the traditional phase differential protections.

IV. Conclusion

This paper presented an approach based on the performance assessment of some phasor-based differential protection functions upon the occurrence of different disturbances associated to the power transformer operation.

The usage of the harmonic content of the differential current in the harmonic restraint and harmonic blocking schemes

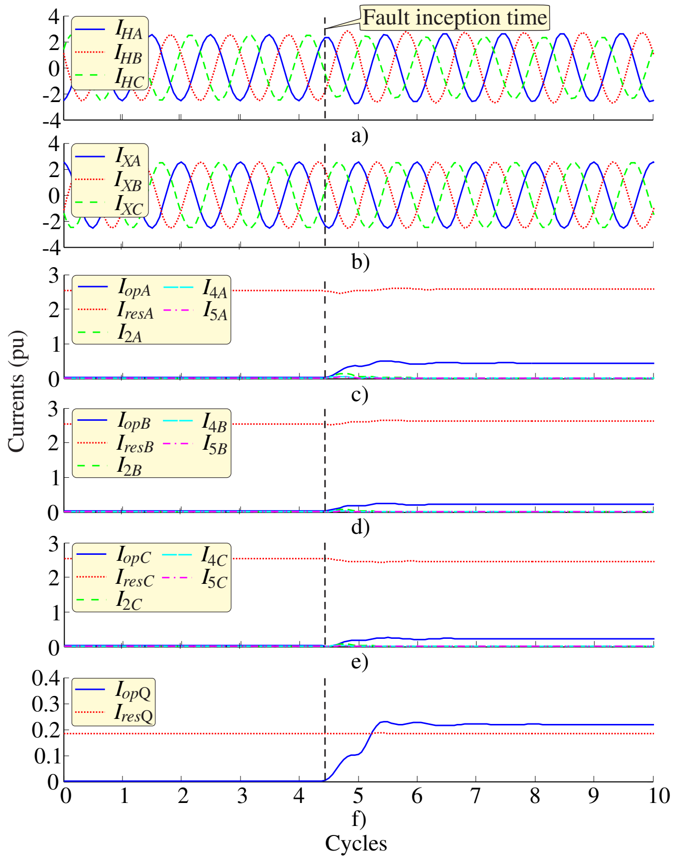

Fig. 9. Currents due to a turn-to-turn fault involving only 2% of the wye winding: a) Currents at the high-voltage side; b) Currents at the low-voltage side; c) Differential currents at phase A; d) Differential currents at phase B; e) Differential currents at phase C; f) Negative-sequence differential currents.

was essential in preventing relay misoperation during inrush conditions and external fault with CT saturation, as well as was able to discriminate appropriately a transformer energization event followed by a fault. In addition, a negative-sequence differential element operating in parallel with the traditional differential element proved to be efficient in an incipient internal fault detection.

Based on the assessed disturbances, the phasor-based differential protection scheme with its functions well adjusted can be quite selective, being properly applied to the power transformer protection. However, the protection with phasor-based functions may face delays in the internal fault detection due to the required time in the estimation of the harmonic components in the transition from the pre-fault to the post-fault periods, suggesting further studies which might leverage the development of faster protection methods.

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