

Developing Busbar protection with new differential characteristics to solve the breakpoint settings of digital commercial relays

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ABSTRACT

The current commercial characteristics of the digital differential relays have many breakpoint settings of time delay due to Current Transformer Saturation “CT-SAT” and error. This can decrease the sensitivity of the Merz-Price circulating current protection relays. However, to enhance the stability of this type of relays, the operating threshold boundary is increased. This will cause serious limitations for the relays during faults occurrence inside the Bus-bar zone. The protection characteristic of such relays is based on the phasor quantities, in such case the secondary current during the CT-SAT equals to zero. To improve the Merz-Price circulating current protection characteristic, the relay operation should depend on the features of the faulted instantaneous current rather than the phasor quantities. The paper develops new Merz-Price circulating current characteristic based on the wavelet transform of the noises generated by the fault. The captured noises have valuable information during the CT-SAT. The study shows the performance improvement in system sensitivity and stability of the new characteristic. All types of the faults are successfully detected due to current saturation, ratio mismatch, early and late saturation.

1. Introduction

The traditional Merz-Price circulating current concept is based on the current magnitude for estimating the restraining and biasing values. The significant imbalance comes from the secondary current of a current transformer with a resistive burden which collapses to zero when SAT occurs and it remains at zero until the time when the next zero crossing would have occurred [1].

The Merz-Price circulating current concept is carried out by balancing the secondary current of the CT for all of the circuits connected with the bus and then bridging this balanced circuit with the operating coil of the relay. Current transformers may saturate and cause the Merz-Price circulating current to work in not ideal case. The low impedance measuring principle employs the zone-selective Merz-Price circulating current as the operating quantity and the sum of the current magnitudes as the stabilizing signal. The measuring principle must ensure protection stability with SAT on external faults.

Unfortunately, the current transformer may saturate and thus may cause the Merz-Price circulating current to operate in different way. The protection of Busbar requires fast operation, reliability and dependability. The operation of Busbar methods is enhanced in [2,3].

Based on Merz-Price circulating current protection concept, some papers are discussed in [4–11]. Some authors dealt with the problem of

the CT-SAT [12–14]. Some other authors applied the wavelet using many types of functions [15–18]. Most of the techniques ignored the effect of SAT. Some papers have provided additional measures. These methods do not provide accurate solution during severe and early CT-SAT and do not improve the sensitivity of the Merz-Price circulating current characteristic. The differential protection should maintain security during CT-SAT for external faults while keeping high sensitivity and speed of operation for internal low faults. Relay manufacturers provided very little information for the protection engineers to set the relay adequately [19]. Some authors in [20] enhanced the security of differential numerical relay by extracting the 2nd order harmonic using Fast Fourier Transform “FFT” to produce a restraint signal to prevent the relay operation in case of external faults. Some authors did block for the Merz-Price circulating current values during the period of the cycle that the current transformer is saturated. There are many techniques that have developed many break-point settings in the operating characteristic. New digital differential relays provide complex signal processing and decision logic that make their behavior under CT saturation difficult to predict. Some new relays use complicated algorithms to detect CT saturation and prevent relay operation under CT conditions.

The time and frequency localization properties of Continuous Wavelet Transform (CWT) offers a viable and improved option for analyzing the transient characteristics of defect signals. The CWT

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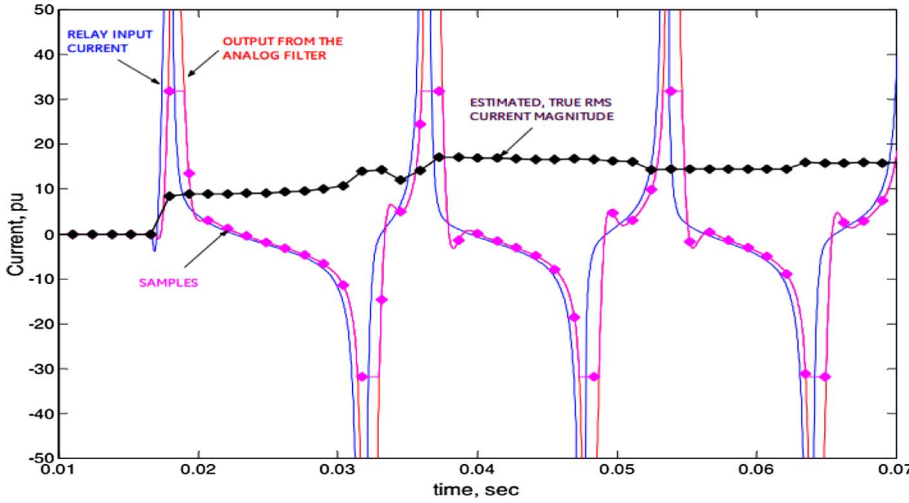


Fig. 1. The true RMS calculation during the CT-SAT [21].

depends on high frequencies superimposed on the faulted signal during SAT.

The technique is based on the windowed wavelet transform of the transients generated from the faults to distinguish between faults in a Bus-bar protection zone from external zone, particularly in case of severe and early SAT. These features can help discrimination the external faults in case of CT-SAT (severe and early cases). The paper introduces new Merz-Price circulating current busbar characteristic with values depending on a windowed signal captured from the transient generated from the faults. The time and frequency information during SAT can be obtained rather than the zero current values produced due to SAT when scan continues signal with specific properties on the current signal. The proposed idea depends on the featured noises of the current signal extracted from the saturation period not from the current magnitude. The time and frequency data impeded in the current signal during the SAT can be obtained instead of the zero current values. The proposed technique ignores the breakpoint settings of the commercial operating characteristic and introduces new Merz-Price circulating current characteristic depending on small pickup setting.

Fig. 1 shows an example of the relay input current and the output from the secondary during the CT-SAT. If the true RMS value is estimated from the secondary side, as shown in the figure the relay is subjected to 64kA of fault current, and measures “only” 10–15 pu of the current (50–75A secondary, or 500–750A primary). As shown in the figure it can be estimated by only about 1% of the true current, but still 10–15 times relay rated current [21]. All the current relays used are based on the current magnitude during the CT-SAT that cause relay failure. The relays consider the period of saturation equals to “zero”. The proposed idea has the novelty while this period is studied well and more features rather than “zero” values are extracted from it. The provided idea ignores the multi-breakpoint settings of the commercial characteristic and introduces new Merz-Price characteristic without breakpoints and with small setting values for relay acceleration.

2. Limitation of commercial merz-price circulating current characteristic

The operating principle of the Merz-Price circulating current is based on current Kirchhoff's Law. This compares the amount of current entering and leaving the protected zone and the check zone. During normal operation, the current flowing into the area and the check zone concerned is equal to the current flowing out of the area. In this case, the net currents are canceled out. When a fault occurs the Merz-Price circulating current that arises is equal to the derived fault current. Merz-Price circulating current may also be generated under external fault conditions due to CT error. To provide stability for through fault

conditions the relay adopts a biasing technique, which effectively raises the setting of the relay in proportion to the through fault current thereby preventing relay mal-operation. The commercial bias characteristic with Merz-Price circulating current technique depends on bias characteristic as given in Fig. 2(a). It is a comparison between the Merz-Price circulating and the restraining current. This is the most common characteristic for current commercial relays. A fault is detected if Merz-Price circulating current increases the set slope of the bias characteristic. Normally the characteristic is obtained to guarantee the stability of protection during external faults. Most of the error come from the different specification and characteristic of CTs. Consequently, such CTs cause differing performance. Most algorithms perform as follows:

$$\text{Circulating Current: } i_{diff}(t) = \left| \sum \vec{i} \right| \quad (1)$$

$$\text{Bias or Restraining current: } i_{bias}(t) = \sum |\vec{i}| \quad (2)$$

If the slope of the bias characteristic at certain zone (zone x below the slope) = kx The tripping can be permitted using the bias element as;

$$i_{diff}(t) > kx \cdot i_{bias}$$

As shown in Fig. 2(a) for Phase Fault elements:

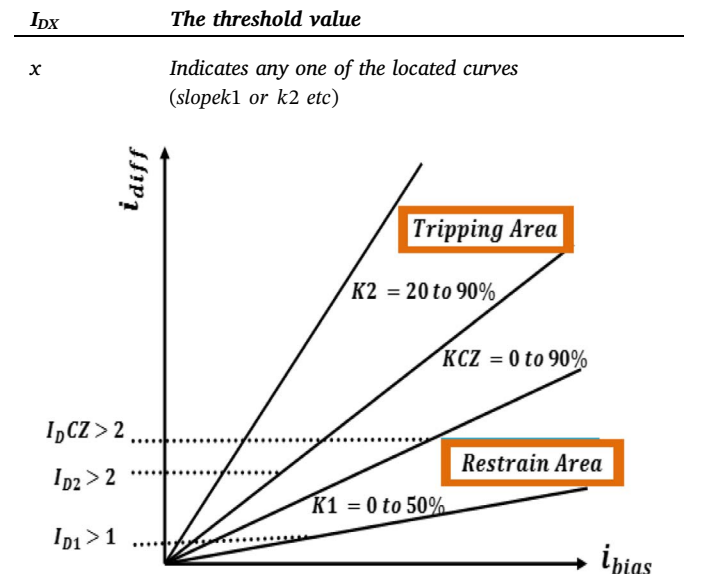


Fig. 2. (a) The P740 characteristic [22] (b) New Merz-Price circulating characteristic (c&d) Shannon wavelet effect during SAT.

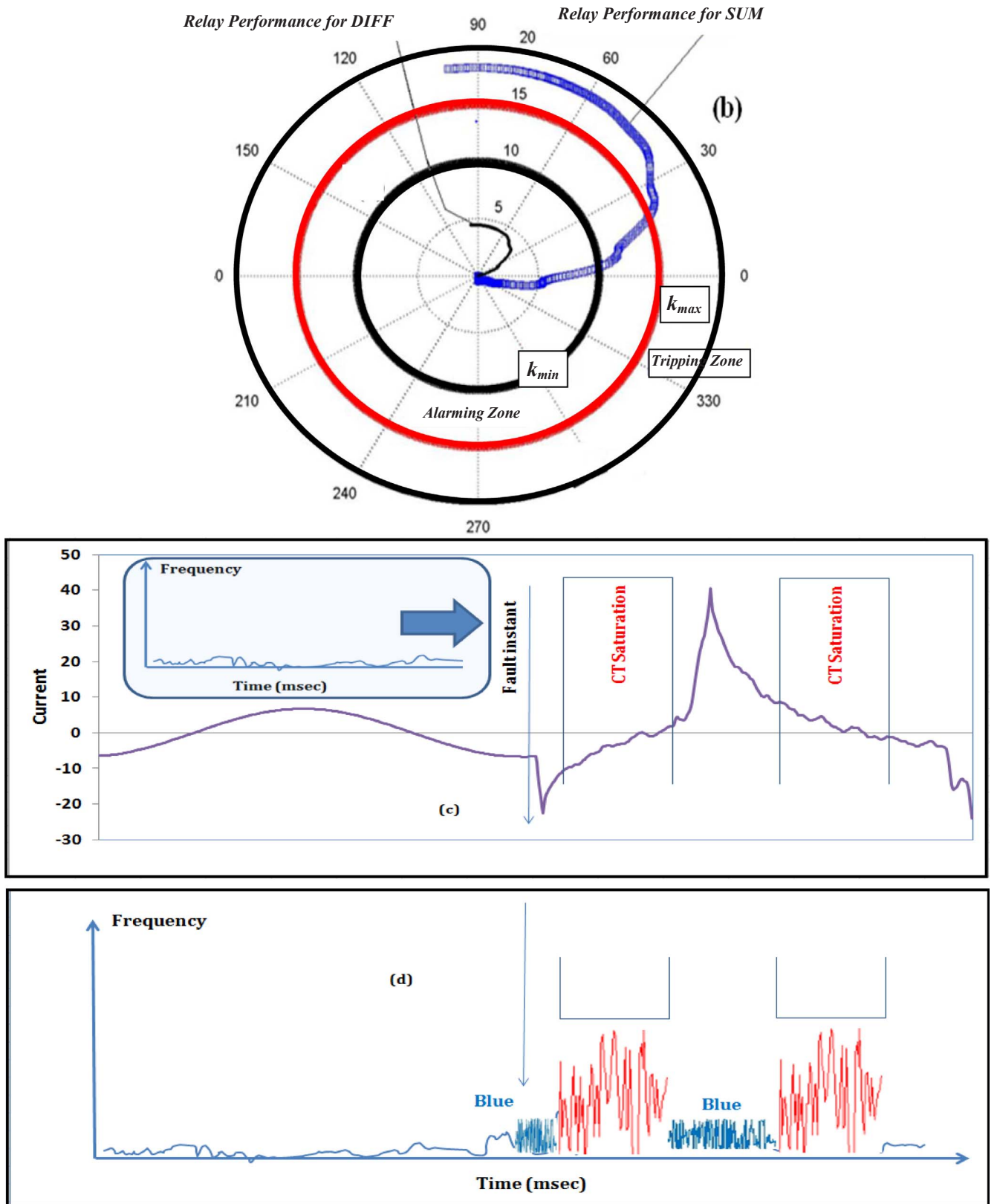


Fig. 2. (continued)

k_{CZ} Check Zone slope adjustment
 $I_{D/CZ}$ Check Zone differential current threshold
 k_2 Phase current slope adjustment 0.20...0.90 (step 0.1)
 k_1 Circuitry fault threshold 0.00...0.50 (step 0.01)

k_{min} and k_{max} Stabilizing factors for the new characteristic (pick up values)

The main Merz-Price circulating current element of the commercial relays can operate when the Merz-Price circulating current exceeds threshold $I_{DX} > 2$. The setting is adjusted above the normal full load

current. The phase characteristic is defined according to the next protection settings:

Area above $I_{DX} > 2$ (i.e. High set differential current threshold setting and the set slope of the bias characteristic $k_2 \times I_{bias}$). The setting can be adapted above the rated load current. During the fault occurrence on the busbars in a substation, the Merz-Price circulating values of current in the faulted area is equal to the values obtained in the whole scheme. This is the operation of the “Checking-Area”.

There are some misoperation reasons in Merz-Price circulating current Busbar protection techniques such as the wrong location of the isolators/CBs or a failure of the CT. Such mentioned problems will cause the Merz-Price circulates current in the connected nodes. This can produce a Merz-Price circulating current in one or more current nodes. If there is a monitoring element for the incoming and outgoing currents, the net value of the current is almost equal zero in the healthy cases and an error will lie with the zone’s assumption of the plant position at certain point in time [22]. The setting is selected to be as low as possible (minimum suggested setting is 2% of the biggest transformer primary winding) but also permit for standing Merz-Price circulating current (As an example, the transformer mismatch and magnetizing current losses) (i.e., 5 to 20% is a typical application range). The Merz-price circulating value is initiated and equals the saturated value during the external fault current associated with SAT. In some cases, the Merz-Price can measure circulating values of the current and may be estimated as an internal fault causing undesirable tripping at a substation busbar.

The characteristic of the “Checking-Area” can be resolved as the Zone above the $I_D CZ > 2$ value of the Merz-Price circulating threshold and the setting of the slope of the characteristic bias kCZ . I_{bias} , where kCZ is the bias slope value in the “Checking-Area”. One of the main limitations of this area operation is the origin of the slope at Bias-characteristic that should be zero. Slope $k_2(I_D > 2)$ is advised to be 60% that guarantee stability even in case of merit ratio events.

Some techniques are used to block the circulating measurement during the period of CT-SAT. This is done by short-circuiting the circulating path; a low-burden is located on the terminal of the CTs. In this case the Merz-Price circulating relay is blocked from responding on the spill current. The use of any technique for inhibiting operation, to enhance stability performance for through faults, must not be allowed to diminish the ability of the relay to respond to internal faults. If the CTs carrying fault current is not saturated there will be little current in the circulating circuit to operate the relay quickly for fault currents exceeding the minimum operating level, which is adjustable between 20% and 200% rated current.

During the case of internal faults with SAT effect, the SAT-detectors will prevent the operation by making short circuit on circulating path of the Merz-Price relay. However, the obtained inhibit pulses can remove only an insignificant portion of the circulating current, so the operation of the relay is therefore virtually unaffected. The ultimate definition of the restraining signal will bias the relay toward dependability without risking the security while the relay utilizes additional means to face the SAT in external faults. More benefit of this approach is that the restraining signal almost produces a physical compared to an average or sum of current flowing through the CT that is most likely to SAT during given external fault. This is the reason of getting many breakpoint settings in the operating characteristic.

Fig. 2(a) shows the zone of operation for Busbar standard characteristic during SAT (stability zone with different breakpoint settings). The zone of operation, as given in Fig. 2(a), shows the Busbar standard characteristic in case of saturation (different breakpoints settings for obtaining stability zone). However, Fig. 2(b) shows the new developed characteristic for the Merz-Price circulating principle based on signal transform with ignoring the breakpoints setting related to SAT and error. The new characteristic needs to only one setting value known as $kmin$ and does not need to be delayed or blocked during SAT or ratio mismatch. More explanations will be given below.

3. Shannon function to improve relay characteristic

As mentioned above all the traditional techniques are using the Merz-Price circulating characteristic with different breakpoint settings, depending on the current values. In this section, a method for filtering the features of the current signal in case of CT-SAT is given. SHANNON sampling theorem can be considered as a scheme suitable for analyzing different functions ranging in multi-frequency bands. A SHANNON wavelet function is given as a compressed signal method. The features filtered by SHANNON are proposed in this paper for discrimination between faults inside the Busbar zone from faults external to bus zone (mainly in case of saturation). The continuous transform in case of SHANNON function is applied.

A SHANNON CWT basis function is featured within a signal transform method to detect faults during SAT while the current signal magnitude is approximately zero. The phenomenon of SAT and its impact on the proposed technique is analyzed. The old Merz-Price circulating characteristic with many breakpoint settings based on current magnitude will be improved using the new characteristic.

A signal function $\varnothing(t)$ of the SHANNON has a small wave as one of the main feature. It is oscillating in a certain way to discriminate between different frequencies [23,24]. This of course will help catching small frequencies that impeded in the saturation period. The signal contains both the analyzing $S(t)$ shape and the window. Most of the functions, $\varnothing_{a,b}(t)$, are given from a chosen mother signal $\varnothing$ as follows [23,24];

$$\int_{-\infty}^{\infty} |\varnothing(t)|^2 dt < \infty \quad (3)$$

$$c_{\varnothing} = 2\pi \int_{-\infty}^{\infty} |\varnothing(t)|^2 / |\omega| d\omega < \infty \quad (4)$$

where $c_{\varnothing}$ is the Fourier Transform of $\varnothing$. The function $\varnothing$ is the mother signal. If $\varnothing$ confirms the conditions defined before, then the real signal of the Wavelet Transform with respect to $\varnothing(t)$ (Wavelet function) is given as:

$$S(b,a) = 1/\sqrt{a} \int_{-\infty}^{\infty} \varnothing'(t-b/a)s(t)dt \quad (5)$$

where $\varnothing'$ is the conjugate of the complex $\varnothing$, and is described on the (b,a) OPEN plane ($b \in R, a > 0$). The factor b described as the “shifted time” and the factor a is described to the “waved analyzed” as scales. So, $\varnothing_{a,b}(t)$ is given as

$$\varnothing_{a,b}(t) = a^{-1/2} \varnothing(t-b/a) \quad (6)$$

It is described by “rescaling by a ” and is shifted by b , and then Eq. (5) is described by “a scalar” or “inner product” of the signal $S(t)$ and the function $\varnothing_{a,b}(t)$ as

$$S(b,a) = \int_{-\infty}^{\infty} \varnothing'_{a,b}(t)s(t)dt \quad (7)$$

The function $\varnothing(t)$ validates the condition of the admissibility, Eq. (4), the original signal $S(t)$ that is given from the “Signal Transformer” through the inverse equation as follows:

$$s(t) = 1/c_{\varnothing} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S(b,a) \varnothing_{a,b}(t) da db / a^2 \quad (8)$$

The scale and position affect on the CWT coefficients. Also, the choice of the wavelet affects on the values of the coefficients. By continuously varying the values of the scale parameter, a , and the position parameter, b , you obtain the CWT coefficients $S(b,a)$. The dependence of the CWT coefficients on the function and analyzing wavelet. The smaller the scale factor, the more “compressed” the wavelet. Conversely, the larger the scale, the more stretched the wavelet. There is clearly a relationship between scale and frequency. The longer scales correspond to the most “stretched” wavelets. The more stretched the wavelet, the longer the portion of the signal with which it is being compared, and therefore the coarser the signal features measured by the wavelet

coefficients. The general correspondence between scale and frequency is given as; with small scale a , the wavelet is compressed and rapidly changing the details with high frequency ω . For long scale a , the wavelet with stretching can be get and slowly changing and the coarse features with low frequency can be obtained [23,24].

The developed idea is based on filtering the features of the current signal during the SAT. It is not relying on phase quantities of current values as used in the previous concept of Merz-Price circulating principle. The features of filtration are considered as signal compression. Subsequently, it will be very useful to apply filtered features. As given in Fig. 2(c&d), points appearing at different scales indicate the existing of sudden changes in the signal. The signal de-composition includes of estimating signal coefficients between the unhealthy and wavelet signals. If the value is large, the different coefficients become strong, otherwise becomes weak. If the value of the signal is typical to itself at various scales, then the signal coefficients also will be typical at many scales.

Concerning the coefficients plot, as the y-axis shows the scale, this matching generates characteristic pattern very clear during SAT period. As explained above the Busbar characteristic does not need for the breakpoint settings shown in Fig. 2(a). Fig. 2(b) indicates the provided Busbar characteristic after affecting the SHANNON sampling based on spikes filtered during SAT. The SHANNON sampling method in the real time domain is obtained from the inverse Fourier transform [22,23] as:

$$\psi(k) = \sin\pi(k-1/2) - \sin 2\pi(k-1/2)/\pi(k-1/2) \quad (9)$$

3.1. Novelty for features detection by SHANNON signal during zero values caused by SAT

In cases of fault occurrence (before and during the CT saturation) there are different frequencies are generated. Both frequencies are captured and considered. Simply, the signal function is moved with adjusted time windows on the current signal to be used to capture and analyze different events of faults generated transients. Assume a CT is modeled by a current source while the ratio current is fed to the magnetizing impedance in parallel with the burdens. At each level of excitation, different frequencies along the period of fault (before and after the CT saturation) produce high frequencies. In this case the reactance to represent the magnetizing of CT is non-linear and different values of reactance can be obtained. In case of low excitation the slope $d\phi/di$ represents low inductance and produces very low amount of magnetizing current compared to the burden current. At medium excitation, the slope is little high and the magnetizing current is small compared to the burden current. During high excitation, the B–H curve gives maximum slope in transition to saturation [29].

The signal function is moved with adjusted time windows on the current signal to be used to capture and analyze different events of faults generated transients. At some time intervals, where the current changes rapidly, the function has better visualization of signal characteristics. Fig. 2(c) shows how analysis by signals using SHANNON function can detect a typical-similar signal in case of SAT. The function can catch a typical-similar signal in case of SAT. The analysis was performed with the “continuous signal graphical tool”. A repeating image in the signal coefficients plot is characteristic of a signal that looks typical on different scales. The similarity is in having typical frequency components. In this case, the mother signal values are highly selective in time and frequency to have detecting features. The basis function creates different scales via chopping up typical function/or data-space using various scale values. The method can be applied with scales at different basis FUNCTION. Fig. 2(c&d) shows a sample signal and its SHANNON signal map. The map moves as a continuous window on the current signal to catch similar matched signals, Fig. 2(c). The signal coefficients with largest values (red as a maxima, blue as a minima) identify individual extreme of the signal, Fig. 2(d). The close periodicity of one contribution to the signal is clear in the energetic

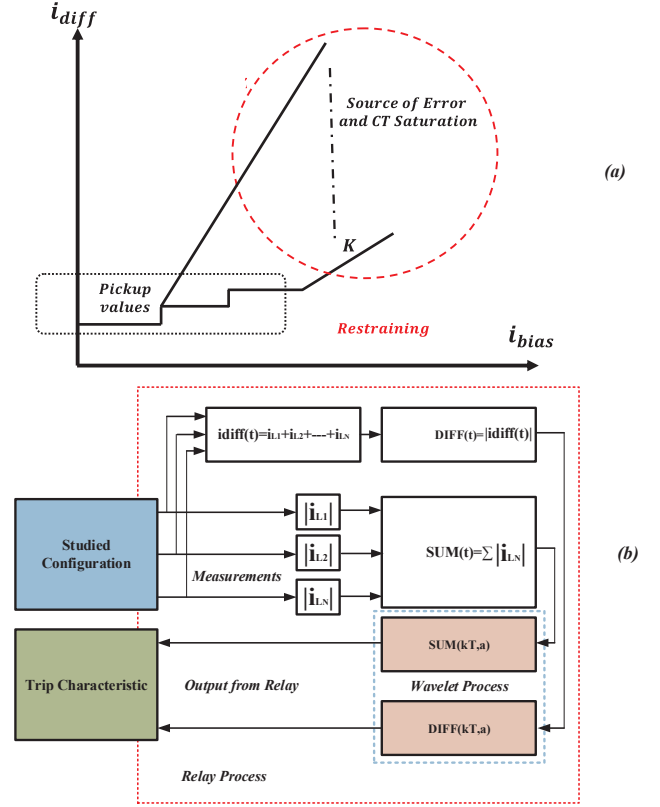


Fig. 3. (a) Slopes to avoid error in Merz-Price Relay, (b) Relay process using the wavelet and the new C/S.

contributions for a horizontal strip of the map. The noise is clearly distributed in the top of the map, indicating to higher frequencies, Fig. 2(c).

The large spikes are featured during the SAT with non-zero values. During SAT, high spikes appear with the continuous signal transform coefficients provided at various SCALES. The coefficient values assign the outcomes of regression of the unhealthy signal provided up the signals. The Merz-Price circulating busbar based on protection algorithms rely on measuring the absolute value of the current for clearing the busbar faults. When the transformer saturates, the magnetizing impedance is assumed to go to zero and the secondary current also tends to go to “ZERO” at that instant. So, the breakpoint settings shown in commercial relays given in Fig. 2(a) appears.

4. Proposed technique

The suggested method depends on filtering the framed signal transform of transients extracted from the fault, to discriminate between faults in the busbar section or external to it, specifically during CT-SAT.

The faults bring spikes that are filtered from the circulating current “DIFF” (sum of the line currents as a magnitude)-the “operating quantity -” and from the sum (sum of the line currents as absolute values) of the current magnitudes “SUM”-the restraining. The magnitude values of signal transform based on SHANNON basis function are applied on the “DIFF” and on the “SUM” signals. Mathematically, these can be given as $DIFF(kT, a)$ and $SUM(kT, a)$ based on (5) and (6). The circulating current can be calculated in all feeders as;

$$i_{diff}(t) = i_{L1} + i_{L2} + i_{L3} + \dots + i_{LN} \quad (10)$$

$$DIFF(t) = |i_{diff}(t)| \quad (11)$$

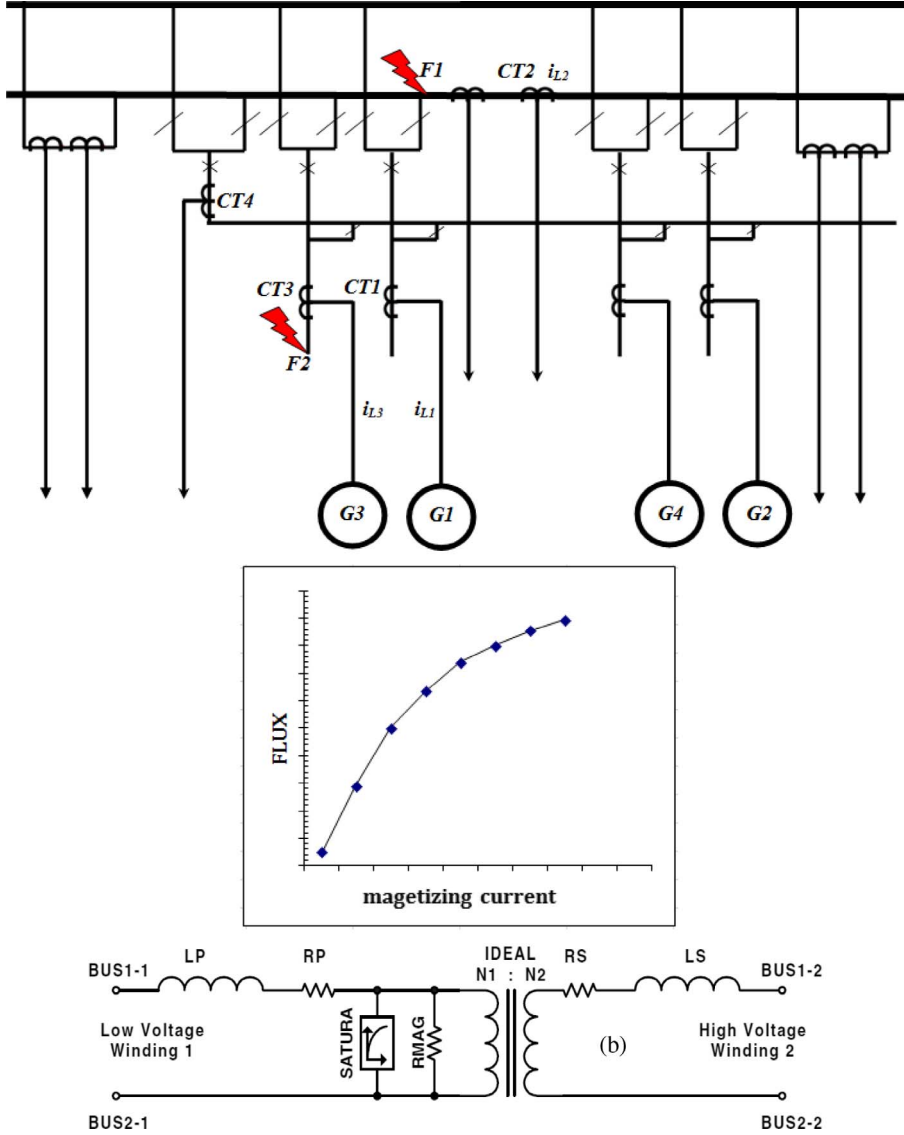


Fig. 4. System topology under study and the CT model with CT characteristic [26].

$$SUM(t) = |i_{L1}| + |i_{L2}| + |i_{L3}| + \dots + |i_{Ln}| \quad (12)$$

$i_{L1}, i_{L2}, i_{L3}, i_{Ln}$ are the currents in the different lines connected by the Busbar. $DIFF(kT, a)$ and $SUM(kT, a)$ can be calculated using SHANNON function as;

$$DIFF(kT, a) = \sum_n |1/\sqrt{a} \cdot T \cdot \phi[(nT - kT)/a] \cdot DIFF(t)| \quad (13)$$

$$SUM(kT, a) = \sum_n |1/\sqrt{a} \cdot T \cdot \phi[(nT - kT)/a] \cdot SUM(t)| \quad (14)$$

Eqs. (13) and (14) are used to calculate the absolute quantities of the Continuous Wavelet Transform of the differential and summing currents indicated in (11) and (12). $DIFF(kT, a)$ and $SUM(kT, a)$ are the absolute values of the CWT of the $DIFF$ and SUM of the current magnitudes respectively. The letter T is the time period. k and n are integers and " a " is the SCALING factor. Fig. 3(a) shows the source of error during SAT and the reason of using breakpoint settings. Fig. 3(b) shows the relay process using the wavelet and the new C/S. Eqs. (13) and (14) of the phases are estimated by a fixed data window at each sampling time ($1/4$ cycle). The signal window shifts continuously to the right so that at every sampling instant a new sample is included and the oldest sampling is discarded. The representation of the idea is specified in the following section as: the loci of $DIFF(kT, a)$ and $SUM(kT, a)$ are given as a trajectory in Fig. 2(b) above. One stabilizing factor k_{min} is

given on the characteristic. Two functions $DIFF(kT, a)$ and $SUM(kT, a)$ are used to identify the internal and external faults. When the trajectory of $DIFF(kT, a)$ crosses k_{min} and the trajectory of $SUM(kT, a)$ does not cross k_{min} the fault is indicated as an internal in the zone. Otherwise the fault is external. This can be described as:

$$\left\{ \begin{array}{l} DIFF(kT, a) \geq k_{min} \\ SUM(kT, a) < k_{min} \end{array} \right\} \text{ internal fault}$$

$$\left\{ \begin{array}{l} SUM(kT, a) \geq k_{min} \\ DIFF(kT, a) < k_{min} \end{array} \right\} \text{ external fault}$$

This means the operating quantity of the features extracted is greater than the restraining value. But, when the trajectory of $SUM(kT, a)$ crosses k_{min} and $DIFF(kT, a)$ does not cross k_{min} this indicates that the fault is external. Another stabilizing factor k_{max} can be used to assure tripping or blocking. As shown from the new characteristic (Fig. 2(b)) that the breakpoint settings of the curve given in Fig. 3(a) and related to CT measuring errors can be avoided. The operating threshold boundary, raised to enhance the stability of the relays, can be avoided using the new characteristic while it is ignoring the breakpoint settings of errors and SAT and depends only on small pickup value as k_{min} .

To get high sensitivity for the relays, it should be adjusted enough

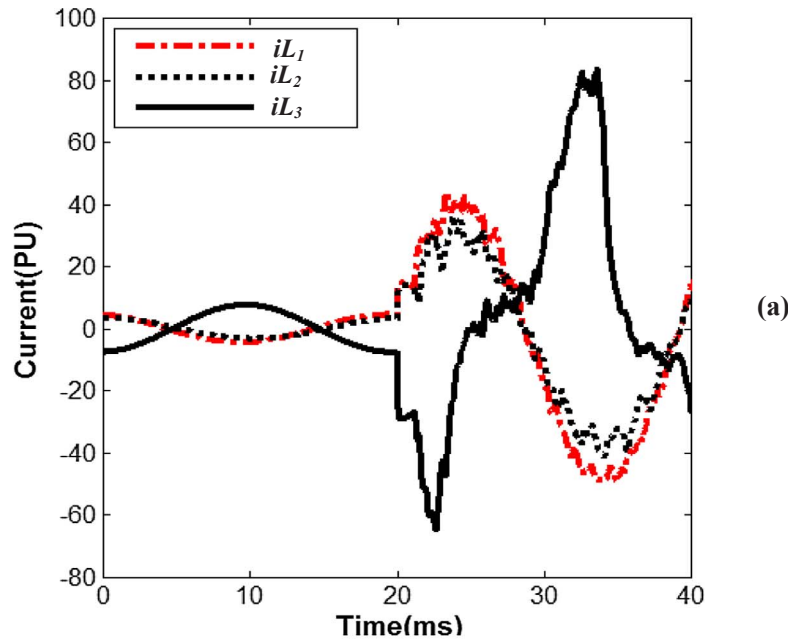
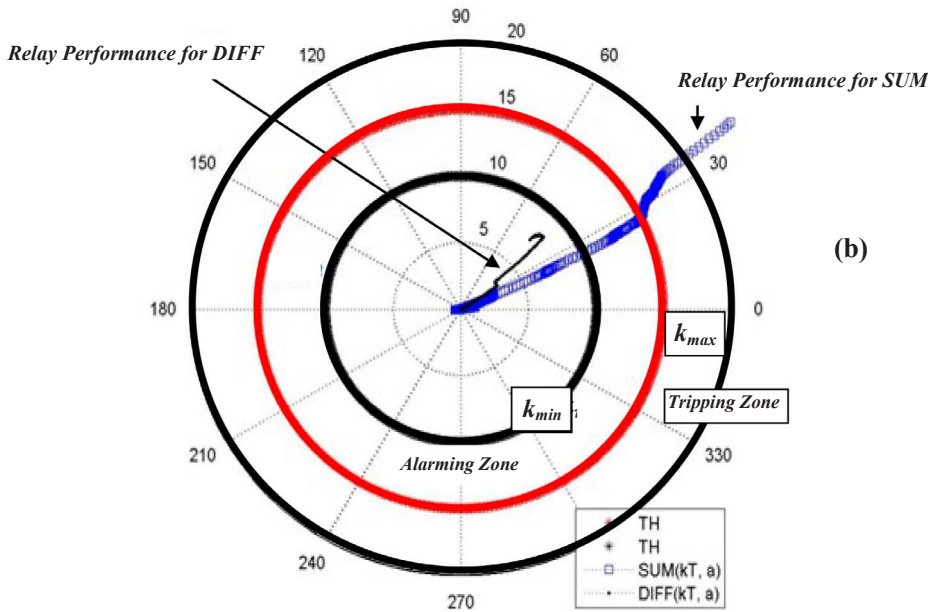


Fig. 5. **External Fault:** Line currents and SAT with new Merz-Price circulating characteristic.



to guarantee detection for entire faults inside the zone. Relays with more sensitivity are not required during use the new characteristic. All the faults as being internal or external are detected, with no need for increasing sensitivity. This is not the case of the commercial characteristic that needs increasing the sensitivity and tends to decrease security of the operation. Fig. 3(b) shows all steps of relay process using the equations of "DIFF" and "SUM" using the wavelet technique and the new characteristic of the Merz-Price circulating relay.

5. System configuration

There are many busbar configurations. The busbar configurations in the substation can be single or double. The status of the fundamental power plant varies and successively provides changes. Whole conditions should be adjusted for entire the Busbar protection technique. The configuration shown in Fig. 4(a) has been simulated. For testing and verifying the different fault cases, data is generated using a configuration modeling through Alternative-Transient-Program (ATP) [25,26]. Parameters of the system configuration are listed in [27,28]. The system

shown in Fig. 4(a) was subjected to different fault events. The results obtained from the tests with the CT saturation effects are used under sampling frequency of 20 kHz. A scaling factor with optimum value equal to 46 is selected for the study. k_{min} and k_{max} are selected as 10% and 15% to cover the transformer mismatch and magnetizing current losses) (i.e., 5–20% is a typical application range). The sources are modeled with three separate generators and the circuit is with a positive sequence that calculated from the fault level. Fig. 4(b) shows the CT model used in the study. The C-800(1200: 5, $R_s = \text{zero}$) CT is used. The λ/i curve with a saturation point (0.8A, 4Vs) is used with the CT model.

6. Relay testing

To test the relay operation according to the above (13) and (14), many fault events are simulated using the studied configuration with CT model given in Fig. 4.

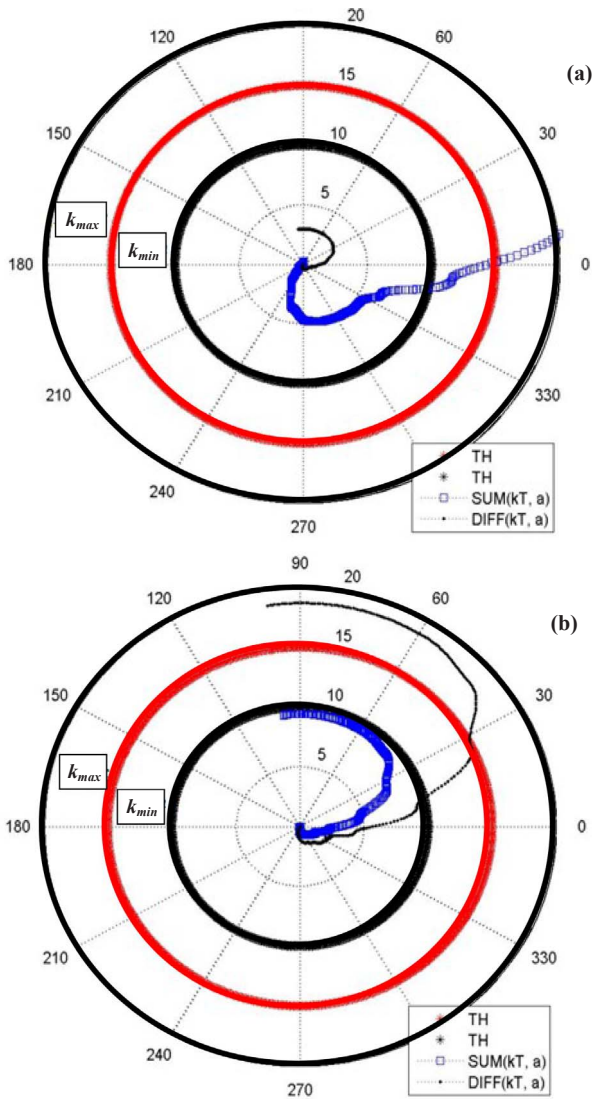


Fig. 6. (a) **External Fault**: case with ratio-mismatch and the performance of new characteristic of the relay, (b) **Internal Fault**: The relay performance due to A-B-C to ground fault in zone fault.

6.1. RelayTest-1 (External fault)

Fig. 5(a) shows the three currents i_{L1} , i_{L2} , and i_{L3} with CT3 saturated. The fault is located on point F_2 outside the zone as shown in studied configuration given in Fig. 4. Fig. 5(b) shows the loci of the $SUM(kT, a)$ and $DIFF(kT, a)$. As shown in figure, the $SUM(kT, a)$ path crosses the setting value k_{min} and the $DIFF(kT, a)$ path does not cross k_{min} . This indicates that the suggested technique properly determines the case fault outside the zone. The path of $SUM(kT, a)$ also crosses the second setting value k_{max} , which means the circuit breakers of all the lines connected by faulted zone should be blocked from tripping. The procedure of data measurement initiates when the detector element begins. The detector element applies the over-current concept Δi given in [27]. The result obtained from the tests was used with a sampling frequency 20 kHz.

6.2. RelayTest-2 (External fault) - ratio error "20% in CT"

The Merz-Price circulating relays can properly discriminate between the internal and external faults while they carry sufficient amount of information. The two line ends almost have measuring errors due to the different characteristics the reason that causes false operation for the

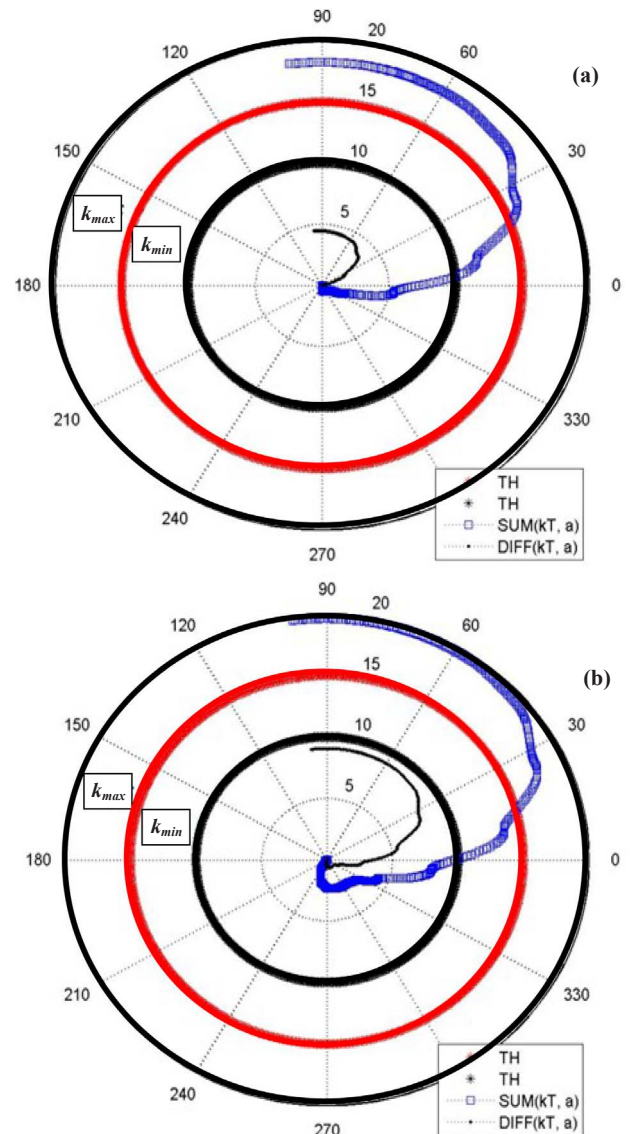


Fig. 7. (a) **External Fault**: Three phases to ground fault and the relay trajectories, (b) **External Fault**: The relay trajectories due to non-saturated part at the beginning.

Merz-Price circulating relays. For this reason, the circulating current needs to be provided with an operating threshold with two high slopes. This has a serious effect on the sensitivity of the relay and may be insensitive for low fault currents. Fig. 6(a) shows a case study with external fault occurred at F_2 with a ratio error of "20% in CT3" (see Fig. 4). To ensure stability in the conventional relays, the bias threshold is increased; this will prevent miss operation and reduce relay sensitivity. Fig. 6(a) shows the new characteristic of the Merz-Price circulating relay with minimum value of pickup k_{min} . As given in the figure, the contour of the $SUM(kT, a)$ crosses the threshold values (k_{min} and k_{max}) to indicate that the fault is external. The new characteristic is still sensitive for low fault current.

6.3. RelayTest-3 (Internal fault)

Fig. 6(b) shows the circulating currents in three lines for A-B-C to ground fault and zero ohms in the area fault. This event displays the path of the $DIFF(kT, a)$ crosses the setting value k_{min} . The studied case tends to trip the entire breakers joint with the area fault after confirmation from crossing the second setting value k_{max} . The case is defined as an internal fault.

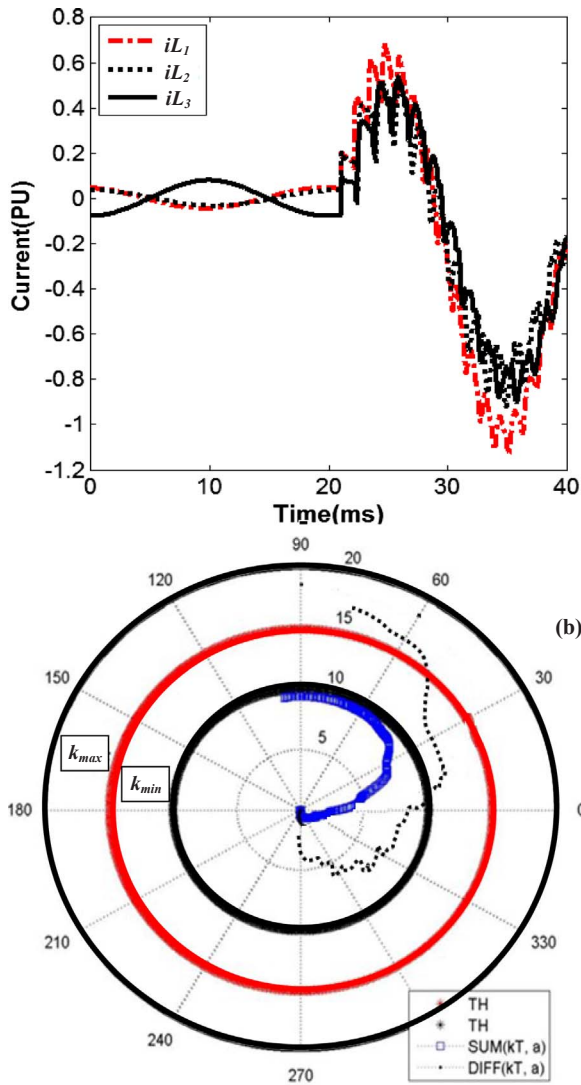


Fig. 8. Internal Fault: The relay performance due to A- to ground fault in zone fault and high fault resistance with relay performance (b).

6.4. RelayTest-4 (External Fault)- Late SAT

The conventional relays are exclusively active when the SAT takes place at the beginning cycles due to faults. The SAT appears late. Most commercial relays detect this late SAT using block zone that causes mal-operation in many other faulted cases. The effect of “CT3” SAT due to a fault occurred at F_2 is verified (see Fig. 4). Three phases to ground fault are given. The relay trajectories of $DIFF(kT, a)$ and $SUM(kT, a)$ are shown after and before SAT, see Fig. 7(a). The suggested setting pointed out that the $DIFF(kT, a)$ is below the boundary of characteristic and $SUM(kT, a)$ crosses the setting that lead to blocking. The commercial Merz-Price circulating characteristics are depending on the magnitude values of the current which drop out the proper operation of such faults.

6.5. RelayTest-5 (External Fault)- non-saturated part at the beginning

The waveform for some types of external faults showed a non-saturated part at the beginning just after fault occurrence. The non-saturated part can only appear at a short period. The conventional relays are suffering from these problems and will delay the operation of the slope curve and consequently will increase it to let the system stable. The proposed idea utilizes the features extracted by SHANNON function due noises generated from the waveform currents and do not depend on

the magnitude value of the current. To test this case, two phases fault external the area fault at point F_2 was tested. Fig. 7(b) shows the paths of the $DIFF(kT, a)$ and $SUM(kT, a)$. The suggested setting indicated that the $DIFF(kT, a)$ under the set characteristic that lead to blocking.

6.6. RelayTest-6 (Internal Fault)- high fault resistance

The fault current is limited due to high fault resistances or through arcs to ground. During ground faults and high fault resistance the current is limited to a minimum values, see Fig. 8(a). The provided concept in this paper does not depend on the magnitude values of the current, but it applies the SHANNON wavelet function to correlate with the high frequencies generated due to the fault signal. The performance of the proposed idea is used to distinguish well the faults associated with high path resistance. To show this case, a single line to ground in the bus-protection zone at F_1 with a fault resistance equal to 130 ohms was simulated. The action of the provided technique is shown in Fig. 8(b). The high fault resistance can slow the movement of the path but still works properly.

7. Conclusions

The current transformers may saturate and thus may cause the conventional Merz-Price circulating schemes to work differently. The main reason of getting the breakpoint settings is the time delay taken during SAT and error. The main idea of novelty is that the SAT phenomena can generate some noises that corresponding to high frequencies, these noises are not with zero values. These noises are distributed on the signal map due to wavelet function that used as features for identifying the SAT period. The paper developed new characteristics based on wavelet function. The features captured by the Wavelet technique during the fault is used to improve the limitation of commercial relays based on Merz-Price circulating characteristic. The new developed characteristics do not need for such breakpoint settings.

The results showed that the idea is successful in identifying the faulted zone during current transformer saturation and also at the early and severe saturation. Almost 100% of the internally and externally faults are detected without increasing the relay sensitivity. This is not the case for the commercial characteristics that need to increase sensitivity. This will also affect on the security of the operation. The parameters of the Pickup characteristic of the commercial Merz-Price circulating protection can be adjusted for $I_d > \text{“Pickup value”}$ and at the $k\text{-FACTOR}$ that takes 15 to 50 msec operating time. The proposed new characteristic can reach to 7 msec operating time covering all cases of internal and external Busbar faults.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ijepes.2017.11.006>.

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