

Over-current relay implementation assuring fast and secure operation in transient conditions

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ABSTRACT

In order to reduce hazardous effects of over current caused by faults, faster operation of over-current protections is desirable which means maximum sensitivity of the over-current relays to the current and a minimum reaction time. This high sensitivity may lead to operation of relays in normal transient events, such as transformers energizing and induction motors starting. Therefore, proper methods must be used to prevent mal-trip of the relays, due to these transient currents. This paper presents a new method to discriminate over currents caused by fault from transformer energizing and induction motors starting. In this method, a criterion function is introduced in terms of variation of fundamental component amplitude of current signal over consecutive segments. The criterion function is then used in over-current protection, and faults are precisely discriminated from non-fault switching. The performance of this method is demonstrated by simulation of different faults and switching conditions on the IEEE 13 bus test system using Electromagnetic Transients Program (EMTP) and field measured data.

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1. Introduction

Over-current protection is one of the most important parts of any power distribution system. When a fault occurs huge amount of current flows that can damage power system components. Therefore, over-current relays must de-energize the faulted line as fast and accurate as possible to protect the system from the hazardous effects of the fault. To do this, a relay protection should be sensitive enough. On the other hand, high sensitivity sometimes causes mal-trip of relay protection when there is no fault in the system. In the deregulated power market this directly leads to penalty compensation to the customers that suffer from the blackout [1]. It is noticeable that relays are particularly more vulnerable to these transients in the deregulated power systems in which the lines are almost used in their maximum capacity. Therefore, identification of the factors that produce these mal-trips and introducing procedures for their discrimination from the real fault cases are very important.

In [1], the factors producing these mal-trips in the viewpoint of over-current relays have been investigated. Induction motor starting and transformer energizing are two most important sources of

these mal-trips. In [2], effects of over currents on the operation of over-current relays due to these switching have been studied.

Normally, in order to prevent mal-trip of over-current relays resulting from these transients, a longer delay is initiated for relay trip command; therefore, as time passes and amplitude of the transient current diminishes, the mal-trip of the relay is prevented. This imposed delay, slows down the relay operation during the fault and consequently reduces its sensitivity.

Since magnetizing inrush current generally contains a larger second order harmonic compared to that of the fault, sensing this large harmonic seems to be a proper means to restrain the relay during inrush transient phenomenon [3]. However, second order harmonic components in the magnetizing inrush currents tend to be relatively small in the modern power transformers because of improvements in the power transformer core material [4]. Moreover, the second order harmonic component may also be generated during the faults, and in some cases it can be close to or larger than that of the magnetizing inrush current [5].

In [6], a system has been developed to discriminate over current due to faults from that of the induction motor starting in underground coal mines. In order to prevent explosions and fires in underground coal mines which can be happened due to faults, protective device must be set with a maximum sensitivity to current and a minimum reaction time. Extremely low current settings may interfere with mining operations by reacting to normal transient events, such as the starting of motors. To overcome this problem, the proposed system monitors the phase angle between the

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voltage and current and discriminates faults from motor starts based on the relatively large phase angle between voltage and current in the case of motor-start. The drawback of using this method in over-current protections is the need to measure voltage in addition to current that increases the cost of hardware implementation.

A wavelet-based signal processing technique is an effective tool for power system transient analysis and feature extraction [7,8]. In [9], the wavelet transform (WT) has been utilized for feature extraction and an artificial-neural-network (ANN)-based classifier is developed to distinguish feeder inrush currents from fault currents. The problem associated with this method is the need to huge number of training patterns produced by simulations of various cases. Moreover, that might need re-training for use in other power systems. In [10], a method based on wavelet coefficients over a specific frequency band is defined. As this frequency band may vary for different networks and switching conditions, it is not robust and accurate for all scenarios.

In [11], an off-line method has been presented for distinguishing fault, transformer energizing and induction motor starting from each other in data obtained by power quality monitors. This off-line method is most convenient for classification of the recorded data in power quality application not protection purpose.

In [12], the concept of symmetrical components has been used and a method for preventing the undesirable relay operations due to over currents (following a switching) has been presented. However, it needs the data from all three phases and cannot work base on single-phase data.

In [13], the optimal Bayes classifier is utilized to develop a method for discriminating the fault from non-fault events. The proposed method has been designed based on extracting the modal parameters of the current waveform using the Prony method. By feeding them to the classifier, the fault case is discriminated from the switching case. However, this algorithm needs training process, which requires training data, and calculation process with Prony method.

This paper proposes the method based on variation of fundamental component amplitude of current signal which describes a criterion function that precisely discriminates over current caused by fault from those of transformer energizing and induction motor starting. Since this method is based on the data obtained from the sampled current; which is taken normally in the over current relays, it prevents the mal-trip of relays with no extra cost.

The proper performance of the proposed method is studied by simulating various faults and switching cases (motor starting and transformer energizing) using EMTP. Moreover, the proposed algorithm is tested using field measured data that shows the accuracy of the proposed algorithm.

2. Study of different cases

In this part, the main features of over current due to different cases (fault, transformer energizing and induction motor starting) are described.

2.1. Induction motor starting

The starting of a large induction motors leads to a current typically 5–6 times the rated current. Generally, the starting current has a very high initial peak which is damped out after a few cycles, normally no more than two cycles depending on the circuit time-constant [14], and after that drops rapidly to a multiple value of its nominal level, and is maintained during most of the acceleration period. The current is then smoothly reduced to the nominal value that depends on the steady-state mechanical load of motor.

Solid state starters and variable-frequency drives (VFD) can keep line current during starting at any preset value and obviate difficulties of direct across-the-line starting [15]. If the utility power system is quite stiff then direct-on-line starting will likely be the preferred which provides the highest possible starting torque without the use of a drive, and the shortest acceleration times and most economical solution for a typical variable-torque load, such as a pump [16]. The high amount of current due to this kind of starting may cause a trip in a sensitive over-current relays.

The star-delta starting can roughly reduce the starting currents to 3–4 times the motor full-load current. The transient inrush current due to the temporary disconnection of the motor from the supply line in so-called “open circuit transition” switching procedure, which because of lower cost is the most common method of star-delta starting, should be considered. Current surges can typically attain peak values of up to 20 times the motor full load current rating and generally last for 10 to about 40 ms [17]. The same happens in the case of the auto-transformer motor starting.

These transient currents can influence the operation of highly sensitive over-current relay, particularly when many switching happen simultaneously. This may be occurred during energizing a feeder that has not been used over a long time, which may lead to high starting current that affects the operation of relays. Therefore, fault current must be diagnosed from these transient currents.

2.2. Transformer energizing

When a transformer is energized, magnetizing inrush current is expected. The magnitude of this current depends on the factors such as switching instant, source impedance, residual flux in the core, transformer size, and design. This inrush current could reach values as high as 25 times full-load current and will decay with time until a normal exciting current value is reached. The decay of the inrush current may vary from times as short as 20–40 cycles to as long as minutes for highly inductive circuits [18] which might have hazardous effect on the locally installed over-current relays [2]. According to [19,20], one main characteristic of magnetizing current is that its fundamental component amplitude varies with time.

2.3. Arcing fault

Distribution systems are exposed to faults involving arc phenomena. The arc current can be described mathematically using the process presented in [21–23]. According to [21–23], fundamental component amplitude of arc current does not vary with time.

2.4. Fault

Applying Kirchhoff's voltage law to R – L equivalent model of the fault in power system [24] leads to the following differential equation:

$$E_{\max} \sin(\omega t + \varphi) = Ri + L \frac{di}{dt} \quad (1)$$

where R is the resistance of the line and L is the inductance of the line.

By solving (1), the current will be as follows [24]:

$$i(t) = e^{-(R/L)t} \left\{ \frac{-E_{\max}}{\sqrt{R^2 + \omega^2 L^2}} \sin \left[\varphi - \tan^{-1} \left(\frac{\omega L}{R} \right) \right] \right. \\ \left. + \frac{-E_{\max}}{\sqrt{R^2 + \omega^2 L^2}} \sin \left[\omega t + \varphi - \tan^{-1} \left(\frac{\omega L}{R} \right) \right] \right\} \quad (2)$$

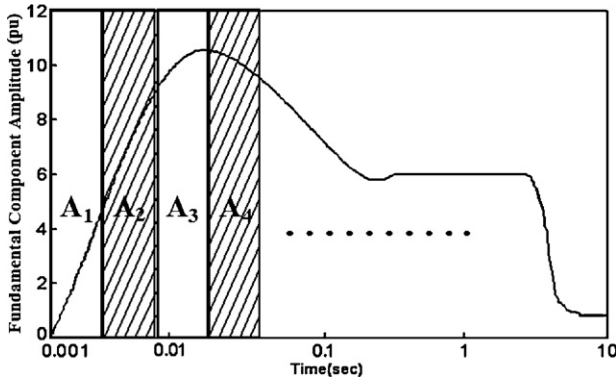


Fig. 1. Scheme of the principle of proposed method.

According to (2), fault current comprises a part which damps with time and constant part with fundamental frequency.

3. Proposed method

According to previous section, the main differences between the fault case and the induction motor starting and transformer energizing are their fundamental component amplitudes. In the case of fault, amplitude of the fundamental component is constant and time independent, but in the case of transformer energizing and induction motor starting, the amplitude of fundamental component is time-dependent. Therefore, the variation of fundamental component amplitude of current signal can be a good feature for discrimination of the fault case from the switching case.

It is notable that the exponentially decaying dc offset, which is considerable in the case of fault and induction motor starting, can affect accuracy of fundamental component amplitude calculation [25]. Here, least square method [26] has been used to calculate the fundamental component amplitude while exponentially decaying is considered. After calculating the fundamental component amplitude of the current signal, a criterion function should be proposed that the over-current relay can discriminate fault from non-fault switching.

Fig. 1, which belongs to the fundamental component amplitude of induction motor starting current [27], shows the idea of proposed criterion function.

A criterion function is defined as follows where parameter C stands for Classifier. By using it, the overcurrent condition can be classified into either fault case or non-fault case (induction motor starting/transformer energizing).

$$C_j = \begin{cases} \frac{A_j - A_{j-2}}{A_{j-2}} & j = 2 \dots n \text{ if } A_{j-2} \neq 0 \\ 0 & \text{if } A_{j-2} = 0 \end{cases} \quad (3)$$

where

$$A_j = \sum_{k=\frac{jN}{4}}^{\frac{(j+1)N}{4}} I_m(k) \quad j = 0 \dots n$$

n is the total samples, N is the number of samples per cycle, $I_m(k)$ is the fundamental component amplitude, A_j is the area below the fundamental component amplitude in a quarter of a cycle.

In (3), parameter C monitors the variation of amplitude of the fundamental frequency component of the current over time. The proposed method tracks the behavior of fundamental component amplitude by using group of samples within each window in Fig. 1. This way the results are more reliable since the calculated value is

averaged over the group of samples instead of using an individual sample.

In the case of a fault, induction motor starting and transformer energizing, at inception time, C will increase largely because the fundamental component amplitude increases from the normal level to over current level due to these phenomena. C will increase until the fundamental component amplitude reaches its maximum value. After this point, C will be different in fault case from that of the transformer energizing and motor starting, which is explained below.

For a periodic signal represented by sinusoidal function, $i(t) = I_m \sin(\omega t + \alpha)$, where I_m is the amplitude that could be either constant or time-varying, ω is the angular frequency and α is the phase angle.

(1) when I_m is constant

$$A_j = \sum_{k=\frac{jN}{4}}^{\frac{(j+1)N}{4}} I_m(k) = I_m \times \left(\frac{N}{4} \right) \quad (4)$$

Therefore,

$$C_j = \frac{A_j - A_{j-2}}{A_{j-2}} = \frac{I_m \times (N/4) - I_m \times (N/4)}{I_m \times (N/4)} = 0 \quad (5)$$

(2) When I_m is time-decaying

Obviously $A_j < A_{j-2}$, therefore $C_j < 0$.

In the case of transformer energizing and motor starting, C becomes largely negative, because the fundamental component amplitude will decrease as time passes; in the case of fault, it will be almost zero because fundamental component amplitude stays constant. The following function is defined to detect the fault from non-fault cases:

$$\text{Flag} = \begin{cases} 1 & \text{if } C_j < \varepsilon \\ 0 & \text{others} \end{cases} \quad (6)$$

where ε is threshold value. If Flag becomes 1 it means that the over current is due to non-fault switching (transformer energizing or induction motor starting) and mal-trip of the relay is prevented. If flag remains zero, operation of the relay is not prevented and trip signal is issued according to the relay characteristic.

To determine the value of ε in (6) the chi-square criterion is used [28,29]. The chi-square is one of the most popular statistical means for determining whether an observed sample belongs to a specific category.

If $X_1, X_1, \dots, X_N$ are samples with mean μ and variance σ^2 , the random variable $z = (x - \mu)^2 / \sigma^2$ has a chi-square (χ^2) distribution with 1 degree of freedom. Using 95% confidence interval criterion (which is an accepted and commonly used value for classification purpose) on σ^2 the following equation holds:

$$Z \leq \chi_{0.05,1}^2 \quad (7)$$

Substituting random variable z into (7), the threshold is defined as follows:

$$\varepsilon = X_{\text{threshold}} = \mu + \sqrt{\chi_{0.05,1}^2 \times \sigma^2} \quad (8)$$

where according to chi square distribution tables $\chi_{0.05,1}^2$ is 3.84.

To have fast, secure and dependable over-current relay the following procedure for setting the relay is proposed.

The relay should have two time-current characteristic, fast and slow. The slow characteristic is set conventionally with imposed delay for preventing mal-operation during non-fault switching. The

fast characteristic does not have such a delay because it is super-vised by the proposed method which detects non-fault switching.

If fault happens, it is detected by the proposed method and fast characteristic is not blocked and the relay issues trip command. If non-fault switching happens, the proposed method detects it and blocks the fast characteristic until the current goes back to normal level. In this way the fault is cleared quickly without endangering the security of the relay during non-fault switching. It is notable, during non-fault switching only the fast characteristic is blocked and slow characteristic (which is set conventionally with imposed delay) is still in operation. In case the faults are mistaken with the induction motor starting and transformer energizing and fast characteristic is blocked, the relay clears the fault according to the conventional settings. Therefore the dependability of the relay is assured and is not affected by the proposed method.

4. Simulation results

To investigate the merit of the proposed method, the distribution system shown in Fig. 2 [30] is modeled using EMTP. This system is based on the IEEE 13 bus radial distribution test feeder [31]. The current waveforms are sampled 20 samples per cycle which is in the range of a typical sampling rate found in protective relays. The higher the sampling rate is selected the better horizontal resolution would be achieved which means more accurate estimation of fundamental frequency component. If the proposed method works properly for such a low sampling frequency, it would work properly for higher sampling frequencies as well. Many non-fault and short circuit events at different times were applied to this system. Various parameters which have considerable effect on the

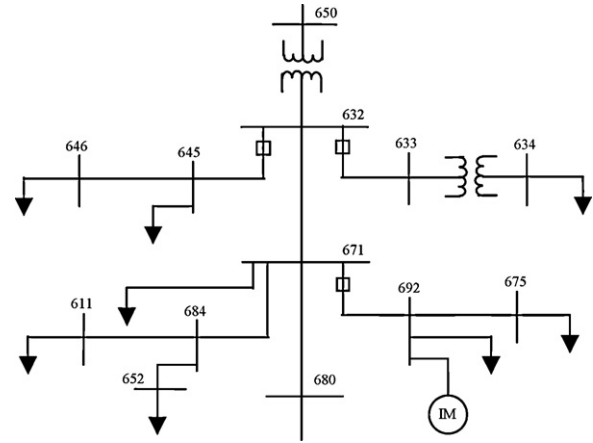


Fig. 2. Schematics of IEEE 13 bus test system [30].

characteristic of the inrush current signal during transformer energizing, e.g. core residual flux, non-linearity of transformer core and switching instant were changed and the current signals were analyzed by the proposed method.

Different motor starting cases for motors with different ratings at different places and times were studied. Faults (including arc) with different types in various places of the power system and over different times were applied.

According to the simulation results and (8) $\varepsilon = -3\%$ is chosen as threshold in (6) which can reliably discriminate fault cases from non-fault cases in different networks. Due to suitability of the proposed feature extraction procedure in (5), fault cases and

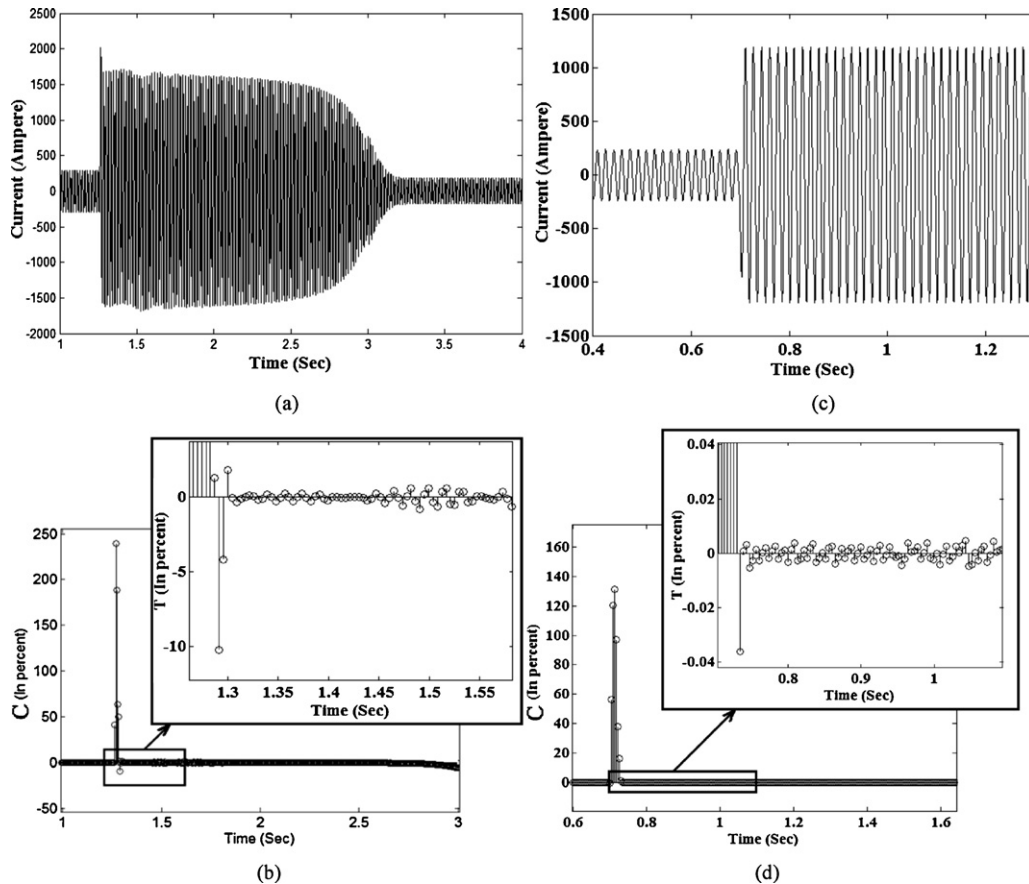


Fig. 3. (a) Current of phase C due to induction motor starting (simulated), (b) C values due to induction motor starting, (c) current of phase C due to fault (simulated), and (d) C values due to fault.

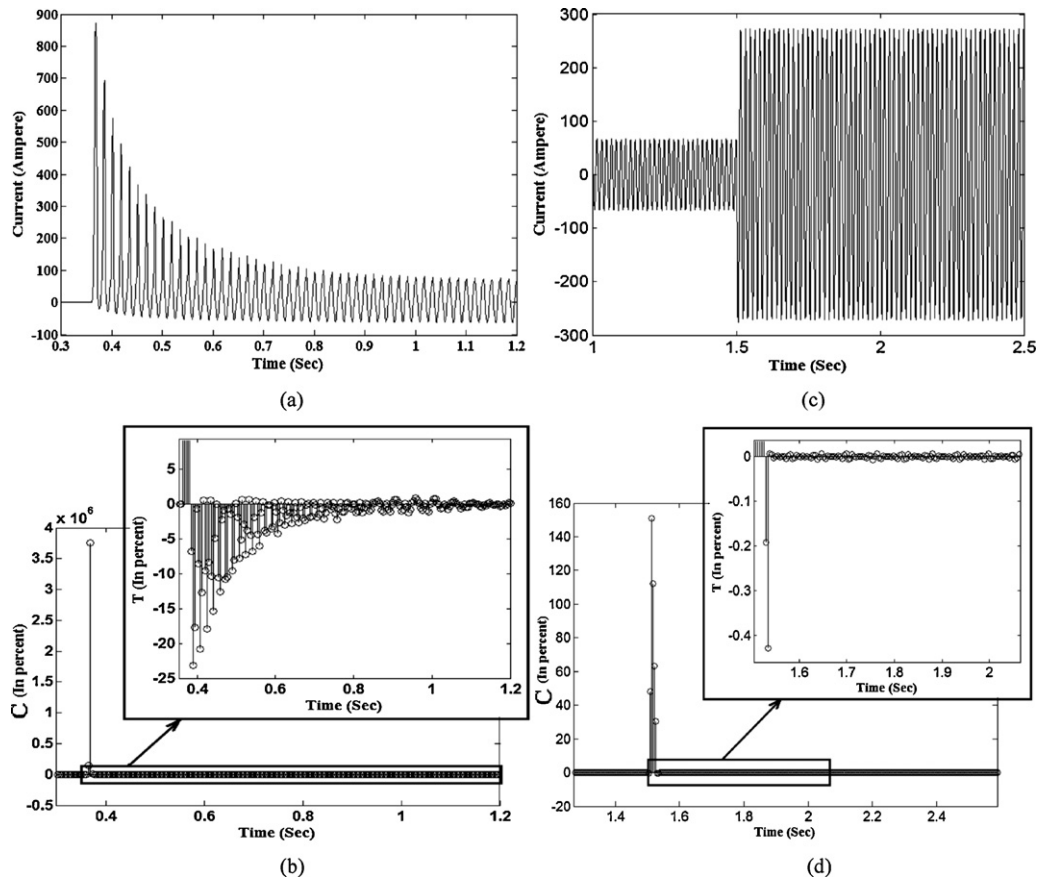


Fig. 4. (a) Current of phase A due to transformer energizing (simulated), (b) C values due to transformer energizing, (c) current of phase A due to arc (simulated), and (d) C values due to arc.

transient cases (induction motor starting and transformer energizing) build up two categories that can be distinguished by using threshold value of $\varepsilon = -3\%$. This fact is demonstrated in the subsequent sections through applying the proposed method on a simulated distribution system and field measured data gathered from four totally different networks. However, as setting of ε is an offline effort, it is possible to consider the ε as a parameter of the relay and is determined according to (8) during the process of setting and coordination of protective relays.

Performance of the proposed method is compared with that of conventional inverse-time over-current relay. The inverse-time relay (CO-8) clears fault faster than the more inverse-time relays

(very inverse and extremely inverse) for low-current faults. This is important especially in highly loaded networks which minimum fault values and load currents are comparable. However, it does not provide much margin for inrush currents [32]. The results show that how the proposed method can help the over-current relay to have fast and secure operation. In the following section some cases are studied in detail.

4.1. Induction motor starting

In this case, a 0.8 MVA induction motor at bus-bar #692 is switched at $t = 1.26$ s. Fig. 3(a) shows current of phase C seen by

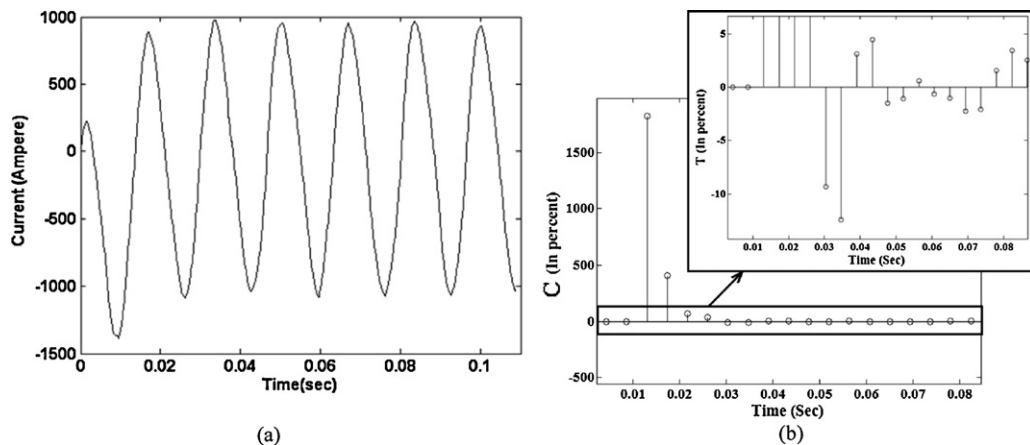


Fig. 5. (a) Line – current waveform for start of 950 V 165 hp motor (recorded) [6] and (b) C values due to induction motor starting.

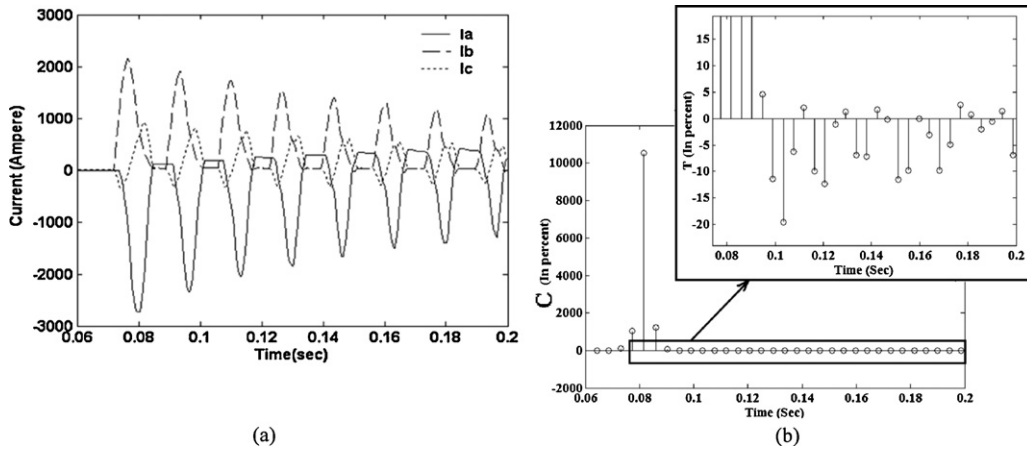


Fig. 6. (a) Three phases inrush currents due to transformer energizing (recorded) [34] and (b) C values due to transformer energizing.

the relay at bus-bar #671 and Fig. 3(b) shows C. In this case Flag becomes 1 at $t = 1.291$ s because C becomes smaller than threshold value (-3%). It means that non-fault is discriminated in less than 2 cycles after its occurrence.

In order to prevent mal-operation of the over current relay during the startup conventionally the relay is set as follows. According to Fig. 3(a) the normal maximum load current is 300 A, so the pickup value is set at $1.5 \times 300 = 450$ A. The average over current value derived from pickup value during startup period (1.8 s) is 1470 A, an equivalent of 3.3 times pickup value. The relay operating time at 3.3 times pickup value should be slightly more than 1.8 s. For the CO-8 relay, this means a time dial setting (TDS) of 3. In the proposed method startup current is discriminated from fault current using the method explained in previous sections. There is no need to impose extra delay (by changing the TDS of the over-current relay). A TDS of 0.5 is selected.

Now, consider the following scenario: a phase-ground fault occurs at bus-bar #675 at $t = 0.7$ s. Fig. 3(c) shows the current of phase C seen by the relay at bus-bar #671 and Fig. 3(d) shows C. In this case C stays bigger than the threshold value (-3%), which implies the over current is due to fault. Therefore, the relay is not blocked by the proposed method. According to CO-8 characteristic with TDS of 0.5 the operation time for 2.7 times the pickup ($1200/450 \approx 2.7$) is 0.4 s. On the contrary, the conventional relay with TDS of 3 operates after 3 s. Therefore, the proposed method operates almost 7 times faster than traditional methods. It is because, as explained above, for preventing mal-operation of the relay during startup a delay was imposed in conventional relay using TDS.

The proposed method uses least square method to estimate fundamental frequency amplitude, decaying dc component and harmonics, which are possible sources of errors, and takes them into account in the calculations. Moreover, the white Gaussian noise with the signal-to-noise ratio of 10 dB is added to the original signal and the proposed method is applied again. In this case C also stays bigger than the threshold value (-3%), which implies the over current condition is correctly detected due to fault.

4.2. Transformer energizing

In this case, the transformer at bus-bar #633 is energized at $t = 0.36$ s. Fig. 4(a) shows the current of phase A seen by the relay at bus-bar #632 and Fig. 4(b) shows C. In this case Flag becomes 1 at $t = 0.386$ which means non-fault is discriminated 1.56 cycles after its occurrence, which is very fast for the over-current relays.

According to Fig. 4(a) the normal maximum load is 65 A, therefore the pickup value is set at $1.5 \times 65 = 97.5 \approx 100$ A. In

conventional over-current relay TDS of 1 is selected to prevent mal-operation during transformer energizing. The proposed method does not need this imposed delay and TDS of 0.5 is selected.

Now consider the following scenario: a fault arc that happens at bus-bar #634 at $t = 1.5$ s is modeled according to the well-known Warrington formula [33]. Fig. 4(c) shows the current of phase A seen by the relay at bus-bar #632 and Fig. 4(d) shows C. In this case, C stays bigger than the threshold value (-3%), which means the over current is due to fault. According to CO-8 characteristic with TDS of 0.5 the operation time for 2.7 times the pickup is 0.4 s. The conventional relay with TDS of 1 operates after 1 s. Therefore, the proposed method operates almost 2.5 times faster than traditional methods. The procedure is repeated while the Gaussian noise with the signal-to-noise ratio of 15 dB is added to the original signal. In this case C also stays bigger than the threshold value (-3%), which means the fault is detected correctly.

5. Field-measured data analysis

In order to study the proposed algorithm in the real condition, it is tested using field-measured signals. To demonstrate the robustness of the proposed method the cases are selected from totally different networks compared to simulated network. As the results show, in contrast to other classification methods which depend on the system under study, the proposed method is robust due to suitable feature extraction and does not need retraining for different networks. This is another important advantage of the proposed method.

5.1. Induction motor starting

In order to study the accuracy of the proposed algorithm in the case of motor starting the current acquired from 950 V 165 hp motor is considered. Fig. 5(a) [6] shows line-current waveform. Data acquisition process has been described in [6] and Fig. 5(b) shows C. In this case, Flag becomes 1 at $t = 0.03$ s which means non-fault is discriminated less than two cycles after its occurrence accurately.

5.2. Transformer energizing

Performance of the proposed method has been verified using results from field test transformer energizing of a 138/21 kV 315 MVA in the BC Hydro system [34]. Fig. 6(a) [34] shows inrush current of the transformer and Fig. 6(b) shows C of phase A. In this

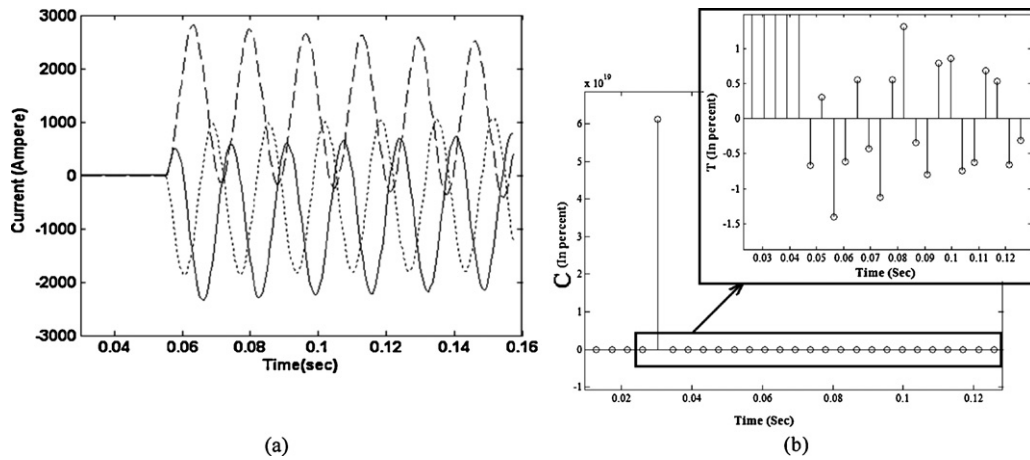


Fig. 7. (a) Three-phase short-circuit test results (recorded) [35] and (b) C values due to fault.

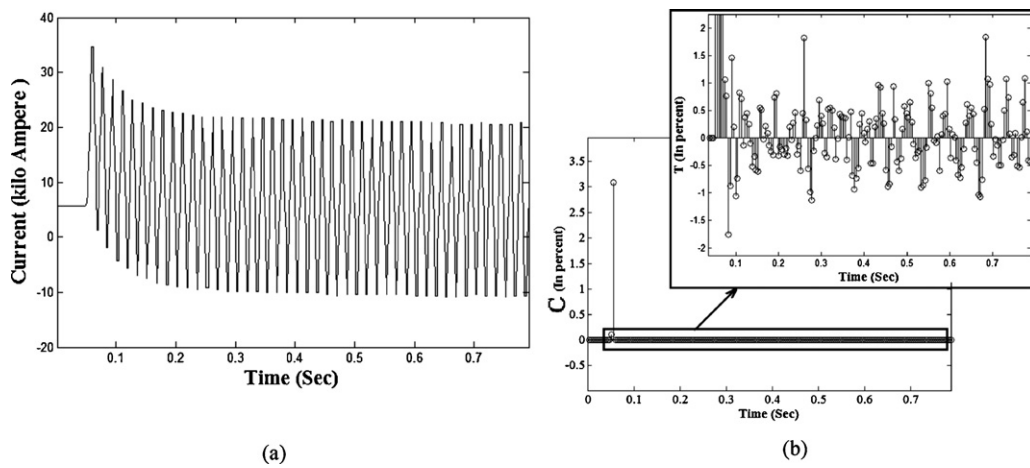


Fig. 8. (a) Current of arc fault occurrence (recorded) [23] and (b) C values due to arc.

case Flag becomes 1 at $t=0.01$ s which means non-fault is discriminated 1.5 cycle after its occurrence.

5.3. Fault

In this case, accuracy of the proposed method is investigated using fault current tested in a power-testing laboratory, which described in detail in [35]. Fig. 7(a) [35] shows currents due to three phase fault and Fig. 7(b) shows C. In this case, C stays bigger than the threshold value (-3%), which implies the over current is due to the fault.

5.4. Arcing fault

Fig. 8(a) [23] shows the measured current of arc fault with source voltage of 14 kV phase-to-ground and Fig. 8(b) shows C. In this case, C stays bigger than the threshold value (-3%) which implies the over current is due to fault.

6. Conclusions

This paper introduced a method for discriminating fault from transformer energizing and induction motor starting in over-current relays. The proposed method is based on the fact that the fundamental component amplitude of current signal decays in the case of induction motor starting and transformer energizing while stays constant in the case of faults. A criterion function using this

difference over different segments was defined which can detect fault from non-fault conditions quickly and accurately.

- As the proposed method is based on the data obtained from the sampled current, which is taken normally in the over current relays, it prevents the mal-trip of relays with no extra cost.
- The proposed method does not require high frequency sampling. Therefore, it is suitable for over current relays, which commonly have low sampling frequency.
- According to the presented results, depending on the location of fault and fault current amplitude, the proposed method can make the overcurrent relays more than seven times faster.
- The merit of the proposed method was demonstrated by simulating various cases on a typical power system and the proposed algorithm was also tested using field-measured data. The simulated data as well as test results show that the proposed algorithm is accurate.

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