Different Methods of Differentiating Inrush Current from Internal Fault Current in Transformer

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ABSTRACT

When a transformer is energized the phenomenon of magnetizing inrush current occurs and causes a pseudo tripping signal to the differential relay which leads to the problem of mal operation or false tripping of the relay. In order to avoid this false tripping of the differential relay and for safe operation of the transformer the distinction of inrush current with internal fault current is very important. Conventionally, second harmonic restraint relay is used but as size of power system network is increasing day by day the electrical network is becoming more and more complicated and some disadvantages of conventional system are slowly understood. Therefore, some other methods which can also be used for proper distinction between inrush current and internal fault current are highlighted in this paper. Different techniques used for discriminating inrush current from internal fault current are discussed and some conclusion has been drawn.

Keywords

Second harmonic; Equivalent Instantaneous Inductance (EII); Instantaneous Magnetizing Inductance (IMI); Morphological Gradient Algorithm (MGA); Sinusoidal Proximity Factor (SPF); Waveform Singularity Factor (WSF); Finite Element Method (FEM); Inrush current; Wavelet Transform

1. INTRODUCTION

A Power transformer is an essential component in electrical power systems and the relays used for its protection must be reliable, dependable, and should take less operating time. Differential protection is mostly used for the protection of transformer. However, false tripping of differential relay occurs when a transformer is energized. This is because of magnetizing inrush current phenomenon which occurs when the transformer is energized. Therefore, distinction of inrush current from internal fault is very important in order to improve the reliability and security of differential protection. Some of the method used for recognition of inrush current from internal fault current are voltage restraint [2],second harmonic restraint, dead-angle restraint, flux-based inrush restraint [3],wavelet transform [4-5],inverse inductance[6],transformer model-based modal analysis [7], power differential [8], hyperbolic s transform[9], low frequency component of Discrete wave transform[10],Scheme of waveform symmetry. Techniques using Fuzzy logic and artificial intelligence system have also been developed. [11-14].

In this paper some of the method or ways for differentiating inrush current from internal fault current has been discussed. These discussions are a review of the work done by the researchers. Based on the discussion some conclusion has been drawn.

2. INRUSH CURRENT

When transformer is energized, the core flux and the corresponding exciting current undergo a transient before reaching steady state values. The severity of the switching transient is related to the instant of switching. Under steady state condition if the applied voltage is sinusoidal, the instantaneous value of common flux in the core (with no residual flux) changes from $-\varphi_{maximum}$ to $+\varphi_{maximum}$ in half cycle to balance the applied voltage and lag its voltage by 90 degree. If the transformer is switched on at the instant of its positive peak then the flux rises from zero and transformer is switched on with normal magnetizing current, the same would happen if the applied voltage is at its negative peak at the switching instant. However if at the instant of switching, the applied voltage is at zero and say going toward positive then the flux must change from zero to $2\varphi_{maximum}$ in half cycle for a flux less core and if the flux contains residual flux then this value will increase because of the effect of residual flux. This gives a rise to almost double the flux and is known as doubling effect and further causes a huge magnetizing inrush in the primary current. An analogous situation would arise when applied voltage is going toward negative. The value of inrush current can reach five times the full load current in the transformer and is therefore nearly 100 times the normal no load current.[15-16] Figure 1 displays the diagram of generation of inrush current in the transformer.

Techniques are invented which can be used to study inrush current such as Finite Element Method[17-19], Coupled Electromagnetic model[20], Operational Matrices[21].Investigation of several factor which affect inrush current of transformer is done using Finite Element Method[22]. Inrush current also causes forces on the transformer winding and sometimes these forces can be greater than short circuit forces. It can be minimized by using superconductor, controlled switching, sequential phase energization technique, Virtual air gap technique, changing distribution of the coil winding [23-30].

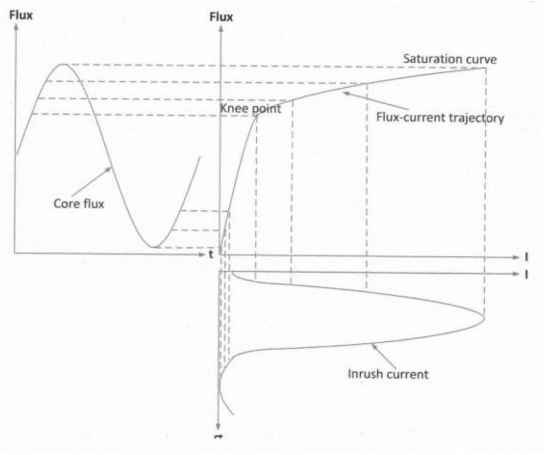


Fig 1: Inrush current generation in transformer

3. METHODS

3.1 Wavelet based method

In this method first the transformer model with sufficient precision are used for inrush current and short circuit current measurement. The simulation shows current waveform with respect to time (in seconds) for both the cases. Then wavelet transformation maps the time function of the result obtained into a two dimensional function of α and t.α is called scaling factor and t is the change of the function along the time axis. Daubechies family wavelets are selected for the investigation. Results using wavelet transformation for inrush current and short circuit current were quite different from each other and thus this method provides a way to distinguish inrush current from short circuit current [43].

3.2 Virtual third harmonic restraint

In this method the technology of waveform construction is used. Inrush current shown in fig.2 has a dominant even harmonic component in it. By using waveform construction technique the spiry pulse is moved for half cycle in backward direction and then reversed. This will form a waveform as shown in fig. 3.In fig.3; the practical inrush current shown by thin line is the same current waveform which has been shown in fig.2 while the thick line shows the result after applying the process of wave construction. Now this waveform contains a dominant third harmonic component in it. However it to be noted that the third harmonic component is not really very teeming in the whole process. It is only because of the waveform construction the third harmonic comes in picture. This method offers many advantages over conventional second harmonic relay. Firstly, the operating time has reduced. Secondly, the restrain scheme can be performed by phase. Thirdly, the problem of symmetrical inrush current can also be solved [35].

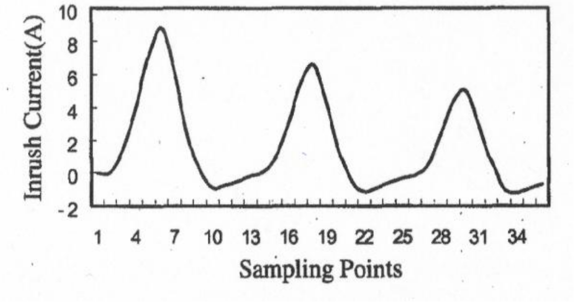


Fig 2: Transformer inrush current diagram

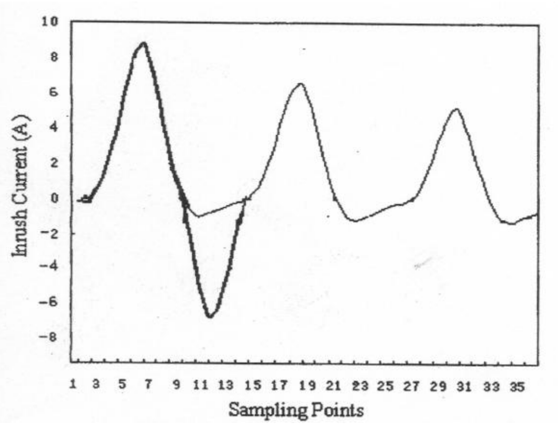


Fig 3: The Diagram of virtual third harmonic restraint scheme

During practical application of this method some problems should be taken care to maintain the reliability of the system.

1. The DC component should be removed in order to avoid the mal operation of the relay.
2. The symmetrical axis of the spiry pulse and data window should beat same position.
3. The threshold value for the operation of relay should be carefully selected.

3.3 Inductance based technique

3.3.1 EII based technique

The change in Equivalent Instantaneous Inductance (EII) in case of inrush current and internal fault is the criteria used for distinguishing inrush current and internal fault current. Experiments were conducted for verifying the performance of this technique and it was found that, there is extreme variation of the Equivalent Instantaneous Inductance (EII) for inrush current, but the value of EII for faulty phase is almost constant.

During normal operating state of power transformer and for internal fault condition, the iron core is not saturated and the value of magnetizing current is extremely small, which results in the approximately constant Instantaneous Magnetizing Inductance (IMI) so the operation lies in the linear area of the magnetizing characteristic. But in case of inrush current the core of transformer moves between saturation and non saturation region of operation due to this a sudden variation of the IMI, as shown in Fig. 4

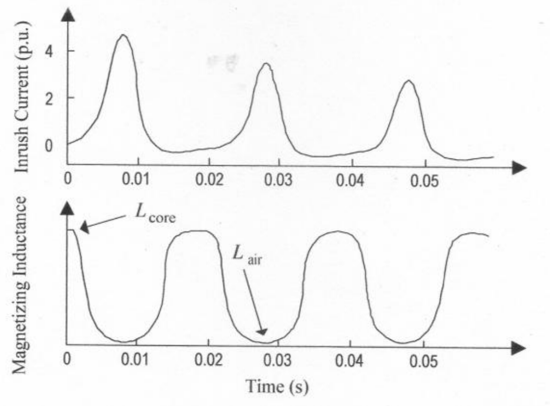


Fig 4: Diagram showing the variation of IMI waveform

There are two methods which are used to compute the value of EII. First method is Indirect method while second method is Direct method.

Indirect method: When the supply of 50Hz is given to the transformer the value of IMI varies and it has a fundamental frequency of 50Hz. The value of fundamental frequency component of variation of IMI in case of normal operation and internal fault condition is zero and same is with the value of EII while this is not the case for inrush current. Thus the above mentioned criterion is used to differentiate inrush current from internal fault or normal operation of transformer. If the magnitude of the fundamental frequency component in the EII is more than the threshold or pick up value, then there is inrush current in the transformer and the relay tripping is blocked, if it is more than the threshold value then relay operating signal is send.

Direct method: The RMS expression which gives the variation in EII is given as

$$\Delta\bar{L}_k=\sqrt{\frac{1}{N}\sum_{i=1}^{N}[L_k(i)-\overline{L_k}]^2} \qquad (1)$$

$$\bar{L}_k=\frac{1}{N}\sum_{i-1}^{N}L_k(i) \qquad (2)$$

Where, N is number of samples in a single frequency cycle . $\Delta\bar{L}_k$ is criterion which sets the threshold and is used to distinguish the inrush current from the internal fault . If $\Delta\bar{L}_k$ exceeds a threshold or pick up value, the relay take it is as inrush current and the operation of relay is blocked. If this value is less than the threshold value the relay takes it as internal fault. The second method of analysis is successful in producing the result in time as well as in frequency domain analysis, while first method is effective only in frequency domain [1].

3.3.2 Instantaneous Inductance technique

In this method voltage and current signal are used to find the differential inductance of the transformer from the primary side. The differential inductance is calculated from every phase of the transformer. An algorithm is developed which compared this value of differential inductance with the threshold value. If this value is more than the threshold value then it is inrush current else it is internal fault. The operating time of this method is also very less(5ms ,less than 1/4th of the power frequency cycle).This method works even when there is variation in the tapping of transformer, fault resistance comes into picture, saturation of Current Transformer(CT) occurs [40].

3.4 Short Window Filter Algorithm

For calculation of magnitude of transformer differential current the data window in one cycle Fourier filter is considered. Short data window is used for the detection of inrush detection. Data window for filter algorithm is shown in fig. 5. W_1 shows the data window of Fourier filter which is having span of one power frequency cycle. W_2 shows the data window for short-window filter algorithm and its span is shorter than span of one power frequency cycle.

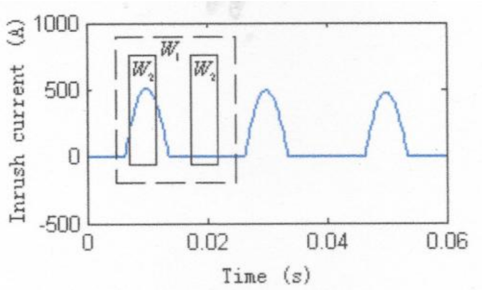


Fig 5: Data window of filter algorithm

When Fourier analysis for full window is done, the signal magnitudes found for inrush current will not change or very little change will be there.

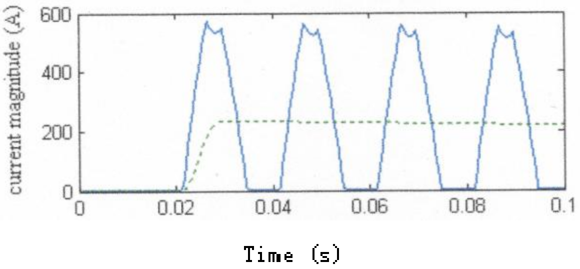


Fig 6: Data window of filter algorithm

On the contrary, when the analysis for short window by applying short window algorithm was done, the value of inrush current calculated by short-window filter algorithm will be different from full window analysis. The variation in magnetizing inductance is shown by solid lines in fig 6. However, this is not the case in the analysis of internal fault current. The result is shown as the dotted line for full window and solid line for short window filter algorithm (Fig.6 and Fig.7)

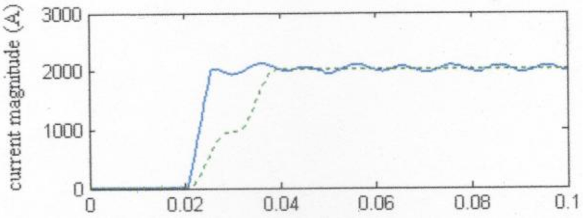


Fig 7: Magnitude of internal fault current

Based on the above discussion inrush current detection criterion is set. The detection criteria is given by

$$K=\sum_{K=1}^{N}\frac{I_{mshortwindow}-I_{mFourier}}{\sum_{K=1}^{N}I_{mFourier}}\geq C_{th} \qquad (3)$$

Where, $I_{mshortwindow}$ shows the magnitude evaluated by short window filter, $I_{mFourier}$ shows the magnitude evaluated by Fourier filter, N is sampling rate and C_{th} is the value of pickup threshold for detecting inrush current in differential relay [36].

3.5 Waveform Singularity Technique

In this technique, waveform singularity factor is used to differentiate inrush current from internal fault current in power transformer.

Algorithm:

For sinusoidal wave form,f(t) can be described as

$$f(t)=A\sin(\omega t+\theta) \qquad (4)$$

Where, magnitude of sinusoidal waveform is denoted by A, Angular frequency of power signal is denoted by ω, and initial phase angle is represented by θ.

Time interval for quarter cycle Δt is $0.5\frac{\pi}{\omega}$

f (t) for instant t + Δt is

$$A\cos(\omega t+\theta) \qquad (5)$$

f(t) for instantt+ Δt/2is

$$A\cos(\omega t+\theta+\pi/4) \qquad (6)$$

g(t) is defined as

$$g(t) = f(t) + f(t + \Delta t) - \sqrt{2}\, f(t + \Delta t2) \qquad (7)$$

The value of g(t) is constant with time and is ideally equal to zero, g(t).But in case of practical current waveform harmonics comes into picture. So, a waveform singularity factor is used to evaluate this difference

$$h(t) = \frac{1}{e}\sqrt{\frac{1}{N}\sum_{t=t_k}^{t=t_k+2\Delta t}(g(t)-e)^2} \qquad (8)$$

$$e = \frac{1}{N}\sum_{t=t_k}^{t=t_k+2\Delta t} g(t) \qquad (9)$$

Where, N is no. of samples per power frequency cycle. When internal fault occurs the value of h(t) is zero and when magnetizing inrush current comes into picture this value is non zero. If the WSF of every phase gets more than the threshold or pickup value of 1.0, the relay will take it as inrush current and blocks the tripping. For all values less than or equal to 1.0 the relay will take it as an internal fault and will operate. The theoretical value of threshold is around zero. Thus h(t), also known as Waveform Singularity Factor (WSF) provides a measure to differentiate inrush current from internal fault current [37].

3.6 Sinusoidal Proximity Factor

The difference in the value of SPF in case of inrush current and internal fault current is a measure to distinguish internal fault current from inrush current. The algorithm used for the calculation of SPF is explained below

The sinusoidal waveform can be expressed as

$$f(t) = A\sin(\omega t + \theta) \qquad (10)$$

Where, magnitude of sinusoidal waveform is denoted by A, Angular frequency of power signal is denoted by ω, and initial phase angle is represented by θ.

Let a signal f (t) is defined which has n even numbers of sampling point. For sampling point at the instant t_k

$$f(t_k) = A\sin(\omega t_k + \theta) \qquad (11)$$

Time interval for quarter cycle Δt is $0.5\frac{\pi}{\omega}$

$f(t_k)$ for the instant t+ Δt is

$$A\cos(\omega t_k+\theta) \qquad (12)$$

Normalizing f(t) and multiply equation (11) and (12)

$$\rho(t_k)=\sin(2\omega t_k + 2\theta) \qquad (13)$$

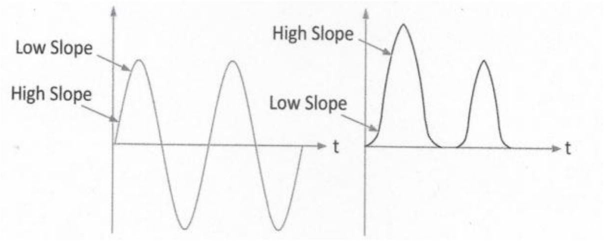
This is the expression for pure sine wave. But for practical current waveform harmonics comes into picture. So a sinusoidal proximity factor (SPF) is used to evaluate this difference.

$$\eta(t_k) = abs(\rho(t_k) - \sin(2\omega t_k + 2\theta)) \qquad (14)$$

Where, η is the SPF and abs stands for absolute difference between $\rho(t_k)$ and $\sin(2\omega t_k+ 2\theta)$ .When internal fault is there, the value of SPF is close to zero and when magnetizing inrush current is generated there is a drastic variation in the value of SPF. Therefore, SPF is a measure to distinguish between inrush current and internal fault current. If the value of SPF of some phase is less than the threshold or pick up value of 0.5, the relay take this as an internal fault and gets tripped and for values greater than or equal to 0.5 the relay senses it as inrush current and dismisses the tripping. This method is more useful when the value of internal fault current is low [38].

3.7 Identifying the Difference between the Waveform of Inrush Current and Internal Fault Current

The distinction between inrush current and internal fault current can be done by identifying the difference between the waveform of inrush current and internal fault current. The different features of inrush current and internal fault current are shown in fig 8.



(a) (b)

Fig 8: (a) fault current, (b) inrush current.

From the figure we can see that the internal fault current waveform has high slope at the time of switching and after some time duration its slope gets reduced while in case of inrush current the slope at the time of switching is low and it increases till the time current reaches its maximum value. This distinction is used to discriminate the current as inrush current or internal fault current. The methods are discussed as below.

3.7.1 Improved Morphological Gradient Algorithm

In order to identify the slope feature of the waveform an improved Morphological Gradient Algorithm (MGA) is used. Fundamental morphological operator dilation and erosion are used in this scheme. Dilation and erosion for a one dimensional signal is given as

$$(f\oplus g)(x) = \max\{f(x-s)+g(s), x\in D_f, s\in D_g\} \qquad (15)$$

s

$$(f\ominus g)(x) = \max\{f(x+s)-g(s), x\in D_f, s\in D_g\} \qquad (16)$$

s

Where f is the field, g stands for structuring element (SE), field of definition of f and g are denoted as D_f and D_g respectively. For edge detection morphological gradient used is:

$$G(f)=(f\oplus g) - (f\ominus g) \qquad (18)$$

Structuring element defined to find the rising and falling edges are

$$g^{+} = \{0_1,0_2,....0_l\} \quad (19)$$

$$g^{-} = \{0_1,0_2......0_l\} \quad (20)$$

Where g^{+} is used for rising edge and g^{-} is used for falling edge. For the length of flat SE of 3, the improved morphological gradient for inrush current and internal fault current is as shown in figure 9(a) and 9(b).

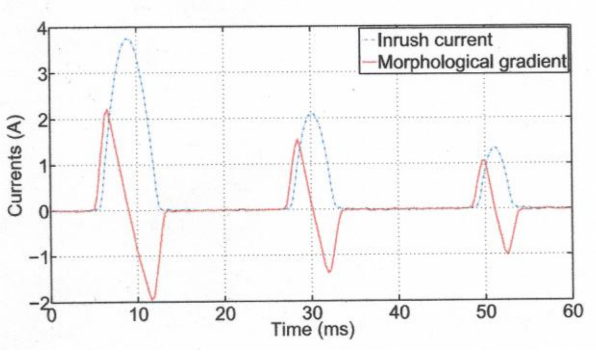


Fig 9: (a) Morphological gradient for inrush current.

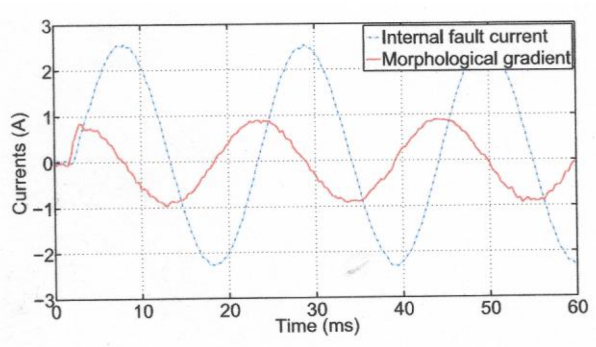


Fig 9: (b) Morphological gradient for internal fault current

Based on these differences between the patterns of waveform, the inrush current can be distinguished with internal fault current in the sampling window of half a long cycle. For the sake of quantification the criterion used for discrimination is

$$\sigma = \frac{\max\{|Gs|\}}{|\max\{Is\}-\min\{Is\}|} \quad (17)$$

Where, current signal in the data sampling window is represented by Is and morphological gradient is represented by Gs. The value of σ is very high in case of inrush current as compared to its value in case of internal fault current. For the next half cycle, if the gradient result shows a flat waveform, then it is inrush current otherwise, there is internal fault [41]. The above process is explained with the help of flow chart as shown in figure 10.

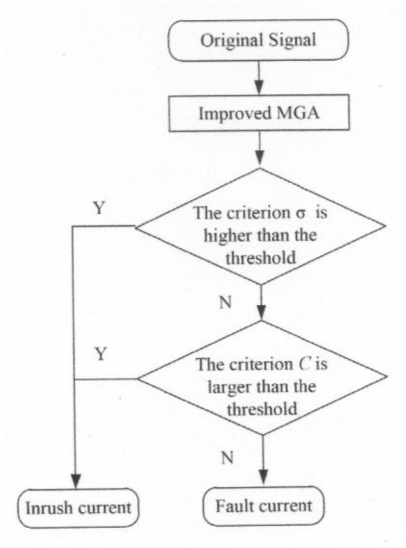


Fig 10: Flow chart of the scheme.

3.7.2 Using mathematical Morphology

The above discussed morphological approach fails when CT is saturated so a new method is developed using morphological fundamentals as described above. It uses two different algorithms the first algorithm can discriminate between inrush and internal fault currents when there is no CT saturation. When CT gets saturated, the first algorithm fails to provide a decision. In this case, the second algorithm which uses a symmetrical morphological gradient criterion is triggered automatically to differentiate between internal fault and inrush current in the system. This method can also be used to detect sympathetic inrush current [42].

3.7.3 Wavelet Based Technique by using Finite Element Method

Discrete wavelet transform (DWT) is applied to the differential current and distinct characters and features for inrush current and internal fault current is extracted based on the wavelet components. With the help of these character and features the current will be recognized as inrush current or internal fault current. The ability of the wavelet transform to focus on short time intervals for high frequency components and long-time interval for low frequency components provides a better way of investigation for signals which have localized impulses and oscillation. So, wavelet decomposition is very helpful for studying transient signals. It also helps in finding a much better current characterization with more reliable distinction. The process of execution of DWT is shown in fig. 11 in which s denotes the original signal and high pass filter and low pass filter are denoted as HPF and LPF respectively.

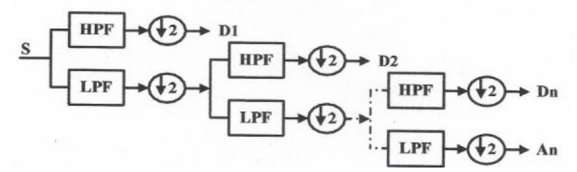


Fig 11: Implementation procedure of DWT.

By observing the waveform for inrush current and internal fault current (fig. 8) it can be said that in case of fault current the magnitude of high frequencies at starting time has falling trend, while in case of inrush current the trend has a rising. These trends and features are found in the frequency level D3 when simulation based on Finite Element Method was done. Finite element method gives a more realistic method of simulation. Thus the above mentioned criteria can be used for differentiating inrush current from fault current. This method is relatively faster method and can differentiate inrush current from fault current in less than quarter a cycle if the supply is of 50Hz [39].

4. CONCLUSIONS AND FUTURE SCOPE

Among the above mentioned techniques all the techniques can be used in real life situation but instantaneous inductance and wavelet based technique are relatively faster as compared to other techniques. Also, Instantaneous inductance technique and morphological technique are better than other techniques because they work even when CT is saturated. For future scope, efforts are needed to remove the DC decaying component. Better mechanism for finding optimum position of data window needs to be developed. The sensitivity for the method of sinusoidal proximity factor should not be limited to low level internal faults only. The application of EII can be extended to transformers with more number of turns. Efforts should be made to reduce the operating time of relay. More study is needed in setting up the threshold criterion of the relay.

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