

**A REVIEW OF TECHNIQUES USED FOR DISCRIMINATION OF INRUSH
CURRENT AND INTERNAL FAULT CURRENT OF A POWER TRANSFORMER****¹Purushottam R. Bharambe, ²Sudhir R. Paraskar, ³Saurabh S. Jadhao**Assistant Professor^{1,3}, Professor & Head², Department of Electrical Engineering, SSGMCE, Shegaon
prbharambe@gmail.com¹, sraparaskar@gmail.com², ssjadhao@gmail.com³**ABSTRACT**

The transformer draws a magnetizing inrush current during the energization. This current has a magnitude six to eight times the rated current which may lead to false tripping of the differential relay causing the problem of unnecessary disconnection of the transformer from the supply mains. The proper discrimination between the transformer inrush current and internal fault current is necessary in order to avoid the false tripping of the differential relay and for the proper operation of the transformer. The second harmonic restraint relay is used in the conventional protection system for discrimination between the inrush current and internal fault current. The energy demand is increasing nowadays, so in order to feed the ever-increasing power demand, the size and complexity of the emerging power system is increasing. In order to protect the emerging power system and its important components like a transformer, we need a fast, stable & a reliable protection system. Therefore, the ongoing research is now focused on developing novel algorithms for the proper distinction between inrush current and internal fault current. This paper presents a review of various techniques used for discrimination between the inrush current and an internal fault current of the transformer. This will help the new researcher working in this area.

Keywords: Transformer, magnetizing current, fault current, differential protection

1. INTRODUCTION

Transformer is a highly efficient static electrical machine that plays an important role in the power system. It is a valuable component of power system, so it is necessary to have a fast and proper operating protection scheme for the safety and proper functioning. In case of transformer two types of faults occurs namely internal faults and external faults. The faults, which occur inside the transformer are known as internal faults. The faults, which occurs outside the transformer or at the terminals of transformer are caled as external faults. Internal fault may cause severe damage to the transformer winding within a short duration if proper care is not taken by the protection system. Protection system of transformer depends upon the transformer rating, working condition, tap changing scheme and loading condition of the transformer. In small rating distribution transformers high voltage fuses are used for the protection. Buchholz relay protection is used for transformer having rating above 500 kVA. Buchholz relay provides the protection against the incipient faults occurring in the transformer. In addition, with Buchholz relay, over current protection with restricted earth fault protection is used in large rating distribution transformers. The differential protection scheme is applied for the protection of power transformers.

Differential Protection is an apparatus protection. The primary current and secondary current of the power transformer is compared by the differential relay and if any difference found in the current then the relay will give trip signal to both primary and secondary circuit breakers. Differential protection of the transformer should be provided with a proportional bias to avoid the tripping of relay for through faults. Figure 1 shows the differential protection scheme applied to three phase transformer.

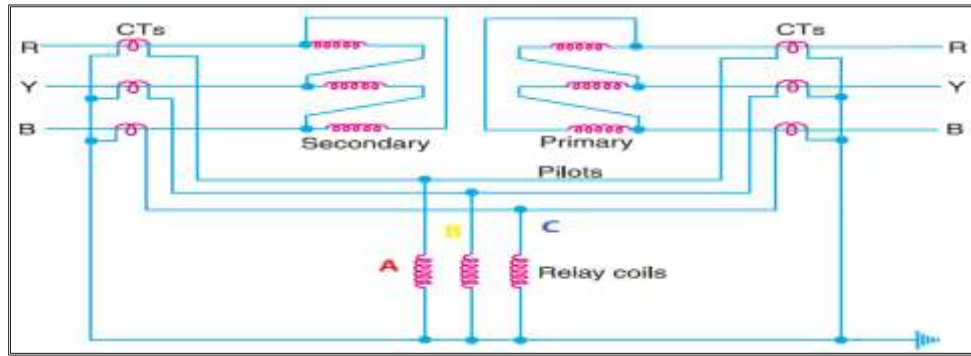


Figure 1: Differential Protection of Transformer

Sometimes the differential current may found to be significant without an internal fault due to the CT saturation, turn ratio changes as a result of tap changing & magnetizing inrush current. The major challenge in the differential protection of power transformer is to avoid the false tripping of the relay due to improper discrimination between the magnetizing inrush current and fault current.

The magnitude of magnetizing inrush current is high as compared to the internal fault current of transformer. Several approaches such as harmonic restraint, voltage and flux restraint, inductance-based method, pattern recognition method and artificial Intelligence methods such as, neural network and fuzzy logic have been developed for discrimination between inrush & internal fault current of transformer. These methods have their advantages as well as their limitations. In this paper, the comparative study of various inrush & internal fault current discrimination techniques is given for reference and to identify the scope for new researcher.

2. INRUSH CURRENT IN TRANSFORMER

Before energization the flux is zero in the core of transformer. The flux will not reach the steady-state instantly. The flux in the transformer core will increase from its zero value at the time of energization and as per Faraday's law of electromagnetic induction the rate of change of flux is responsible for induction of voltage in the windings which is given by the equation $e = d\phi/dt$. The total flux will be integral of the voltage wave which is given by

$$e = E \cdot \sin\omega t = \frac{d\phi}{dt} , \quad \phi = \int e \cdot dt = E \int \sin\omega t \cdot dt$$

If the transformer is energized at the voltage zero instant then the flux wave will also start from the same origin as voltage waveform, the value of flux after first half cycle of the voltage waveform is given by

$$\phi_m = \frac{E}{\omega} \int_0^\pi \omega \cdot \sin\omega t \cdot dt = \phi_m \int_0^\pi \sin\omega t \cdot d(\omega t) = 2\phi_m$$

Where ϕ_m is the maximum flux. The core of transformer generally gets saturated when the flux is above the maximum steady-state flux. During the energization of transformer, the maximum value of flux will rise to twice the steady-state maximum value.

The core of transformer gets saturated when the flux exceeds the steady-state maximum value, hence the transformer draws a heavy current to produce the rest of flux. This heavy current drawn by the transformer during energization is called as the magnetizing inrush current. The magnitude of this current may be up to ten times the rated current of the transformer.

The operation of differential relay is affected by the interference of inrush current in a power transformer. High magnetizing inrush current affect the rating of fuses or breakers, it also introduces noise and distortion back into the supply mains. Hence it is very much essential to discriminate inrush current from the internal fault

current to improve the protective system of transformer. Figure 2 shows the magnetizing inrush current of transformer along with the applied voltage.

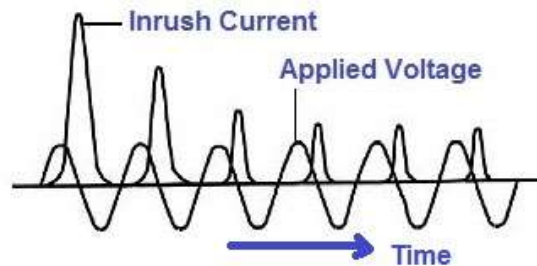


Figure 2: Magnetizing Inrush Current of Transformer

3. INRUSH AND INTERNAL FAULT CURRENT DISCRIMINATION METHOD

Several techniques are available in the literature for discrimination between inrush and internal fault current of transformer. Few of the most commonly used techniques are reviewed in this paper.

3.1 HARMONIC RESTRAIN TECHNIQUE

The harmonic restraint method is the most commonly and widely used technique for discrimination between inrush current and internal fault current in the transformer. It is the classical way to restrain the false tripping of the differential relay during energization. This method is based on the assumption that the magnetizing current contains the high level second harmonic component. In this method the magnitude of the second harmonic in the differential current is compared with the fundamental frequency component.

As the second harmonic component is predominant in case of inrush and is less predominant in case of internal faults. The new relay retains the simple principle for the design of the variable-percentage differential unit. This will also provide the supervision of inrush phenomenon with the second-harmonic restraint [1].

The recommended set point is twenty percentage of fundamental current for the second harmonic restraint in the relay. A lower setting is required for lower level second harmonic restraint which may affect the tripping time of the differential relay under the fault conditions [2].

Rectangular transfer technique is used to calculate the Fourier sine coefficients and Fourier cosine coefficients of the fundamental, second, third and fifth harmonics. These coefficients are used in the blocking techniques and harmonics restrain used in the differential protection system [3]. The ratio of second harmonic power spectrum to fundamental power spectrum based on autoregressive processes is used for the identification of inrush current [5].

The development of algorithm is done on the basis of behavior of second harmonic components of the differential currents under inrush and fault conditions. The time variation of the second harmonic of differential current is used to define the criterion function. The sign of the criterion function are evaluated for the three phases. The internal faults current is discriminated from inrush current within a half cycle after the occurrence of event. This algorithm does not involve thresholding [6].

If fault occurs during the transformer energization then it is found that the protection system fails to discriminate between inrush current and fault current. In the new method a Taylor series is used to extract the fundamental and second harmonic components from the inrush current and fault currents. The second harmonic component is predominant in case of inrush hence second harmonic restrain is used for its discrimination [7].

Differential relays which are using the second harmonic restraint and the blocking differential elements in parallel will operate faster than the differential relays using single differential element. Parallel operation

increases the operating speed. For unbalance faults the negative-sequence differential element gives higher sensitivity than the conventional differential element. Improved sensitivity will help to detect the turn-to-turn faults [41].

In order to maintain the security of relays in case of inrush phenomenon the second harmonic restraint principle is adopted. In recent years, the magnetic characteristics are improved by using good core materials due to this the second harmonic components gets lowered in magnetizing inrush currents; in contrast, the second harmonic components get increased in case of short circuit currents due to CT saturation and the due to the effect of distributed capacitance of the EHV line. This makes the choice of an appropriate harmonic restraint ratio more difficult. A fast flux restraint algorithm is suggested to identify the inrush current based on the sampled values of voltage/current. This algorithm determines the rate of change of magnetic flux in the transformer core to determine the status of saturation status of the transformer. The status of saturation is traced by a counters group. The threshold of counter is used to decide whether the relay should generate the trip command to isolate the transformer [43].

3.2 SIGNAL PROCESSING TECHNIQUES

A new method is used to discriminate the internal and external faults on both side of transformer by using sequence component of current. Fast Fourier Transform (FFT) is used to calculate the magnitude and phase angle of current signals. This magnitude and phase angle is further used to calculate the sequence component of current. A principle of differential protection is applied to the sequence component in order to identify the internal fault and external fault of transformer. Various cases of internal fault and external fault are simulated using the simulation software including the magnetizing inrush, CT saturation and high fault resistance conditions. The proposed method found to be efficient and perfect for discrimination of internal and external faults of transformer [52].

The new scheme time and frequency of the energy signal is done by using the wavelet decomposition. The wavelet transform divides the energy signal in time and frequency. This will provide more description about each signal. This method highlights the difference between the inrush current and fault current. The discrimination function value is zero for inrush current. When the value of discrimination function is smaller than zero then there exist an internal fault in the transformer [8].

The monitoring of non-stationary signal is done by using the wavelet transform. The wavelet is used to discriminate between the inrush current and internal fault current of transformer. The proposed wavelet-based technique uses the wavelet coefficient of the energy signal. The variation in the signal is utilized to discriminate the transformer faults. The resolution of the method is good as compared to an FFT. The algorithm gives trip signal in case of internal fault and blocks tripping signal during external faults [16].

A wavelet packet transform is used to discriminate between the internal faults and external faults of the transformer under the protection zone. This method is also used to discriminate the inrush current from the internal fault current of the transformer. In this method the fault current and pre-fault voltage signals are used for discrimination. If the value of fault current and pre-fault voltage goes below the negative threshold value then it is an external fault. In order to discriminate between the inrush current and internal fault current of transformer the sum of wavelet coefficient from level one to seven is used. This value shows the level of the inrush signal. In the discrimination process this value is compared with the wavelet coefficient in zeroth window [9].

A discrete wavelet transforms and correlation coefficient-based method of digital differential protection of transformer is suggested. The proposed algorithm includes both online and offline operation of the transformer. In this method the differential current for 10 half cycles is decomposed up to 5th level and the detailed coefficients of 5th level are used for discrimination. The correlational coefficient is obtained from the wavelet decomposition of the recorded signal and the pre-recorded signal upto 5th level and is used to discriminate the inrush current and internal fault current. If the value of correlation coefficient is more than 0.8 then it is a inrush current otherwise it is internal fault currents [10].

A DWT based new algorithm is proposed for the discrimination of inrush current and internal fault currents of transformer. In this algorithm the differential current of three phase power transformer is decomposed using DWT up to five levels. The energy percentage of the decomposed detailed coefficients and the correlation coefficient are calculated using the sliding window technique. Detection of the inrush and internal fault current is done by calculating the values of correlation coefficients and computing the number of dips occurring in the values of correlation coefficients for differential currents. If the dips in each in correlation coefficient is greater than 1 then the case is inrush current and for other values it is internal fault current [11].

The different natures of power transformer currents are recognized by using the new method proposed in [12]. The proposed scheme is based on fifth level decomposition using discrete wavelet transform. In this algorithm DWT detail coefficients are estimated for the third and fourth level. The ratio of the median absolute deviation of the detailed wavelet coefficient for fourth level to the median absolute deviation of the detailed wavelet coefficient third level is evaluated using the sliding window technique. The magnitude of the estimated ratio, wave shape and time locations give the required signature in order to identify the type of the transformer current.

The development of new scheme for discriminating different currents in power transformers is done on the basis of two-level wavelet packet transform. In this method the signature is obtained based on the frequency of sub-bands in order to recognize the type of current in the power transformer without decomposing the current signal [13].

In this method the three-phase differential current of the transformer is decomposed using the Discrete wavelet transforms in order to detect the internal faults of transformer using spectral energy change. Wavelet packet transform is used to discriminate the inrush and internal fault current of transformer. From the wavelet analysis it is found that both normal current and inrush current does not show any higher frequency component [14].

A hybrid technique based on the combination of wavelet packet transform and dqo transformation of the three-phase differential current signals is used. Using the hybrid dq-WPT technique the information required to discriminate the current in power transform is based on the sub-band frequencies of the differential current [15].

In this technique the state-space equations of a transformer under study are estimated. The estimation of HV winding current is done by Extended Kalman filter estimator. For healthy transformer the extended Kalman filter estimator precisely estimates the HV winding current and for faulty condition the extended Kalman filter estimator perform poorly. In this method the difference between the estimated and the measured values of HV winding currents is used for discrimination of the inrush current and internal fault current [18].

A unique criterion is established for the fast and precise discrimination of inrush current and internal fault current based on the asymmetry of inrush current waveform [19].

3.3 MICROPROCESSOR BASED TECHNIQUE

A Microcontroller based protection system is used for the protection of power transformer. This system consists of hardware circuitry used to discriminate between inrush current and internal fault current. This protection system works reliably and it does not generate the trip signal in case of normal operation, inrush phenomenon and external fault conditions. The operating time of this scheme is very less [49].

3.4 COMBINATION OF SIGNAL PROCESSING AND SOFT COPUTING TECHNIQUES

Soft computing techniques are used to find solutions to complex real-life problems. It is tolerant of uncertainty, imprecision, partial truth, and approximations. It is based on the structure of human mind. It includes techniques such as artificial neural networks, genetic algorithms, machine learning, fuzzy logic, and expert systems. The theory of soft computing was evolved in 1980s, it is now become a major area of research in engineering. The soft computing techniques are nowadays used in many applications. With the development of highly efficient and low-cost digital processors hardware the applications of soft computing techniques are increasing and will continue to expand.

3.4.1 WAVELET - SVM

A support vector machine (SVM) based differential protection scheme provides an effective discrimination of inrush and internal faults in a power transformer. The wavelet transform is used for feature extraction, the extracted features are given as input to the SVM classifier. The simulation results are used to test the performance of the developed algorithm [17].

3.4.2 DFT - ANN

A hybrid method of DFT and ANN combination is used to discriminate the inrush current and internal-fault currents in power transformer. In the preprocessing module the DFT over full-cycle is determined for feature extraction. The extracted features are used to determine the second harmonic ratio (SHR). This SHR is given as an input to the ANN for classifying the inrush current and internal fault current [20].

The internal faults, external faults and inrush phenomenon of the transformer are simulated in MATLAB environment. The captured current signals are analyzed using Maximal Overlap Discrete Wavelet Transform (MODWT) with DB4 wavelet for feature extraction. These extracted features are used for training the Decision Tree (DT) and Artificial Neural Network (ANN) classifiers. This method discriminates the internal, external faults, and inrush phenomenon with a good accuracy [36].

A new differential protection scheme called convolutional light-gated neural network (CLGNN) is a combination of deep neural networks (DNN), convolutional neural network (CNN) and light-gated recurrent unit (LGRU). This scheme automatically extracts the features from the original signal. The result shows the accuracy and reliability of the discrimination scheme. The robustness of the scheme is evaluated by considering the impacts of superconducting fault current limiter (SFCL), CT saturation, and series compensation [39].

A Hilbert transform and Artificial Neural Network based new algorithm is used for discrimination between inrush current and internal fault current. The performance of the proposed algorithm is evaluated by using the custom-built laboratory transformer. The proposed algorithm successfully discriminates the inrush current and internal fault current [42].

3.4.3 EWT - SVM

A EWT and SVM combination is used for discrimination of inrush current and internal fault current of power transformer. EWT algorithm is used for feature extraction from the generated data. These features

are further given SVM training. The testing of different kernel functions of SVM is done for accuracy improvement using test vectors [22].

The least- squares technique is used for discrimination of inrush current and internal fault current of transformer. The difference between the fitted signals and the normalized differential currents is calculated. Maximum range of the fitted signals is used to define the simple criterion. Using this criterion, the discrimination takes place within half cycle [23].

The discrimination technique based on Random forest extracts the features from the differential current of transformer. Various internal faults and inrush phenomenon are simulated for an existing power transformer [24].

A correlation coefficients analysis based new technique is used for discriminating the inrush and internal fault of a transformer. The technique depends on the changes in current waveforms that occur during the faults. Auto-correlation has been added to cross-correlation in one scheme for better fault discrimination and to increase speed in detecting the fault within a very short time. This technique overcomes the CT saturation problem. The testing of this new algorithm is done practically using the LabVIEW and MATLAB. The results show that this algorithm can detect and correctly identify the inrush and internal fault of a transformer [26].

A new algorithm for the differential protection of power transformer is based on the instantaneous current-value and negative sequence current signals. For the reliable operation of the proposed algorithm the ratio of the operating and restraint negative sequence current signals is integrated. Various faults are simulated using Alternative Transients Program (ATP) for testing the performance of propose algorithm. The results shows that the proposed algorithm is able to discriminate the internal faults with less severity [27].

The transformer interturn fault detection system (TIFDS) is used for the detection of internal faults at incipient stage. This system takes care of unbalance load condition. By computing correction coefficients, the TIFDS algorithm makes the transformer symmetrical and sets primary current to zero. This symmetry gets disturbed in case of internal fault. The magnitude of neutral current shows the severity of the fault and its inclination shows the phase with predominant fault [28].

A calculated power based differential protection scheme is capable of discriminating the inrush and internal fault of transformer to prevent the maloperation of protection scheme due to inrush. Two-port network equivalent is used for calculated power. The practical implementation of the algorithm can be done by microcomputer relays [40].

3.5 FPGA TECHNIQUE

A new method is proposed for discrimination of inrush current and internal fault current on the basis of nature of current waveform, magnitude and duration. In this algorithm the magnitude and duration of both inrush current and internal fault current are compared with the help of FPGA. After comparison the FPGA makes the decision and gives the output to provide the trip signal in case of internal fault and to pass the inrush current [21].

3.6 REAL-TIME DISCRIMINATION TECHNIQUES

A new technique used for detection of less severe internal faults under live operation of dry-type transformers requires two low-cost flux sensors. The capability of this technique is tested by developing a prototype device for transformer health monitoring. This device can detect the two turns short circuit fault within three cycles. This methodology works effectively under the loading and unbalance conditions. In this method less number of sensors are required [31].

A real-time proposed algorithm detects the interturn faults in 1-phase transformers. Initially the primary winding voltage and current data of healthy transformer is captured experimentally. Then the healthy indicator value is computed and is compared with the actual indicator value for detecting the interturn winding fault. Experimental result shows that the proposed algorithm detects the incipient interturn winding faults under any load condition [32].

The current harmonic analysis of no-load and light load transformer is used for detection of inter-turn winding fault. A trend is analyzed for specific harmonic components in the presence of fault for detection. A signature analysis is done to take the decision. The verification of this approach is done by using different vector groups of 3-phase transformer. This algorithm can detect 2% interturn fault at incipient stage [33].

In this method interturn fault identification system and the detection of winding displacement is done by using the search coil. The algorithm precisely detects the location of the fault. Voltage analysis of search coil is done to discriminate the interturn fault and radial winding displacement. Impedance analyzer plots are used to verify the results experimentally. The proposed method works accurately irrespective of the operating condition and configuration of transformer [34].

In the online method the leakage inductance variation is used to monitor the deformation of transformer winding. Parameters are identified from the leakage inductance for transformer protection. The dynamic data of transformer parameters is accurate for protection and online monitoring of transformer [35].

A microprocessor-based online system is proposed for the identification of inrush current and internal fault current of transformers. This system uses digital algorithm working on the basis of transformer model. The proposed algorithm implemented using microprocessor is capable of transformer health monitoring and controlling the operation of differential protection scheme. The proposed system is capable of detecting the internal faults of transformer [37].

A protective scheme for the protection of power transformer is suggested in this scheme the differential relay will not generate the trip signal in case of magnetizing inrush and external faults. However, it will rapidly operate the differential relay in case of internal faults. The sensitivity of the proposed scheme is such that it can detect winding faults at incipient stage. This is a simple and online scheme used for protection and is based on the instantaneous values of voltage and current. In this scheme the positive sequence admittance is calculated for the two sides of transformer and contour is plotted for discriminating the internal and external faults. This scheme also detects the minor fault by comparing the locus diagram of healthy case and faulty case and gives alarm or tripping signal when the fault level increases [38].

A digital algorithm is proposed to identify the inrush current and internal faults current in power transformer. In this algorithm the current circulating in the delta connected winding is estimated and it requires positive sequence and negative sequence impedances of the transformer. The ability of the algorithm is tested in the laboratory using TMS320C25 digital signal processor [43].

3.7 MATHEMATICAL MORPHOLOGY

The proposed mathematical morphological scheme contains two parts. In the first part the discrimination of inrush current is done without considering the CT saturation by using the morphological gradient (MG). In the second part the discrimination of inrush current is done considering the CT saturation by using the morphological gradient (MG). The experimental and simulation results shows that the proposed mathematical morphological scheme improves the accuracy of discrimination of inrush current [45].

In mathematical morphological scheme the current signal is decomposed into multiresolution levels on the basis of analysis operators and synthesis. This scheme can easily discriminate between inrush and internal fault currents when the inrush comprises low second harmonic component and the internal fault current comprises high second harmonic component. The simulation of power transformer can be done using ATP [46].

4. GENERALIZED ALGORITHM FOR REAL TIME DISCRIMINATION BETWEEN INRUSH AND INTERNAL FAULT CURRENT

The real time monitoring of transformer is necessary in order to protect the transformer. If any abnormal condition occurs in the transformer then the resulting current is high. The conventional transformer protection finds difficult in discriminating the high magnitude inrush current and internal fault current. The basic operating principle of this algorithm can be well described with the help of the block diagram shown in figure 3. This system consists of five steps. In the first step continuous monitoring of voltage and current signals of transformer is done with the help of sensors, transducers, and a data acquisition system. The voltage and current signals captured by the data acquisition system are preprocessed using the signal processing technique available in the literature. After preprocessing the signals, the optimum features are extracted from it by the application of optimization technique available in the literature. These optimal features are further processed using the appropriate artificial intelligence technique available in the literature for discrimination. The result of discrimination is used to make the final decision about the generation of tripping signal for transformer protection.

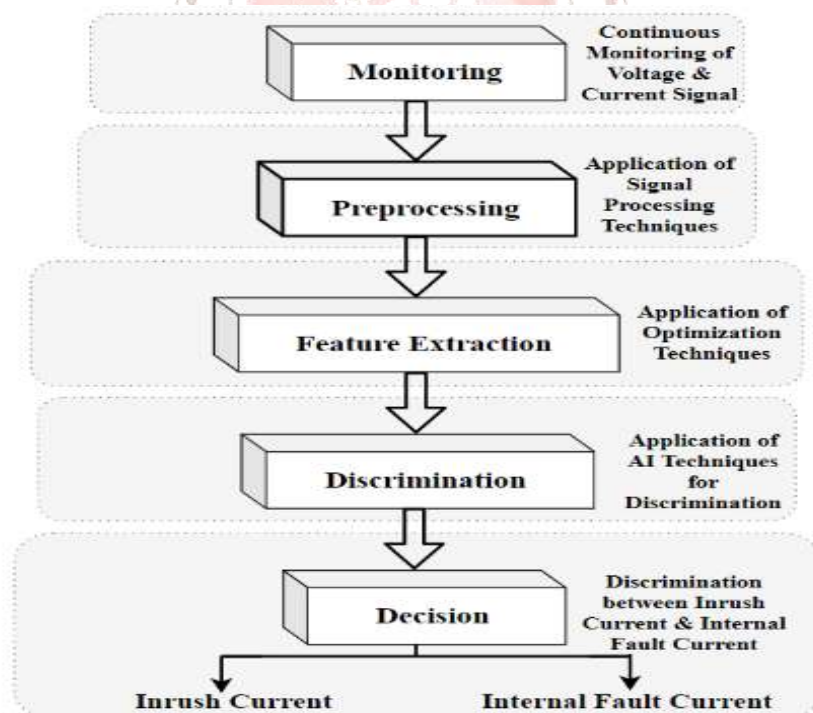


Figure 3: Block diagram of Real-Time Discrimination System

A number of signal processing techniques are available in the literature but they have several advantages and disadvantages. Figure 4 shows the classification of signal processing techniques on the basis of domain along with the specific technique available under the respective domain.

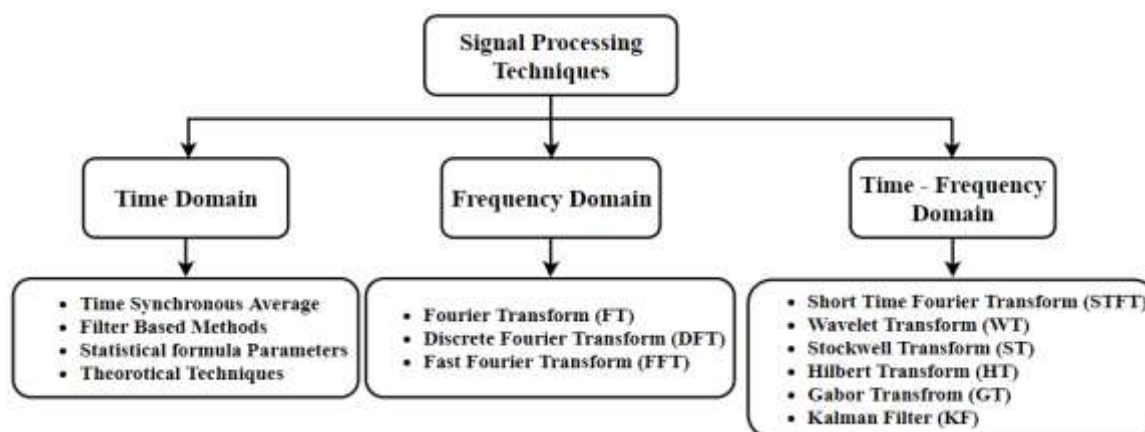


Figure 4: Signal Processing Techniques

A number of soft computing techniques are available in the literature but they have several advantages and disadvantages. Figure 5 shows the classification of soft computing techniques along with the sub-categories of the specific technique.

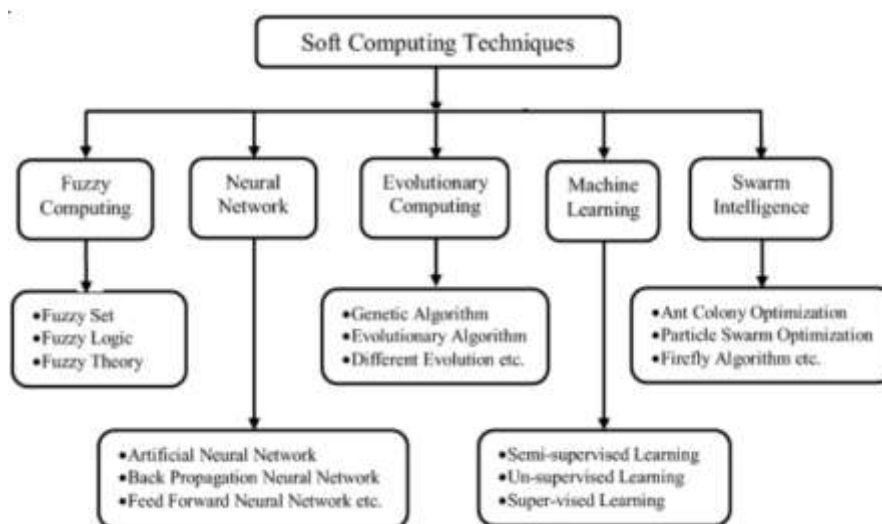


Figure 4: Soft Computing Techniques

5. CONCLUSION

Power transformers is at the heart of power system and it plays a key role in modern power systems. Hence its protection is of great importance to assure stable and reliable operation of the power system. The inrush current phenomenon is one of the major cause for mal-operation of the differential protection system. Hence accurate & fast discrimination of inrush current & fault current is necessary. In this paper, an analytical and extensive review of various techniques used for discrimination between inrush current & internal fault current of transformer with their advantages & limitations is presented. The choice of the approach adopted is mainly depends on the rating of transformer, application and detection time. It has been found that most of the researchers are inclined towards the use of signal processing and soft computing techniques for the discrimination of inrush current & internal fault current of transformer.

6. FUTURE SCOPE

From the rigorous literature review, it is found that there is still scope to find a better method to discriminate the inrush and internal fault current of transformer on the basis of accuracy, computational time, and complexity. Most of the research work is carried out on synthetic data. The real-time data must be applied to

test the accuracy of the algorithm. Most of the methods are based on single-phase data. In practice, our electrical power system is a three-phase system hence, it is required to work on the three-phase real-time system for discrimination of inrush and internal fault current of transformer. The data acquisition system captures the surrounding noise along with the voltage and current signal. Feature extraction and classification algorithms poorly perform in a noisy environment. Hence it is required to denoise the signal before applying the algorithm. There is a need to develop a new algorithm that can work effectively under both noiseless and noisy environments. Therefore, there is a scope to develop a universal algorithm that can be applied to any power transformer irrespective of the rating.

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