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Review on Power Transformer Protection Scheme with Non-Linear Load

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Abstract -- This abstract illustrates differential protection philosophy for Power Transformer (PT) in the presence of non-linear loads, using combined Discrete S-Transform (DST) and Support Vector Machines (SVMs) methods. Discrimination between internal fault and magnetizing inrush condition is a very challenging task in PT differential protection scheme. Therefore, discrete s-transform is used to extract the time and frequency division information simultaneously from the relaying signal (i.e. differential current) and then the different features like peak, rms and difference between different entities of rows from discrete s-transformed decomposed amplitude and phase matrices in terms of information of the original signal. And then these features of the relaying signal are used to train and test the SVM to detect internal fault. The PT is modelled in PSCAD/EMTDC software to obtain the relaying under different operating conditions. The proposed algorithm is evaluated in MATLAB under different operating conditions of PT and the tested data is simulated in PSCAD/EMTDC by varying inception angle, fault location, loading conditions of PT.

Indexed Terms: - Power Transformer (PT), Discrete S-transform (DST), Short Time Fourier Transform (STFT), Support vector machine (SVM)

I. INTRODUCTION

Now a day's power transformer is a very essential and energetic component of electric power system. Due to its reputation and cost, its protection requirement to be lectured properly. The protection should be quick and consistent. Correct constant monitoring of power transformer can deliver initial caution of electrical disaster and avoid losses. It can reduce damages and improve the consistency of power supply. Therefore, high prospects are forced on power transformer protective relays. Prospects from protective relays consist of reliability (no missing operations), safety (no false tripping), hurry of process (short fault clearing time) and steadiness [1]. Differential relaying protection scheme is used for power transformer. This differential scheme tactic equates the currents at all nodes of the protected transformer by calculating and monitoring a differential current. The magnitude of differential current larger than no-load magnitude indicates an internal fault. Addition to these, with the advancements in the field of silicon technology and power electronics, converters have widely been employed to control different electrical loads in power system. Also, with the ever-increasing need for improving the modern lifestyle, the use of non-linear loads using converters is increasing day by day, So the protection of PT in the presence of non-linear load is considered in this work.Based on the characteristics of current and voltage waveforms, AC loads are categorised into two categories fist one is the linear load and the second one is the non-linear load. Linear circuit is defined in such a way that follows the superposition principle between input and output. That means output is directly proportional to the input. In an AC circuit instantaneous voltage signal follows the sinusoidal pattern that results into sinusoidal instantaneous currents in the circuits. From the above statement it is clear that in case of linear loads impedance doesn't changes with time. That means resistor, inductor and capacitors are linear loads because their values don't change with time. So in a linear circuit the current waveform follows the same characteristics as voltage waveform but there exist phase differences depending on the different linear components. In some case like saturation of the magnetic circuit in transformer introduces non-linearity between voltage and currents, so there exists degrees of linearity. AC motors are nearly linear because their load current carries little distortion with sinusoidal nature. A load is considered non-linear if its impedance changes with the applied voltage. That means when sinusoidal voltage will be applied to this kind of loads the current drawn by these loads will not be sinusoidal. These currents will have higher order harmonics other than fundamental. This current interacts with the impedances of power system and causes additional waveform distortion of voltages that will have impact on distribution system equipment and other loads connected to it[2].

In the past years the non-linear loads were only presents inside the heavy industries for various applications such as in electrolyte refining due to heavy rectifier, variable frequency drives (VFD) for speed control applications and also in the arc furnaces. The harmonics introduced by these industries are localized and often addressed by knowledgeable person.

With rapid enhancement in the field of digital technologies the harmonic problems are very common in the commercial buildings as well. The primary source of non-linear loads is due to power conversion equipment such as rectifier for mobile, laptop, LED TV, LED lights, and switched mode power supply (SMPS) for computers, printers, banking machines, fridge, photocopiers, broadcasting equipment. The SMPS which converts ac-dc-ac for power quality purposes for loads is a very non-linear in characteristics. Their proliferation has made them a substantial portion of the total load in most commercial buildings. Power transformers are devices that take place into power transformers, in which 70% of these faults are caused by short-circuits in its windings. In case of magnetizing inrush large current flows in the source side. This large current from the source results in large differential current, which in turn causes the relay to operate undesirably. Owing to this reason, conventional differential relays are blocked for few initial cycles of energization which makes the relay operation delayed on switching-in of the transformer on faults [1]. Therefore, discrimination between magnetizing inrush and internal fault condition is the key to improve the security of the differential protection scheme. The proposed work on new waveform identification constructed differential protection of power transformer, first of all we are generated differential current for the different operating condition of the power transformer. Then this differential current passes through S-transform, because it is a time-frequency analysis technique which joins dual categories of properties of wavelet transform (WT) and short time fourier transform (STFT). After Individually complex value of S-transform confines the real and imaginary components of the spectrum self-sufficiently and can be transformed to amplitude spectrum and phase angle values corresponding to S-transform. Then with the help of S-transform we compute the different features such as peak, standard deviation and mean of the transformed signal can be extracted in terms of information of the original signal. These features are used for classification purposes. Finally, these features are used by SVM to discriminate internal fault from other disturbances. To achieve above protection method, it needs PSCAD/EMTDC to simulate the different operating conditions and create differential currents (relaying signal) and then MATLAB to process these different relaying signal to discriminate internal fault from other disturbances.

II. DIFFERENTIAL PROTECTION

Differential current relay is exercising to protect power transformer in condition of internal fault. It is mostly two types:

2.1 Differential Relay: -

The differential relay is exclusive that works when there is a difference between two or more comparable electrical quantities exceeds a predetermined value. In differential relay arrangement circuit, there are dual currents invent from dual slices of an electrical power circuit. These dual currents meeting at a joint point where a relay coil is connected. Conferring to Kirchhoff Current Law, the resulting current flowing through the relay coil is unknown but accumulation of dual currents, coming from dual dissimilar portions of the electrical power circuit. If the polarization and amplitude of equally currents are so used to that the phasor sum of these dual currents, is zero at normal operating disorder. Consequently, there will be no current flowing through the relay coil at usual operating conditions. But due to any irregularity in the power circuit, if this balance is exhausted, that means the phasor sum of these two currents no longer remains zero and there will be non-zero current flowing through the relay coil thereby relay being operated. In current differential scheme, there are two sets of current transformers each connected to either side of the equipment protected by differential relay. The ratio of the current transformers is so select, the secondary currents of both current transformers ties each other in magnitude.

The polarities of current transformers are such that the

require continuous monitoring and fast protection because they are essential to the electrical power systems. About 10% of faults take place into power transformers, in which 70% of these faults are caused by short-circuits in its windings. In case of magnetizing inrush large current flows in the source side. This large current from the source results in large differential current, which in turn causes the relay to operate undesirably. Owing to this reason, conventional differential relays are blocked for few initial cycles of energization which makes the relay operation delayed on switching-in of the transformer on faults [1]. Therefore, discrimination between magnetizing inrush and internal fault condition is the keyto improve the security of the differential protection scheme. The proposed work on new waveform identification constructed differential protection of power transformer, first of all we are generated differential current for the different operating condition of the power transformer. Then this differential current passes through S-transform, because it is a time-frequency analysis technique which joins dual categories of properties of wavelet transform (WT) and short time Fourier transform (STFT). After Individually complex value of S-transform confines the real and imaginary components of the spectrum self-sufficiently and can be transformed to amplitude spectrum and phase angle values corresponding to S-transform. Then with the help of S-transform we compute the different features such as peak, standard deviation and mean of the transformed signal can be extracted in terms of information of the original signal. These features are used for classification purposes. Finally, these features are used by SVM to discriminate internal fault from other disturbances. To achieve above protection method, it needs PSCAD/EMTDC to simulate the different operating conditions and create differential currents (relaying signal) and then MATLAB to process these different relaying signal to discriminate internal fault from other disturbances.

2.2 Percentage Differential Relay

This is considered to reply to the differential current in the term of its slight relation to the current flowing through the protected sector. In this kind of relay, there are restraining coils in accumulation to the operating coil of the relay. The restraining coils yield torque reverse to the operating torque. Under normal and through fault conditions, restraining torque is larger than operating torque. Thereby relay remains inactive. When internal fault arises, the operating force exceeds the bias force and hence the relay is operated. This bias force can be used to by varying the number of turns on the restraining coils. As shown in the figure 1.2, if I_1 is the secondary current of CT1 and I_2 is the secondary current of CT2 then current through the operating coil is (I_1-I_2) and current through the restraining coil is ((I_1+I_2)/2) . In normal and through fault condition, torque produced by restraining coils due to current ((I_1+I_2)/2) is greater than torqueproduced by operating coil due to current$(\mathrm{I}_1-\mathrm{I}_2)$ but in internal faulty condition these become opposite. And the bias setting is defined as the ratio of$(\mathrm{I}_1-\mathrm{I}_2)$ to $\left(\frac{\mathrm{I}_1+\mathrm{I}_2}{2}\right)$.

$$\text{Bias setting in percentage} = \frac{\mathrm{I}_1-\mathrm{I}_2}{(\mathrm{I}_1+\mathrm{I}_2)/_2}\times 100\%$$

Percentage differential relay without restraining coil is measured as a simple differential relay. Number of turns in restraining coil and operating coil chooses the slope of the differential relay [3]. Slope of the differential relay is in between differential current vs. restraining current (biased current).

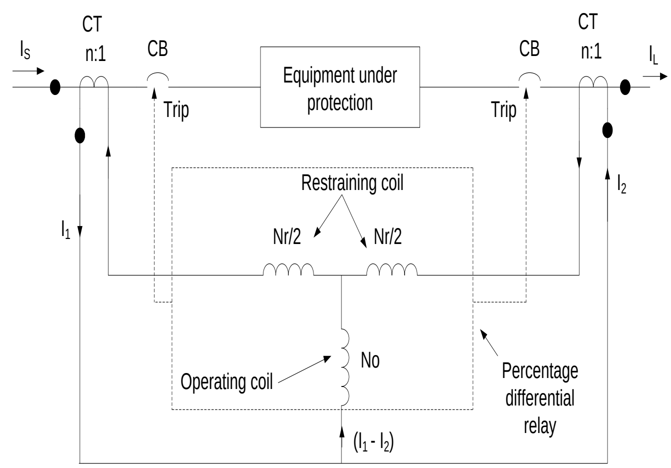
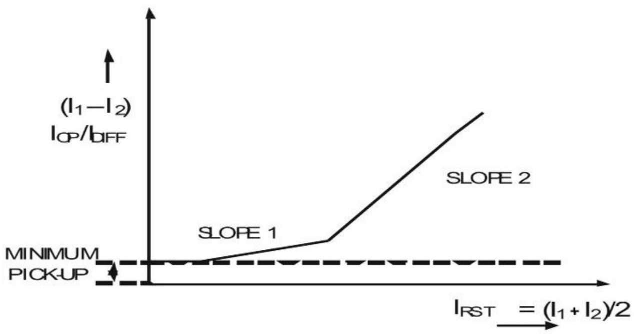


Figure 1. Percentage differential relay

The percentage differential relay can be complete safer to mal-operation on 'external fault' by cumulative the slope of the characteristic. That's why the dual slope percentage differential current relay is used. Where slope1 gives high sensitivity for internal faults and slope2 gives high security for external fault. The magnitude of slope2 is greater than slope1 to achieve



proper sensitivity and security. Knee point of dual slope differential current is decided where saturation of CT is started.

Figure 2**.** Operating characteristics of % differential relay

III. ENVELOPE EXTRACTION AND SEGMENTATION OF AN IMPULSIVE EVENT

Events' amplitude and frequency is an important feature for enabling the detection of any component of the PCG signal. This feature is partially in accordance with the expert human thinking model by which, some sounds are separated from each other. However, the amplitude of the signal represented by the envelopegives a simpler and more realizable representation than the amplitude of original heart sound and frequency information. In this thesis, only two types of envelope creation techniques are used. These techniques are discussed below:

S-Transform:

The S-transform is a time-frequency analysis technique which incorporates dual types of properties of wavelet transform and short time fourier transform. S-transform is combining a frequency dependent resolution of the timefrequency space with absolutely referenced local phase in- formation. This permits to describe the meaning of phase in a local spectrum. It also exhibits a frequency invariant amplitude response, while maintaining a direct relationship, frequency dependent resolution is provided by S-transform with the Fourier spectrum [9].

The relation between the S-transform and Fourier transform of a time series h(t) can be written as,

$$s[\tau, f] = \int_{-\infty}^{\infty} H(\alpha + f)\; G(f, \alpha) e^{j2\pi\alpha\tau} d\alpha \qquad (3.1)$$

Where, Gaussian window function $G(f, \alpha) = e^{-\frac{j2\pi^2\alpha^2}{f^2}}$, $f \neq 0$.

The discrete analog of equation (3.1) is being applied to calculate the discrete S-transform. During the computation, it takes the advantage of the effectiveness of the convolution theorem and fourier transform.

If h[kT], k varying from 0 to N – 1, denotes a discrete timeseries analogous to h(t) with a time interval of T for sampling, equation (3.2) shows the discrete fourier transform.

$$H\left[\frac{n}{NT}\right] = \frac{1}{N} \sum_{k=0}^{N-1} \mathrm{h}[kT] e^{-\frac{j2\pi nk}{N}} \qquad (3.2)$$

Where, N is the number of samples/cycles.

Using equations (3.1) and (3.2) and making $f \rightarrow {}^{n}/_{NT}$ and $\tau \rightarrow jT$, the discrete time seriesh[kT]'s S-transform isgiven by equation (4.3).

$$H\left[jT, \frac{n}{NT}\right] = \sum_{m=0}^{N-1} H\left[\frac{m+n}{NT}\right] e^{-\frac{j2\pi m^2}{n^2}} e^{-\frac{j2\pi m}{N}} \; n \neq 0 \qquad (3.3)$$

Where j, m, and n are samples vary from 0 to N-1.

The output of the S-transform from equation (3.3) is a complex matrix of size $\left(\frac{N}{2} + 1\right) \times \mathrm{N}$. It is known as S-matrix in which rows are related to frequency and columns to time complex values[4].

Each complex value of S-transform localizes the real and imaginary components of the spectrum independently and can be converted to amplitude spectrum and phase angle values corresponding to S-transform[9]. Moreover, features such as peak, rms and difference between different entities of rows of the transformed signal can be extracted in terms of information of the original signal. The three features consist of peak, rmsand difference between different entities of rows of phase contour and maximum magnitude of frequency component of S- transform provides highest internal fault and inrush condition discrimination and hence, these features are used for the process.

IV. SUPPORT VECTOR MACHINES

Support vector machines are supervised learning model related with learning algorithm that examines set of data for classification or regression determinations. Now SVM is used for classification determinations. SVM as a classifier takings training data sets of two classes (class1 and class2) later that it figures the model that allocates new data set into any class1 or class2.

SVMs are constructed on the awareness of discovery a hyper-plane that finest splits a dataset into two class, in case of two-dimensional data points the hyper-plane would be a line (one dimension a smaller amount than the dimension of the input data).

A decent parting is realized by the hyper-plane that has the largest distance to the nearest training-data point of any class (so-called functional margin), since in general the larger the margin the lower the generalization error of the classifier [18].

Figure 3 shows three hyper-plane H1, H2 and H3, where H1 clearly does not classify the input data sets, but H2 and H3 both are intelligent to classify.

Due to the fact that H3 has high functional margin than the H2 hyper-plane, H3 would be the best hyper-plane that would lead to the minimum generalization error.

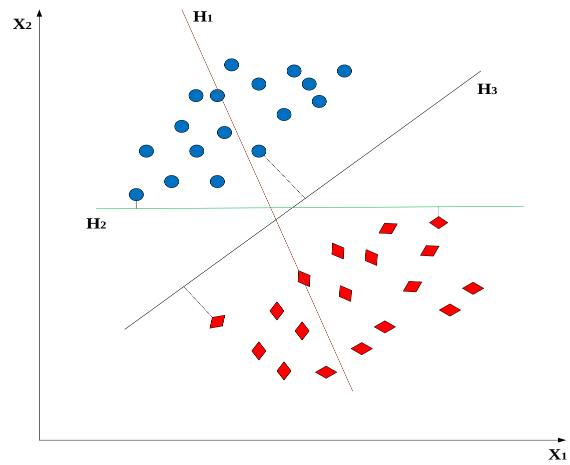


Figure 3. Choosing proper hyper-plane to classify two types of datasets

SVMs are a cluster of learning machines for resolving pattern recognition difficulties professionally. SVMs attempt to discovery the hyper-plane, which splits optimally the training patterns according to their classes (i.e. hyper-plane with maximum boundary margin). They have a decent simplification performance over traditional methods, since their training is founded on the principle of structural risk minimization (SRM) (i.e. minimizing the upper bound on the expected risk), while the training traditional methods is based on empirical risk minimization (i.e. minimizing the number of the training error). SVMs have a high computational effectiveness in terms of rapidity and difficulty [17]. They are similarly additional desirable when dealing with high dimensional data as they are additional robust than traditional approaches which may over-fit the data. The description of SVMs classification can be explained as follows:

4.1. Linearly Separate Data

Let us consider a linear classification problem targeting to invention ideal separating hyper-plane with maximum margin. Assuming that for the set of n training data:

$$T = \left\{(\vec{x_i}, y_{\mathrm{i}});\ \vec{x_i} \epsilon \mathrm{R}^d, y_{\mathrm{i}} \epsilon \{1, -1\}\right\} \qquad 4.1$$

Where,

i=1, 2, 3…. n;

$\vec{x_i}$ is a d-dimensional input vector

y_i indicate class 1 or -1 for the corresponding $\vec{x_i}$

For this $\vec{x_i}$ it is possible to novelty a maximum margin hyper-plane that linearly splits the suitable class as shown in the figure 3. In such case hyper-plane can be defined by the formula $\vec{w}\,.\vec{x_i} - b = 0$; where $\vec{w}$ is a weight vector and b is a bias. Additionally, it is possible to novelty two hyper-planes with no points between them one is $\vec{w}\,.\vec{x_i} - b = 1$ and another one is $\vec{w}\,.\vec{x_i} - b = -1$, then a distance between these two hyper-plane is called margin$= \frac{2}{\|\vec{w}\|}$.

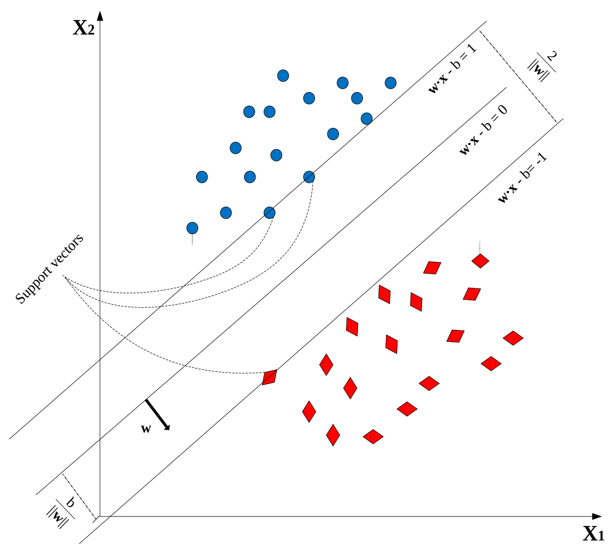


Figure **Error! No text of specified style in document.**. Hard margin classifier

Then class 1 (1) and class 2 (-1) for the input vector is represented by the following formulla.

Or

For improved SVM classifier this margin should be maximum, it resources the $\|\vec{w}\|$ should be minimum. This finding $\vec{w}$ and b can be completed by several optimization techniques. But this optimization problem is resolved by introducing Lagrange multipliers and then class of the unknown data x may be determined as follows:

$$\mathrm{Class}(\vec{x}) = \mathrm{sign}(\vec{w}\,.\vec{x} - b) \qquad 4.4$$

Where,

$$\vec{w} = \sum_{i=1}^{N_{sv}} \alpha_i y_i \vec{x_i} \qquad 4.5$$

Where,

$\vec{x}$ is a input vector to be classify

$\vec{x_i}$ is a support vector

y_i is a class of given support vector

α_i is a Lagrange multiplier

N_{sv} is a number of support vector

b is a bias value (calculated during trainingprocess)?

4.2. Linearly Non-Separable Data

In case when training data can’t be able to become separated by linear hyper-plane then these input vector gets mapped into the one higher dimension feature space in such a way so that the mapped data gets separated by linear hyper-plane for this purpose, nonlinear function is used. Then the class of unknown data x may be expressed as follows:

$$Class(\vec{x}) = sign(\sum_{i=1}^{N_{sv}} \alpha_i y_i \emptyset(\vec{x_i}).\emptyset(\vec{x}) - b) \qquad 4.6$$

$$K(\vec{x_i}, \vec{x}) = \emptyset(\vec{x_i}).\emptyset(\vec{x}) \qquad 4.7$$

$$\vec{w}\,.\vec{x_i} - b > 1 \text{ , if } y_i = 1 \qquad 4.2$$

$$\vec{w}\,.\vec{x_i} - b < -1 \text{ , if } y_i = -1 \qquad 4.3$$

Then the decision function of SVM is:

$$Class(\vec{x}) = sign(\sum_{i=1}^{N_{sv}} \alpha_i y_i K(\vec{x_i}, \vec{x}) - b) \qquad 4.8$$

The most common kernel functions are:

- Linear: $k(\vec{x_I}, \vec{x}) = (\vec{x_I} \cdot \vec{x})^d$
- Polynomial: $k(\vec{x_I}, \vec{x}) = (\vec{x_I} \cdot \vec{x} + 1)^d$
- Gaussian radial basis function: $k(\vec{x_I}, \vec{x}) = \exp(-\gamma \|\vec{x_\iota} - \vec{x}\|^2)$, for $\gamma > 0$
- Hyperbolic tangent: $k(\vec{x_\iota}, \vec{x}) = \tanh(k\vec{x_\iota} \cdot \vec{x} + c)$, for some (not every) $k > 0$ and $c > 0$.

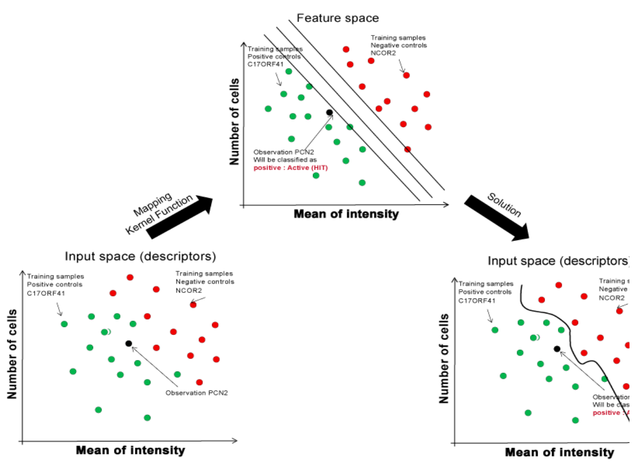


Figure 5. Non-linear based SVM classification

4.3 Soft Margin

It may happen that even in new feature space it is impossible to split this space into two classes. Then, soft margin method may be employed to moderate optimization constraints. Soft margin method allows the classifier to misclassify some examples, what is illustrated in figure. This method introduces two parameters (used in training process)[19].

ξ_i is a slack variable that allow patterns to be in the margin $(0 \le \xi_i \le 1$, margin errors) or to be misclassified ($\xi_i > 1$).

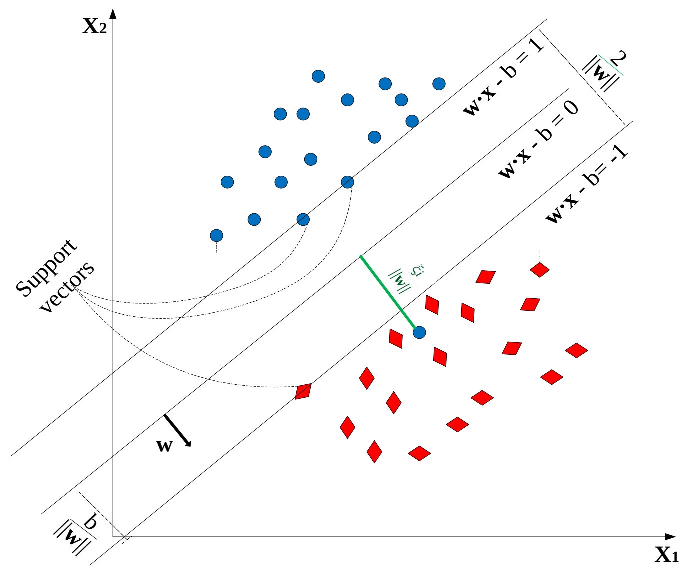


Figure 1. Soft margin classifier

The proposed work explains the novel waveform based differential protection of power transformer. First differential current will be generated for the different operating conditions, then this protection algorithm needs to perform S- transform decomposition of the differential current and then feature choice to accomplish the best fault detection precision using SVM classifier [19]. The flow of operating current (differential current) as said below offers the clearest picture of the work:

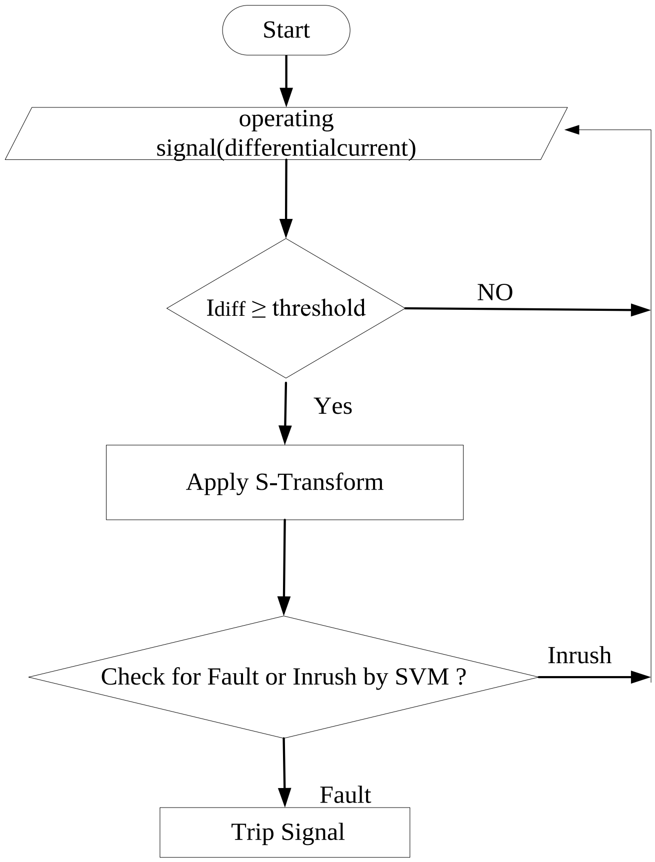


Figure 7. Flow chart of proposed work

V. CONCLUSION

The proposed protection based on combined S-transform (DST) and SVM algorithm provides a differential protection for Power Transformer. Which provides much more security than the other existing DWT, ANN and conventional dual slope percentage differential-based protection. Here DST extracted the different frequency and time-based information into s-matrix from differential current. This s-matrix leads to the very good features that further goes to the SVM based classifier and to detect the internal fault from magnetizing inrush current.

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