Improving Transformer Protection by Detecting Internal Incipient Faults

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***Abstract*—This paper proposes a new S-Transform (ST) based method for protection of power transformers by considering internal incipient faults. S-transform is a powerful analytical tool that has the property of Fourier and wavelet transforms. The Hyperbolic S-Transform (HST) is used to extract features of inrush current, internal and internal incipient faults, from the differential currents. A decision has been made using extracted features to discriminate internal incipient faults, magnetizing inrush currents and internal faults. In order to study the efficiency of the proposed method, it is implemented in MATLAB environment and tested with simulated faults and inrush cases under EMTP software. In order to simulate internal turn to turn, turn to earth and internal incipient faults, the transformer is modeled using 8×8 RL matrices obtained from the subroutine BCTRAN of EMTP software. The signals are infected with noise and the performance of the algorithm in noisy environments is studied.**

Keywords- transformer; incipient fault; inrush current; S-transform; protection.

I. INTRODUCTION

The power transformer is an important component of the overall elements of the power system. The transformer protection is an essential part of the system protection. 70-80 percent of the failures in transformers which occur over a period of years are finally caused by short circuits between turns. On-line condition monitoring of transformers can provide early warning of electrical failure and could prevent catastrophic losses [1]. Mostly, there is an aging-arcing process before a turn to turn short circuit. This process is called incipient fault. So, detection of internal incipient fault in power transformer is an early warning of internal fault. Several algorithms are proposed to discriminate between different transient phenomena in transformers. In [2] a gas analysis based algorithm has been proposed. This method is off-line. In [3] an algorithm based on neural networks is presented for detection and classification of internal faults. A transformer fault detection methods based on wavelet transform and correlation factor has been suggested in [4]. The internal incipient fault is not studied in [3-4]. In [5-6] discrete wavelet transform based algorithms for discriminating the incipient faults have been suggested. These schemes are influenced by noise because of using wavelet transform. Also, the frequency properties of the decomposition filter band are not ideal and suffer leakage effect where the frequency of the analyzed signal is close to the edge of a frequency band [7]. Since the ST is less influenced by noise, S-transform based algorithms have been proposed for overcoming the noise problems in [7-10]. In these methods the internal incipient, the turn to turn, the turn to earth faults is not studied.

In this paper an S-transform based scheme for distinguishing between inrush current, internal incipient fault, internal short circuit and internal faults while transformer energization, is suggested. The ST has been used and the differential currents of the faulty phases are analyzed. A decision has been devised using the standard deviation and the spectral energy of the S-matrix to discriminate different transient phenomena in transformer. Unlike algorithms that use wavelet transform, the proposed algorithm is not affected by noise. The suggested method is capable of distinguishing between incipient fault current and other transient current in transformers even in noisy environments.

II. REVIEW OF S-TRANSFORM

Continues Wavelet Transform (CWT) of a time series signal *u(t)* can be defined as series of correlation of the time series with a wavelet function :

$$CWT = \int_{-\infty}^{+\infty} u(t) w(\tau - t, a) dt \qquad (1)$$

The S-transform of function *u(t)* can be defined as a CWT with a specific wavelet multiplied by a phase factor. The S-transform, suggested by Stockwell et al. [11], of a time series *u(t)* is:

$$S(\tau, f) = \int_{-\infty}^{+\infty} u(t) \begin{bmatrix} |f| \big/ \sqrt{2\pi} \\ \times exp\left(- f^2 (\tau - t)^2 \big/ 2 \right) \\ \times exp(-2\pi i f t) \end{bmatrix} dt \qquad (2)$$

where S is the S-transform of $u(t)$, which is a signal varying with time, τ is a parameter which controls the position of Gaussian window on the time axis and f denotes the frequency. The ST is a time-frequency analysis technique, containing features of both wavelet transform and Short Time Fourier Transform (STFT). The ST is not a wavelet transform, because the oscillatory function. The generalized S-transform is obtained from original S-transform by replacing the Gaussian window with a generalized window [11]:

$$S(\tau, f, p) = \int_{-\infty}^{+\infty} u(t)\, w(\tau - t, f, p)\, exp(2\pi i f t) dt \qquad (3)$$

where p denotes a set of parameter that govern the shape of window. S-transform windows must satisfy (4):

$$\int_{-\infty}^{+\infty} w(\tau - t, f, p) d\tau = 1 \qquad (4)$$

Because of (4), averaging of ST over all values of τ is Fourier transform of $u(t)$, therefore, provides a join between ST and Fourier transform and guarantee that ST is invertible:

$$\begin{aligned} &\int_{-\infty}^{+\infty} S(\tau, f, p) d\tau = \int_{-\infty}^{+\infty} u(t)\, exp(-2\pi i f t) \times \\ &\int_{-\infty}^{+\infty} w(\tau - t, f, p) d\tau dt = \int_{-\infty}^{+\infty} u(t)\, exp(-2\pi i f t) dt \\ &= U(f) \end{aligned} \qquad (5)$$

The hyperbolic S-transform is obtained from the generalized S-transform, by replacing the generalized window with a hyperbolic window [11]:

$$\begin{aligned} w_{hyp} &= \frac{2|f|}{\sqrt{2\pi}(\gamma_f + \gamma_b)} \\ &\times exp\left[\frac{- f^2 \left[X(\tau - t, \{\gamma_f, \gamma_b, \lambda^2\}) \right]^2}{2} \right] \end{aligned} \qquad (6)$$

where

$$\begin{aligned} X(\tau - t, \{\gamma_f, \gamma_b, \lambda^2\}) &= \left[\frac{\gamma_f + \gamma_b}{2\gamma_f \gamma_b} \right] (\tau - t - \zeta) \\ &+ \left[\frac{\gamma_f - \gamma_b}{2\gamma_f \gamma_b} \right] \sqrt{(\tau - t - \zeta)^2 + \lambda^2} \end{aligned} \qquad (7)$$

In (5) γ_f and γ_b are forward-taper and backward-taper parameters, respectively. λ denotes the positive curvature parameter and X is hyperbola in $(\tau - t)$ its shape is determined by these parameters. ζ is defined as:

$$\zeta = \sqrt{\frac{(\gamma_f - \gamma_b)^2 \lambda^2}{4\gamma_f \gamma_b}} \qquad (8)$$

However a symmetrical window provides better frequency resolution than an asymmetrical window. So, at high frequencies, where the window is narrow and time resolution is good, a symmetrical window can be used. At low frequencies an asymmetrical window may be used, but as frequency increases, the shape of the window converges toward the Gaussian window.

The ST of a discrete time series $U[kT]$ is given by:

$$S[n, j] = \sum_{m=0}^{N-1} U(m + n) G(m, n) exp(i2\pi m j) \qquad (9)$$

where N is the total number of samples and n, m and j varies 0 to $N-1$. $U(m, n)$ denotes the frequency shifted discrete Fourier transform $U[m]$, and $G(m, n)$ is the Fourier transform of the hyperbolic window.

III. THE PROPOSED SCHEME

In the suggested method, the HST is applied to the differential currents of faulty phases. The time-frequency contours are obtained after HST. It is seen that the time-frequency Contours are interrupted in a consistent time interval in cases of inrush currents but they are interrupted randomly in cases of incipient faults and the contours present consistently in an internal fault. Moreover, the spectral energy and the standard deviation of the S-matrix are calculated. It is found that the spectral energy and the standard deviation of the S-matrix have high values in the cases of internal faults, while they have lower values during inrush currents. Also, the spectral energy and the standard deviation in the incipient fault cases have lower values with respect to inrush currents.

IV. SYSTEM UNDR STUDY

In order to analyze the performance of the proposed scheme it is implemented in MATLAB environment and tested with simulated fault and inrush cases under EMTP software. The system under study is shown in Fig.1. The simulated transformer is a three phase power transformer with the rating of 100kVA, 5500/410V [12]. The primary winding has 1556 turns wound in 8 layers and the secondary winding has 67 turns wound in 2 layers. The transmission lines have been modeled by π sections.

A. Power Transformer Model

A transformer terminal model can be known in terms of winding resistance, self and mutual inductances. Therefore, 6×6 RL matrices from BCTRAN routine can be formed for a three phase two winding transformer. Also, 7×7 and 8×8 matrices can be derived for turn to ground and turn to turn fault studies in a three phase two winding transformer, respectively [12]. In order to study the turn to turn, the turn to earth and also the internal incipient faults, b-phase of primary winding is divided into three parts with 1148, 97 and 311 turns. Therefore, 8×8 matrices are considered for the modeled transformer.

Fig.1 Simulated system

B. *Internal Incipient Fault Model*

The winding insulation deterioration is a major cause of internal incipient winding faults in transformers. Degradation of the winding insulation is occurred due to some factors such as moisture and electrical, thermal and mechanical stresses. Internal incipient fault model is a combination of an aging and an arcing part [13-14]. The aging part of the model consists of parallel connected r_{ag} and c_{ag} . r_{ag} and c_{ag} represent the lossy part and capacitance of the dielectric, respectively. The arc occurs when sufficient voltage is across the degraded insulation. The arcing part of the model is represented by a square voltage (E) and a high resistance that increases with time (R_t), connected in parallel.

Various cases such as extinction period, burning period, and non-arcing, can be presented by controlling S1 and S2.When S1 is closed and S2 is open, the model represents the burning period. When S1 and S2 are open, it models the non-arcing period. Otherwise, it represents the extinction period. Fig.2 shows combination of aging and arcing models, connected to transformer winding.

V. Results and Discussion

The differential current signals are obtained from secondary side of CTs under various operating conditions, (i.e. internal incipient fault, inrush current, energizing while the internal fault, internal turn to turn and turn to ground faults and internal fault in transformer terminals), fault resistances and inception angles. A sampling rate of 5 kHz is considered for the algorithm, i.e. 100 samples per power frequency cycle based on 50 Hz. Typical time-frequency contours and differential currents at various conditions are shown in Figs.3-10. A typical differential current and it's time-frequency contours for an internal incipient fault between turns 311 and 408, are shown in Fig.3. As it is seen, the contours are presented only during the arcing period and occur randomly and they are not consistent. Fig.4 illustrates the contours for an inrush current. It is found that the contours do not present randomly. They are interrupted but there is a consistent time interval between them. Fig.5 shows the contours for a turn to turn fault between turns 311 and 408. The time-frequency contours for transformer energizing while turn to turn fault occurs between turns 311 and 408, is shown in Fig.6. As it is clear, unlike the inrush current and incipient fault cases, the contours present consistently in Figs.5-6 and they are regular throughout the time. The differential currents and the time-frequency contours for abovementioned cases while contaminated by random noise with SNR up to 20dB are illustrated in Figs.7-10, respectively. It is seen that under the noisy conditions, incipient fault, inrush current and internal faults have the same distribution as above described and the contours are influenced little by noise.

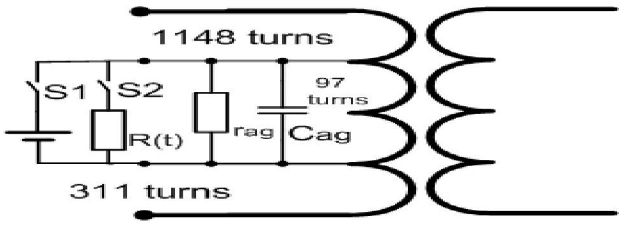

Fig.2 transformer b-phase and incipient fault model

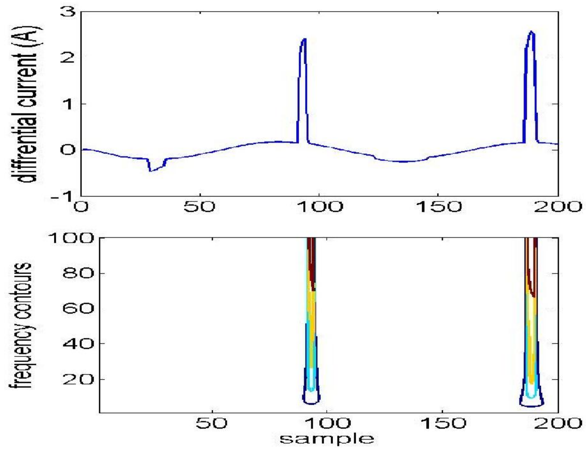

Fig.3 Differential current and S-contours for internal incipient fault between turns 311 and 408 of primary winding.

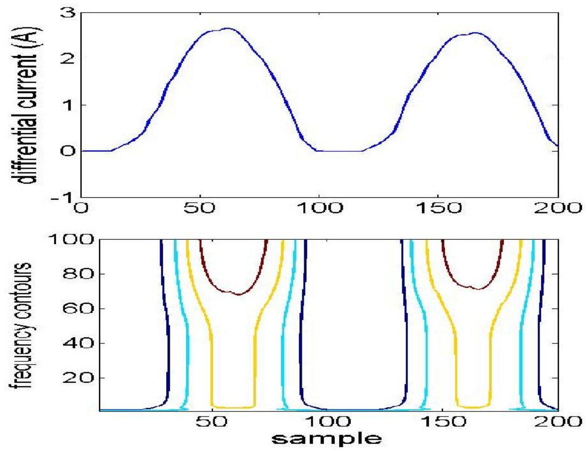

Fig.4 Differential current and S-contours for an inrush current

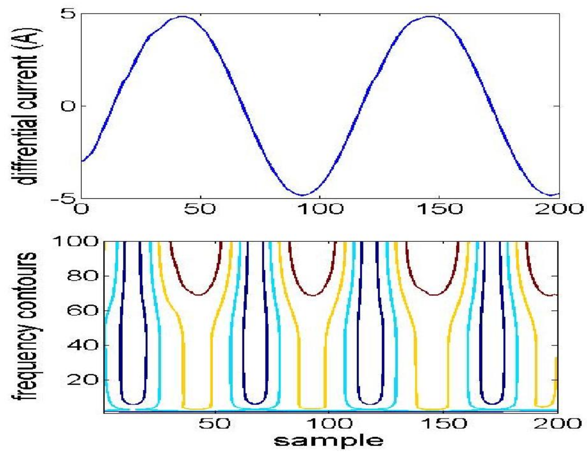

Fig.5 Differential current and S-contours for turn to turn fault between turns 311and 408.

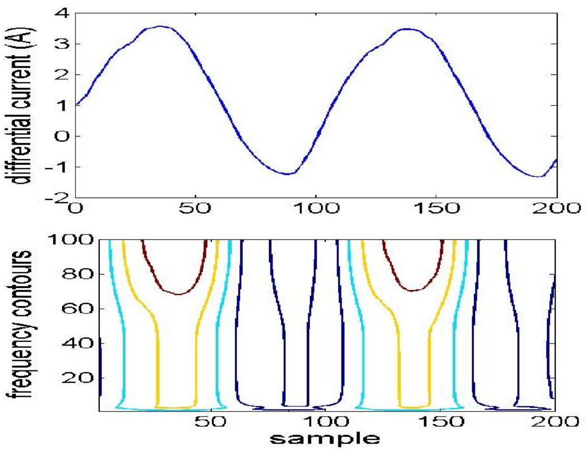

Fig.6 Differential current and S-contours for transformer energizing while turn to turn fault occurs between turns 311 and 408.

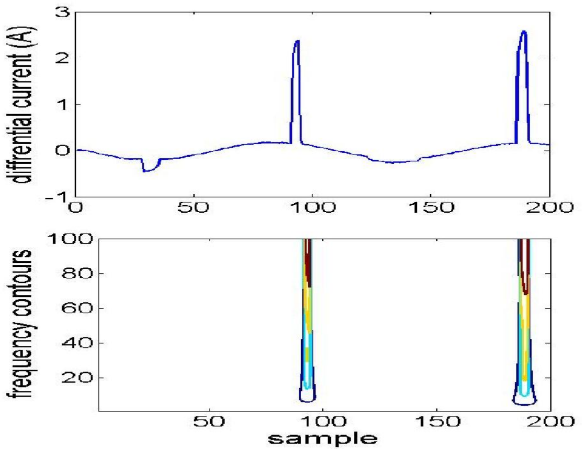

Fig.7 Differential current with SNR 20dB and S-contours for internal incipient fault between turns 311 and 408 of primary winding.

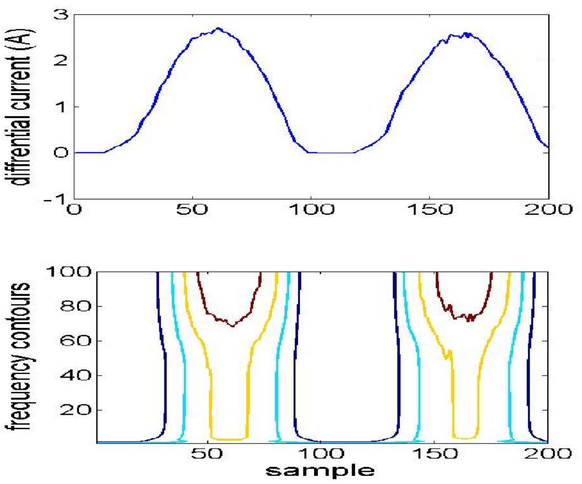

Fig.8 Differential current with SNR 20dB and S-contours for an inrush current.

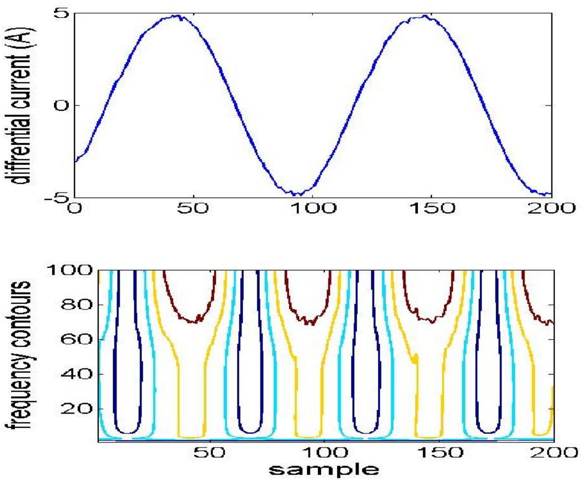

Fig.9 Differential current with SNR 20dB and S-Contours for turn to turn fault between turns 311and 408.

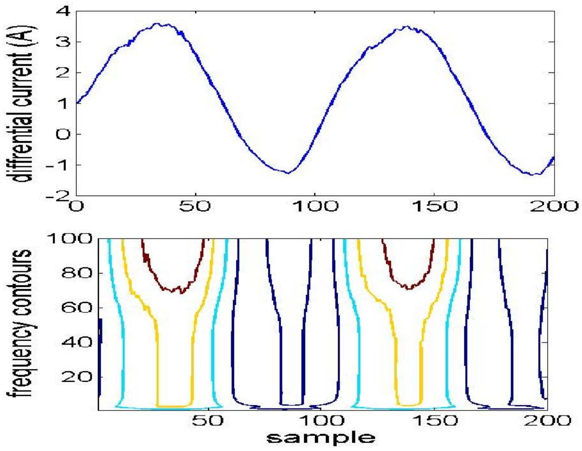

Fig.10 Differential current with SNR 20dB and S-contours for transformer energizing while turn to turn fault occurs between turns 311 and 408.

Various types of incipient faults and internal faults with different resistances and fault angles as well as various energizations with different switching angles were simulated. The results for some cases are given in table (I). The spectral energy and the standard deviation from the HST of the differential current signals are calculated. It is found that the standard deviation and so the spectral energy of the S-matrix in the faulty phases have high values and they have lower values in the cases of inrush currents. Also, it can be seen that the standard deviation and spectral energy in the incipient faults cases are lower than the inrush current cases. So, it is easy to discriminate truly between inrush currents, incipient and internal faults. In the presented cases, the spectral energy values in the faulty phases are between 5.20E+04 and 1.16E+07. But it ranges approximately between 3.65E+02 and 8.47E+02 in the inrush current cases and its values in the incipient fault cases are between 7.53E+01 and 2.58E+02, in the faulty phases. The standard deviation ranges between 8.89E+01 and 1.18E+03 in the internal fault cases and it is between 2.09E+01 and 4.07E+01 in the inrush cases, and it varies from 8.46E+00 to 1.03E+01 in the cases of internal incipient faults. The turn to turn, turn to earth and the incipient faults are simulated in b-phase. Since the

TABLE.I SIMULATION RESULTS

fault type	phase a angle at fault	fault resistance	phase	Without noise		With noise	
				Energy	STD	Energy	STD
b-incp			A	1.77E+00	5.33E-01	1.73E+00	5.33E-01
turns	no	no	B	7.53E+01	8.53E+00	7.50E+01	8.50E+00
311 to 408			C	8.89E+01	8.46E+00	8.87E+01	8.46E+00
b-incp			A	1.86E+00	5.35E-01	1.90E+00	5.35E-01
turns	no	no	B	2.33E+02	9.86E+00	2.34E+02	9.92E+00
311 to 408			C	2.58E+02	1.03E+01	2.54E+02	1.02E+01
b-incp			A	1.72E+00	5.35E-01	1.72E+00	5.37E-01
turns	no	no	B	2.05E+02	9.57E+00	2.02E+02	9.50E+00
311 to 408			C	2.29E+02	9.95E+00	2.32E+02	1.00E+01
			A	7.37E+02	3.15E+01	7.46E+02	3.16E+01
inr noload	45	no	B	5.31E+02	4.07E+01	5.33E+02	4.08E+01
			C	5.20E+02	2.29E+01	5.19E+02	2.29E+01
			A	4.06E+02	3.20E+01	4.06E+02	3.21E+01
inr with load	135	no	B	8.42E+02	2.09E+01	8.40E+02	2.10E+01
			C	7.55E+02	3.94E+01	7.55E+02	3.95E+01
inr			A	8.47E+02	2.31E+01	8.48E+02	2.31E+01
with load	25	no	B	7.06E+02	4.05E+01	7.06E+02	4.05E+01
			C	3.65E+02	2.82E+01	3.66E+02	2.82E+01
inr with load			A	5.98E+02	2.16E+01	6.08E+02	2.16E+01
and int turns	0	0.5	B	5.20E+04	8.89E+01	5.33E+04	8.90E+01
311to 408			C	6.17E+04	1.08E+02	6.21E+04	1.08E+02
inr noload			A	5.65E+02	1.46E+01	5.60E+02	1.46E+01
and int turn	0	2	B	7.63E+05	3.12E+02	7.88E+05	3.13E+02
311 to ground			C	1.16E+07	1.18E+03	1.17E+07	1.18E+03
int			A	1.83E+00	5.23E-01	1.84E+00	5.23E-01
turns	45	0	B	1.83E+06	4.84E+02	1.83E+06	4.84E+02
311 to 408			C	1.84E+06	4.85E+02	1.83E+06	4.85E+02
int			A	1.97E+00	5.31E-01	1.98E+00	5.31E-01
turns	145	1	B	1.44E+05	9.38E+01	1.44E+05	9.38E+01
311 and 408			C	1.45E+05	9.43E+01	1.46E+05	9.43E+01
int			A	1.60E+00	4.75E-01	1.57E+00	4.75E-01
turn	145	7	B	2.09E+05	1.55E+02	2.13E+05	1.55E+02
311 to ground			C	3.34E+06	6.19E+02	3.38E+06	6.20E+02
int			A	1.73E+00	4.52E-01	1.69E+00	4.52E-01
turn	90	5	B	1.26E+06	2.22E+02	1.31E+06	2.22E+02
408 to ground			C	9.97E+06	6.23E+02	9.94E+06	6.22E+02
terminal			A	2.09E+06	5.86E+02	2.09E+06	5.86E+02
ac	15	0	B	5.22E+05	2.93E+02	5.30E+05	2.93E+02
			C	5.20E+05	2.93E+02	5.22E+05	2.92E+02

primary windings are connected as delta, high values are performed in b and c phases in fault cases. If there is not any transient phenomenon, there is no differential current and the scheme is not performed.

In order to study the robustness of the method in noisy environments, random noise with SNR up to 20dB has been added to the differential currents. As it is shown in table (I), the spectral energy and the standard deviation of the S-matrix are influenced little by noise.

VI. CONCLUSION

A new scheme for distinguishing different transient currents in transformers is suggested, focused on internal incipient current. The standard deviation and the spectral energy of the S-matrix of the differential currents are calculated. Then, faults can be detected by comparison of the standard deviation and the spectral energy of the faulty phases with threshold values. The proposed algorithm was implemented in MATLAB environment and tested using simulation resulted from the EMTP software. Several cases have been studied to test the performance of the technique. The signals are contaminated with noise and the performance of the algorithm in noisy environment is studied. The simulation results indicate the robustness of the proposed technique even in the noisy environments.

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