WAVELET BASED DIGITAL PROTECTION SCHEME FOR SERIES COMPENSATED MULTI-TERMINAL TRANSMISSION SYSTEM IN THE PRESENCE OF TCSC

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Abstract:*In this paper, a new digital protection scheme for series compensated multi terminal transmission system with thyristor controlled series capacitor(TCSC) is presented. The performance of a distance relay will drastically be affected by the presence of FACTS devices like TCSC in transmission system. The complete digital simulation of TCSC within a transmission system is performed using Matlab/Simulink. The faultindices of all the phases at all the terminals are obtained by analyzing the detail coefficients of current signals through Bior 1.5 mother wavelet. The fault detection, classification, and faulty terminal identification is done with variations in fault distance and fault inception angle for all types of faults and the method is found to be reliable and takes less than half a cycle and almost independent of fault impedance and inception angles.*

Keywords:*multiterminal transmission system, wavelet transform, threshold value, TCSC, fault inception angle, fault indices.*

1. Introduction

The difficulties in obtaining the right-of-way and the increase in the capital expenditure have led to the development of multi terminal transmission lines where more than two terminals are interconnected. The protection of such systems is difficult as compared with two-terminal systems. The multi terminal lines experience problems generated by the intermediate in feed of the currents from the other terminals or an out feed to the terminals, variations in section lengths and source impedances and superimposing of currents which require the system to be protected under fault conditions The multi terminal transmission lines are usually compensated with FACTS devices like SVC,TCSC, UPFC etc., for transmission efficiency and to make necessary corrections of transmission functionality. Power flow along the transmission lines needs to be controlled and FACTS devices received some attention as they can alter power system parameters in order to control power flow. The accurate fault detection and classification are vitally important for efficient transmission as the faults cause interruption of power flow. Quick detection of faults helps in faster maintenance and restoration of supply which results in improved economy and power supply reliability. The TCSC is an important member of FACTS family and is capable of changing the transmission line impedance and load current continuously. A typical TCSC module consists of a series capacitor and a parallel path with an inductor in series with a thyristor valve known as thyristor controlled rectifier(TCR).A metal oxide Varistor(MOV) is used to protect the elements during faults. TCSC possesses complex transient behavior during faults. Wavelet transform is an effective tool in analyzing transient current signals associated with faults both in frequency and time domain.Amany et al have done the work related with DWT and wavelet entropy to analyse fault current signals when FACTS device placed in the mid point of the two terminal transmission line [1].Zahra Moravej et al emphasized the features of three line current samples using S-transform and support vector machines for fault analysis of TCSC compensated transmission line [2]. HaniyehMarefatjou et al considered synchronous voltage and current samples from all ends of the transmission line for detection of faulty section on TCSC connected three terminal transmission line[3].A.Y.Abdelaziz et al have done work by extracting the modal information from the measured signals to classify the faults in a FACTS compensated transmission line[4].W.J.Cheong et al utilized the DWT to decompose the line currents obtained from a single terminal into a series of time-scale representations in TCSC compensated transmission lines [5]. Sayyed Mohammad Nobakthi et al emphasized on time domain modeling of a transmission line to detect faults in front and behind TCSC[6]. Shashikumar et al have done the work related with TCSC compensated and uncompensated lines and observed that the TCSC results in the voltage stability of the transmission lines[7]. Anita kanwar et al observed the behavior of TCSC in transmission line[8]. S.Jamali et al proposed effects of control strategy of TCSC on the apparent impedance measured by distance relays during faults[9]. Bo,Z.Q proposed a protection schemes for multi-terminal transmission circuits such as unit and non-unit schemes. The unit schemes require extensive communication channels between the line ends[10]. Bhalija,B et al proposed a distance relaying scheme to detect high resistance faults on two terminal transmission lines[11]. Brahma and Girgis proposed a fault location scheme for a multi-terminal transmission line using synchronized voltage measurements at all terminals[12].Lyonette,D.R.M et al proposed a different directional comparison techniques for multi-terminal lines, which compare the polarity of fault generated transient current signals[13].B.Bhalija et al proposed a differential protection scheme for tapped transmission lines where outfeed current in case of internal and external faults was considered[14] .Al-Fakhri proposed differential protection scheme for multi-terminal lines using incremental currents [15]. A.I.Megahed, et al proposed wavelet based fault location in two and three terminal lines[16].Yugant A Parate et al investigated the enhancement of power system stability using FACTS devices[17].Suresh Maturu et al observed the performance issues of distance relays for shunt FACTS compensated transmission lines under pre-fault loading conditions[18]. There must be some innovative methods to be developed for multi terminal transmission line protection. In this paper, wavelet multi-resolution analysis is used for detection and classification of faults and faulty terminal identification on four terminal transmission system. Detail D1 coefficients of current signals at all the four ends are used to detect and classify the faults. The current signals are analyzed taking into consideration that sum of the current coefficients at all the four terminals.

2. Wavelet Analysis

Wavelet Transform (WT) is an efficient means of analyzing transient currents and voltages. Unlike Discrete Fourier Transform, WT not only analyses the signal in frequency bands but also provides non-uniform division of frequency domain i.e. WT uses short window at high frequencies and long window at low frequencies. This helps to analyze the signal in both frequency and time domains effectively. A set of basis functions called wavelets, are used to decompose the signal in various frequency bands, which are obtained from a mother wavelet by dilation and translation Hence the amplitude and incidence of each frequency can be found precisely. Wavelet Transform is defined as a sequence of a function {h(n)}(low pass filter) and {g(n)} (high pass filter). The scaling function $\varphi(t)$ and wavelet $\Psi(t)$ are defined by the following equations.

$$\varphi(t) = \sqrt{2\sum h(n)\varphi(2t-n)},$$
$$\psi(t) = \sqrt{2\sum g(n)\varphi(2t-n)} \qquad (1)$$

where $g(n) = (-1)^n\ h(1-n)$. A sequence of {h(n)} defines a Wavelet Transform.

This method, like the Fourier transform, provides information related to the frequency composition of a waveform, thus it is more appropriate than the familiar Fourier methods for the non-periodic, wide-band signals associated with electromagnetic transients. Wavelet Transform provides a new tool for signal processing in contrast to the traditional Fourier analysis that averages frequency features both in time and frequency. Wavelets allow the decomposition of a signal into different levels of resolution which gives a much better signal characterization and a more reliable discrimination. The multi resolution Analysis of Wavelet can be utilized effectively in analyzing the power system transients. The feature extraction property of Wavelets Transforms is exploited in the area of protection of transmission line to detect and classify the faults on various components. There are many types of wavelets such as Haar, Daubachies, Symlet, Bior etc. The selection of mother wavelet is based on the type of application and after extensive work with all wavelets, Bior-1.5 was found to be effective and has been selected as mother wavelet.

3. Faulty Phase and Faulty Terminal Identification

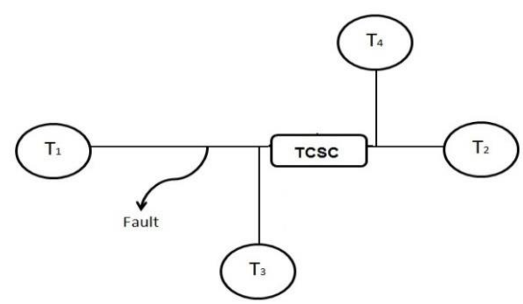

Fig.1.Single line diagram of the proposed four terminal Transmission system.

Figure 1 shows the single line diagram of the multi terminal transmission system considered along with the various blocks of the proposed scheme. Four 110-km 400 KV transmission lines compensated with Thyristor controlled series capacitor (TCSC) at the middle of the second terminal are interconnected. The TCSC consists of a fixed capacitor and a thyristor controlled reactor(TCR) in each phase which circulates current pulses which add in phase with the line current. The scheme is evaluated using 400KV, 50Hz four terminal transmission system whose line parameters are R_0=0.1888Ω/Km, R_1=0.02Ω/Km, L_0=3.5Mh/Km, L_1=0.94mH/Km, C_0=0.0083µf/Km., C_1=0.012µf/Km. A sampling frequency of 16kHz is chosen to capture the high frequency content of current signals .The system is modeled in Matlab Simulink environment. The network is simulated for various fault situations. Exhaustive simulations were carried out for L-G, L-L, L-L-G, L-L-L faults occurring at different locations along the paths of Terminal 1 to Terminal 2, Terminal 2 to Terminal 3, Terminal 3 to Terminal 1, and Terminal 4 to Terminal 1. For each type of fault at a particular location, the fault inception angle was varied to evaluate the performance of the proposed scheme. Influence of fault resistance also being considered with value of 5 ohms. Synchronized sampling of three phase currents at all terminals was carried out and the detail D1 coefficients were used for detection and classification of the type of fault. The three phase currents of the local terminal are analyzed with Bior1.5 mother wavelet to obtain the detailed coefficients ($D1_1$) at terminal 1 over a moving window of half cycle length. These $D1_1$ coefficients are then transmitted to the remote end. The detailed coefficients received from the remote end at bus2 ($D1_2$) are subtracted from the local detail coefficients ($D1_1$) to obtain effective D1 coefficients ($D1_E$). The Fault Index (I_{f1}) of each phase is then calculated as $I_{f1} = \Sigma|D1_E|$

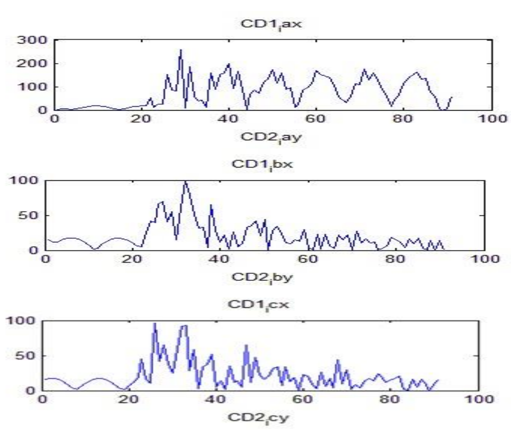

Fig. 2A.Three phase currents Ia,Ib,Ic at all terminals for A-G Fault at terminal-1

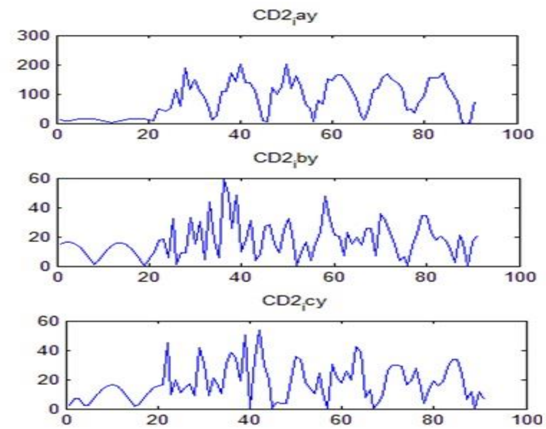

Fig. 2B.Three phase currents Ia,Ib,Ic at all terminals for A-G Fault at terminal-2

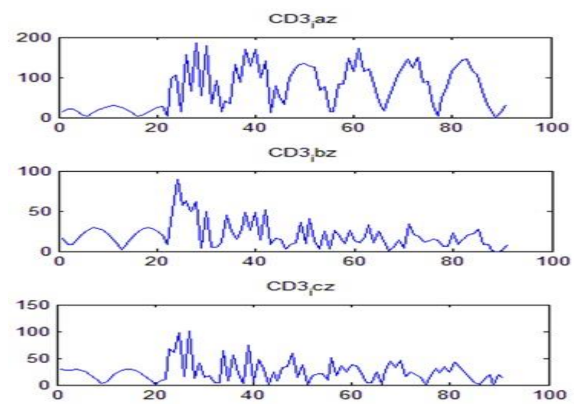

Fig. 2C.Three phase currents Ia,Ib,Ic at all terminals for A-G Fault at terminal-3

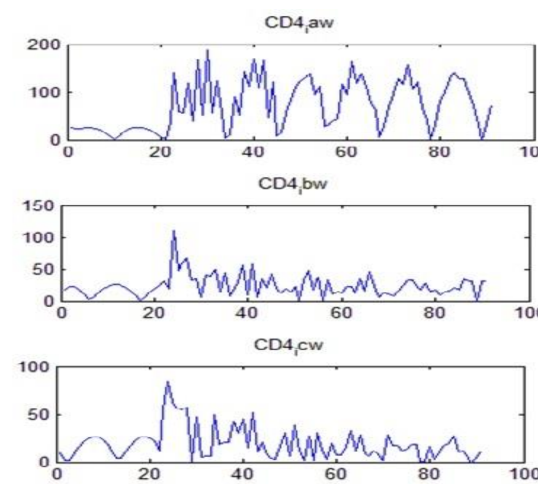

Fig. 2D.Three phase currents Ia,Ib,Ic at all terminals for A-G Fault at terminal-4

The performance of the scheme in detecting and classifying the faults i.e. line-to-ground, line-to-line, line-line-to- ground, triple-line-to- ground is evaluated. In all the cases studied, the scheme is able to detect the faults. The fault inception angle is varied from 20^0 to 180^0 for all types of faults. The simulations show that the fault inception angle has a considerable effect on the phase current samples and therefore on Wavelet Transform output of post-fault signals.

Digital Protection scheme involves the analysis of current signals of all the three phases at all the terminals. The impedance measurement involves both the voltage and current signals to be analyzed and takes more time to measure faulty section impedance thereby the relay operation. The faulty phases will be identified with the analysis of only current signals and fault clearing time will be less than half cycle. The digital protection Scheme involved the comparison of all phases with Threshold value, where the faulty phase(s) indices have higher value compared with the Threshold value and the healthy phase indices are less than the Threshold value and therefore the digital values of the fault indices play a significant role in the protection of Multi terminal transmission system.

The Wavelet transform has the capability of decomposing the current signal into approximate and detail coefficients and the algorithm developed for decomposition up to 1st level where the fault indices are obtained for analysis.

The TCSC model has been obtained from the library and configured according to the multi terminal transmission system considered and the parameters are TCR inductance = 0.043H, TCSC capacitance = 21.9µF with Quality factor 500.

Table. 1A. Variation of fault indices with distance at a fault inception angle of 80 degrees for A-G fault from terminal-1

	Fault Indices			
Distance ,Km	Ia	Ib	Ic	Th
10	857.78	194.85	149.055	400
20	828.10	181.32	153.254	400
30	799.36	169.75	140.07	400
40	768.96	156.01	109.4359	400
50	822.719	193.47	179.809	400
60	679.166	175.31	182.238	400
70	791.736	147.31	139.2871	400
80	672.827	131.59	146.5166	400
90	721.159	167.02	165.4404	400
100	730.023	215.27	211.9616	400

Table. 1B. Variation of fault indices with distance at a fault inception angle of 140 degrees for A-G fault from terminal-1

	Fault Indices			
Distance, Km	Ia	Ib	Ic	Th
10	1021.53	213.623	198.346	400
20	983.274	195.986	180.712	400
30	951.755	189.209	173.9387	400
40	892.527	156.924	139.2211	400
50	980.151	209.015	193.8009	400
60	882.658	131.154	147.7977	400
70	892.367	130.826	110.4519	400
80	823.937	150.543	121.1589	400
90	826.888	127.370	146.2211	400
100	789.096	169.873	213.1937	400

Table. 2A. Variation of fault indices with distance at a fault inception angle of 80 degrees for A-B-G fault from terminal-1

	Fault Indices			
Distance, Km	Ia	Ib	Ic	Th
10	861.870	1197.37	239.2416	400
20	843.548	1160.60	225.8193	400
30	835.370	1132.68	197.5501	400
40	819.743	1095.04	218.2396	400
50	810.732	1013.84	199.5977	400
60	832.673	1114.15	206.7199	400
70	808.016	984.558	173.3522	400
80	802.400	1012.26	139.405	400
90	789.202	929.493	265.3433	400
100	754.762	948.461	155.0431	400

Table. 2B.Variation of fault indices with distance at a fault inception angle of 140 degrees for A-B-G fault from terminal-1

	Fault Indices			
Distance, Km	Ia	Ib	Ic	Th
10	1020.84	836.598	202.0659	400
20	993.978	813.291	190.4665	400

30	961.758	791.896	176.7574	400
40	956.736	798.000	178.0937	400
50	982.946	735.993	209.2095	400
60	861.312	736.331	173.5501	400
70	899.691	719.343	127.2004	400
80	862.319	716.423	133.2863	400
90	849.027	685.529	174.9137	400
100	799.841	666.773	185.6983	400

Table. 3A. Variation of fault indices with distance at a fault inception angle of 80 degrees for A-B-C fault from terminal-1

	Fault Indices			
Distance, Km	Ia	Ib	Ic	Th
10	871.221	1207.06	946.3649	400
20	859.546	1184.53	921.922	400
30	842.170	1164.16	915.4111	400
40	826.169	1148.01	910.3884	400
50	845.369	1121.60	918.0149	400
60	823.528	1057.51	694.4002	400
70	764.680	1153.44	1071.16	400
80	809.943	1067.12	897.7287	400
90	856.635	1068.28	939.9741	400
100	796.598	1019.13	867.8811	400

Table. 3B.Variation of fault indices with distance at a fault inception angle of 140 degrees for A-B-C fault from terminal-1

	Fault Indices			
Distance, Km	Ia	Ib	Ic	Th
10	1037.35	838.640	1167.058	400
20	1019.00	825.266	1142.824	400
30	1001.10	810.926	1128.646	400
40	986.273	792.315	1111.2	400
50	973.572	784.564	1093.665	400
60	870.581	760.107	953.8955	400
70	1029.11	758.666	1188.215	400
80	926.247	721.425	1096.466	400
90	897.574	746.619	1055.635	400
100	920.523	727.164	1061.662	400

Table. 4A. Variation of fault indices with fault inception angle for A-G Fault at a distance of 50Km from terminal-1

	Fault Indices			
FIA	Ia	Ib	Ic	Th
20	1213.785	218.4103	166.4834	400
40	948.5853	165.0139	180.6707	400
60	798.8279	169.5681	196.5208	400
80	822.7192	193.4711	179.809	400
100	993.3057	222.2493	161.0434	400
120	1166.583	225.4171	166.0715	400
140	980.1511	209.0151	193.8009	400
160	786.6994	154.555	176.7927	400
180	726.228	120.7775	139.1487	400

Table. 4B.Variation of fault indices with fault inception angle for A-G Fault at a distance of 70Km from terminal-1

	Fault Indices			
FIA	Ia	Ib	Ic	Th
20	1124.904	151.3524	119.513	400
40	915.7691	144.6894	119.6092	400
60	708.3326	123.5008	149.223	400
80	791.736	147.3117	139.2871	400
100	861.509	148.0102	99.67654	400
120	980.5701	128.5979	114.6022	400
140	892.367	130.8264	110.4519	400
160	716.3282	98.71964	112.8271	400
180	739.8275	122.7012	122.2833	400

Table. 5A. Variation of fault indices with fault inception angle for A-B-G Fault at a distance of 50 Kmfrom terminal-1

	Fault Indices			
FIA	Ia	Ib	Ic	Th
20	896.2714	875.264	72.69829	400
40	731.1468	699.8309	83.04849	400
60	719.2751	665.3774	105.6234	400
80	859.598	778.2137	107.0444	400
100	855.1028	940.598	83.72953	400
120	860.8675	822.9443	72.32986	400
140	725.4609	683.3368	76.50972	400
160	713.8453	653.3429	94.90452	400
180	863.1431	776.0464	110.9506	400

Table. 5B.Variation of fault indices with fault inception angle for A-B-G Fault at a distance of 70Km from terminal-1

	Fault Indices			
FIA	Ia	Ib	Ic	Th
20	1099.573	776.8739	145.3024	400
40	890.5396	656.6062	168.868	400
60	703.8563	825.6238	169.4902	400
80	808.0169	984.5581	173.3522	400
100	921.6477	921.053	101.1953	400
120	1063.87	803.5957	121.974	400
140	899.6918	719.3439	127.2004	400
160	736.4774	874.9102	145.2074	400
180	797.3764	1067.422	172.0859	400

Table. 6A. Variation of fault indices with fault inception angle for A-B-C Fault at a distance of 50 Km from terminal-1

	Fault Indices			
FIA	Ia	Ib	Ic	Th
20	1274.802	825.3025	881.8416	400
40	998.9085	793.2114	1154.976	400
60	825.8862	919.9084	1132.207	400
80	845.3698	1121.605	918.0149	400
100	988.0711	998.9036	795.2939	400
120	1145.48	828.5972	906.717	400
140	973.5721	784.5643	1093.665	400
160	787.2419	929.2849	1182.949	400
180	804.1305	1184.398	970.1011	400

Table. 6B. Variation of fault indices with fault inception angle for A-B-C Fault at a distance of 70Km from terminal-1

	Fault Indices			
FIA	Ia	Ib	Ic	Th
20	1035.869	921.222	859.5921	400
40	833.7964	877.7925	1102.034	400
60	712.9426	980.9806	1230.779	400
80	764.6803	1153.44	1071.16	400
100	940.211	999.8945	1000.591	400
120	1142.593	810.726	1036.263	400
140	1029.112	758.6666	1188.215	400
160	901.5481	878.5827	1234.061	400
180	892.9946	1126.941	963.5433	400

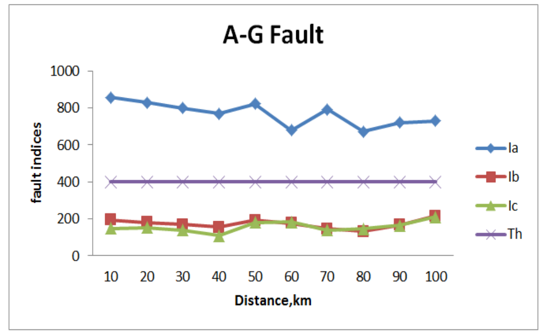

Fig. 3A. Variation of fault indices with distance at a fault inception angle of 80 degrees for A-G fault from terminal-1

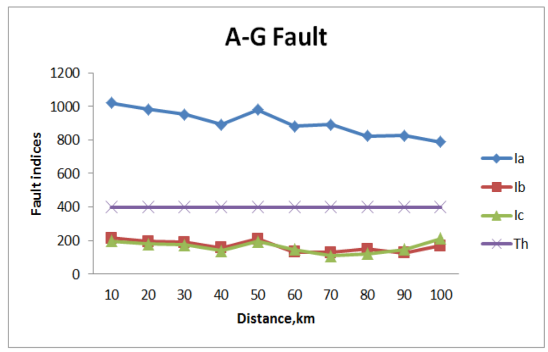

Fig. 3B. Variation of fault indices with distance at a fault inception angle of 140 degrees for A-G fault from terminal-1

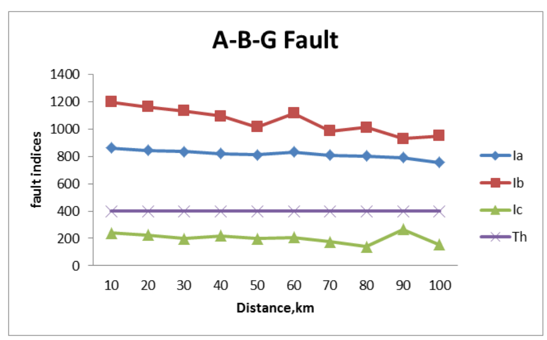

Fig. 4A. Variation of fault indices with distance at a fault inception angle of 80 degrees for A-B-G fault from terminal-1

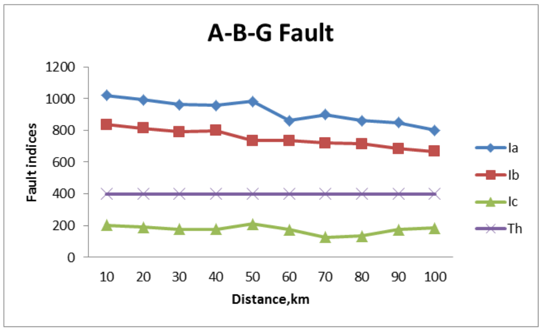

Fig. 4B.Variation of fault indices with distance at a fault inception angle of 140 degrees for A-B-G fault from terminal-1

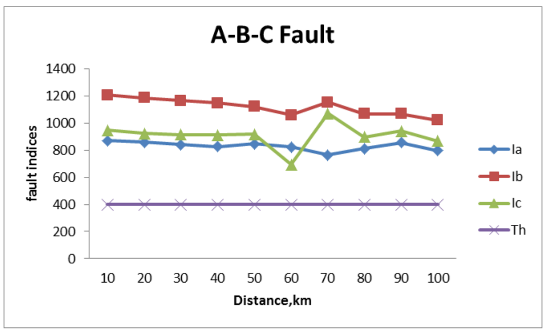

Fig. 5A. Variation of fault indices with distance at a fault inception angle of 80 degrees for A-B-C fault from terminal-1

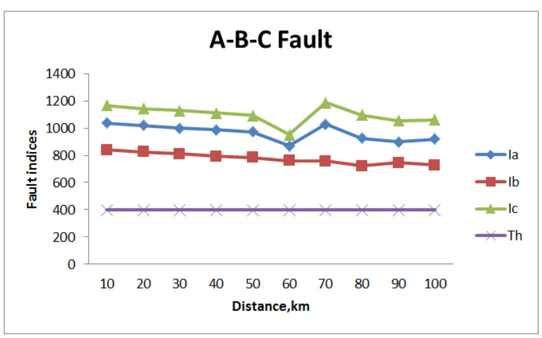

Fig. 5B.Variation of fault indices with distance at a fault inception angle of 140 degrees for A-B-C fault from terminal-1

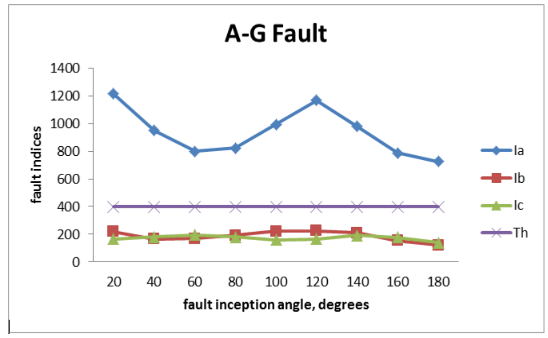

Fig. 6A. Variation of fault indices with fault inception angle for A-G Fault at a distance of 50 Km from terminal-1

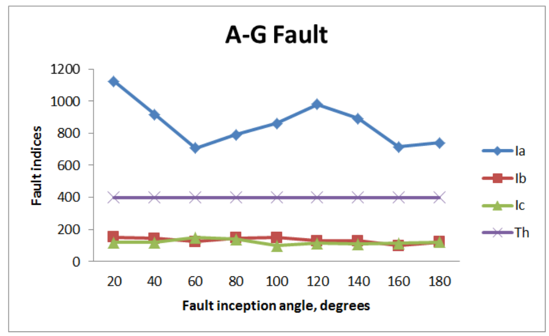

Fig. 6B.Variation of fault indices with fault inception angle for A-G Fault at a distance of70km from terminal-1

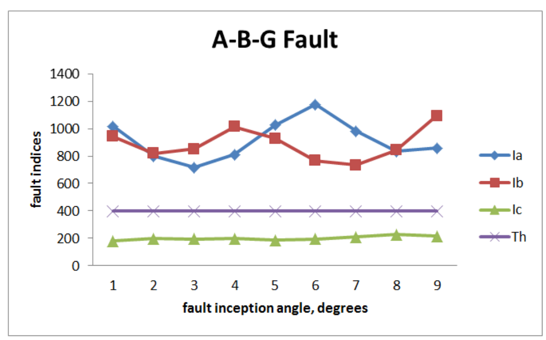

Fig. 7A. Variation of fault indices with fault inception angle for A-B-G Fault at a distance of 50 Km from terminal-1

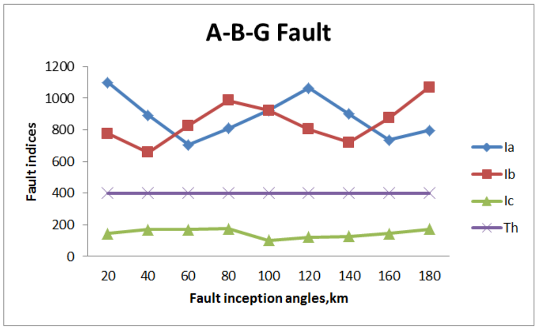

Fig. 7B. Variation of fault indices with fault inception angle for A-B-G Fault at a distance of 70km from terminal-1

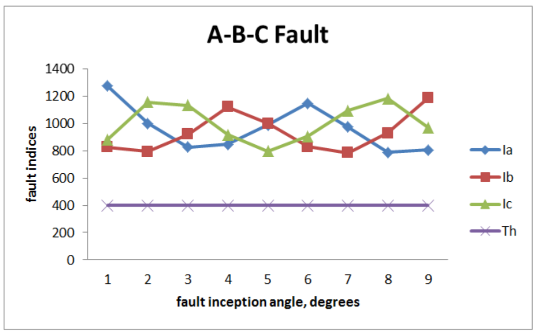

Fig. 8A. Variation of fault indices with fault inception angle for A-B-C Fault at a distance of 50 km from terminal-1

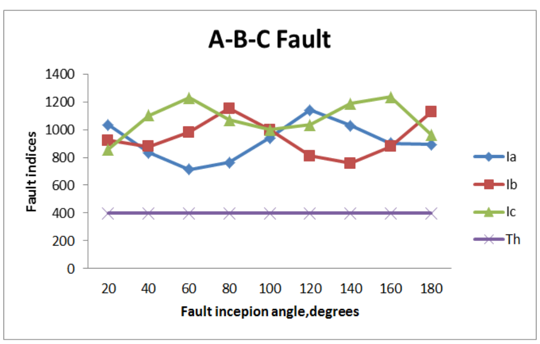

Fig. 8B. Variation of fault indices with fault inception angle for A-B-C Fault at a distance of 70km from terminal-1

4. Faulty terminal identification

The faulty terminals are identified by comparing the fault indices at all the terminals for the same fault and the fault index at the faulty terminal has the largest value as compared with other terminals which clearly identifies the faulty terminal. The identification for different faults is made by considering the variation of fault indices with fault inception angle and distance.

Table. 7A. Variation of fault indices with distance at a fault inception angle of 80 degrees for A-G fault from terminal-1

Distance, Km	T1	T2	T3	T4
10	857.784	434.55	451.39	385.89
20	828.101	408.62	414.50	369.00
30	799.368	492.57	435.14	402.33
40	768.969	510.54	482.62	436.81
50	822.719	499.43	501.98	446.74
60	679.166	600.58	502.87	468.50
70	791.736	586.97	567.42	512.96
80	672.827	609.91	572.76	465.01
90	721.159	651.26	604.29	517.64
100	730.023	724.29	661.70	564.83

Table. 7B.Variation of fault indices with distance at a fault inception angle of 140 degrees for A-G fault from terminal-1

Distance, Km	T1	T2	T3	T4
10	1021.53	521.29	446.03	481.90
20	983.274	526.23	397.01	488.47
30	951.755	593.09	485.97	526.03
40	892.527	626.60	510.05	577.85
50	980.151	615.80	520.51	560.56
60	882.658	678.90	510.00	626.74
70	892.367	657.66	563.97	608.49
80	823.937	722.61	598.13	659.69
90	826.888	803.64	629.33	670.05
100	789.096	849.79	694.49	767.53

Table. 8A. Variation of fault indices with distance at a fault inception angle of 80 degrees for A-B-G fault from terminal-1

distance, km	T1	T2	T3	T4
10	1029.62	554.68	581.95	494.61
20	1002.07	585.12	614.46	520.09
30	984.026	555.12	604.67	529.73
40	957.393	613.12	602.23	575.04
50	912.290	643.75	671.40	577.03

60	973.413	682.02	704.69	602.66
70	896.287	716.07	714.72	645.31
80	907.334	756.08	737.28	672.50
90	859.348	784.43	780.40	706.36
100	851.611	834.77	800.05	750.56

Table. 8B.Variation of fault indices with distance at a fault inception angle of 140 degrees for A-B-G fault from terminal-1

distance, km	T1	T2	T3	T4
10	928.720	527.02	498.97	486.05
20	903.634	512.33	492.74	511.77
30	876.827	534.49	483.26	526.08
40	877.368	574.25	546.86	549.62
50	859.470	580.03	531.73	557.78
60	798.821	635.05	577.90	607.18
70	809.517	643.29	591.12	624.82
80	789.371	686.80	620.76	650.41
90	767.278	710.31	660.60	675.32
100	733.307	765.32	680.27	707.48

Table. 9. Variation of fault indices with distance at a fault inception angle of 80 degrees for A-B-C fault from terminal-1

distance, km	T1	T2	T3	T4
10	1008.21	564.28	575.54	565.08
20	988.666	615.35	627.31	624.64
30	973.916	662.74	689.27	651.40
40	961.524	708.27	685.37	691.78
50	961.663	636.10	657.79	642.31
60	858.482	771.31	743.20	758.26
70	996.426	667.86	723.45	669.31
80	924.932	697.22	743.27	708.23
90	954.966	740.72	768.92	738.90
100	894.539	857.23	833.74	816.03

Table. 9B.Variation of fault indices with distance at a fault inception angle of 140 degrees for A-B-C fault from terminal-1

distance, km	T1	T2	T3	T4
10	1014.35	607.42	622.22	610.34
20	995.698	606.85	641.07	603.48
30	980.225	655.52	664.38	648.83

40	963.263	633.50	663.15	642.68
50	950.600	697.36	727.51	678.15
60	861.528	729.41	718.19	732.67
70	991.998	712.82	721.09	728.38
80	914.713	790.53	782.01	772.52
90	899.942	781.62	799.40	784.08
100	903.116	820.76	829.43	809.64

Table. 10A. Variation of fault indices with fault inception angle for A-G fault at a distance of 50 Km from terminal-1

FIA	T1	T2	T3	T4
20	1213.785	828.8034	673.9642	709.0644
40	948.5853	651.7075	557.4042	632.8877
60	798.8279	493.1451	461.3686	477.2376
80	822.7192	499.4314	501.9816	446.7448
100	993.3057	601.1657	615.6964	501.2584
120	1166.583	697.6099	618.5961	586.9892
140	980.1511	615.8038	520.5109	560.5655
160	786.6994	515.4665	474.0117	464.9675
180	726.228	500.8187	494.8108	416.4506

Table. 10B.Variation of fault indices with fault inception angle for A-G fault at a distance of 70Km from terminal-1

FIA	T1	T2	T3	T4
20	1124.904	772.15	912.427	807.2502
40	915.7691	570.2967	652.658	646.5575
60	708.3326	554.7964	593.5496	571.4427
80	791.736	567.4267	586.9718	512.9672
100	861.509	657.6166	661.3294	543.9559
120	980.5701	731.6601	835.9783	700.0531
140	892.367	563.9726	657.6647	608.4952
160	716.3282	540.4647	566.1796	535.8885
180	739.8275	550.3298	540.6252	476.4374

Table. 11A. Variation of fault indices with fault inception angle for A-B-G fault at a distance of 50 Km from terminal-1

FIA	T1	T2	T3	T4
20	979.1525	756.0954	665.9183	735.8004
40	808.8737	622.2417	571.9405	592.2342
60	785.7111	588.1808	582.9615	541.7611
80	912.2907	643.7542	671.4049	577.0379
100	977.3517	682.775	708.7795	667.072

120	970.8665	641.9249	608.453	629.8675
140	859.4701	580.0352	531.7312	557.7811
160	838.6653	548.5073	540.3641	507.3302
180	974.5149	628.4267	655.0875	563.1694

Table. 11B. Variation of fault indices with fault inception angle for A-B-G fault at a distance of 70Km from terminal-1

FIA	T1	T2	T3	T4
20	938.2234	779.2159	708.844	775.4341
40	773.5729	655.1589	621.3711	638.3728
60	764.7401	640.6031	643.1943	598.7018
80	896.2875	716.0748	714.7221	645.3136
100	921.3503	760.5889	795.7861	727.5425
120	933.7328	728.3008	696.9271	728.2673
140	809.5179	643.2912	591.1252	624.8225
160	805.6938	620.428	612.1554	586.769
180	932.3993	715.8654	716.3199	658.5853

Table. 12A. Variation of fault indices with fault inception angle for A-B-C fault at a distance of 50Km from terminal-1

FIA	T1	T2	T3	T4
20	993.9819	729.2007	759.4485	751.2395
40	982.3653	661.0297	681.707	685.5206
60	959.3339	680.6366	697.9877	694.1302
80	961.6634	636.1067	657.7921	642.3185
100	927.4229	686.2835	702.6701	680.0228
120	960.2647	673.5463	698.1713	659.3323
140	950.6005	697.3602	727.5156	678.1556
160	966.492	720.2462	735.875	694.2951
180	986.2097	723.4654	743.3798	695.659

Table. 12B.Variation of fault indices with fault inception angle for A-B-C fault at a distance of 70Km from terminal-1

FIA	T1	T2	T3	T4
20	938.8944	747.5752	782.4575	796.5243
40	937.8743	686.0703	752.5509	719.5052
60	974.9008	681.732	761.9011	700.2565
80	996.4266	667.8666	723.4522	669.3145
100	980.2322	682.6225	708.7167	668.4482
120	996.5275	729.67	755.9394	728.4609
140	991.998	712.8237	721.0977	728.3839
160	1004.731	718.9379	738.7869	732.537
180	994.493	742.3883	781.181	757.9889

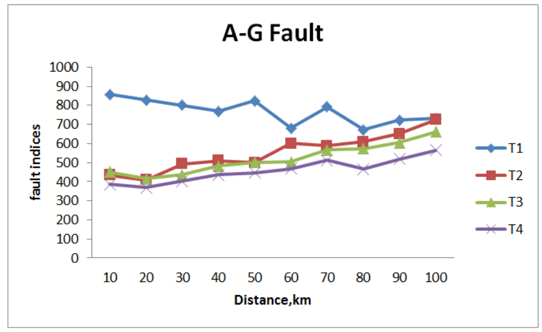

Fig. 9A.Variation of fault indices with distance at a fault inception angle of 80 degrees for A-G fault from terminal-1

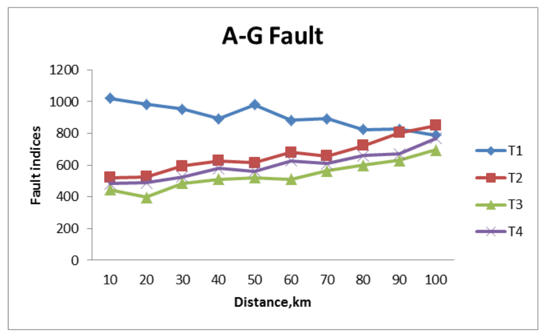

Fig. 9B.Variation of fault indices with distance at a fault inception angle of 140 degrees for A-G fault from terminal-1

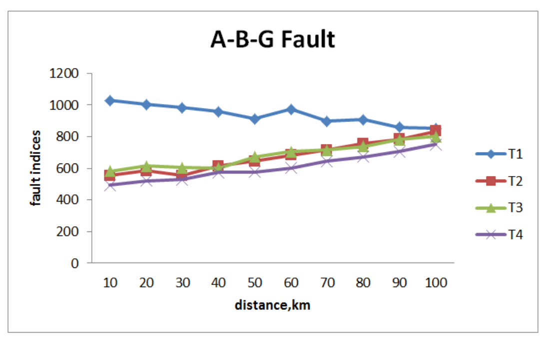

Fig. 10A.Variation of fault indices with distance at a fault inception angle of 80 degrees for A-B-G fault from terminal-1

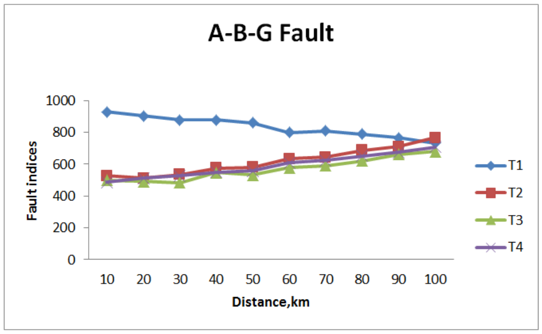

Fig. 10B.Variation of fault indices with distance at a fault inception angle of 140 degrees for A-B-G fault from terminal-1

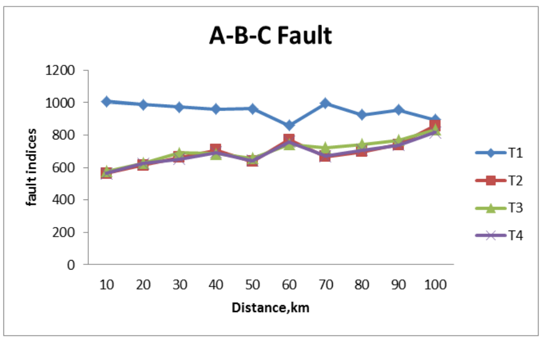

Fig. 11A.**V**ariation of fault indices with distance at a fault inception angle of 80 degrees for A-B-C fault from terminal-1

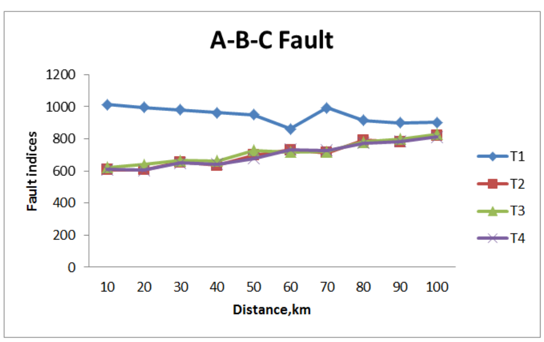

Fig. 11B.**V**ariation of fault indices with distance at a fault inception angle of 140 degrees for A-B-C fault from terminal-1

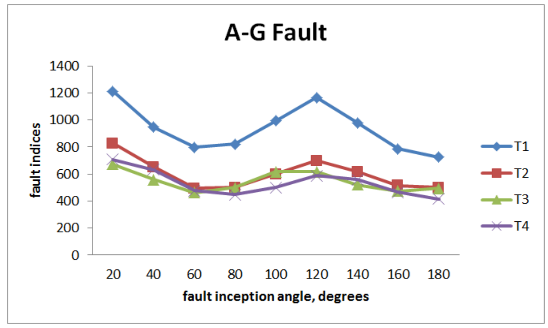

Fig. 12A.Variation of fault indices with fault inception angle for A-G fault at a distance of 50 Km from terminal-1

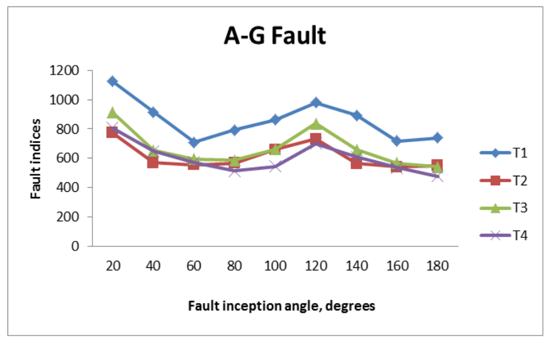

Fig. 12B.Variation of fault indices with fault inception angle for A-G fault at a distance of 70 Km from terminal-1

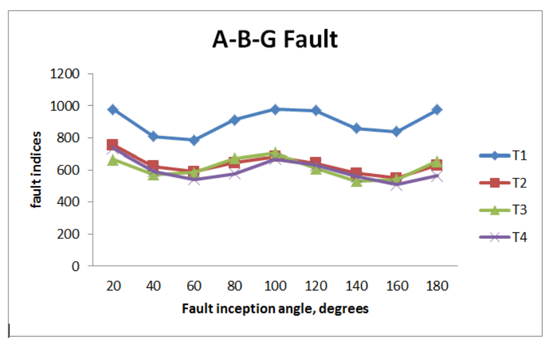

Fig. 13A.Variation of fault indices with fault inception angle for A-B-G fault at a distance of 50 Km from terminal-1

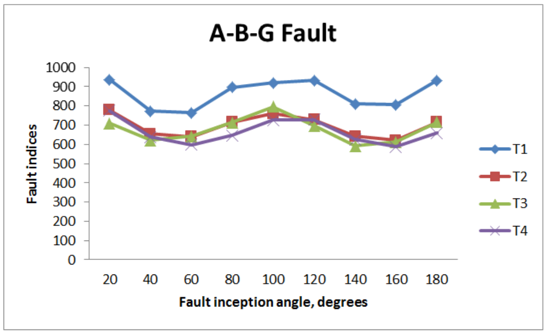

Fig. 13B.Variation of fault indices with fault inception angle for A-B-G fault at a distance of 70km from terminal-1

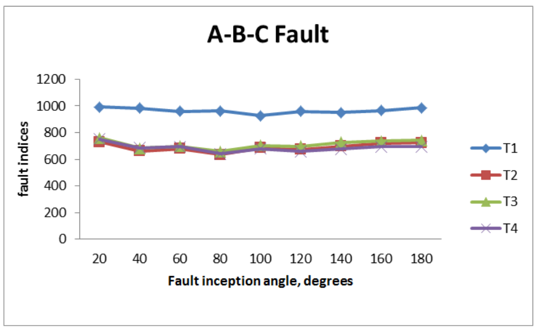

Fig. 14A.Variation of fault indices with fault inception angle for A-B-C fault at a distance of 50 Km from terminal-1

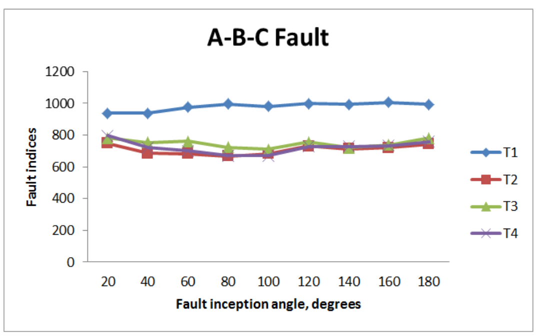

Fig. 14B.Variation of fault indices with fault inception angle for A-B-C fault at a distance of 70 Km from terminal-1

Figures 4-7 illustrate the variation of fault indices of three phase currents with fault inception angle at a distance of 50 Km and 70 Km from Terminal-1 towards the path of Terminal-1 to Terminal-2 for A-G, A-B, A-B-G, A-B-C faults respectively. Figures 8-11 illustrate the variation of fault indices with distance at a fault inception angle 80^0 and 140^0 from Terminal-1 towards the path of Terminal-1 to Terminal-2 for the same type of faults. In both the cases, it is observed that the fault indices of faulty phase is large as compared with that of healthy phase. Thus the number of faulty phases is determined by comparing the Fault Index with a Threshold value (Th) which is taken as 400. Once the faulty phase is identified, then the faulty terminal is identified by considering the fault indices of that particular phase at all the terminals and comparing the index values at all the terminals and the index value of that particular phase at the faulty terminal is higher than the index value of the same phase at the remaining terminals. Figures 12-15 illustrate the variation of fault index of current of phase 'A' at all the terminals for A-G fault, fault indices of phases A and B for A-B and A-B-G faults, fault indices of phases of A,B,C for A-B-C fault at a fault inception angle of 80^0 and 140^0 with variation in distance from Terminal-1 towards the path of Terminal-1 to Terminal-2, it is observed that the fault indices of that particular phase(s) at faulty terminal is(are) higher as compared with that of other terminals. Figures 16-19 illustrate the variation of fault index of current of phase 'A' at all the terminals for A-G fault, fault indices of phases A and B for A-B and A-B-G faults, fault indices of phases of A,B, C for A-B-C fault at a distance of 50km and 70km from Terminal-1 towards the path of Terminal-1 to Terminal-2, it is observed that the fault indices of that particular phase(s) at faulty terminal is(are) higher as compared with that of other terminals. Thus the number of faulty phases are determined by comparing the Fault Index with a Threshold value (Th) and the faulty terminal is identified by comparing the fault index of the same phase(s) at all the terminals and the faulty terminal fault index will be higher than the other terminals for the same phase which identifies the faulty terminal.

4. Conclusions:

The conventional distance relay is likely to over reach or under reach depending upon the mode, type of FACTS devices incorporated in the transmission system can be rectified by wavelet based multi-resolution analysis approach that is applied for effective fault detection, classification and faulty terminal identification in multi-terminal transmission lines. The above algorithm has been implemented for all types of faults with variations in fault inception angle and fault distance and location of TCSC at all terminals. The results indicate the accuracy in fault detection, classification and faulty terminal identification. This scheme is proved to be unaffected by the presence of TCSC by testing the protection scheme on same transmission system without TCSC. The proposed protection scheme is found to be fast, reliable and accurate for various types of faults on transmission lines with and without flexible AC transmission control device such as TCSC at different locations and with various inception angles.

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