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Modeling and Simulation of Digital Distance Protection Scheme for Quadrilateral Characteristics using PSCAD

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Abstract — *In this paper, quadrilateral distance relay characteristic is implemented for the protection of 400 kV transmission line network using PSCAD. In Indian 400 kV transmission lines, twin-moose conductors are generally used. Hence, in this paper, transmission line parameters are used for simulating different configurations of power system network. To check the performance of quadrilateral characteristic, ground faults and phase faults are done considering various effects, such as variation of fault resistance, power transfer angle, system loading etc. FFT algorithm is used to measure phasor quantities to obtain apparent impedance. Distance relays having quadrilateral characteristics are most suitable for EHV transmission lines for different types of faults. In this paper, an actual network of 400 kV transmission system of Gujarat state has been simulated. Simulation of existing system helps the engineering students and protection engineers to know the behavior of actual distance protection scheme in the existing power system network.*

Keywords: Distance protection, Relay modeling, Quadrilateral characteristic, EHV transmission system, PSCAD/EMTDC

I. INTRODUCTION

Electrical power system incorporates generators, transformers, transmission lines, loads etc. System is so designed that power can be delivered to utilization point from generating stations with economy and reliability. If fault occurs in the system and remains for longer time period, it causes severe damage to the major equipment in the system. So the fault needs to be clear within the fraction of seconds. Distance relays are economical and reliable for protection of EHV transmission line and can be used with different characteristics according to requirement. Quadrilateral characteristic is well-suited for the protection of EHV lines due to less tendency of mal-operation because of fault resistance.

Distance protection is as a primary protection for transmission line network. Distance relays use voltage and current signals measured at the relay location to calculate the impedance of the transmission line to be protected. For distance relays, actuating quantity is impedance. So, for each zone of protection, the impedance limit is pre-specified which is known as reach of the relay. For selectivity of zone, distance relay is provided by using different impedance reach with time delay according to settings. The combination of an impedance reach and associated time delay is known as a protection zone. During healthy operating condition, the apparent impedance seen by the relay must be larger than the impedance reach of the relay. When apparent impedance is less than the impedance reached, it has observed that fault occurs and the relay energizes the circuits to trip the circuit breaker which isolate the faulted system from healthy system.

In this paper, algorithm for quadrilateral characteristic is developed in PSCAD and effect of relay under-reach and over-reach is observed considering the fault resistance and direction of power flow by varying power angle.

II. RELAY MODELING IN PSCAD

PSCAD (Power Systems Computer Aided Design) is time domain simulation software for analysis of transients in electrical systems. PSCAD is a collection of programs, which provides graphical user interface to electromagnetic transients program (EMTP). It is also known as PSCAD/EMTDC. EMTDC (Electromagnetic Transients with DC Analysis) was first developed in 1976 and has been continuously developing in its possibility and capabilities. PSCAD is provided with library of power system component models which are useful to set up the simulation software. Collectively they provide accurate, flexible and fast solution for the efficient time-domain program for analysis and simulation of various electrical system transients and control networks. PSCAD is software that makes use of intelligent techniques to computerize the power quality evaluations for improved accuracy and efficiency since manual analysis takes considerable time and would require special knowledge

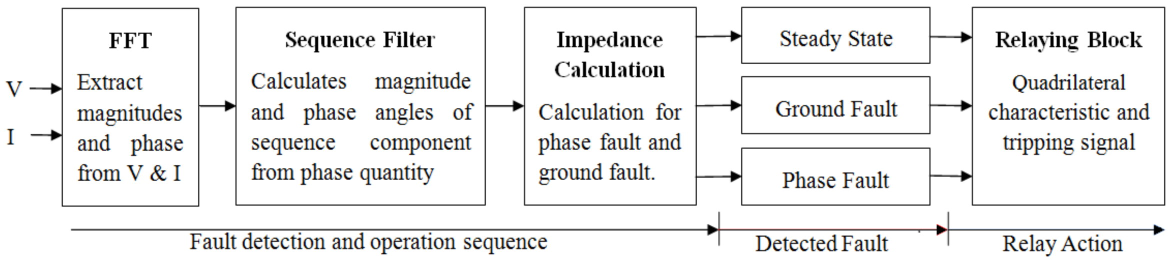

Figure 1: Block diagram of distance relay modeled in PSCAD

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A. Fast Fourier Transform

When the fault occurs in the system, the voltage and current waveforms are distorted due to presence of harmonics and DC decaying component. To compute the apparent impedance, one must consider the value of voltage and current at fundamental frequency. Therefore, various phasor estimation algorithms are used to reject unwanted harmonic contents from the current and voltage signals and to retain the quantity of interest. In this paper, FFT is used to remove DC component and harmonics and estimate the complex phasor element at fundamental frequency. In PSCAD, the FFT is used to determine fundamental components magnitude and phase of the input signal as a function of time. The input signals are sampled before they are decomposed in the harmonic constituents. The FFT block is inherently provided with Anti-aliasing filter. The use of AAF is required to limit the noise and effect of harmonic components. In distance protection, impedance measurement uses information contained in the sinusoidal steady state components of 50 Hz. So, the filtering is required to preserve the steady state component and remove other components [2], [3].

B. Sequence filter

The sequence filter is used to calculate magnitudes and phase angles of positive, negative and zero sequence components from the three phase quantities (three phase voltages and currents).

The sequence components are computed based on transformation equation given below [4]:

$$\begin{bmatrix} V_0 \\ V_+ \\ V_- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Where, α is complex number operator defined as α=e^ (j120°).

C. Calculation of impedance for ground and phase faults

A single line diagram of the portion of the power system having a transmission line between two buses A and B is shown in the figure 2. Fault with fault resistance R_f occurs at point F at x% of transmission line from bus A [5].

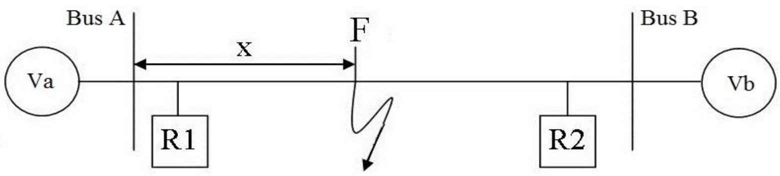

Figure 2: Single line diagram of double-infeed transmission line

For phase A to ground fault, relay measures the impedance of the line as shown in equation (1) up to the fault point x when fault resistance is zero [5],

$$x \cdot Z_1 = \frac{V_{AR}}{I_{AR} + k_0 \cdot I_{0R}} \quad ...(1)$$

Where, V_{AR} and I_{AR} are voltage and current quantity of phase A measured at relay point

I_{0R} is zero-sequence current

k_0 is zero-sequence compensation factor which is given as

$$k_0 = \frac{Z_0 - Z_1}{Z_1} \text{...(2)}$$

Where, Z_0 and Z_1 are zero sequence and positive sequence impedances of transmission line.

When the effect of fault resistance R_F is considered, the apparent impedance measured at the relay point is given as [5],

$$Z_R = x \cdot Z_1 + \frac{I_F}{I_R} \cdot R_F \text{...(3)}$$

Now, for phase faults, assume an AB fault,

$$x \cdot Z_1 = \frac{V_{AR} - V_{BR}}{I_{AR} - I_{BR}} = \frac{V_{ABR}}{I_{ABR}} \text{...(4)}$$

III. SIMULATION SETUP FOR DOUBLE INFEED TRANSMISSION LINE IN PSCAD

The Figure 3 shows the simulation setup of double infeed transmission line in PSCAD/EMTDC software. In this scheme, the transmission lines are represented using the Bergeron model. This model represents the L and C parameters of a pi-section in a distributed manner. It is accurate only at the specified frequency and it is most suitable for the studies where the specified frequency load flow is most important like for relay studies. The advantage of this model is that it is not required to use a tower component to represent a line, rather we can enter the line data in the form of impedance or admittance to model a three-phase system [2]. The system operates at 400 kV, 50 Hz. Transmission line length considered is 280 km. Generally, twin-moose conductor is used in 400 kV systems. Therefore, line parameters are taken from MiPower software for twin-moose conductor as given in Appendix [A].

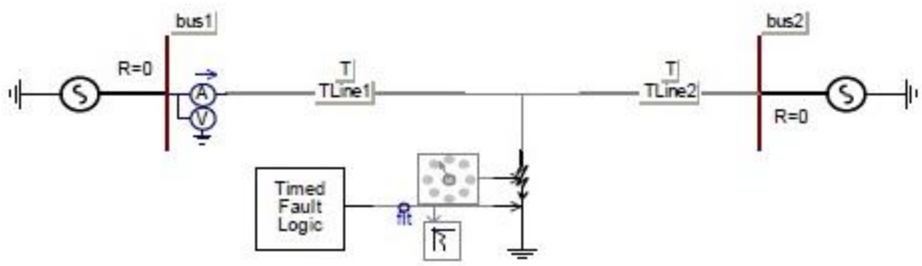

Figure 3: Simulation setup for double infeed scheme in PSCAD

IV. Settings of Quadrilateral characteristics

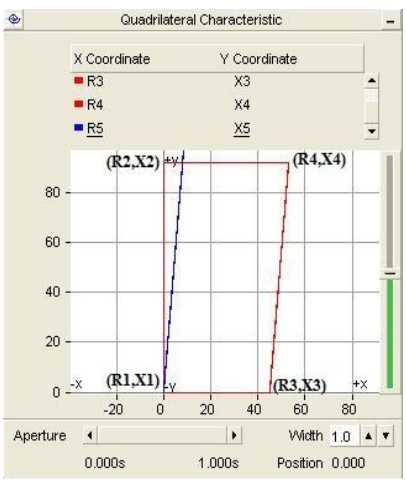

Figure 4: Quadrilateral characteristic plot

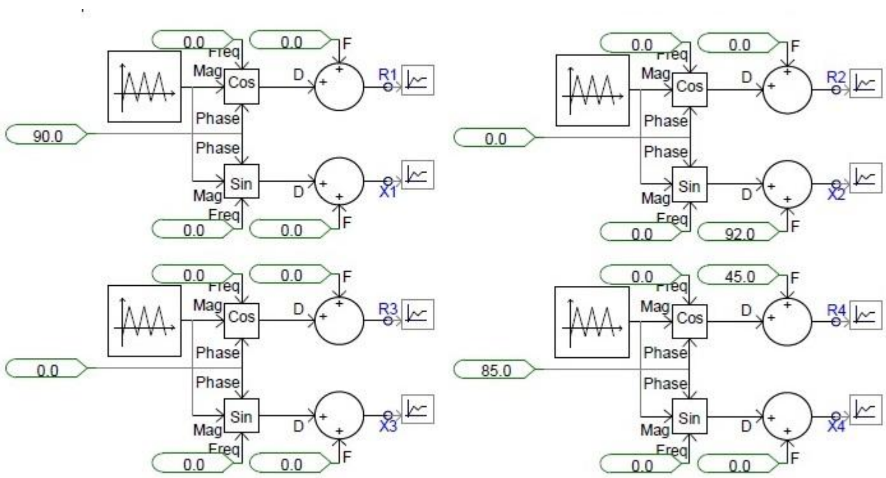

Figure 5: Logic to plot quadrilateral characteristic in PSCAD

For first zone of protection, 80% impedance of total line length is set as reach of relay. Here, for 280 km long line, line impedance at 224 km is 17.06+j91.61 ohms. Figure 4 shows the quadrilateral characteristic obtained for impedance reach of 45+j91.61 ohms. At the relay point, when apparent impedance calculated falls below the preset reach impedance value, relay sense the fault and gives trip command. Since the quadrilateral characteristics are highly flexible to the fault resistance coverage, we can expand the resistive reach of relay [6]. In figure 5, logic implemented to plot quadrilateral characteristic is shown. Four pulse generators are used to plot the graph.

V. Simulation results

To check the performance of given relaying scheme for different ground faults, single-line-to-ground fault and double-line-to-ground fault are simulated on 400kV, 280 km long two-ended transmission line. Faults are simulated at 20%, 40%, 60% and 80% of line length at various power transfer angles (δ). Power angles are varied from 20˚ to -20˚ in step of 10˚. Effect of fault resistance is considered for 10 ohm and 50 ohm.

A. Ground faults

For ground faults, apparent impedance is calculated by using equation (1) at various fault locations of x km. When fault resistance is added, equation (3) is used for impedance calculation at relay point [5].

1. L-G fault

For L-G fault, system is simulated at different power angles and results are shown in tables. Table 1 shows the value of R and X at the instant of fault at different fault locations on line when power transfer angle (δ) is 20˚. Similarly, for power angle 10˚,-10˚ and -20˚, relay operating point locus is shown in figure 6 to figure 9. Effect of fault resistance is also simulated for 10 Ω and 50 Ω. We can easily analyze the relation between power transfer angle and fault resistance from the figures. As we decrease the power transfer angle (δ) at bus A the ability of relay to coverage high resistance fault is decreases.

Table 1

δ=20˚						
Fault location (x% of line length)	Rf=0 Ω		Rf=10 Ω		Rf=50 Ω	
	R	X	R	X	R	X
20	3.16492	23.0851	10.9138	22.2632	37.8099	19.3084
40	7.05248	46.008	17.068	43.8758	50.3998	36.7103
60	11.7009	68.8241	26.117	64.1591	70.4179	49.8728
80	17.0631	91.6125	43.736	79.9203	110.323	51.3156

Table 2

δ =10˚						
Fault location (x% of line length)	Rf=0 Ω		Rf=10 Ω		Rf=50 Ω	
	R	X	R	X	R	X
20	2.98577	23.1903	10.9942	22.7277	40.6988	20.4762
40	6.34986	46.4479	16.9896	45.2507	55.4716	40.0395
60	10.1552	69.8477	26.0369	67.1659	80.7082	56.165
80	14.3827	93.4778	45.462	86.3441	138.718	59.5989

Table 3

δ =-10˚						
Fault location (x% of line length)	Rf=0 Ω		Rf=10 Ω		Rf=50 Ω	
	R	X	R	X	R	X
20	2.58177	23.2906	10.8804	23.7095	46.7996	25.3044
40	4.72914	46.8549	15.9253	47.9991	65.7714	52.727
60	6.5088	70.765	23.6673	73.4029	104.76	85.0368
80	7.91963	95.0946	43.9206	102.491	252.99	140.924

Table 4

δ =-20˚						
Fault location (x% of line length)	Rf=0 Ω		Rf=10 Ω		Rf=50 Ω	
	R	X	R	X	R	X
20	2.37287	23.2812	10.6724	24.1854	49.4554	29.4626
40	3.891	46.7973	14.9163	49.2067	69.1236	63.4668
60	4.62585	70.5869	21.2361	76.1595	112.178	114.936
80	4.59233	94.6904	39.1865	111.105	304.324	351.59

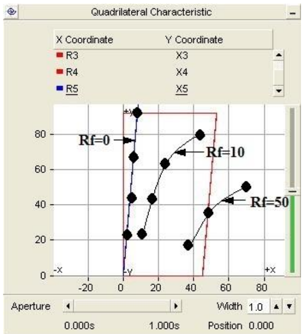

Figure 6: δ=20˚

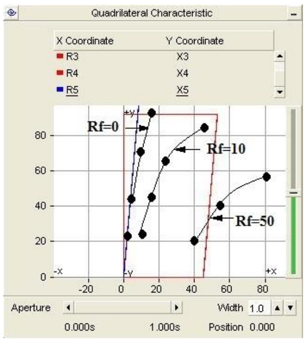

Figure 7: δ=10˚

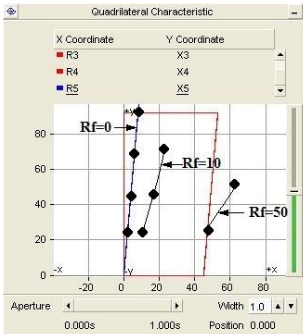

Figure 8: δ= -10˚

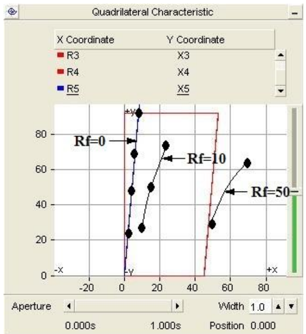

Figure 9: δ= -20˚

2. L-L-G fault

For LLG fault, phase AB to ground fault is simulated on given transmission system. The value of R and X at the instant of fault is shown in table 5 to table 8 for different power transfer angle (δ). Figure 10 to figure 13 shows the relay operating point locus with and without fault resistance.

Table 5

δ=20˚						
Fault location (x% of line length)	Rf=0 Ω		Rf=10 Ω		Rf=50 Ω	
	R	X	R	X	R	X
20	1.77363	18.6142	13.6273	17.7475	52.0067	14.6126
40	3.4678	37.3627	19.0043	35.1098	66.2542	27.7367
60	5.21014	56.3835	27.888	51.4152	89.288	37.0174
80	7.0245	75.8227	48.9723	63.3868	134.179	35.9628

Table 6

δ=10˚						
Fault location (x% of line length)	Rf=0 Ω		Rf=10 Ω		Rf=50 Ω	
	R	X	R	X	R	X
20	1.77363	18.6142	14.0092	18.0947	57.692	15.0352
40	3.4678	37.3627	19.7674	36.0614	75.8504	29.5742
60	5.21014	56.3835	29.5582	53.4796	107.56	40.1819
80	7.0245	75.8227	54.2521	68.0204	179.116	36.2801

Table 7

δ=-10˚						
Fault location (x% of line length)	Rf=0 Ω		Rf=10 Ω		Rf=50 Ω	
	R	X	R	X	R	X
20	1.77363	18.6142	14.6051	19.0218	72.6809	20.2285
40	3.4678	37.3627	20.8397	38.5013	103.13	42.6357
60	5.21014	56.3835	32.0271	59.0298	172.302	69.3032
80	7.0245	75.8227	64.4873	83.3224	502.498	108.43

Table 8

δ=-20˚						
Fault location (x% of line length)	Rf=0 Ω		Rf=10 Ω		Rf=50 Ω	
	R	X	R	X	R	X
20	1.77363	18.6142	14.7786	19.589	81.7547	27.3117
40	3.4678	37.3627	21.0381	39.9566	120.618	60.7567
60	5.21014	56.3835	32.4867	62.5149	225.662	129.996
80	7.0245	75.8227	67.8386	95.2834	449.427	1764.31

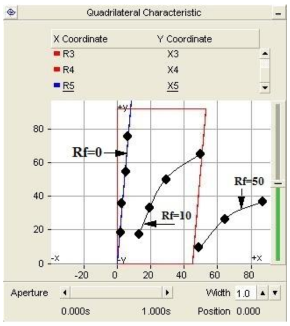

Figure 10: δ=20˚

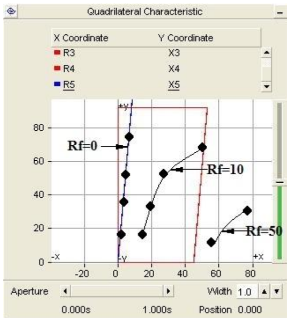

Figure 11: δ=10˚

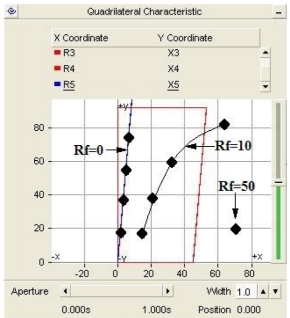

Figure 12: δ=-10˚

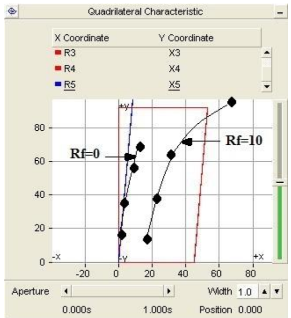

Figure 13: δ=-20˚

B. Phase fault

In the simulation of phase fault, equation (4) is used to calculate apparent impedance at relay location [5].

1. L-L Fault

For AB fault, system is simulated and values of R and X are shown in table-9. The fault impedance locus is shown in figure 14 which shows that quadrilateral characteristics is able to cover the phase fault efficiently as all relay operating points lies inside the preset boundary.

Table 9

Fault location (x% of line length)	R	X
20	1.77363	18.6142
40	3.4678	37.3627
60	5.21014	56.3835
80	7.0245	75.8227

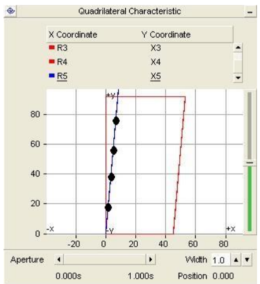

Figure: 14 Relay operating points for LL fault

VI. SIMULATION OF 400 KV TRANSMISSION NETWORK OF GUJARAT STATE

To check the performance of relay in existing power system network, 400 kV power network of Gujarat region is simulated in PSCAD as shown in figure 15. In this network, 18 substations and 20 transmission lines are interconnected as listed in Appendix B. In this system, working of relay is checked for short, medium and long length transmission line. The system is simulated for phase and ground faults.

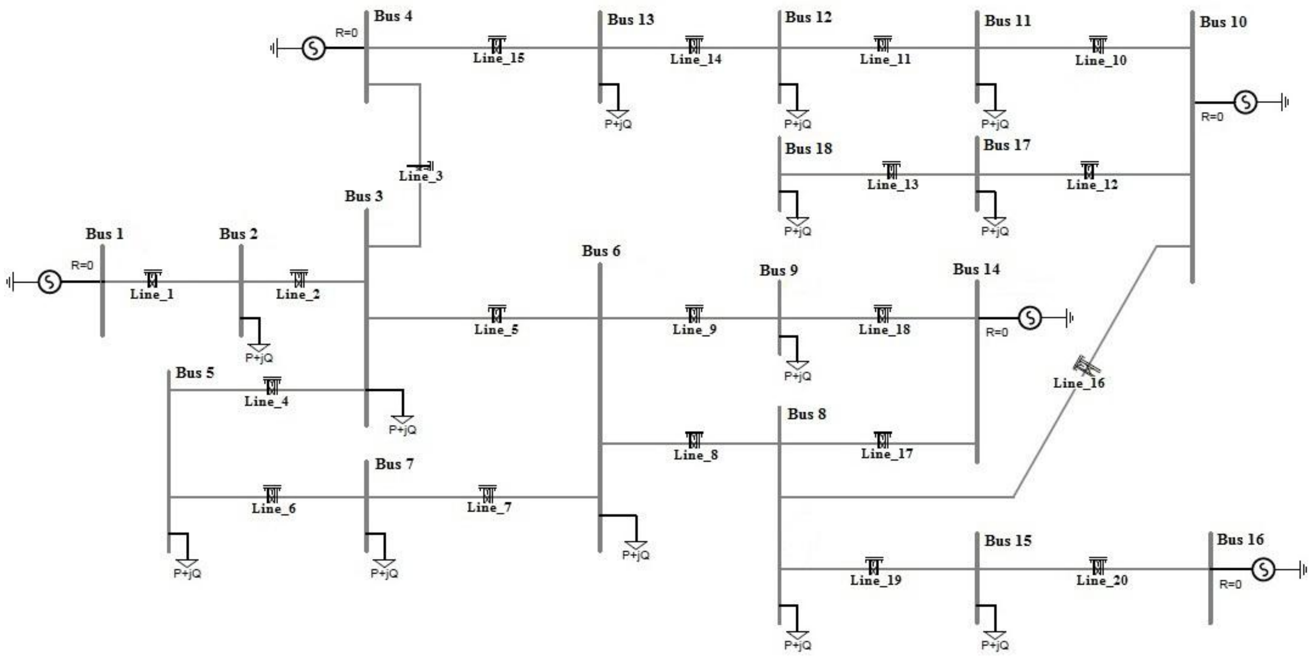

Figure 15: 400 kV transmission network of Gujarat region simulated in PSCAD

Table 10 L-G Fault

Fault location (x% of line length)	Short line Line_1		Medium line Line_15		Long line Line_11	
	R	X	R	X	R	X
80	1.72933	19.16	5.3247	58.4377	6.80548	96.045
70	1.5	16.6242	4.61418	50.7957	6.17193	83.759
60	1.2908	14.2915	3.9494	43.5823	5.47214	71.6696
50	1.0808	11.9611	3.26453	36.0978	4.71299	59.7306

A. Ground Fault

In transmission network, A-G fault is simulated to study the behavior of the relay. For short transmission line, line-1 is simulated where relay location is on bus 1. Figure 16 shows the operating points of relay for the same. Figure 17 shows the relay operating point locus for medium transmission line-15, where relay located at bus 4. Figure 18 shows the relay operating points for long transmission line 11, where relay location is at bus 12. Table 10 shows the value of R and X at various fault location for different length of the transmission line.

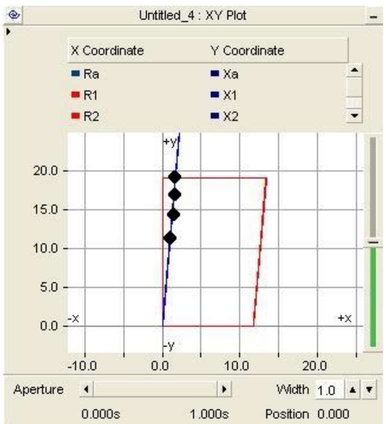

Figure 16: Short T-line

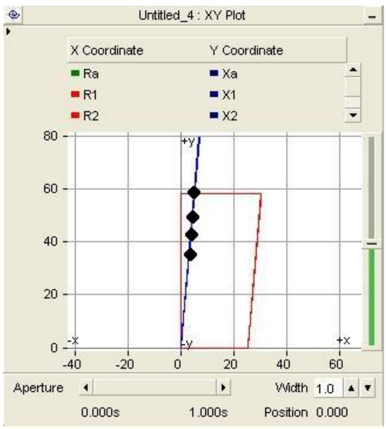

Figure 17: Medium T-line

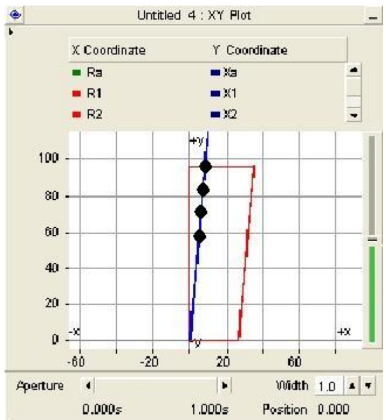

Figure 18: Long T-line

B. Phase fault

To study check the relay behavior in power transmission network during phase fault, AB fault is simulated for short transmission line having length of 72 km. Similarly, one can simulate the system for medium and long length transmission line. Table 11 shows the relay operating point at various fault locations for AB fault. Figure 19 shows the operating points on quadrilateral characteristic which describes the movement of relay operating point with respect to change in fault location x.

Table 11

Fault location (x% of line length)	R	X
80	1.82096	19.1474
70	1.59381	16.6158
60	1.38414	14.2861
50	1.17429	11.9579

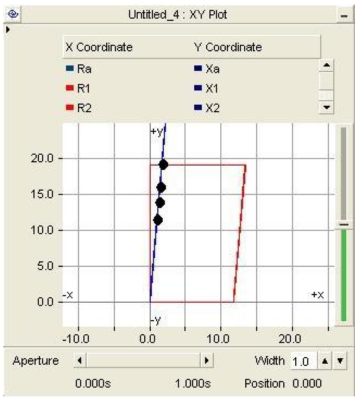

Figure 19 Operating points for LL fault

V CONCLUSION

In this paper 400 kV, 280 km typical two ended transmission line is and model of quadrilateral relay is simulated using PSCAD/EMTDC software. Here, the performance of quadrilateral characteristics is evaluated for different fault location with different power transfer angle (δ) for LG, LLG and LL faults with and without considering the effect of fault resistance. The simulation results show that quadrilateral characteristic is greatly suitable for high resistance fault.

A computer model of protective relays is economical and feasible alternative to investigate the performance of relays and protection systems. It permits researchers and students to observe the performance of relay in a very detailed way and to know the processes in each internal module of the relay. So distance relay is modeled in this paper explains the working of relay in easy manner.

In two-ended transmission line, for LG and LLG faults, relay gives better coverage for fault resistance, though as power transfer angle (δ) decreases the ability of relay to detect fault with higher fault resistance is decreases. Thus, for resistive faults, power transfer angle effects the relay operation. For LL faults, relay gives satisfactory operation to protect transmission line.

To check the performance of relay in the network of more than one transmission line and more than two infeed, the existing power network of Gujarat state is simulated. Performance of relay is checked for short, medium and long transmission line and relay gives satisfactory operation for the same.

Appendix A

Transmission line parameters	
Positive sequence R_1	0.029792×10^{-3} [ohm/m]
Positive sequence X_{L1}	0.332×10^{-3} [ohm/m]
Positive sequence X_{C1}	288.288[ohm-m]
Zero sequence R_0	0.16192×10^{-3} [ohm/m]
Zero sequence X_{L0}	1.24×10^{-3} [ohm/m]
Zero sequence X_{C0}	446.428 [ohm-m]

Appendix B

The power transmission network of Gujarat for 400 kV is taken from official website of SLDC Gujarat [7]. Line length is obtained by using geographical distance between two substations from Google Maps [8].

Bus Data

Bus No.	400 kV Substation location	Load	
		MW	MVAR
1	Mundra	-	-
2	Varsana	500	25
3	Hadala	400	20
4	Vadinar	-	-
5	Jetpur	400	20
6	Choraniya	600	35
7	Amreli	400	25
8	Asoj	600	30
9	Kasor	500	30
10	Vanakbori	-	-
11	Dehgam	600	30
12	Vadavi	550	25
13	Halvad	450	25
14	Sardar Sarovar	-	-
15	Kosamba	1000	30
16	Ukai	-	-
17	Soja	450	30
18	Kansari	500	25

Transmission Lines Data

Transmission line No.	Line Length (in km)
1	72
2	159
3	135
4	78
5	128
6	77
7	146
8	181
9	140
10	85
11	363
12	130
13	138
14	229
15	216
16	82
17	111
18	144
19	131
20	94

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