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A Relaying Scheme for Detection and Classification of Shunt Faults in Six-Phase Transmission System Based on DFT-FIS Approach

V. Ashok[a], Anamika Yadav[1]

[a]Research Student, Department of Electrical Engineering, National Institute of Technology Raipur , C.G., India
[b]Assistant Professor, Department of Electrical Engineering, National Institute of Technology Raipur , C.G., India

Abstract

Hitherto many schemes based on the fuzzy system have been protected by a three-phase transmission system, but not by a six-phase transmission system. This paper sets out a novel protection scheme based on DFT-FIS approach for detection/classification of shunt faults in a six-phase transmission system. In this scheme, two separate DFT-FIS modules have been designed to detect the presence of fault in any of the six-phase(s) and to identify the presence of ground in the fault loop, thus classifying all 120 types of fault in a six-phase transmission line. The six-phase voltage and current signals are collected at one end of the transmission line only, thus circumvent dependence on a communication link for remote end data. A wide-range of fault simulation studies were carried out in MATLAB/Simulink environment for all possible shunt fault combinations by varying fault locations, fault inception angle, fault resistance, short circuit capacity (SCC) of the source and at various fault conditions such as: close-in faults, remote-end faults, high resistance faults, including CT saturation. Furthermore, the relay operation time in fault detection/classification is less than one-cycle (<16.67ms) and since the scheme does not experience any malfunction it is deemed reliable and adaptable.

Keywords: Fuzzy Logic, Discrete Fourier Transform (DFT), fuzzy inference system (FIS), protective relaying, fault detection, fault classification, Relay operation time (RT)

1. Introduction

In the current global scenario, demand for electrical energy is increasing year-on-year due to rapid industrialization and urbanization. It is essential to augment the power transfer capability of the existing transmission system to meet the rising demand. However, transmission of power beyond the existing ultra-high voltage levels encounters some restrictions due to the techno-environmental issues involved. Other alternative power transmission systems, such as HVDC, require huge capital investment for installation and maintenance. In this context, a higher phase order transmission system has been proposed to meet growing electricity demand. The higher phase order is defined as the use of a greater number of phases than the conventional three-phase transmission system. The higher phase order may consist of six, nine, twelve phases with phase displacement of 60°, 40° and 30° degrees respectively. Among all higher phase order transmission systems, the six-phase transmission system gives more advantages such as: decrease in conductor surface gradient, audible noise level and radio intervention as well as improvement in thermal loading capability, surge impedance loading (SIL), lower corona losses, voltage regulation and good compatibility for the existing double circuit three-phase transmission system within the same right-of-way [1]. Since, $V_L = V_P$ the equations (1) - (4) indicate that the power transfer capability of the six-phase transmission system is greater (73%) than that of the normal existing double circuit three-phase transmission system.

$$V_{AN} = V_{BN} = V_{AB} \quad (1)$$

$$I_{AN} = I_{BN} = I_{AB} \quad (2)$$

$$2(P_{3\phi}) = 2(\sqrt{3}V_L I_L cos\Theta) \quad (3)$$

$$1P_{6\phi} = 6(V_L I_L cos\Theta) \quad (4)$$

In addition, it is impractical to convert a double circuit three-phase transmission system to a single circuit six-phase transmission system, while adopting the existing three-phase protection system. The design of a suitable relaying scheme is very complex in the case of a six-phase transmission system, because there is a larger number of possible faulty phase combinations. The fault analysis of a (Multi-Phase) six-phase transmission system was proposed using

*Corresponding author: Anamika Yadav, ayadav.ele@nitrr.ac.in
Email addresses: ashokjntuk@gmail.com (V. Ashok), ayadav.ele@nitrr.ac.in (Anamika Yadav)

symmetrical component theory in [2]. A computer program was developed to design a six-phase transmission line in [3]. Evaluation of the ground level electric field and a method of suppressing fault currents were reported for a six-phase transmission line [4]. Transient switching over voltages and significance of switching surges were demonstrated for a six-phase transmission line in [5]. Capacitive switching phenomena, significance TRV studies were carried out for a six-phase transmission line and some of the issues are compared to a three-phase transmission system in [6]. Transient stability of a 4-bus test system was investigated after conversion of a double circuit three-phase transmission system to a single circuit six-phase transmission system and critical clearing time was compared for both configurations [7]. Classification of faults and faulted phase selection approach using wavelets for six-phase transmission were reported in [8]. Performance characteristics for six-phase and twelve phase transmission were evaluated related to power flow and voltage stability and some comparisons were made for the two configurations [9]. The propagation characteristics and their three-phase representation for six-phase transmission lines were presented and transposed and non-transposed transmission lines configurations analyzed [10]. A comprehensive digital simulation was performed with arc modeling technique on a 326KV six-phase transmission system to study various fault arcing transients and some tripping and auto-reclosing concepts were discussed [11]. The fault location on a six-phase transmission line with unsynchronized phasors was presented without assuming transposition of conductors [12]. A new wavelet technique for detection of fault-induced high-frequency transient currents in six-phase transmission lines was reported in [13]. Adaptability of existing three-phase distance relays and its complications for six-phase transmission lines were discussed in [14]. Protection of NYSEG's six-phase transmission line and adopting three-phase digital relays for tripping action was demonstrated in [15]. A microprocessor based relaying scheme was demonstrated in a six-phase transmission line using energy spectral of wavelet coefficients [16]. An ultra-high speed relaying scheme for a six-phase transmission system was reported in [17]. Overcurrent protection by a numeric relay for a six-phase transmission line was illustrated in [18]. The complexity of fault analysis in a six-phase transmission system is much higher than in a three-phase system. The total number of possible shunt fault combinations is 120 and among all these faults, there are 23 fault combinations which are distinctive with a different combination of phase displacement between the lines. Analysis of all faults can be confined to the 23 significant fault combinations for the purpose of performing simulation studies on a six-phase transmission system [19]. A fault detection, classification and location scheme based on DFT and ANN for a six-phase transmission line using single end data was reported in [20]. There are many schemes [21–26] which employ a fuzzy system to protect three-phase transmission systems. A fuzzy logic based fault detection/classification approach for a three-phase transmission system using current samples is explained in [21] followed by appropriate statistical techniques. The fuzzy inference system approach for detection of shunt and simultaneous series-shunt faults with the location of faults in a double circuit transmission system was reported in [22]. The directional relaying problem with fault classification and fault location estimation using a fuzzy inference system is discussed in [23]. Another fuzzy logic based fault classification scheme for single and double circuit power transmission lines was reported in [24], [25]. A single-phase auto-reclosing protection scheme for a double circuit transmission line is discussed in [26] using FIS. The influence of sampling frequency on a fault location detection algorithm based on artificial neural networks was reported in [27]. Another technique based on fisher information, which measures the stability of the electric signals, and combined with wavelet analysis for faulty phase selection of a power distribution network wasreported in [28]. The optimal planning and clustering of smart low-voltage distribution networks into autonomous Micro Grids within a green field area is discussed in [29] using imperialist competitive algorithm. While fuzzy based algorithms have been used for different protective relaying tasks of three-phase single-circuit or double-circuit transmission system, not a single paper has been reported for the protection of a six-phase transmission line. In this paper, a novel protection scheme is proposed based on the DFT-FIS approach for detection/classification of shunt faults in a six-phase transmission system. No papers have reported this approach to date. Further, section 2 deals with the proposed methodology and corresponding algorithm with data preprocessing techniques as well as the design of DFT-FIS modules for detection/classification of shunt faults. In section 3 a detailed analysis of results and interpretations at different fault scenarios are set out in table form. Section 4 concludes on the significance and effectiveness of the proposed methodology and its adaptability in a six-phase transmission system for the purposes of providing a suitable protection scheme.

2. Methodology

The concept of fuzzy logic was developed by Professor L. A. Zadeh at the University of California in 1965. This concept is analogous to the human sensation and interpretation process. Unlike the conventional control stratagem, which is an equestrian event control, fuzzy logic control is a range-to-point or range-to-range control. The output of a fuzzy logic controller is a derivative from fuzzification/defuzzification of both the inputs/outputs and its associated membership functions. A crisp input is converted into several members of the associated membership functions based on its value. From this point of view, the output of a fuzzy logic controller is based on its members of the associated membership functions, which can be deliberated as a range of inputs [21]. If X is a group of entities denoted generally by x, then a fuzzy set M in X is defined as a set of well-ordered pairs:

$$M = \{(x, \mu A(x)), x \epsilon X)\} \tag{5}$$

From equation (5), where $\mu A(x)$ is a membership function for the fuzzy set M. This membership function maps each component of X (the universe of discourse) to a membership grade between 0 and 1. The key objective of fuzzy logic is to represent and reason within a specific form of knowledge expressed in a linguistic way. The prodigious accessibility of linguistic variables is that they can be amended via linguistic verges applied to primary terms. These linguistic verges can be accompanied by certain membership functions. To implement the fuzzy logic technique, the following three steps are required:

- Fuzzification—Converts conventional data or crisp data into fuzzy data.
- Fuzzy Inference Process—Combining linguistic fuzzy data with the fuzzy decision rules to derive corresponding fuzzy output for a related membership function.
- Defuzzification—Using different methods (generally centroid method uses) to compute the crisp output from the corresponding fuzzy output which is obtained from the fuzzy inference engine.

Generally, two types of fuzzy inference systems (FIS) are used in fuzzy logic based systems:

- Mamdani fuzzy inference
- Takagi-Sugeno fuzzy inference.

In this proposed methodology, the Mamdani-type fuzzy inference engine is used with three triangular membership functions with two input variables (current & voltage) and one output variable. The triangular membership function is more appropriate, because even a small change in the input magnitude can be identified and corresponding output will be considered for the relaying operation. The linguistic descriptions of input membership functions are I_{LOW}, I_{MED}, I_{HIGH}, V_{LOW}, V_{MED}, V_{HIGH} and output membership functions are TL, TM, and TH. The structure of the fuzzy controller and its fuzzy rules may vary with the type of application.

2.1. DFT-FIS Based Fault Detection and Classification

In this protection scheme, two separate DFT-FIS modules were designed to detect the presence of fault in any of the six phases and to identify the presence of ground in the fault loop in a six-phase transmission line. The DFT-FIS module designed for fault detection in one phase is also applicable for fault detection in other phases. This significantly reduces the complexity and saves a good deal of time compared to another scheme based on ANN [20] which requires a long time for training, fault data set generation and selection of ANN architecture. The same DFT-FIS is used for remaining phase fault identification, thus the total number of fuzzy modules used in this relaying scheme is seven: six DFT-FIS modules for faulty phase detection and one module for ground fault detection. The six-phase currents and voltages measured at one end of the line are processed using Discrete Fourier Transform (DFT) and the fundamental components of each phase currents and voltages obtained after processing are taken as input to the DFT-FIS_1 module for detection of phase faults. Further, for ground fault detection zero sequence currents have been taken as input to the DFT-FIS_2 module. Hence there will be six outputs for faulty-phase detection corresponding to six phases and one output for ground fault detection. Each input has been distributed in three ranges with a triangular membership function: they are LOW, MED, HIGH and the corresponding outputs are TH (1) in the case of fault and TL (0) in the case of No-fault condition. Therefore the fuzzy inference engine will work based on the type of membership function used and its fuzzy rules.

The rules defined for fault phase detection are as follows:

- If current is high (I_{HIGH}) and voltage is low (V_{LOW}) then Trip is high(TH)
- If current is medium (I_{MED}) and voltage is medium (V_{MED}) then Trip is low(TL)
- If current is high (I_{HIGH}) and voltage is high (V_{HIGH}) then Trip is high(TH)
- If current is high (I_{HIGH}) and voltage is medium (V_{MED}) then Trip is high(TH)
- If current is medium (I_{MED}) and voltage is high (I_{HIGH}) then Trip is high(TH)
- If current is medium (I_{MED}) and voltage is low (V_{LOW}) then Trip is high(TH)
- If current is low (I_{LOW}) and voltage is high (V_{HIGH}) then Trip is high(TH)
- If current is low (I_{LOW}) and voltage is medium (V_{MED}) then Trip is high(TH)
- If current is low (I_{LOW}) and voltage is low (V_{LOW}) then Trip is high(TH) The rules defined for identification of ground faults are as follows:
- If zero sequence current is low (I_{LOW}) then Trip is low (TL)
- If zero sequence current is medium (I_{MED}) or high (I_{HIGH}) then Trip is high(TH).

2.2. Proposed Algorithm for Fault detection and Classification of Shunt Fault

The instantaneous voltages and currents were collected from a relaying point at bus_1 with a sampling rate of 1.2 kHz. These voltage and current samples are pre-processed through a second order low-pass butter-worth filter at a pass-band of 480 Hz to eliminate higher order harmonics from the signal and also processed through a DFT (Discrete Fourier Transform) block to get fundamental components of voltage and current. The fundamental voltage and current signals

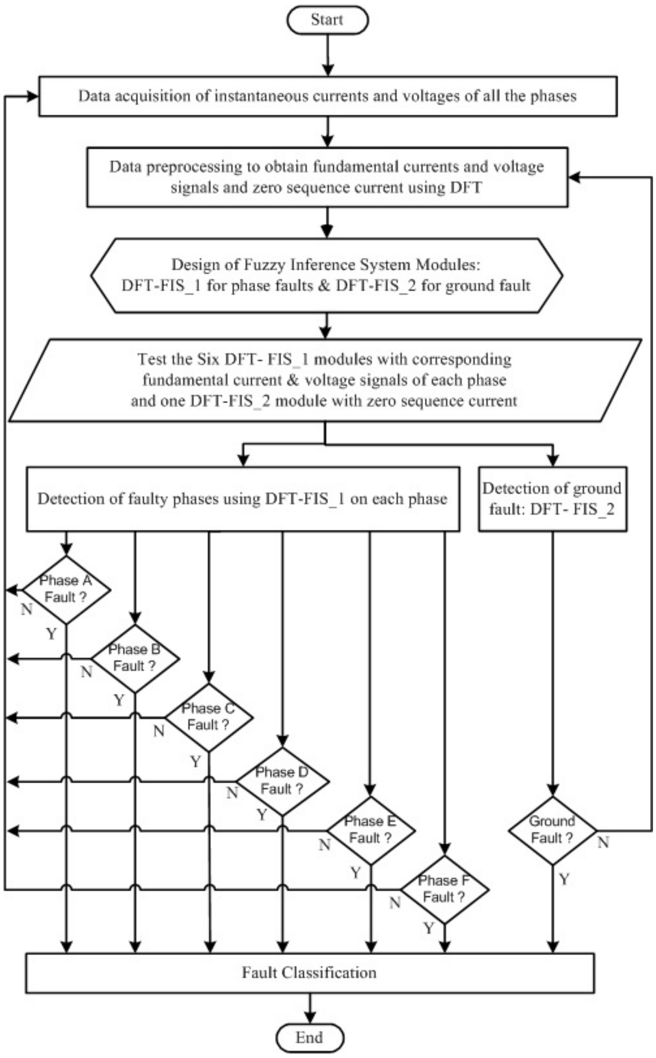

Figure 1: Flow chart of proposed relaying algorithm

are taken as input to the fuzzy inference system (DFT-FIS_1) to detect phase-phase faults and zero sequence currents are taken as input to the fuzzy inference system (DFT-FIS_2) to identify ground faults. The proposed relaying scheme was evaluated for different shunt fault combinations with ground and without ground faults in a six-phase transmission system by varying different fault parameters such as: fault inception angle, fault resistance, and fault location. Fig. 1 illustrates the flow chart of the proposed relaying scheme and the same description was developed.

2.3. Power System Network Under Study

The six-phase transmission system of the Allegheny Power System (APS) was taken as a reference model for various simulation studies. This transmission system (APS) configuration has been widely used by many researchers to conduct various types of simulation studies. This transmission system (APS) had line voltage of 138kV, 60Hz frequency, with a two bus system (McCalmont & Springdale) and a single circuit six-phase transmission line, 68 km in

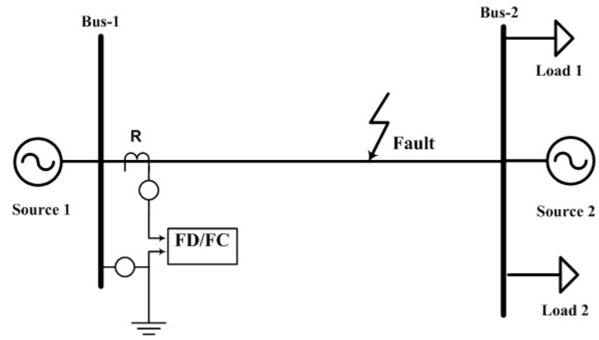

Figure 2: Schematic diagram of a six-phase transmission

length [1, 2]. The short circuit capacity (SCC) and X/R ratio of sources 1 & 2 were taken as 1250 MVA and 10 respectively. Loads 1 & 2 are connected to bus-2 with P=80 MW, Q=60 MVAR each. Fig. 2 illustrates the block diagram of the single circuit six-phase transmission system on which simulation studies were carried out using MATLAB/Simulink software.

3. Results and Discussions

To evaluate the performance of the proposed methodology, extensive simulation studies were carried out for all 23 shunt fault combinations which are significant in six-phase transmission system by varying different fault parameters such as fault resistance (0-110Ω), fault inception angle (0°-360°) and fault location (1-67km). The response of the proposed relaying scheme was verified in a power system network under numerous operating conditions, by varying different power system network parameters such as; voltage (+/-5%), frequency (+/-0.2%), short circuit capacity (+/-250MVA), X/R ratio (10-60), load (+/-50MVA) and load angle (0°-10°) of source-1. The sensitivity and security of the proposed algorithm were also investigated in the case of malfunction of power system components (measuring devices) in extreme situations such as CT saturation. The results and responses of the proposed algorithm were elaborated in following case studies:

3.1. Response of Proposed Relaying Scheme at Boundary Conditions: (Close-In Faults & Remote-End Faults)

Table 1: Response of proposed relaying scheme at close-in faults (L_f =1km, R_f =5Ω & $Ø_f$ =0°)

Fault Type	Fault Detection Time(ms)							
	A	B	C	D	E	F	Gd	RT
ABCDEFG	4.1	2.5	2.5	2.5	2.5	4.1	—	2.5
BCDEFG	—	2.5	2.5	2.5	2.5	4.1	4.1	2.5
ABCDG	5.0	2.5	2.5	3.3	—	—	3.3	2.5
ABDG	4.2	2.5	—	2.5	—	—	6.6	2.5
BFG	—	2.5	—	—	—	4.1	3.3	2.5
EG	—	—	—	—	3.4	—	2.5	2.5
ABCDEF	4.2	2.5	2.5	2.5	2.5	4.1	—	2.5
BCDEF	—	2.5	2.5	3.3	2.5	4.1	—	2.5
ABDF	5.0	3.3	—	5.8	—	5.8	—	3.3
BDF	—	2.5	—	2.5	—	4.1	—	2.5
AD	4.1	—	—	3.3	—	—	—	3.3

Table 2: Response of proposed relaying scheme at remote-end faults (L_f =67km, R_f =100Ω & $\varnothing_f$ =270°)

Fault Type	Fault Detection Time(ms)							
	A	B	C	D	E	F	Gd	RT
ABCDEFG	9.1	7.5	8.3	5.0	5.8	10.0	5.8	5.0
BCDEFG	—	7.5	8.3	5.0	5.8	10.0	6.6	5.0
BCEFG	—	7.5	8.3	—	5.8	10.0	5.0	5.0
BDFG	—	8.3	—	5.8	—	9.1	—	5.8
ADG	10.0	—	—	5.8	—	—	5.0	5.0
DG	—	—	—	5.8	—	—	6.6	5.8
ABCDEF	4.1	6.6	8.3	3.3	5.0	4.1	—	3.3
BCDEF	—	7.5	7.5	3.3	5.0	4.1	—	3.3
CDEF	—	—	5.8	4.1	5.8	4.1	—	4.1
ABF	4.1	7.5	—	—	—	3.3	—	3.3
BF	—	10.0	—	—	—	4.1	—	4.1

It is very important to test the response of the proposed relaying scheme for near-end (close-in) faults since the voltage will be very small (approximately zero) at near to the relaying point and where the conventional relays may fail to operate. Table 1 provides the response of the proposed relaying scheme for different types of shunt faults which occur very near (1km) to the relaying point. Table 2 shows the response of the proposed relaying scheme for far-end (remote-end) faults, which occur far away from the relaying point or remote end of the line/section. In Table 2 it can be observed that fault detection and classification were done for different types of shunt fault combinations at 67 km (approximately 98.5% of the line length) from the relay point where the conventional relays may fail to operate (zone-1 setting of conventional distance relay is 80% of the line/section). Table 1 & 2 illustrate the performance of the proposed algorithm for Phase B-C-D-E-F-Ground fault whereas the relay operation time was 2.5 ms for close-in fault and 5.0 ms for remote-end fault conditions. The relay operation time for detection/classification of all shunt fault combinations is within one-cycle time (16.67 ms) only. Therefore the results of both cases (close-in & remote-end faults) show the capability of the proposed relaying algorithm for detection and classification of shunt faults in a six-phase transmission system without any malfunction.

3.2. Response of Proposed Relaying Scheme at Different Fault Locations

The effectiveness of the proposed relaying scheme has been validated for different shunt fault combinations by varying fault location from 1 km to 67 km from the relay location by assuming fault inception angle and fault resistances with 135°, 30Ω respectively. It can be observed from the results of Table 3 that the effectiveness of the proposed algorithm has no impact on variation of the fault location and the fault detection and classification of shunt faults were also done within one-cycle time.

3.3. Response of Proposed Relaying Scheme at Different Fault Resistances

In general, phase to ground faults may occur with or without fault resistance and this fault resistance is caused by arcs and tower grounding. Mostly, this fault resistance is in the range of 10-20Ω but it varies to very much higher values in some cases such as a live conductor resting on high-resistance ground (sand or rock). With high fault resistances, the fault current flow at the relaying point is very small compared to other fault conditions and it may lead to mal-operation of the relay. Therefore it is very important to investigate the impact of fault resistance on the proposed relaying algorithm, where the selectivity and reliability are more concerned in the relaying scheme. In spite of this, different types of shunt faults were considered for the purpose of evaluating the effectiveness of the proposed protection algorithm by varying fault resistance from 1-110Ω. Table 4 sets out the results of DFT-FIS based fault detection and classification of phase-A-B-C-D-E-F-Ground fault at 60km distance from the relaying point with R_f = 110Ω, $\varnothing_f$ = 45° and the relay operation time was 6.2 ms. The results prove the ability of the proposed relaying algorithm to detect/classify shunt faults within one-cycle time (16.67 ms) at different fault resistances.

3.4. Response of Proposed Relaying Scheme at Different Fault Inception Angle

The fault inception angle is the most vital parameter where the conventional relays mal-function due to the presence of the DC component in the fault current. Moreover, the influence of the fault inception angle is more significant at zero degrees ($\varnothing_f$ =0°). It is very important to examine the impact of the fault inception angle on the proposed relaying algorithm. In this context, different types of shunt fault combinations were simulated by varying the fault inception angle from 0° to 360° at 45 km distance from the relay location though keeping fault resistance constant (R_f =80Ω). The results of Table 5 show that the influence of variation of the fault inception angle (specifically for DC offset current at $\varnothing_f$ = 0°) on the proposed relaying algorithm was not considerable and the response of relay operation time is less than one-cycle time (<16.67ms) for all shunt faults.

3.5. Response of Proposed Relaying Scheme at CT Saturation Condition

It is very important to consider the DC effect when measuring the high amount of fault currents, since it may lead to saturation of the current transformer. Due to the saturation of the current transformer, the corresponding protection relay will experience overreach. In order to evaluate the effect of CT saturation on the proposed relaying scheme, extensive simulation studies were carried out at 1km distance from the relay location. To replicate the CT saturation effect, a saturable transformer of prototypical model was considered as the current transformer at the relaying point by assuming the fault inception angle, fault resistance as $\varnothing_f$ = 0°, R_f =0Ω. In this context, Fig.3 illustrates a unique shunt fault combination of phase F-to-Ground fault and the relay operation time was 4.1ms. Table 11 presents the response of the proposed relaying scheme in the case of CT saturation condition for different types of shunt fault combinations. However, the fault detection and classification were done within one-cycle time thus, it is more suitable for protection of a six-phase transmission system.

Table 3: Response of proposed relaying scheme at different fault locations (R_f =30Ω & $Ø_f$ =135°)

Fault Type		Fault Detection Time(ms)							
	L_f (km)	A	B	C	D	E	F	Gd	RT
ABCDEFG	1	6.2	3.7	3.7	2.8	2.8	6.2	—	2.8
BCDEFG	10	—	3.7	3.2	2.8	2.8	7.0	2.8	2.8
ABCDG	20	7.0	3.7	4.5	2.8	—	—	2.8	2.8
ABDG	30	7.0	3.7	—	2.8	—	—	3.7	2.8
CDG	40	—	—	—	3.7	—	—	2.8	2.8
CG	50	—	—	5.3	—	—	—	4.5	4.5
ABCDEF	60	8.7	4.5	5.3	2.8	3.7	8.7	—	2.8
BCDEF	67	—	4.5	5.3	3.7	3.7	8.7	—	3.7
ABDF	1	8.7	3.7	—	2.8	—	4.5	—	2.8
BDF	10	—	3.7	—	2.8	—	6.2	—	2.8
AD	20	7.0	—	—	4.5	—	—	—	4.5

Table 4: Response of proposed relaying scheme at different fault resistances (L_f =60km & $Ø_f$ =45°)

Fault Type		Fault Detection Time(ms)							
	R_f (Ω)	A	B	C	D	E	F	Gd	RT
ABCDEFG	110	6.2	8.7	7.9	6.4	7.0	6.2	—	6.2
BCDEFG	100	—	7.9	7.9	7.0	7.0	6.2	5.4	5.4
BCEFG	90	—	7.0	7.0	—	7.9	6.2	4.5	4.5
BDFG	80	—	5.4	—	7.0	—	7.0	—	5.4
ADG	70	5.4	—	—	7.9	—	—	3.7	3.7
AG	60	5.4	—	—	—	—	—	3.7	3.7
ABCDEF	50	5.4	7.0	3.7	6.2	7.9	5.4	—	3.7
BCDEF	40	—	3.7	3.7	5.4	7.0	5.4	—	3.7
ABCD	30	4.5	7.0	3.7	8.7	—	—	—	3.7
ABF	20	4.5	3.7	—	—	—	3.7	—	3.7
BF	10	—	3.7	—	—	3.7	3.7	—	3.7

Table 5: Response of proposed relaying scheme at different fault inception angles (R_f =80Ω & L_f =45km)

Fault Type		Fault Detection Time(ms)							
	$Ø_f$ (Deg)	A	B	C	D	E	F	Gd	RT
ABCDEFG	0	6.6	4.1	4.2	7.5	6.6	6.6	—	4.1
BCDEFG	45	—	4.5	4.5	6.2	7.0	5.4	4.5	4.5
ABDFG	90	4.9	7.4	—	4.9	—	4.9	4.1	4.1
ABFG	135	7.8	5.3	—	—	—	7.8	4.5	4.5
BFG	180	—	4.1	—	—	—	6.6	3.2	3.2
BG	225	—	7.0	—	—	—	—	2.8	2.8
ABCDEF	270	9.1	6.6	7.5	4.1	5.0	9.1	—	4.1
BCDEF	315	—	5.4	5.4	3.7	3.7	9.5	—	3.7
BCEF	360	—	3.3	4.1	—	11.6	12.4	—	3.3
ABD	0	14	4.1	—	9.1	—	—	—	4.1
BC	45	—	4.5	4.5	—	—	—	—	4.1

Table 6: Response of proposed relaying scheme for variation in supply voltage and frequency (L_f =35km, R_f =20Ω & $Ø_f$ =60°)

Fault Type	Power System Parameter		Fault Detection Time(ms)							
	V_S (kV)	F (Hz)	A	B	C	D	E	F	Gd	RT
ABCDEFG	131.1	60	3.8	6.3	3.7	4.7	5.5	3.8	—	3.7
BCDEFG	134.5	60	—	3.8	3.8	4.7	5.5	3.8	3.8	3.8
ABDFG	138.0	60	3.8	6.3	—	4.7	—	3.8	2.2	2.2
ABFG	141.4	60	3.8	3.8	—	—	—	3.0	3.0	3.0
BFG	144.9	60	—	3.0	—	—	—	3.0	4.7	3.0
FG	138.0	59.88	—	—	—	—	—	3.8	3.8	3.8
ABCDEF	138.0	59.92	3.8	6.3	3.0	4.7	6.3	3.8	—	3.0
BCDEF	138.0	59.97	—	3.8	3.8	4.7	5.5	3.8	—	3.8
BCEF	138.0	60.02	—	3.8	3.0	—	9.7	5.5	—	3.0
ABD	138.0	60.07	4.7	6.3	—	7.2	—	—	—	4.7
BC	138.0	60.12	—	3.0	3.0	—	—	—	—	3.0

Table 7: Response of proposed relaying scheme for variation in SCC (MVA) and X/R ratio (L_f =25km, R_f =15Ω & $Ø_f$ =90°)

Fault Type	Power System Parameter		Fault Detection Time(ms)							
	SCC (MVA)	X/R (Ratio)	A	B	C	D	E	F	Gd	RT
ABCDEFG	1250	60	3.3	5.8	6.6	3.3	4.1	3.3	—	3.3
ABCDEG	1250	50	3.3	5.8	6.6	3.3	4.1	—	4.1	3.3
BCEFG	1250	40	—	5.8	5.8	—	4.1	3.3	3.3	3.3
BDFG	1250	30	—	5.8	—	3.3	—	3.3	—	3.3
ADG	1250	20	3.3	—	—	4.1	—	—	3.3	3.3
AG	1000	10	4.1	—	—	—	—	—	3.3	3.3
ABCDEF	1100	10	4.1	5.8	6.8	3.3	4.1	4.1	—	3.3
ABCDE	1200	10	3.3	5.8	6.6	3.3	3.3	—	—	3.3
ABCD	1300	10	4.1	4.9	10.8	4.1	—	—	—	4.1
ABF	1400	10	3.3	5.8	—	—	—	3.3	—	3.3
BF	1500	10	—	7.4	—	—	—	3.3	—	3.3

Table 8: Response of proposed relaying scheme for variation in load angle and load-1&2 (L_f =50km, R_f =40Ω & $Ø_f$ =180°)

Fault Type	Power System Parameter		Fault Detection Time(ms)							
	$\nabla\delta^0$(Deg)	S_{load}(MVA)	A	B	C	D	E	F	Gd	R_T
BG	0	150	—	4.9	—	—	—	—	4.1	4.1
BFG	1	160	—	4.1	—	—	—	6.6	4.9	4.1
ABDG	2	170	6.6	4.1	—	9.1	—	—	5.7	4.1
ABCDG	3	180	5.7	4.1	4.1	9.1	—	—	7.4	4.1
BCDEFG	4	190	—	3.2	4.1	7.4	4.1	6.6	7.4	3.2
ABCDEFG	5	200	5.7	3.2	3.2	6.6	4.1	5.7	—	3.2
ABCDEF	6	210	6.6	3.2	3.2	4.9	3.2	6.6	—	3.2
BCDEF	7	220	—	3.2	3.2	4.1	3.2	5.7	—	3.2
ABDF	8	230	10.7	3.2	—	6.6	—	7.4	—	3.2
BDF	9	240	—	2.4	—	2.4	—	4.9	—	2.4
AD	10	250	4.9	—	—	4.9	—	—	—	4.9

Table 9: Response of proposed relaying scheme for phase- ground faults at different sampling rate (L_f =55km, R_f =200Ω ,$Ø_f$=300°)

Fault Type	Sampling Rate(kHz)	Fault Detection Time(ms)							
	N_s	A	B	C	D	E	F	Gd	RT
AG	2.4	10.7	0	0	0	0	0	9.8	9.8
ADG	2.4	11.1	0	0	8.6	0	0	5.3	5.3
BFG	2.4	0	7.3	0	0	0	14.0	5.7	5.7
BCG	2.4	0	7.3	7.3	0	0	0	0	7.3
BDFG	2.4	0	7.3	0	8.2	0	11.5	0	7.3
ABFG	2.4	10.3	7.8	0	0	0	13.6	7.8	7.8
ABDG	5.0	9.8	7.4	0	5.4	0	0	6.0	5.4
BCEFG	5.0	0	6.8	7.2	0	4.6	10.4	3.0	3.0
ABDFG	5.0	9.6	7.6	0	5.0	0	9.8	9.0	5.0
ABCDG	5.0	9.6	7.2	6.8	6.0	0	0	3.8	3.8
BCDEFG	5.0	0	7.0	7.0	4.8	4.4	10.0	9.4	4.4
ABCDEFG	5.0	9.4	7.0	7.0	4.8	4.4	10.0	0	4.4

Table 10: Response of proposed relaying scheme for phase- phase faults at different sampling rate (L_f =10km, R_f =50Ω ,$Ø_f$ =225°)

Fault Type	Sampling Rate(kHz)	Fault Detection Time(ms)							
	N_s	A	B	C	D	E	F	Gd	RT
AD	1.0	8.5	0	0	8.5	0	0	0	8.5
BF	1.0	0	2.5	0	0	0	3.5	0	2.5
BC	1.0	0	2.5	4.5	0	0	0	0	2.5
BDF	1.0	0	2.5	0	4.5	0	3.5	0	2.5
ABF	1.0	3.5	3.5	0	0	0	2.5	0	2.5
ABD	1.0	5.5	6.5	0	6.5	0	0	0	5.5
BCEF	1.2	0	2.5	2.5	0	8.5	8.5	0	2.5
ABDF	1.2	7.0	7.8	0	4.5	0	4.5	0	4.5
ABCD	1.2	7.0	7.8	4.5	5.3	0	0	0	4.5
BCDEF	1.2	0	2.8	2.8	4.5	6.1	3.6	0	2.8
ABCDEF	1.2	3.6	3.6	2.8	4.5	6.1	3.6	0	2.8

Table 11: Response of proposed relaying scheme at CT saturation condition (L_f =1km, R_f =0Ω & $Ø_f$ =0°)

Fault Type	Fault Detection Time(ms)							
	A	B	C	D	E	F	Gd	RT
ABCDEFG	2.5	2.5	2.5	3.3	2.5	4.2	—	2.5
BCDEFG	—	2.5	2.5	3.3	2.5	4.1	4.1	2.5
ABDFG	5.0	2.5	—	3.3	—	5.0	4.1	2.5
ABFG	4.1	2.5	—	—	—	4.1	3.3	2.5
BFG	—	2.5	—	—	—	4.1	3.3	2.5
FG	—	—	—	—	—	4.1	4.1	4.1
ABCDEF	2.5	2.5	2.5	3.3	2.5	4.1	—	2.5
BCDEF	—	2.5	2.5	3.3	2.5	4.1	—	2.5
BCEF	—	2.5	2.5	—	3.4	4.1	—	2.5
ABD	5.0	2.5	—	2.5	—	—	—	2.5
BC	—	2.5	2.5	—	—	—	—	2.5

3.6. Response of Proposed Relaying Scheme Under various Operating Condition

Table 6 demonstrates the performance of the proposed protection scheme at numerous operating conditions of power system network by varying transmission system voltage in a range of +/- 5% and frequency in a range of +/- 0.2% as per the grid code further keeping the fault parameters as perpetual (L_f =35km,R_f =20Ω & $Ø_f$ =60°). The results from Table 6 confirm the efficacy of the proposed relaying scheme for detection and classification of all shunt fault combinations and the relay operates within one-cycle time for both cases. To validate the performance of the proposed relaying scheme at unique operating conditions of the power system network by varying the source1 parameters such as; short circuit capacity (SCC), X/R ratio in a range of +/-250MVA and (10-60) respectively. Table 7 exhibits the response of the proposed relaying algorithm for detection and classification of different shunt fault combinations by assuming corresponding fault parameters as L_f = 25km, R_f = 15Ω & $Ø_f$ = 90° and relay operates within one-cycle time for both cases. Fig.4 illustrates the Phase-B to F fault at short circuit capacity (SCC) =1500MVA & X/R ratio =10 thus relay operation time is 3.3ms. It is also very important to assess the performance of the proposed relaying scheme at vital operating conditions through a change in load angle from 0°-10° and change in load-1&2 in a range of +/-50MVA. Table 9 shows the response of the proposed relaying scheme for different shunt fault combinations at vital operating conditions by presuming fault parameters as L_f =50km, R_f =40Ω & $Ø_f$ = 180°.

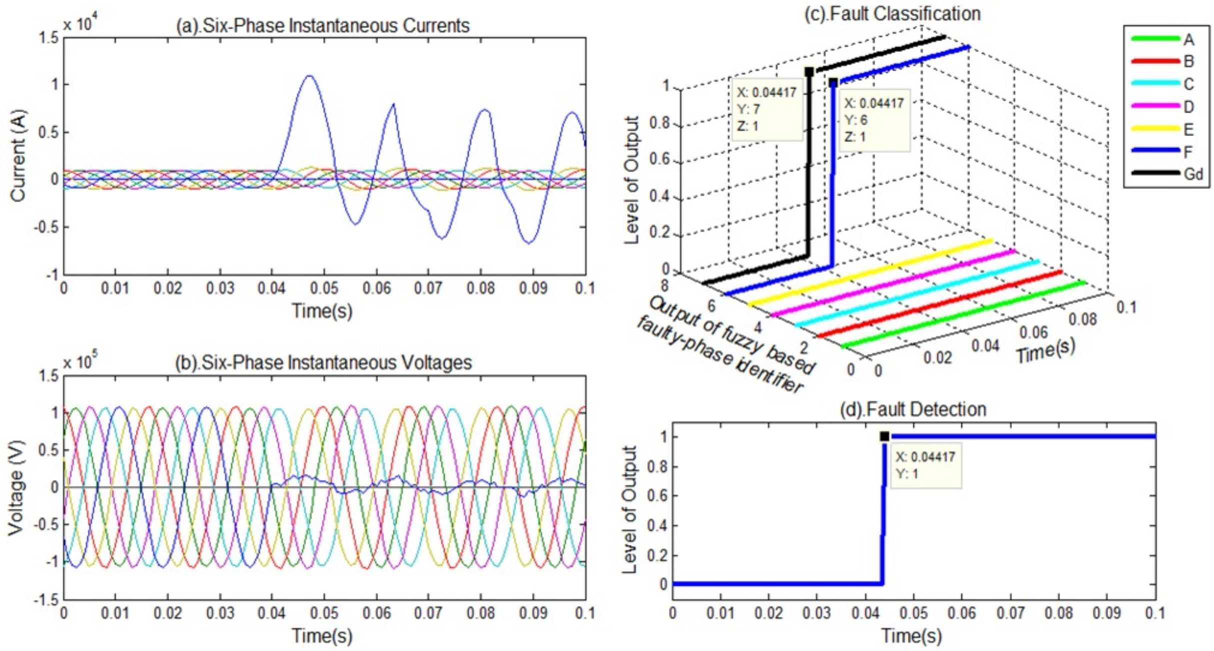

Figure 3: DFT_FIS based fault detection/classification for Phase-F to Ground fault at CT saturation condition (L_f =1km, R_f =0Ω & $Ø_f$ =0°): (a) Six-phase instantaneous currents (b) Six-phase instantaneous voltages (c) Fault classification (d) Fault detection

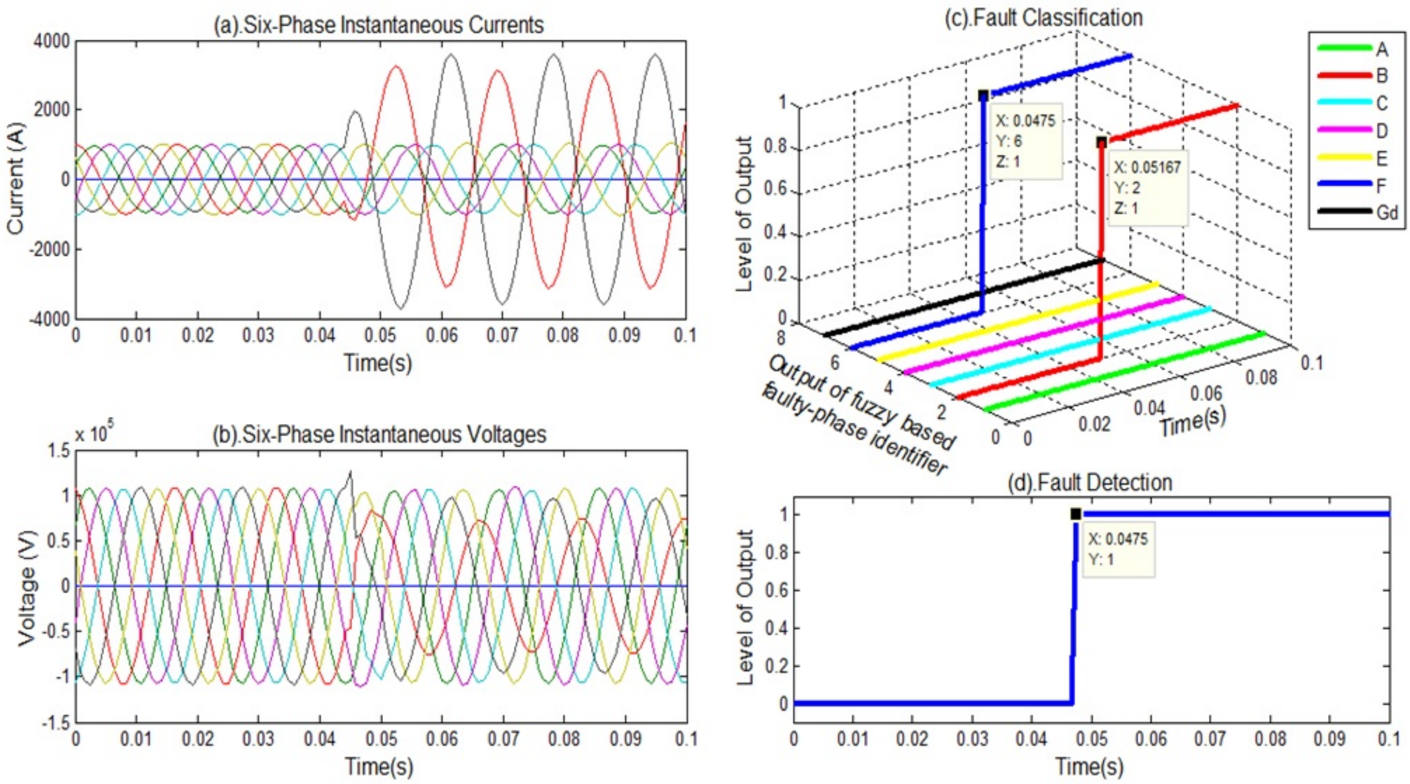

Figure 4: DFT_FIS based fault detection and classification for Phase B-to-F fault at SCC=1500MVA & X/R ratio=10 (L_f =25km, R_f =15Ω & $Ø_f$ =90°): (a) Six-phase instantaneous currents (b) Six-phase instantaneous voltages (c) Fault classification (d) Fault detection

3.7. Response of Proposed Relaying Scheme at Different Sampling Rate

It is very important to evaluate the influence of sampling frequency on the performance of the proposed scheme in fault detection and classification, because collection and process of data samples leads to quick and reliable operation of the protective relay. So the impact of sampling rate was evaluated with various sampling frequencies such as; 1.0 kHz, 1.2 kHz, 2.4 kHz and 5.0 kHz which are sampling frequencies generally found in commercial digital fault recorders used by researchers and protection engineers [24,27]. Table 10 depicts the response of the proposed relaying scheme for detection/classification of phase-to-ground faults (L_f = 55km, R_f =200Ω & $Ø_f$ =300°) and Table 11 depicts the response of the proposed relaying scheme for phase-to-phase faults (L_f =10 km, R_f =50Ω & $Ø_f$ =225°).

3.8. Performance Evaluation of Proposed Relaying Scheme for Detection/Classification of Shunt Faults

To obtain the overall performance of the proposed relaying algorithm and its ability with faulty-phase discrimination an assessment was made using different performance evaluation metrics. The percentage of accuracy was illustrated in Fig.5 for different types of shunt fault combinations. Extensive simulation studies were performed in a six-phase transmission system; moreover, a total of 120 fault events were simulated out of 66 phase to ground faults and 54 phase to phase faults. In relation to Table 12 the mean accuracy of the proposed relaying scheme was reported as 98.02%. In Table 12 the sensitivity of the proposed scheme represents the true positive rate (TPR), showing the ability of the proposed relaying algorithm in detection and classification of shunt faults and true positive rate and showing the rate of fault tripping when the system is at fault condition so that the relaying algorithm is properly discriminating the faulty condition. Specificity (False Positive Rate=1-Specificity) shows the rate of false tripping of the relaying algorithm in a transmission system. The minimum false positive rate shows the efficacy of the relaying algorithm in discrimination of healthy condition and it avoids false tripping when the system is at No-fault condition. The precision of the relaying algorithm demonstrates the range of operation of relay in terms of repeatability and reproducibility in the case of fault detection/classification. F score gives the weighted average or harmonic mean of precision and sensitivity; the best case indicates its value reaches "1" and the worst case indicates its value reaches "0". It is also worth mentioning the computer system configuration when performing soft computing techniques, because the processor speed and internal memory capacity of the CPU play an important role in various simulation studies. In this paper all the simulation studies were carried out on an Intel® Core(TM) i5-3230M CPU@2.60GHz processor with 4GB RAM, 64-bit Windows 8 operating system and the modeling/simulation of the power system network was done using MATLAB 2013a software. The processing speed of the CPU also improves the simulation time for the detection/classification of faults by capturing and preprocessing data samples without a delay in time and enhances the efficacy of the proposed relaying algorithm without showing any malfunction.

4. Conclusion

In this paper the proposed relaying scheme based on the DFT-FIS approach for detection and classification of shunt faults in a six-phase transmission system was employed successfully. To evaluate the efficacy of the relaying scheme, extensive simulation studies were performed at numerous operating conditions with variation in a number of fault parameters such as fault resistance, fault location, and fault inception angle. The results obtained in this paper demonstrate that the proposed scheme properly detected/classified all shunt fault combinations within one-cycle time from the inception of fault. It shows however 98.02% mean accuracy for detection/classification of all distinctive shunt faults. In addition, a total number of 120 fault events were tested on 98.5% of the line length accurately. The simulation results and its interpretations show the reliability and adaptability of the proposed relaying scheme in a situation where the normal existing three-phase relaying scheme is unfeasible for a six-phase transmission system. It is not affected by variation in fault parameters at vital operating conditions of the power system network.

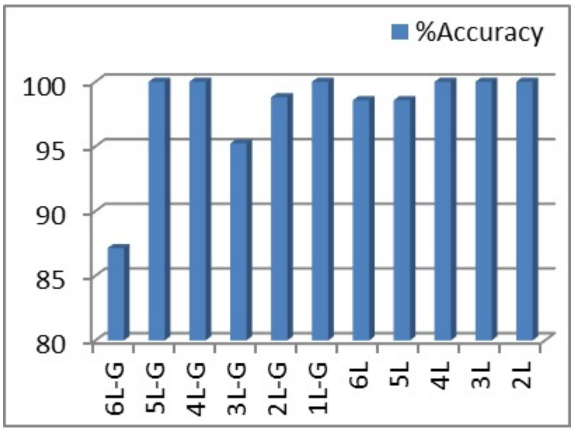

Figure 5: Percentage of accuracy of the proposed relaying algorithm for detection/classification of different shunt fault combinations

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Table 12: Performance evaluation metrics of proposed relaying scheme for detection/classification of shunt fault combinations

Fault Type	%Accuracy	Sensitivity	Specificity	Precision	F score
6L-G	87.14	0.87	0.00	1.000	0.931
5L-G	100.0	1.00	1.00	1.000	1.000
4L-G	100.0	1.00	1.00	1.000	1.000
3L-G	95.23	0.91	1.00	1.000	0.956
2L-G	98.80	0.97	1.00	1.000	0.985
1L-G	100.0	1.00	1.00	1.000	1.000
6L	98.57	1.00	0.90	0.983	0.991
5L	98.57	1.00	0.95	0.980	0.990
4L	100.0	1.00	1.00	1.000	1.000
3L	100.0	1.00	1.00	1.000	1.000
2L	100.0	1.00	1.00	1.000	1.000

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