A Study of Comparative Fault Analysis & Fault Time in a UPFC Integrated Wind Farm

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Abstract: This paper discusses the study of fault analysis and fault time in a Unified Power Flow Controller (UPFC) integrated wind farm. Here wind farm is included in UPFC compensated transmission line to verify the fault detection analysis & fault time using the DWT (Discrete wavelet transform). The importance of using DWT algorithm is that it can detect the fault at any variation of the line parameter. The fault time using this scheme is very accurate, effective as it involves less carrier communication and the fault time remains within 20msec. The scheme works when the line is faulted and it extracts the phase current from the current transformer placed at both sending and receiving end of the transmission line. The most versatile signal processing of DWT algorithm is used here to obtain the spectral energy (SE) of each phase at sending and receiving end of the line. Then the differential spectral energy (DSE) is computed with the difference of SE evaluated at each end of the line. The DSE value of each phase is the major factor for deciding the existance of shunt fault pattern. The simulation result shows the performance of the scheme with varying wind speed. The simulation results are compared to the conventional scheme to justify the accuracy of the proposed scheme. Different parameter variations are considered such as repeated phase fault in case of double circuit line of circuit-1 & circuit-2, UPFC and wind speed variation, CT saturation, fault resistance.

Keywords UPFC, Wind-farm, Fault Detection (FD), Fault Time (FT).

1. Introduction

Flexible AC Transmission (FACT's) device is used in the existing transmission line for controlling the power (real and reactive power), enhancing the transmission capacity & stabilty of the line. The UPFC is one of the most versatile FACT's controller [1] used many parts of the world. The advantage of using this is it can control and protect the line in both shunt and series control mode. The shunt mode of of UPFC [2,3] operates in STATCOM (Static Synchronous compensator) mode and series mode which operates in SSSC mode (Static Synchronous series controller). It's operation and fault analysis is really a challenging topic for the researcher. Though it provides the instantaneous control and self-governing mechanism to compensate the power, voltage magnitude and angle to protect the damage of the equipment and enhances the transmission capacity of the transmission line. However during the transient/ fault condition the fault analysis is a major challenging concern for the power system engineer. The conventional approach of travelling wave theory [4] is suggested but the difficulty of using this scheme is that of requirement of bulky hardware setup. It is costly affair and requires regular maintenance for subsequent tripping signal. ANN and fuzzy logic are also considerd [5,6] but this scheme fails to provide accurate results because of inaccurate phasor input data and large numbers of neurons involvement. A heuristic approach like fuzzy logic [7] is also suggested but it is not effective as the processor requires to filter out the fundamental frequency signal from high frequency contaminated signal. Therefore the scheme unable to compute the fault analysis and detect the fault & response time in an accurate manner. Kalman filter approach [8] is suggested but it's accuracy is not high enough to measure the fault analysis at critical fault condition and it also involves large numbers of unlike filters. The machines intelligence method like SVM [8, 9] and DT [10] are also addressed for fault classification analysis. However, it is highly susceptible when SNR becomes more than 30 dB which produces the error and computational burden. However the above methods are incapable to address the problem if the UPFC compensated transmission line is integred to wind farm. As the wind power has been coming with the largest contribution to the power generation throughout the world. The major challenging issue is that how the fault analysis can be carried out at different wind speed without disturbing the wind farm. The literature survey of different induction genrator is carried out diffently. The most significant induction generator is the double fed induction generator (DFIG). Before a decade the SCIG (squirrel cage Induction generator) is widely used in the wind fed integrated network [11] by means of QSTDC algorithm (quasi static time domain simulation). However it is unable to provide sufficient fault detection at the critical parameter variation of the line. The transmission line protection in an offshore wind farm is illustrated where wind speed is more predominant compared to onshore and the wind speed varies throughout the day [12]. The FCIP (fault component integrated power) is discussed [13] but it fails to address the fault detection in many extreme case of the operation of the line.

The most predominant based DFIG (Double fed Induction Generator) is popularly employed as it provides better performance analysis [14] as compared to Single Fed IG. The generator power output is always nonlinear in nature to the wind speed, in that case the wind speed is beyond the rated speed as a result of which the wind farm sometimes may not contribute to supply the power to grid, in this situation the wind farm is disconnected from the grid. To improve the performance and maintain the power quality the placement and sizing of DFIG based wind farm integrated with most versatile FACT's device (UPFC) is important to improve the voltage stability [15]. The above-mentioned schemes are also outlined in various works of literature w.r.t detection, classification and response time. However, the few works of literature discusses the protection of a UPFC transmission line which makes the scheme more challenging. The strong motivation behind this scheme is to develop an algorithm which detects the different shunt fault at an earliest possible of time with the variation of UPFC compensated line parameter such as multi-phase fault in double circuit line, UPFC operating condition (series voltage magnitude and angle control), UPFC location and wind speed variation including wind farm simulation are validated to verify the performance of the scheme. The proposed scheme discusses the comparative study of fault and fault time in a Unified Power Flow Controller (UPFC) integrated wind farm. Here the process starts with retrieving the fault current from the current transformer placed at both sending end and receiving end of the UPFC compensated transmission line. Then the spectral energy (SE) which is the square of the fundamental current of each phase is obtained at sending end and receiving end of the line using DWT and DFT algorithm. The differential spectral energy (DSE) of each phase is computed from the difference of SE obtained at sending end and receiving end of the line. This DSE is the key factor for deciding the fault pattern. This scheme is devided into five different section. Section-1 covers the introduction, section-2 discusses signal processing part of DWT algorithm, Section-3 discusses the methodology, Section-4 describes the results. Section-5 is the discussion part and Section-6 is the conclusion part of the proposed scheme.

2. Signal Processing of DWT

The DWT [16, 17] signal processing algorithm has been used in various application of detection process as it is adative in nature and by the help of windowing technique its scale is stressed/compressed to obtain different frequency resolution. As it involves the large number of filter banks like H.P and L.P filters. This filters divide the input frequency signal into high-frequency (HF) and low-frequency (LF) signal which is discussed in the Mallat's algorithm [17].The performance based on variable-sized, windowing technique. WT analysis occasionally compresses/de-noise the signal lacking significant degradation of performance. It decomposes the signal into the number of basic function set called as wavelets. Mother wavelet [18-21] can be decomposed into the various types of scaled & shifted versions to obtain prototype wavelets. Appropriate mother wavelet selection [19] is also a very important issue for fault signal analysis. For better accuracy Daubechies mother wavelet is choosen at it has many filter coefficients like db4, db6, db8 and db10 etc. However, db4 mother wavelet [20,21] is the most appropriate for fault analysis study.

2.1 *The Modified Continuous WT (CWT)*

The modified CWT is expressed using Eq. (1),

[illegible] (1)

The * denotes complex conjugate, where a_0 and b_0 are the modified dilation and translation parameter. The discretization step of dilation and translation are denoted as k and l. The modified parameter can be expressed using Eq. (2)

$$a = a_0^k \text{ and } b = l b_0 a_0^k \quad (2)$$

Mother wavelet can be expressed using Eq. (3)

[illegible] (3)

Modified wavelet is expressed using Eq. (4) & (5)

[illegible] (4)

[illegible] (5)

DWT coefficients can be written after discretization using Eq. (6)

$$W_\psi f(k,l) = a_0^{-k/2} \int_{-\infty} f(t)\psi(a_0^{-k}t - lb_0)dt \quad (6)$$

2.2 *Three Stage Wavelet Decomposition Tree*

The faulty signals are extracted and processed using wavelet transform [20,21]. In this 1 kHz sampling frequency (20 samples/cycle) is considered in the 50 Hz system. The decomposition of the signal is achieved using 3 different stage of levels. In 1st level of decomposition, a1 (0–500Hz) and d1 (500–1kHz), in 2nd levela2 (0–250Hz) and d2 (250Hz–500Hz) and in 3rda3 (0–125Hz) and d3 (125–250Hz). Therefore, a3 contains fundamental (50 Hz) current component. The 3rdlevel, reconstructed signal (A3) of individual phase current (A, B, C) are obtained from a3 of the concerned phases at both ends of the substation. Fundamental r.ms current signals are obtained from the reconstructed current signal using the DFT approach. The Amplitude and phase of fundamental current are evaluated using Eq. (7)

$$I(k) = |I(k)| \tan^{-1}\left(\frac{\operatorname{Im} I(k)}{\operatorname{Re} I(k)}\right) = A + JB \qquad (7)$$

Where Im and Re denotes imaginary (B) and real value (A) of fundamental current *I(k)*. The amplitude of phase current using Eq. (8)

$$|I(k)| = \sqrt{(A^2 + B^2)} \qquad (8)$$

Spectral Energy of phase current is expressed using Eq. (9)

$$SE_P = |I(k)|^2 \qquad (9)$$

Where P is the phase current

The DSE_P is calculated from the difference of spectral energy evaluated from B-S and B-4 using Eq. (10)

$$DSE_P = SE_{s.e,P} - SE_{r.e,P} \qquad (10)$$

2. Protection scheme including wind farm

The wind farm protection scheme is depicted in Fig. 1(a). Different fault points are provided at sending end bus (B-S), bus B3 and receiving end bus B-4, where wind farm is installed. DFIG wind farm of 25kV, 100MW (2MW X 50 unit) is connected to 400kV substation at receiving end. It is connected through a step up transformer and the rotor is Induction type wound rotor generator. It is designed with the help of IGBT-based AC/DC/AC PWM converter. The stator winding connects to grid of frequency 50 Hz and rotor is connected to the variable frequency via AC/DC/AC converter.UPFC is integrated at mid point of transmission line of 400km length. The UPFC of 100-MVA consists of two 48-pulse VSC and linked side to side of DC capacitors of 2500µF. The UPFC is of two two different mode of connection. STATCOM is connected through a shunt transformer of 15kV/500kV and SSSC through a series transformer (15kV/22kV).UPFC modelling and its controllers are referred from the literature [22]. Fig. 1(a) illustrates the UPFC compensated transmission line which is modelled with the help of Simulink tool box. The UPFC tool box is modified in that dual mode control STATCOM and SSSC mode parameter is changed according to our respective substation voltage, frequency and short circuit ratio. Two substation of same rating of voltage, frequency and short circuit ratio but different phase angle is placed at both end of the transmission line. Bus bar, Fault box are placed according to the circuit diagram only the parameter is modified. Three fault box is placed both at sending end and receiving end of the line and another at mid part of the transmission line for simulation study of different shunt fault using MATLAB code to verify the performance of the fault detection in the compensated line. V_s and V_r are the voltages of substation-1 & substation-2 respectively. The power angle δ (in degree) is the phase difference of V_s and V_r. The voltage, frequency and short circuit level (SCL) of sending & receiving end are equal (V_S =Vr =500 kV, f=50 Hz & SCL=1500MVA) and δ=δs-δr, where, δs=30^0 and δr=0^0 are the phase angle of V_s and V_r .The proposed relaying flow chart algorithm is shown in Fig. 1(b). In this the current signals at both ends of the line are extracted from CT's and fed to signal processing unit of ADC converter which is the combination of DWT and DFT processor. The third level reconstructed current signal (A3) of both end substations are obtained from approximate coefficient (a3) by applying DWT. The fundamental phasors are obtained from A3 by applying DFT using Eq. (7). SE of each phase current at both ends of the transmission line are calculated from fundamental current magnitude using Eq. (9). The DSE_p (DSE of p-phase) is calculated by taking the difference of SE_P obtained from both end of the line applying Eq. (10).The DSE_P are compared with the set threshold (Th) values for fault detection purposes. If the DSE is more than the Th value, then the fault exists within 50% distance from sending bus (B-S). If the DSE is less than Th value, then the fault exists within 50% distance from receiving end bus (B-4). If the fault is external zone then DSE value is neither more or less than the Th value. The UPFC compensated line is divided into four parts of impedance section i.e, Z_{l1}, Z_{l2}, Z_{l3} *and* Z_{l4} respectively. Z_1=0.01537+j0.2783Ώ/km and Z_0= 0.04612+j0.8341142Ώ/km are the positive and zero sequence impedance. The fault detection analysis are tested using mentioned below parameter.

- Fault resistance: Rf
- Fault inception angle: FIA
- Reversing the power flow
- Source Impedance: SI
- Multi-phase fault
- UPFC variation

The current signals are extracted from both ends of CT's and fed to ADC converter. The third level approximate coefficient (a3) is computed by applying DWT and fundamental phasors are extracted by applying DFT using Eq. (7). Spectral Energy [23-25] of each phase current is calculated from fundamental current magnitude using Eq. (9). The DSE_p (DSE of p-phase) is calculated by taking the difference of SE_P obtained from both end of the line using Eq. (10).Then the DSE_P of each phase current is compared with the set threshold. Ten different types of symmetrical & unsymmetrical shunt fault cases are considered.

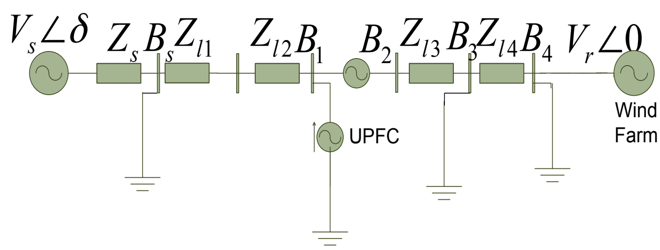

Fig. 1(a). UPFC compensated wind farm integrated transmission line .

3.1 *The studied wind farm power system Network Used*

The simulation results are conducted in 'R2014AMatlab/Simulink' platform at 0.3 seconds (600th sample) of 50Hz base system. This scheme performs based on an assumption of the extracted signal which is time synchronized through GPS. The latency is very less (in micro second) and produces no error in the computation process [26-28].

The following mentioned below cases gives the information of fault detection in comparison to a threshold (Th)

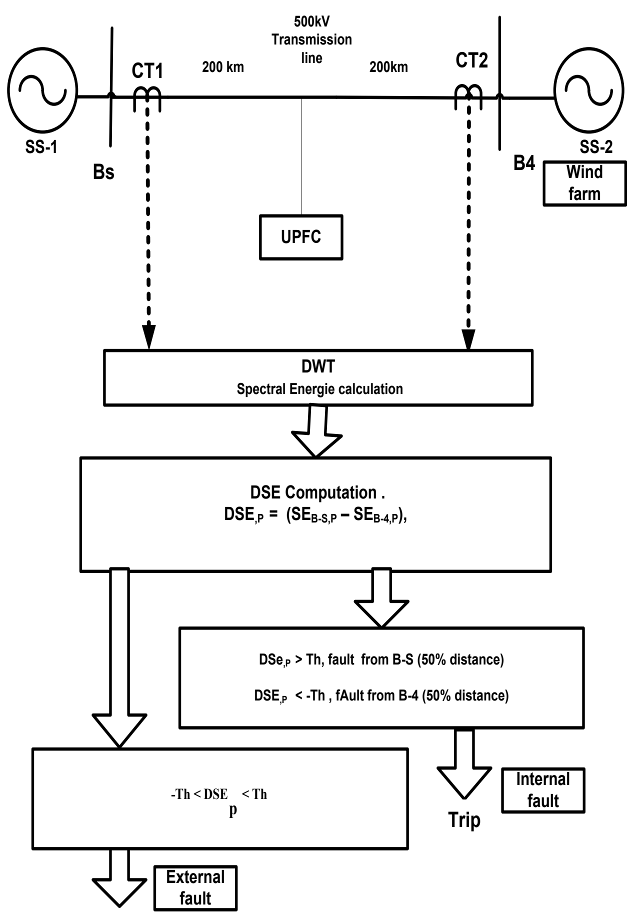

Fig. 1(b). Flow chart of the relaying Scheme

- *DSE_P>Th*: The fault is in p-phase within 50% distance from B-S (before UPFC)
- *DSE_P<-Th*: The fault is in p-phase within 50% distance from B-4 (after UPFC)
- *(-Th< DSE_P< Th):* External fault

The threshold value. Th is choosen to justify the fault in the system and its value is selected after conducting different types of fault simulation analysis and it is found that *Th*=±40. The sign signifies the fault is before UPFC location or the fault is after the UPFC location (+ve sign, fault is before UPFC, i.e, the fault is located within 50% distance from B-S) and (–ve sign, fault is after UPFC, i.e, the fault is located 50% distance from B-4). The Th value is selected after a large number of simulations conducted.

4. Simulation Result and Discussion

MATLAB 2014A is used for UPFC modelling in simulink.

Fig. 2. Shows the A-G fault current at B-S & at B-4 respectively.

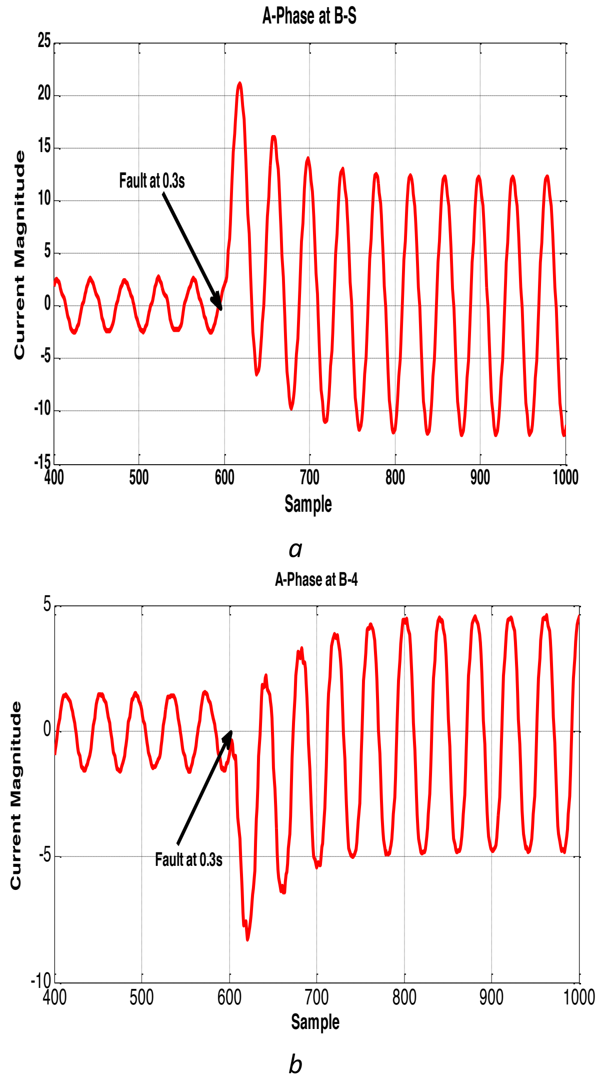

Fig. 2 (a) A-G fault at B-S (**b**) A-G fault at B-4.

4.1 *Rf variation*

The fault resistance, Rf is more significant factor for fault analysis. During the fault it is noticed that Rf value varies from 1Ω to100Ω. Fig. 3 depicts a comparison of A-phase fault at Rf values such as 1Ω, 50Ω & 100Ω. All these crosses Th at 9ms time (less than 20ms) and detects A phase fault. In the table presented below two fault conditions are considered. Fault Condition-1: 100km from B-S (before UPFC). Fault Condition-2: 300km from B-S (after UPFC). In two cases of fault condition it shows that faulty phase current has higher DSE value (more than Th) compared to other phase current. In all table, faulty DSE phase values are denoted as bold numerical which signifies the detection of faulty phase. In addition to this FC signifies the corresponding fault classification. Table 1 presents the DSE Variation at Rf=1Ω.

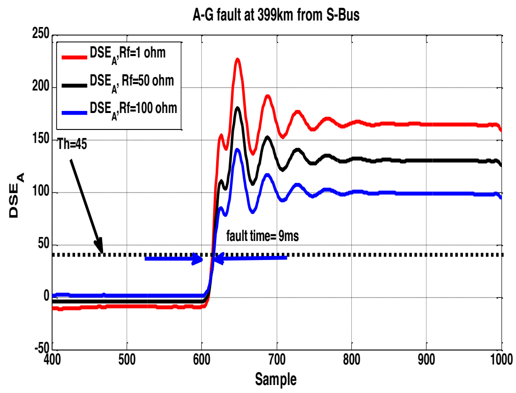

Fig. 3 Rf =1Ω, 50Ω, 100Ω, A-phase fault, 399km from B-S

4.2 *FIA variation*

The performance of fault detection & response time is considered by varying FIA value such as FIA=0^0, 45^0 and 90^0. Fig. 4(a) depicts the comparison of BC phase fault, 150km from B-S at different FIA=45^0 and 90^0 and the fault time remains maximum 12ms. Fig. 4(b) depicts the fault in CA phase-G, 100km from B-S at FIA= 45^0 and 90^0. The fault time is minimum 12ms in FIA= 45 degree as compared to 16ms in 90 degree. Therefore it is decided that, the system is working fine.

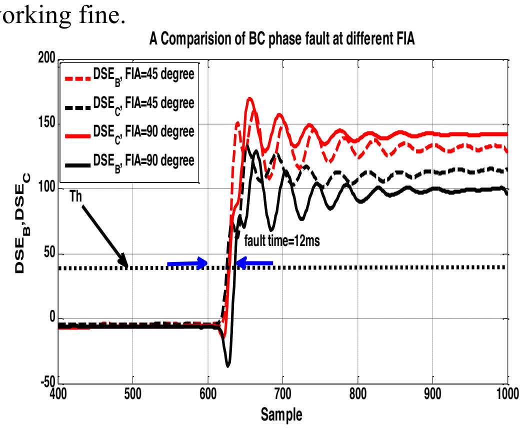

Fig. 4(a). A comparison of BC phase fault, 150km from S-Bus (B-S) at FIA= 45^0 and 90^0

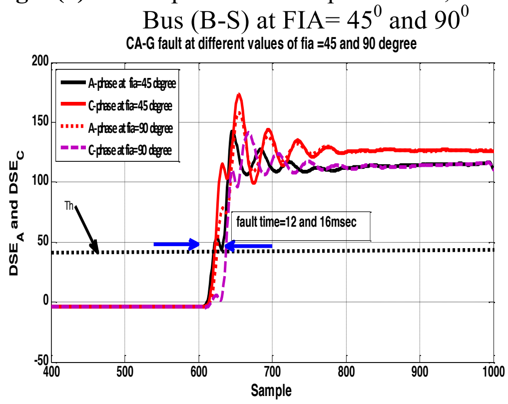

Fig. 4(b). CA phase G fault, 100km from S-Bus (B-S), FIA=45^0 & 90^0

Table 2. Presents the comparison of Rf, fault location, power angle and FIA with reference to existing scheme of SE based ST [29] and DWT [30]. In all such situation of parameter variation, the scheme works successfully to detect the fault.

4.3 *SI variation*

To verify potent of the scheme further, the variation of SI (source impedance) is also taken into consideration. Therefore, it is essential to study the SI influence at different conditions and simulated by increasing the SI value from 0 to 50% increase of NSI. Fig. 5 depicts A phase G fault has occurred at 350km (after UPFC) from B-S in three different condition such as NSI, 30% increase of NSI and 30% decrease of NSI. From all the above case of discussion, it reveals that the fault is detected in 9ms to detect the fault.

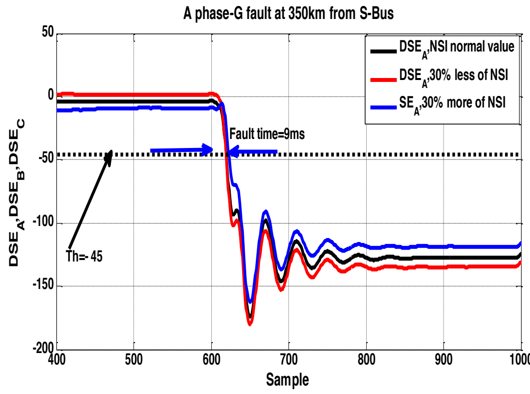

Fig. 5 A-phase-G fault at 350km from S-bus (B-S), SI=Normal SI value, 30% increase and 30% decrease of NSI

4.4 *Revere flow variation*

This is an important issue for fault analysis study. Here the phase angle of sending (δ_1) and receiving end (δ_2) are interchanged. To validate the simulations, the number of cases are conducted for system analysis of the scheme. Fig. 6(a) depicts A phase fault, 100km from bus B-S, Rf=1Ω, 5Ω0 and 100Ω. From this figure, the fault time are recorded for different Rf in 10ms, 12ms and 18ms for 1Ω, 50Ω and 100Ω respectively. In all the cases, the fault time remains within 20ms time.

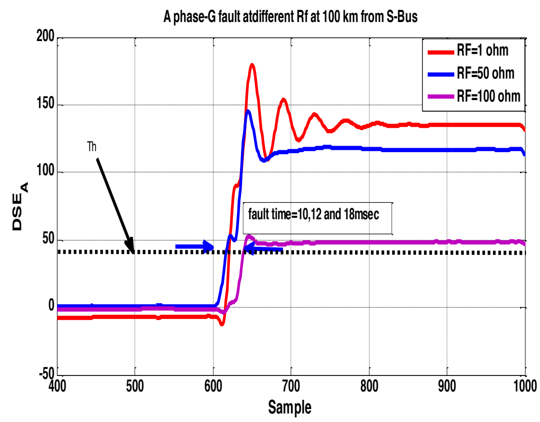

Fig. 6. A phase G fault, phase reversal considering different Rf value.

Thus it is seen that irrespective of fault location in the transmission line for both normal flow and reverse power flow, the scheme is working fine.

4.5 *Effect of UPFC variation*

The UPFC operating condition voltage magnitude (V_{se}) and angle (θ_{se}) are the two important parameter while considering different fault cases. The performance of the scheme is also affected in case of the change in V_{se} and θ_{se}. Few cases of simulation study are prepared to study the behavior of the scheme. The performance of the scheme is presented in Table 3 and Table 4 respectively. The Fig. 7(a) depicts ABC phase-G fault, 150km from B-S, Vse=8% increase in normal Vse. It is clearly seen that all 3 phase takes fault time in 13ms. In a similar manner, Fig. 7(b) an ABC phase fault, 300km from bus B-S for Vse=12% and θ_{se}= 60^0. It detects the fault in 15ms by the variation of both magnitude and voltage angle. It is further noticed that in such cases of variation, the fault time is required to detect the fault in 10ms. Therefore it is concluded that the irrespective variation of Vse and θ_{se}, the scheme works fine to detect the fault in 20ms time which is illustrated in Table 4 and Table 5 respectively.

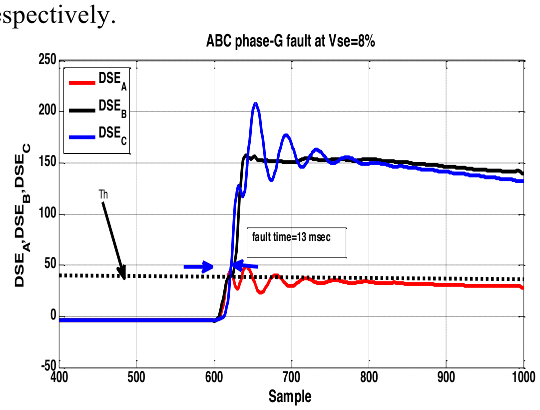

Fig. 7(a). Fault in ABC phase, 150km from bus B-S with UPFC variation, Vse=8% increase in Vse.

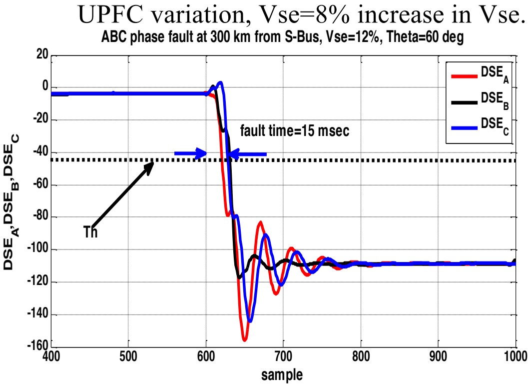

Fig. 7(b). ABC phase fault, 300km from B-S, UPFC variation, Vse=12% increase in Vse and θse=60^0

4.6 *Effect of Multi-phase fault*

Multi-phase fault means fault occurs in three different phases at the same location of fault but at different time span. Here, a special fault case in A, B and C has occurred at the 300km distance from B-S but at different time span (Phase A fault is occurred in 0.3s, Phase B in 0.4s and phase C in 0.5s in a sequence manner). The fault detection and fault time are depicted in Fig. 8. The simulation is processed in same manner one after the other for three different time span 0.3s, 0.4s and 0.5s separately. However, it detects the fault in three different time such as phase A fault is detected in 10ms, phase B fault in 12ms and phase C fault in 14ms respectively.

Therefore the scheme works satisfactorily in case of multi-phase fault analysis.

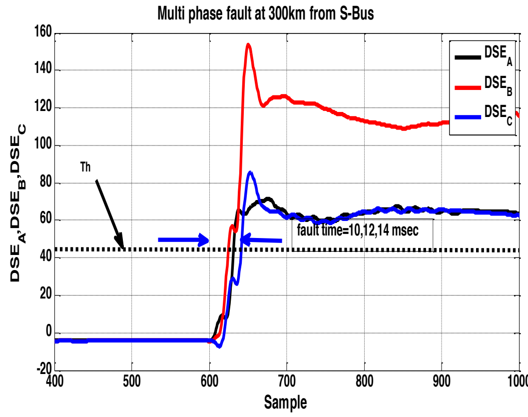

Fig. 8. Multi-phase fault at 300km from B-S (A, B and C-phase at 0.3s, 0.4s and 0.5s respectively)

4.7 *Effect of UPFC Location*

The effect of three different UPFC position is also discussed for fault detection and fault time calculation. The UPFC is positioned at three different places in the 400km transmission line such as 100km, 200km and 300km from bus B-S. Fig. 9 depicts the A phase fault time takes 9ms for UPFC position at 100km, 10ms for UPFC position at 200km and 14ms at 300km. In all such cases, the fault is detected but it takes more time when the UPFC is at 300km. However, the preferred location of UPFC is at mid-point compensated line.

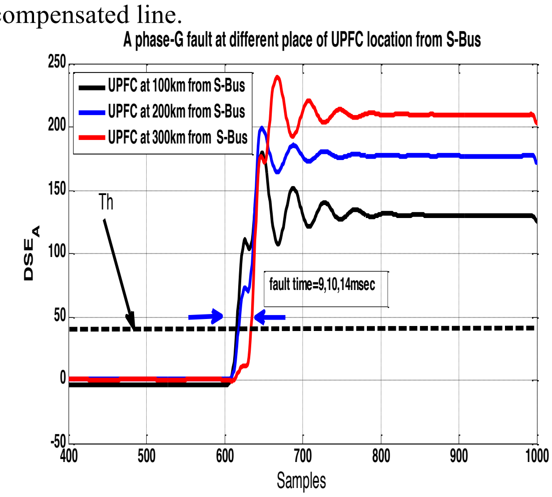

Fig. 9. A-phase G fault at different UPFC location from B-S

4.8 *Effect of UPFC including wind farm*

Effect of wind farm in a UPFC integrated line is an important factor for study of fault analysis. A comparison of different shunt fault analysis are presented in Table 6 to assess the performance indices of UPFC line including wind farm. It is noticed that fault analysis performance is higher in case of including wind farm. The indices here are considered as dependability,

Table 1. DSE of phase current for fault detection & fault time before and after UPFC

Fault	Condition-1: 100km from B-S (before UPFC), Rf=1Ω, Th=40			Condition-2: 300km from B-S(after UPFC), Rf=1Ω, Th= - 40			Classification	Fault time in ms
	A	B	C	A	B	C		<1cycle (20ms)
A-G	**129.69**	34.87	-3.41	**-127**	-43.8	10.55	AG	<20ms
ABG	**126.56**	**54.95**	20.01	**-83**	**-135**	-27.3	ABG	<20ms
B-C	24.28	**125.6**	**113.45**	-28	**-84.2**	**-134**	BC	<20ms
ABC	**129.177**	**129.10**	**129.5**	**-108**	**-108**	**-108**	ABC	<20ms

security and yield. Dependability is the rate of success operation of the relay. Security is to access the degree of incorrect operation of the relay. Yield signifies the exact prediction of fault cases.

Dependability=Σ (Number of Faults predicted) /Σ (Number of Actual fault case)

Security= Σ (Number of false faults predicted)/ Σ (Number of Actual false faults)

Yield= Σ (Number of true faults predicted) / Σ (Number of Actual true faults)

5. Discussion

The fault detection analysis and fault time calculation are proposed considering UPFC integrated line including wind farm. Using the signal processing technique of DWT the fault detection and fault time of different types of phase fault are noted in the simulation figure & table. The fault detection and the fault time of the relay are discussed separately by varying different parameter condition in the above result section. The fault time in each of the different fault cases are presented and further it is compared to the existing literature [29,30] from Table 1 to Table 5. The most significant conclusion drawn here is that the DSE attains positive *Th=40*, in case of fault before UPFC and *Th=-40*, after UPFC (beyond 50% distance from UPFC). The scheme operates satisfactory under different line parameters such as Rf (0-100Ω) which is relatively high, SI (0-50% increase of Normal SI), FIA (0-90 degree), reverse power flow, effect of UPFC operating condition, multiphase fault and effect of UPFC location which is the extreme parameter side of strong and weak system including wind farm. The fault analysis are validated to perform total protection of compensated line. Table 1 presents the performance comparisons of fault before UPFC and after UPFC and its fault time under different variation of parameters of line are considered. It is seen that in all such cases the fault time remains less than 1 cycle (20ms). Table 2 presents the performance comparison of fault time under different parameters like power angle, fault location, FIA and R_f value and compared with the existing approach [29, 30]. It reveals that the fault time remains less than one cycle. Table 3 presents the performance of fault time by varying the operating condition of UPFC (θ_{se} from 0^0 to 90^0 & Vse=5%) before and after the UPFC position and it is observed that the fault time remains less than 20ms and Table 4 shows that performance of varying Vse from 0 to 10% increase of normal Vse at $\theta_{se}=0^0$ with Rf=1Ω, FIA=0^0, NSI. It is noticed that in all the case of UPFC operating condition the fault time remains less than 1 cycle. Table 5 presents a comparison of the proposed DSE scheme with the other existing scheme.

The Differential current scheme (DCS) is the amplitude of phase current which is discussed in Eq. 8. It works to detect the fault but sometimes it fails to detect because of not significant magnitude of faulty phase current, which can't be detected whereas the proposed DSE scheme is the highest accuracy to detect the fault as seen from the Eq. 9 and Eq. 10 as it is the square of the amplitude phase current. So the DSE of any phase current (A, B or C) is more predominant to detect the fault as compared to DCS. Table 6 discusses the performance analysis of UPFC compensated transmission line.

The proposed DSE scheme is unaffected under change in SI, reverse power flow, high Rf value, multi-circuit fault and UPFC parameter variation etc. as compared to existing scheme. Table 6 presents the comparison of proposed DSE scheme with existing scheme including wind-farm.

Table 2. Performance comparison of fault time under different parameters in transmission line.

Fault	Rf in Ω	Location of Fault (km)	FIA (degree)	Power angle (degree)	SE based S-T fault time in cycle period [29]	WT based fault time in cycle period [30]	Proposed fault time in cycle
AB	20	30	45	45	1.24	1.54	< 20ms
BC	50	90	60	60	1.24	1.54	< 20ms
CA	100	160	30	45	1.23	1.53	< 20ms
AG	0	20	30	45	1.24	1.54	< 20ms
BG	50	130	60	45	1.24	1.54	< 20ms
CG	100	180	30	60	1.25	1.55	< 20ms

Table 3. Performance of DSE variation and fault time by varying θ_{se} in respect to UPFC Vse=5%

Fault	θ_{se} (deg)	Condition-1: 100km from bus B-S(before UPFC) Rf=1ohm, FIA=0^0 NSI, Vse=5%			Condition-2: 300km from Bus B-S (after UPFC) Rf=1ohm, FIA=0^0 ,NSI, Vse=5%			Fault time in cycle
		A	B	C	A	B	C	
AB-G	0	**121.1**	**115.52**	12.18	**-115.14**	**-116.17**	-13.15	<20ms
B-G	45	12.53	**131.24**	21.23	-12.6	**-113.17**	12.13	<20ms
ABC	60	**121.3**	**114.2**	**117.8**	**-115.2**	**-123.4**	**-115.2**	<20ms
CA- G	90	**116.3**	13.21	**126.12**	**-114.23**	-14.27	**-122.1**	<20ms

Table 4. Performance of DSE variation and fault time by varying V_{se} at $\theta_{se}=0^0$

Types of fault	Vse in % age	Condition-1: 100km from bus B-S (before UPFC) Rf=1ohm FIA=0^0 ,NSI, $\theta_{se}=0^0$			Condition-2: 300km from bus B-S (after UPFC), Rf=1ohm,FIA=0^0 ,NSI, $\theta_{se}=0^0$			Fault time in cycle
		A	B	C	A	B	C	
AB-G	0	**115.4**	**119.28**	13.17	**-116.7**	**-114**	-23.11	<20ms
B-G	5	14.98	**127.4**	8.63	-21.2	**-125**	-2.81	<20ms
ABC	10	**124.7**	**124.14**	**118.52**	**-119.7**	**-113**	**-118.5**	<20ms
CA-G	15	**127.8**	21.12	**124.16**	**-123.4**	-7.02	**-117.3**	<20ms

Table 5. A Comparison of proposed DSE scheme with conventional differential current scheme (DCS) and distance relaying scheme (DRS)

Fault due to effect of parameter	Proposed scheme	DCS	DRS
Rf variation	Works accurately	Not all the time	under /over reach
SI variation	Works accurately	Not all the time	under /over reach
UPFC variation (Vse & θ_{se})	Affected in small change	Affected in large change	under /over reach
Power flow rverseing	Works accurately	Not all the time	Not all time
Multi-phase fault	Works accurately	Not all the time	Not all the time
External fault	Works accurately	Not all the time	Not all the time

Table 6. Comparison of proposed scheme including wind-farm

Different fault case	Dependability		Security		Yield	
	UPFC including Wind farm	UPFC	UPFC including Wind farm	UPFC	UPFC including Wind farm	UPFC
LG	100	100	100	100	100	100
LL	100	100	99	100	99.5	100
LLG	100	100	100	100	100	100
LLL	100	100	98	100	100	100

5. Conclusion

A critical fault detection analysis in a UPFC compensated line including wind farm is proposed. Here the two important DWT and DFT processor is used to detect the fault at any critical stage or extreme condition of line parameter variation such as fault resistance, source impedance, fault inception angle, UPFC operating condition (V_{se} & θ_{se}), UPFC location with wind speed variation in the line. The DSE is the key factor to take the decision of the line if there is a fault in the line or not. The important point in all such critical case studies is that the fault detection time remains less than 1 cycle (20msec). The performance indices of the line such as dependability, security and yield are also considered to verify the reliability, accuracy and performance of the compensated line. From the simulation study it is revealed that the scheme works perfectly including wind farm at different variation of wind speed. Further the scheme is also compared with DCS and DRS scheme. The performance of the line is illustrated and compared with other existing scheme in the respective table. The novelty of the scheme is that for higher detection accuracy and less processing time 'db4' mother wavelet is used. In addition to this it protects overall protection of the line both internal and external zone of the transmission line.

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