Taylor-Kalman-Fourier Filter Based Back-up Protection for Teed-transmission Line

Abhishek Kumar
Master of Technology, EED,
National Institute of Technology
Warangal, India,
kabhishek1@student.nitw.ac.in

Dr. P Suresh Babu
Assistant Professor, EED
National Institute of Technology
Warangal, India,
drpsb79@gmail.com.

N V Phanendra Babu
Research Scholar, EED
National Institute of Technology
Warangal, India,
phanendra229@gmail.com

Saptarshi Roy
Research Scholar, EED
National Institute of Technology Warangal, India,
saptarshi.roy.ju@gmail.com

***Abstract*- In this paper, a back-up protection philosophy based on second order Taylor-Kalman-Fourier (T^2KF) filter is suggested for a multi-terminal transmission network. The measured current and voltage signals at relaying end will be supplied to the proposed T^2KF filter to estimate of the fault section from the relaying point. This algorithm will estimate the fault impedance in presence of in-feeding effect. The proposed method is tested on a teed-transmission network. The results show that this method has identified the faults in backup zones successfully.**

Keywords—Distance protection; in-feeding; Taylor-Kalman; impedance estimation;

I. Introduction

Generally, multi-terminal transmission line is terminated at the bus bar which may consist either generators or loads at its ends [1, 2]. Multi-terminal transmission lines are occasionally tapped without any breaker. The problem with this is that the relay will be either must always be under-reached or over-reached if there was no communication from the remaining ends to the relay end [3]. If there is a load on one line and relay on another line with generation, the fault that would occur on the third line in a teed-transmission network may lead the relay to go under reach due to out feeding. But, if the generator is placed instead of load then the relay will be overreached. This means that if the zone-1of relay is set with in-feed, then it could see faults beyond the second line. So, multi-terminal lines are prone to mal-operate if their backup zones were not set carefully. Previously, A synchronized measurement based algorithm was developed in [4] by measuring both pre and post fault data. Based on high-frequency transients generated during faults, paper [5] has detected faults. Later, authors [6] presented fault detection algorithm for teed-transmission line using the pre and post fault signals from remote ends. Modelling of multi-terminal transmission line to two-terminal line containing fault section is suggested in [7]. It also uses the information from the remaining ends of network. Recently, a Synchrophasor based fault detection of multi-section three-terminal transmission line is developed in [8]. But all these methods have failed in eliminating the decaying D.C. component.

This paper proposes a backup protection scheme for multi-terminal transmission line using T^2KF filter. Unlike the earlier schemes, this filter will effectively reduce the adverse effects caused by the exponentially decaying D.C component in fault current. This filter estimates the instantaneous values of dynamic voltage and current phasors. The phasors finally obtained from the filter will be considered for the estimation of positive sequence impedance to detect the fault. As the algorithm rejects all harmonics as well as D.C offset, its impedance performance is close to that of desired distance relays [9, 10]. This paper considers in-feeding effect throughout the analysis.

The work carried throughout the paper is follows. Section II explains that how the phasor estimation is done using T^2KF. Section III describes the estimation and compensation to the measured impedance. Results are presented in section IV. Finally, section V concludes the work.

II. Phasor Estimation Using T^2KF Filter

In this section, first, the signal is modelled with Taylor approximation [11], and then estimated using Kalman filtering [12].

Let us consider the following signal,

$$x(t) = m(t)\cos\left(2\pi f_1 + \theta(t)\right) \tag{1}$$

Where $m(t)$ is the magnitude and $\Theta(t)$ is phase. Now, by using complex exponential function, the signal can be modelled as,

$$x(t) = \mathrm{Re}\left\{p(t)e^{j2\pi f_1 t}\right\}, \quad -\frac{T}{2} \le t \le \frac{T}{2} \tag{2}$$

Here, $p(t)$ is called dynamic vector. Its value is $m(t)e^{j\Theta(t)}$.

A. Taylor Approximation:

On applying k^{th} order Taylor approximation with center at t_0, the complex function becomes,

$$p_k(t) = p(t_0) + \dot{p}(t_0)(t - t_0) + \ldots + p^{(k)}(t_0)\frac{(t - t_0)^k}{k!},$$

$$t_0 - \frac{T}{2} \le T \le t_0 + \frac{T}{2} \qquad (3)$$

The state transition matrix corresponding with first k derivatives of Taylor approximation is as below:

$$p_k(t) = p(t_0) + \dot{p}(t_0)\tau + \ddot{p}(t_0)2\frac{\tau^2}{2} + \ldots + p^{(k)}(t_0)\frac{\tau^k}{k!}$$

$$\ddot{p}(t) = \dot{p}(t_0) + \ddot{p}(t_0)\tau + \ldots + p^{(k)}(t_0)\frac{\tau^k}{(k-1)!}$$

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$$p_k^{(k)}(t) = p^{(k)}(t_0) \qquad (4)$$

From equations (3) and (4), the state vector can be calculated as

$$p_k(t) = A_K(\tau)p_k(t_0) \qquad (5)$$

Where $\tau = t - t_0$, $p_k(t_0)$ is the state vector, and

$$A_k(t) = \begin{bmatrix} 1 & \tau & \frac{\tau^2}{2!} & . & . & \frac{\tau^k}{k!} \\ & 1 & \tau & . & . & \frac{\tau^{k-1}}{(k\_1)!} \\ & & 1 & . & . & \frac{\tau^{k-2}}{(k\_2)!} \\ & & & . & . & . \\ & & & & & 1 \end{bmatrix} \qquad (6)$$

is a transition matrix. The truncated signal model is given by

$$x_k(t) = \mathrm{Re}\{h^T p_k(t)e^{j2\pi f_1 t}\} = \mathrm{Re}\{h^T R_k(t)\} \qquad (7)$$

Where, $R_k(t)$ is the rotated vector with a value of

$$R_k(t) = A_k(\tau)e^{j2\pi f_1 \tau} R_k(t_0) \qquad (8)$$

obtained from equation (5). And h^T is to extract its first component, means, it is a row vector with 1 as its first element followed by k zeros. If T_s is the sampling period, then

$$t_0 = (n-1)T_s$$

and $t = nT_s$ (9)

The discrete transition between the rotated vectors becomes:

$$R_k(n) = A_k(T_s)\psi_1 R_k(n-1) \qquad (10)$$

Here

$\psi_1 = e^{j\varphi_1}$, and $\varphi_1 = 2\pi f_1 T_s = 2\pi / N_1$

The final discrete state transition equation can be written as

$$\begin{pmatrix} R_k(n) \\ \bar{R}_k(n) \end{pmatrix} = \begin{pmatrix} \psi_1 A_k(T_s) & 0 \\ 0 & \bar{\psi}_1 A_k(T_s) \end{pmatrix} \begin{pmatrix} R_k(n-1) \\ \bar{R}_k(n-1) \end{pmatrix} \qquad (11)$$

Where, $\bar{\psi}_1$, $\bar{R}_k(n)$ are the complex conjugates of ψ_1, $R_k(n)$ respectively. The truncated signal model is

$$x_k(n) = \frac{1}{2}\left(h^T h^T\right)\begin{pmatrix} R_k(n) \\ \bar{R}_k(n) \end{pmatrix} \qquad (12)$$

B. Kalman Filtering

This section develops Kalman filtering [13]. Using this the state vector model is

$$y(n) = Ay(n-1) + \Gamma v(n) \qquad (13)$$

In which the state transition matrix is from (11),

$$\Gamma^T = \left(h^T h^T\right) \qquad (14)$$

And, white Gaussian $v(n)$ is considered to affect only rotated phasor component. The observation model is

$$x(n) = Hy(n) + w(n) \qquad (15)$$

Where $w(n)$ is the additive white Gaussian noise. And finally, we will have $H=(h^T\ h^T)$. The sequence Kalman recursive process can be described as:

1. Time update

a. state prediction

$$\hat{y}^-(n) = A\hat{y}(n-1) \qquad (16)$$

2. Measurement update

a. Kalman gain

$$K(n) = P^-(n)H^T(HP^-(n)H^T + \sigma_w^2)^{-1} \qquad (17)$$

b. *State update*

$$\hat{y}(n) = \hat{y}^-(n) + K(n)(x(n) - H\hat{y}^-(n)) \qquad (18)$$

c. *Posteriori error covariance*

$$P(n) = (I - K(n)H)P^-(n) \qquad (19)$$

Where, σ_v^2 and σ_w^2 are the input and measurement error variances respectively. The initial calculation for the unknown error covariance matrix starts with the conditions $x(0)=0$ and $P(0)=10^9 I$ [14].

III. Estimation of Impedance

Consider the following teed-transmission test system shown in Fig. 1. It consists generators at buses 1 and 4, and a load at bus 5. The relay R at the beginning of the line L23 estimates the impedance. Let us consider a three phase-ground fault is occurred in line L34 at a distance of *x* kms from tapping point 3.

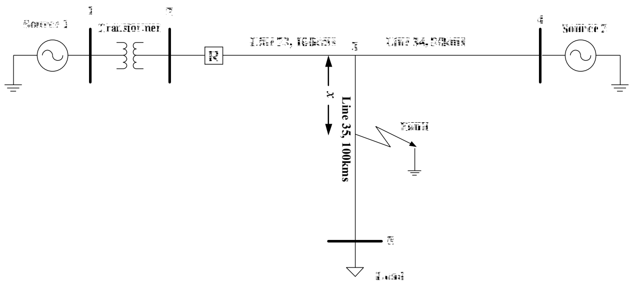

Fig. 1. Teed-transmission test system.

The positive sequence network seen by the relay R for the fault in the section 34 will be modelled as shown in Fig. 2 below:

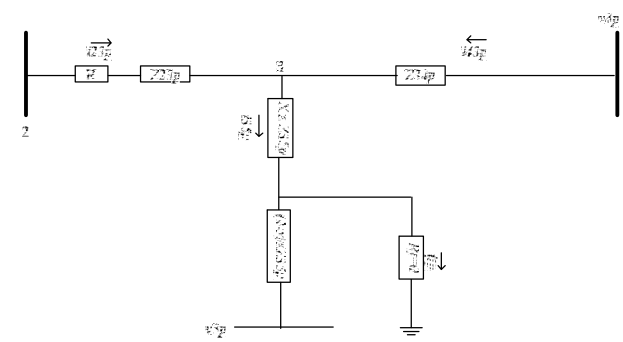

Fig. 2. Positive sequence network

In Fig. 2, Z23p, Z34p and Z35p are the positive sequence impedances of lines L23, L34 and L35. *v2p*, *v4p* and *v5p* are the positive sequence voltages at source, load bus 1 and load bus 2 respectively. The positive sequence voltage seen by relay R is,

$$v2p = z23p \times i23p + xz35p(i23p + i43p) + Rf(i23p + i43p) \tag{19}$$

If the fault resistance is assumed to be zero, then

$$v2p = z23p \times i23 + xz35p(i23p + i43p) \tag{20}$$

The impedance measured by relay R is,

$$z_{1,measured} = z23p + xz35p \times \left(1 + \frac{i43p}{i23p}\right) \tag{21}$$

But the actual impedance is to be:

$$z_{1,actual} = z23p + xz35p \tag{22}$$

So, the compensation has to be done to the impedance measured by relay R, i.e, $z_{1,measured}$. The impedance calculated by compensating the respective measured value is given by,

$$z_{1,calculated} = \left[\frac{z_{1,measured} - z23p}{\left(1 + \dfrac{i43p}{i23p}\right)}\right] + z23p \tag{23}$$

Here, *z23p* is obtained from the system data, *i43p* is the in-feed current whose value is known through the communication between Relaying point and the remote bus 5. This compensation will be done for every sample of impedance estimated from the effective values of voltage and current phasors obtained after Kalman filtering. The flow chart that represents the different stages that are been carried out in this proposed paper is shown in Fig. 3 below.

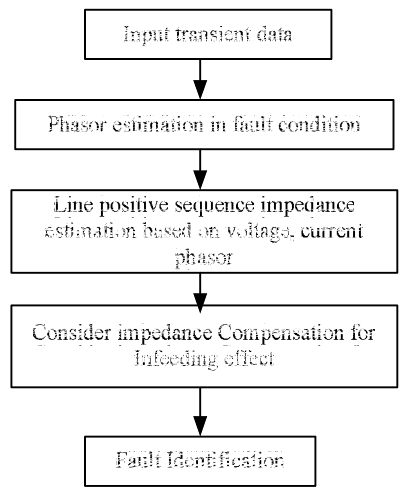

Fig. 3. Flow chart for the proposed methodology

IV. Results and Discussions

The test system is implemented in PSCAD/EMTDC simulation environment. The transient data is imported from this program. A digital second order Butterworth low-pass filter is applied for both voltage and current phasors obtained from PSCAD/EMTDC program. The measurement stage considers sampling rate of 32 samples, for 60 *Hz* system. The performance of the suggested backup protection algorithm is evaluated through the following two cases as discussed below.

Case 1: Permanent 3Φ fault zone-2.

A permanent three phase-ground fault is simulated in zone-2. The fault impedance calculated after estimating voltage and current phasors with T^2 KF technique is shown here below.

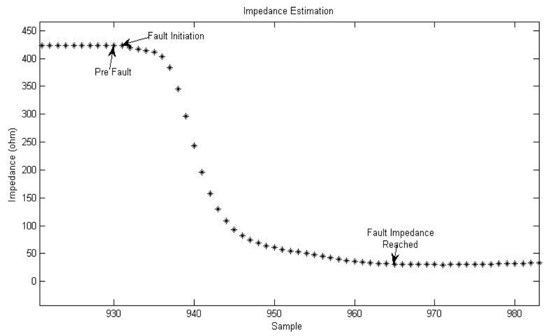

Fig. 4. Impedance for the fault at 90kms in L23

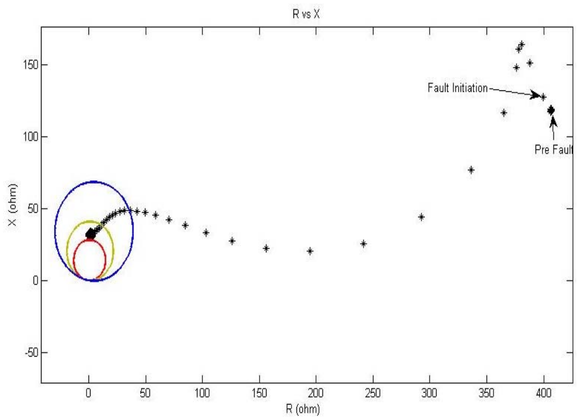

Fig. 5. R-X diagram for the 3Φ fault at 90kms in L23

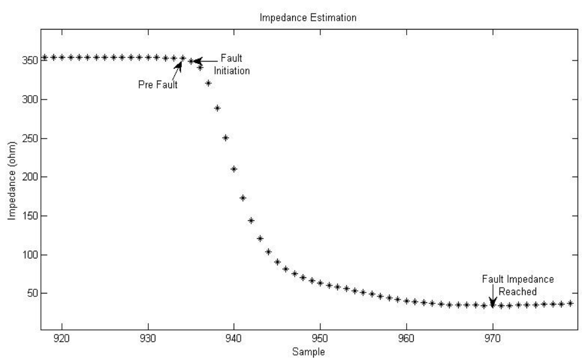

Fig. 6. Impedance for the 3Φ fault at 8kms from 3 in L34, rotor angle 10^0

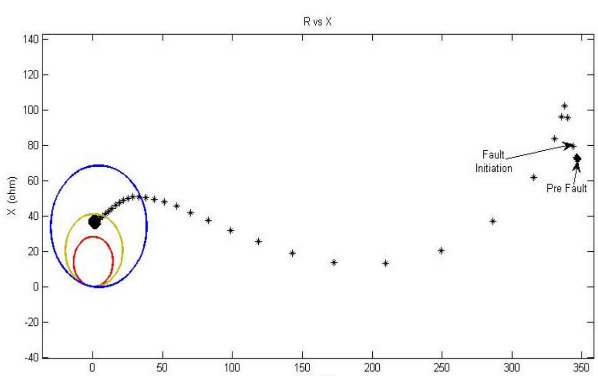

Fig. 7. R-X diagram for the 3Φ fault at 8kms from 3 in L34, rotor angle 10^0

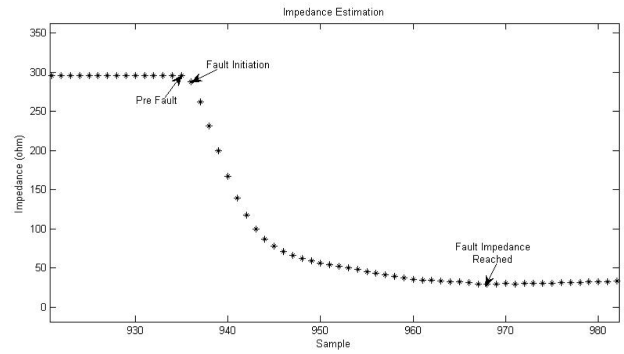

Fig. 8. Impedance for the 3Φ fault at 90kms from 3 in L23, rotor angle 10^0, inception angle 45^0

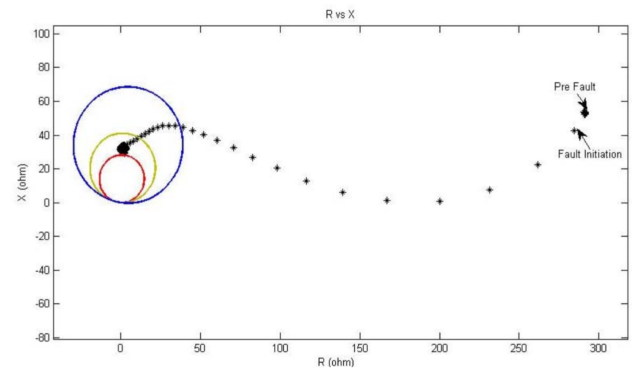

Fig. 9. R-X diagram for the 3Φ fault at 90kms from 3 in L23, rotor angle 10^0, inception angle 45^0

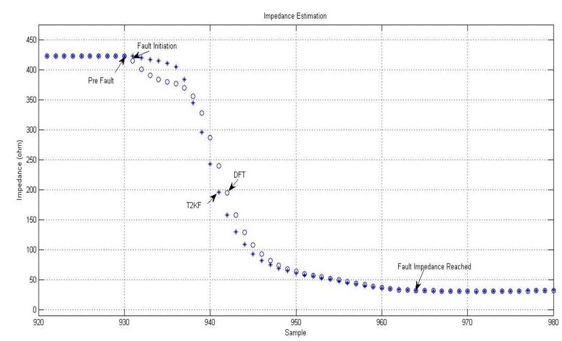

Fig. 10. Impedance comparison for the fault at 90kms in L23 with DFT

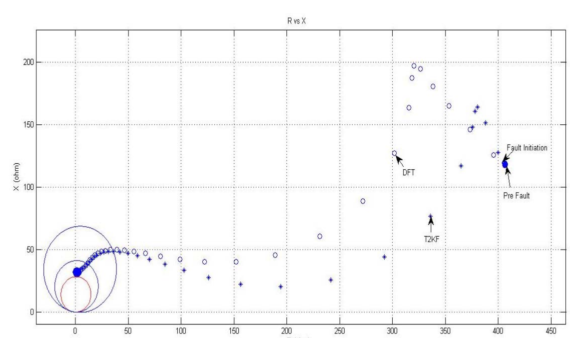

Fig. 11. R-X diagram for the 3Φ fault at 90kms in L23 with DFT

TABLE I. No. of samples taken to detect the fault in zone 2

CASE	samples to reach the zone 3		samples to reach the zone 2	
	DFT	T^2KF	DFT	T^2KF
3 phase fault at 90Km on line 23	21	20	29	27

The results show that, for the zone-2 3Φ fault at 90 kms in L23 from R, this technique converges to the fault impedance 31.8 Ω (the impedance from relay R to fault location) as shown in Fig. 4 and Fig. 6. For this, the algorithm takes 27 samples. Similarly, for another fault in zone-2 (3Φ fault at 8km from 3 in L34), as shown in Fig. 5 and Fig. 7, it takes 31 samples. The number of samples required for this technique to the above two faults are tabulated in Table I. The zone settings of the admittance relay used at R are listed in Table II.

TABLE II. Zone settings of the Distance relay R

Zone	center	Radius
2	1.025+20.585j	20.613
3	4.425+34.2j	34.488

Case 2: Permanent 3Φ fault zone-3.

As shown in Fig. 8 and Fig. 10, this technique takes 20 samples to reach the fault point impedance 48.2 Ω, for the 3Φ fault in zone-3 at 40 kms from 3 in L34. Similarly, for the 3Φ fault in zone-3 at 90 kms from 3 in L35, it takes 29 samples. These results are clearly given in Fig. 9 and Fig. 11. Table III gives the number of samples required to identify zone-3 faults.

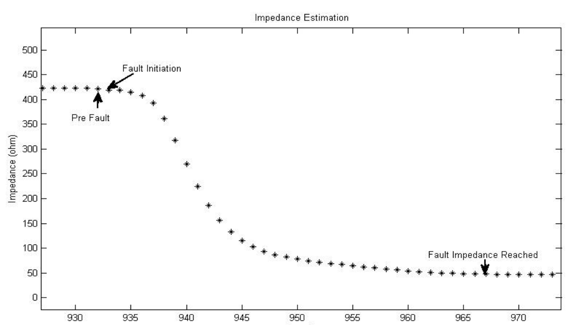

Fig. 12. Impedance for the 3Φ fault at 40 kms from 3 in L34

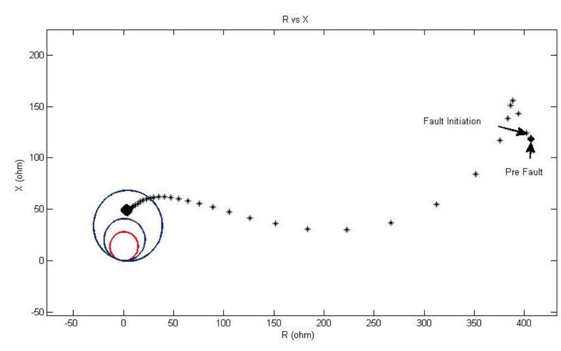

Fig. 13. R-X diagram for the 3Φ fault at 40 kms from 3 in L34

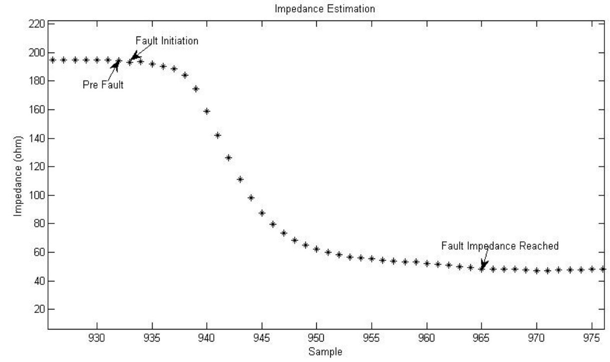

Fig. 14. Impedance for the 3Φ fault at 90 kms from 3 in L35, rotor angle 10^0

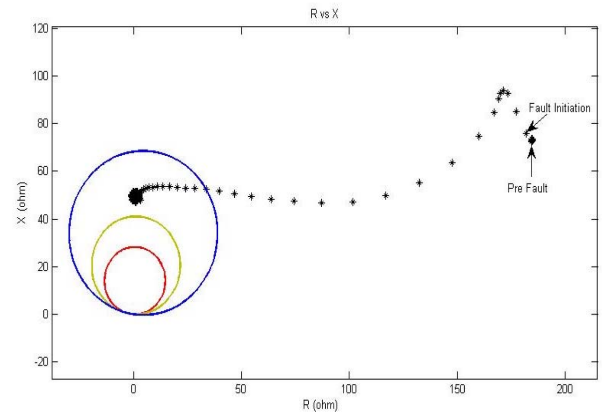

Fig. 15. R-X diagram for the 3Φ fault at 90 kms from 3 in L35, rotor angle 10^0

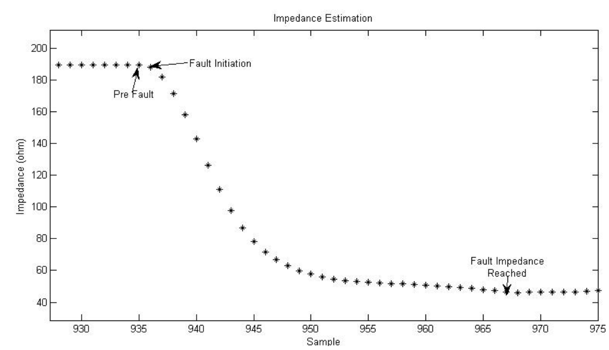

Fig. 16. Impedance for the 3Φ fault at 90 kms from 3 in L35, rotor angle 10^0, inception angle 45^0

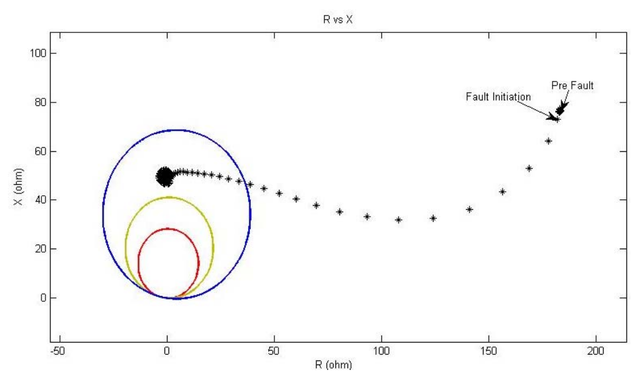

Fig. 17. R-X diagram for the 3Φ fault at 90 kms from 3 in L35, rotor angle 10^0, inception angle 45^0

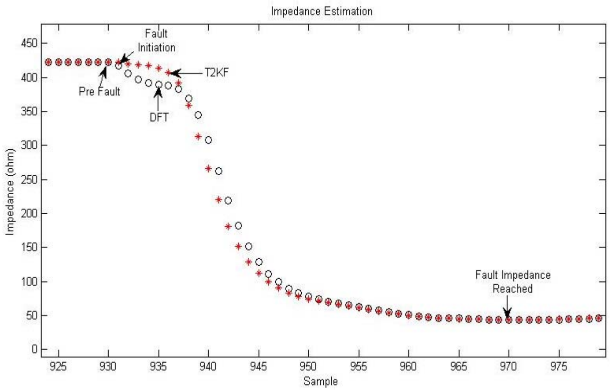

Fig. 18. Impedance comparision for the 3Φ fault at 40 kms in L34 with DFT

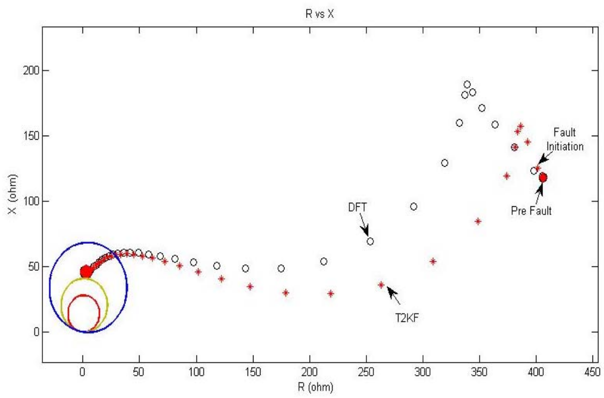

Fig. 19. R-X diagram for the 3Φ fault at 40 kms from 3 in L34 with DFT

TABLE III. No. of samples required to detect the fault in zone 3

CASE	**samples to reach the zone 3**		**samples to reach the zone 2**	
	DFT	T^2KF	DFT	T^2KF
3 phase fault at 40Km on line 34	24	22	-	-

As the impedance reaches the respective zones in minimum time, by observing all the above results, it is clear that the proposed T^2KF based backup protection exhibits best performance. It has an impact on distance relays as this filter handles exponential D.C-offset rejection and harmonics. From R-X diagrams, like other impedance relays, the impedance once reaches faulted zone it does not leave the zone unless the system is recovered from the fault.

V. Conclusion

As it is known, the in-feeding current causes the relay undergo over-reach and moves the fault point far away from the from its actual zone characteristics of the respective relay. The proposed method based on T^2KF could estimates the fault impedance accurately by compensating the in-feeding effect. Simply, it requires the communication from the other ends to the relay end. First, T^2KF measures the voltage and current phasors required for fault impedance measurement and, next, the impedance estimation algorithm calculates the fault impedance approximately close to actual fault impedance by successfully compensating the in-feeding effect. Instead of changing the relay zone setting every time, it calculates the fault impedance. We can compensate the delay in communication if we could reduce the delay time for each zone.

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