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Challenges and Developments in Numerical Distance Protection

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This paper discusses some of the major issues in third-generation numerical distance protections which are being faced by utilities, and the solutions made available for these issues by relay manufacturers. Each discussion is accompanied with simulation results obtained using matlab and simulink. In addition to this, some of the key issues which still need further research are also addressed.

1.0 INTRODUCTION

Protective relays play a vital role in fault clearing process. The main purpose of protective relay is to identify 10 different kinds of faults in power system, i.e. 3-phase to earth faults, 3-phase to phase faults, 3-phase to phase and earth, 3-phase fault and to send a control signal (if the fault is within its zone of protection) to the corresponding circuit breaker to clear the fault.

Power System Protection has seen a massive development in the last century. The very first relays introduced were of electromechanical type having tripping time in the order of few 100s of milliseconds. Although these relays were found to be sluggish and having high operating time when compared with modern digital/numerical relays, they were able to meet the system needs in those periods. In order to meet the rapid growth demand and to ensure reliability, power system was being made to operate in interconnected fashion, which led to other issues like stability and system security during disturbances. This demands high-speed fault clearing times in order to ensure stability and to minimize damages to electrical equipments which were feeding the fault. In order to reduce tripping time relay manufacturers started constructing static relays which were relatively small in size. However, people who are skilled in the art will admit that it is very difficult to achieve user-defined characteristics like quadrilateral characteristic with load encroachment function, lens characteristic and tomato characteristic [1–3].

The paper is organized in the following fashion. Section 2 discusses the literature review, followed by Section 3 which discusses challenges and developments in numerical distance protection and finally conclusion.

2.0 LITERATURE REVIEW

2.1 Numerical Distance Protection

Extra high-voltage transmission lines, in general, are protected by distance protection and it has been serving this task for at-least a century. Numerical distance relay which is used to protect the transmission lines takes two inputs, i.e. voltage from capacitive voltage transformers and current from current transformers. Numerical distance relay processes these inputs using digital signal processors and calculates the apparent impedance. If the apparent impedance is within the set zone of protection, it sends a tripping signal to the corresponding pole/breaker as set in the protection logics. Although it sounds simple, in reality it is very difficult to achieve speed

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and accurately calculate the apparent impedance of the line in the presence of fault resistance, remote end in-feed, loading effects, instrument transformer noise, which result in over-reach and under-reach problems [4,5].

In 1960, Rockfeller [6] suggested that digital computers can be used to protect power system equipment, and this opened up a new research area which finally led to the penetration of digital computers into the relay industry and later emerged as numerical/digital relays. The main advantages of numerical relays over static relays are the tripping time was considerably brought down to one cycle and some relay manufacturers even claim sub-cycle operating times. Johns and Martin [7] were the first to apply the Fourier transform to both current and voltage waveforms using a data window of less than one cycle of power system frequency. Another feature of numerical relays is user-friendly relay setting characteristics, e.g. separate resistive and reactive reach zones can be set in quadrilateral characteristic in distance protection, independent setting for individual zones of protection. Apart from the features mentioned above, present-day relays also provide means to digitally record disturbance, which can be used for post fault analysis by protection engineers. This led to the widespread use of digital/numerical protection throughout the power system network right from Generation, transmission, sub-transmission to distribution.

2.2 Discrete Fourier Transform

The fundamental task of numerical distance protection is to extract the information (fundamental frequency) from the first post fault cycle of current and voltage waveform and utilize this for decision making. In 1971, Ramamoorty [8] suggested extracting the desired fundamental component of voltage and current from faulted waveforms by correlating one cycle of data samples of reference fundamental sine and cosine waves. Although there are several algorithms like discrete Fourier series, discrete Fourier transform, sine, cosine filtering [9], discrete Fourier transform was used in general. The sampled current and voltage signals are fed to the delta algorithm via analog to digital converter. The function of delta algorithm [10] is to detect the fault, fault direction and phase selection. Once the fault is detected by delta algorithm, the high-speed main algorithm gets activated and performs its task within one cycle of power system frequency. The digitized voltage and current data are converted to frequency domain, i.e. phasors using discrete Fourier transform using (1), which are then fed as inputs to the main algorithm to calculate the apparent impedance.

$$F[m] = \sum_{K=0}^{N-1} f[k] e^{-j\frac{2\pi km}{N}} \tag{1}$$

where,

$$f[k] = \sum_{K=0}^{N-1} f(t) \underbrace{\delta(t - t_k)}_{\text{pulse train}}$$

N is the total number of samples in time domain, m is the sample number in frequency domain.

One such case, where DFT is computed for 3 sample signals is, given by (2)

Voltage/current phasors ↑ Time domain Voltage/current Samples ↓

$$\begin{pmatrix} F[0] \\ F[1] \\ F[2] \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 1 & 1 \\ 1 & w^{-1} & w^{-2} \\ 1 & w^{-2} & w^{-4} \end{pmatrix}}_{\text{stored in relay memory}} \begin{pmatrix} f[0] \\ f[1] \\ f[2] \end{pmatrix} \tag{2}$$

where $w = e^{j\frac{2\pi}{N}}$

Precision of the impedance estimation depends on performance of DFT technique used to carry the information from time domain to frequency domain, which is really a challenging task in all protective relays due to frequency excursion [11].

3.0 CHALLENGES AND DEVELOPMENTS

This section discusses the major challenges and developments one by one in each subsection.

In addition to this, some of the current challenges which need further research are also discussed.

3.1 Short Line Length

The most famous and conventional line protection is the mho characteristic shown in Figure 1, where the estimated impedance is used to detect the fault with the help of angle or magnitude criteria. The reason behind the development of this characteristic is due to the olden relay technology, i.e. electromechanical relay, where it is very difficult to achieve user-defined relay characteristics.

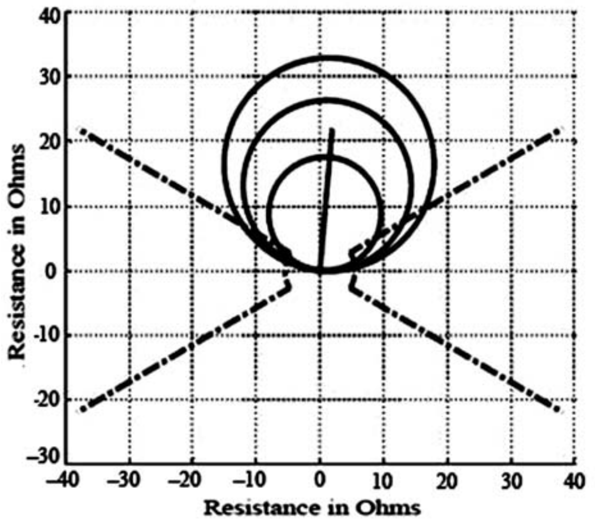

FIG. 1 MHO CHARACTERISTIC WITH LOAD ENCROACHMENT FUNCTION

The main issue with this characteristic is mentioned below:

- A reduced resistive reach at both ends of protected zone.
- When this mho relay is used to protect short transmission line, the overall resistive reach reduces because the radius of circle, which is a function of line impedance, is reduced.

This may result in relay maloperation, as the fault may not be detected due to fault resistance which causes the estimated impedance trajectory to move outside the relay characteristic.

Although during the electromechanical period when people felt it was almost impossible to handle this situation, it was made possible ever since the relays were driven into digital era, where people came up with user-defined characteristic which led to the development of quadrilateral characteristic as shown in Figure 2 thus, the problem of resistive reach due to mho characteristic can be mitigated by using quadrilateral characteristic for protecting short transmission lines, further it is evident from Figure 3 that quadrilateral characteristic increases the resistive reach at zone ends relatively.

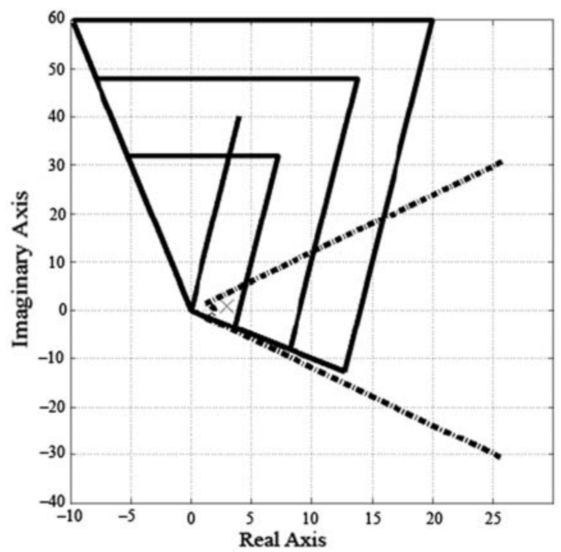

FIG. 2 QUADRILATERAL CHARACTERISTIC WITH LOAD ENCROACHMENT FUNCTION

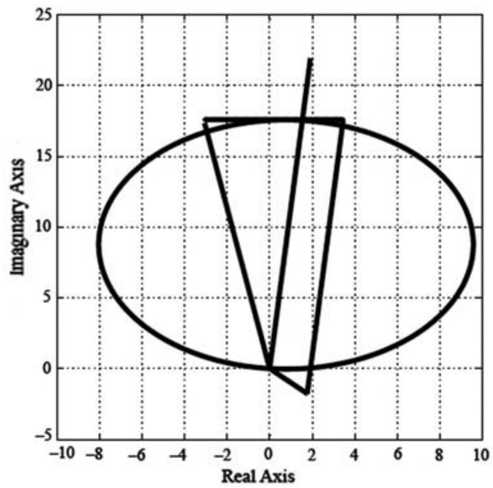

FIG. 3 RESISTIVE REACH IN MHO AND QUADRILATERAL CHARACTERISTIC

3.2 Tripping Time

Ever since the relay design stepped into digital domain, there was a drastic reduction in relay operation time from 200 ms to one cycle, i.e. 20 ms for 50 Hz fundamental frequency. Although it seems quite satisfying for both utility and relay manufacturer, the ever-growing demand on power system demands sub-cycle operating time due to stability issues.

The entire performance of the numerical distance relay depends on the transfer of information from time domain to frequency domain using discrete Fourier transform, which takes time domain information in digital domain as input and gives phasors as output. In order to reduce tripping time, the window size used in discrete Fourier transform should be reduced to achieve sub-cycle tripping time. Although the digital technology permits the use of reduced window size on voltage and current signals, the use of this technique was limited due to its magnitude response as shown in Figure 4.

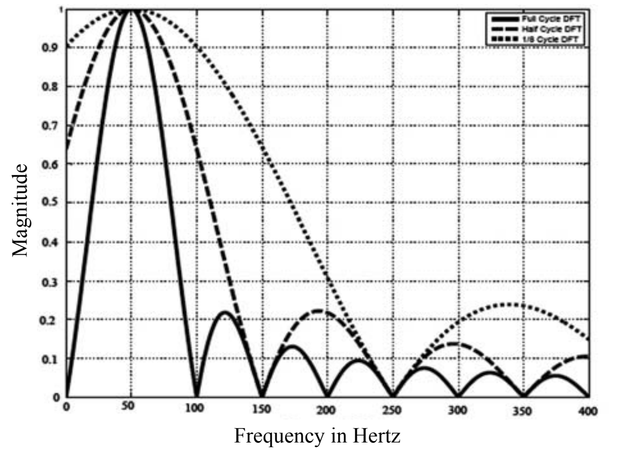

FIG. 4 MAGNITUDE RESPONSE OF FULL, HALF AND 1/8 CYCLE DFT

The following inferences can be made from Figure 4, which clearly indicates the limits for reducing the window size:

- Rejection of DC component in waveforms reduces with reduced window size, which may lead to over-reach problem
- Failure in the rejection of even harmonics if half cycle or 1/8 cycle discrete Fourier transform was used

It is quite interesting to know that this problem is still under research and researchers started attacking this problem by capturing the high-frequency information using wavelet transform. Wavelet transform is slightly different from short-time Fourier transform, where dilated and translated mother wavelet is used to capture information. One such dilated and translated mother wavelet (Mexican Hat) is shown in Figure 5.

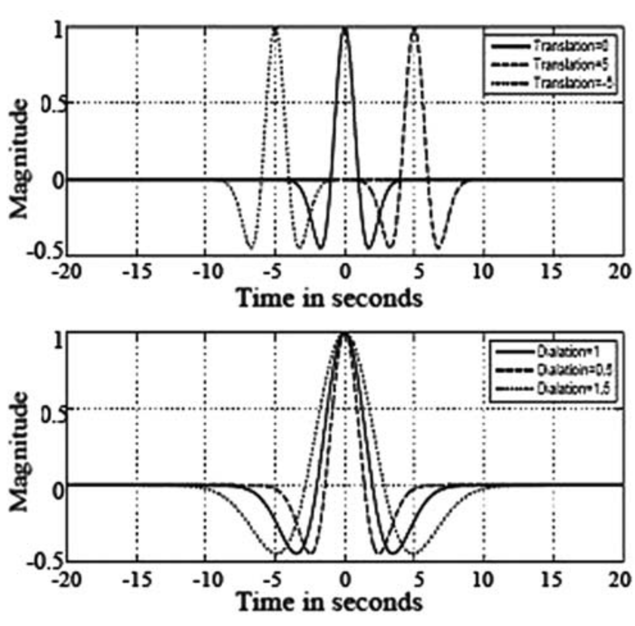

FIG. 5 MEXICAN HAT WAVELET

3.3 Over-reach

Over-reach in numerical distance protection may cause selectivity problem in protective relays. If selectivity has to be retained, then zone 1 reach should be reduced as indicated in Figure 6. This results in delayed tripping time of zone 2, for faults which occur in 0–20 % and between 80 % and 100 %; for typical zone 1 reach setting of 80 % of transmission line length [12].

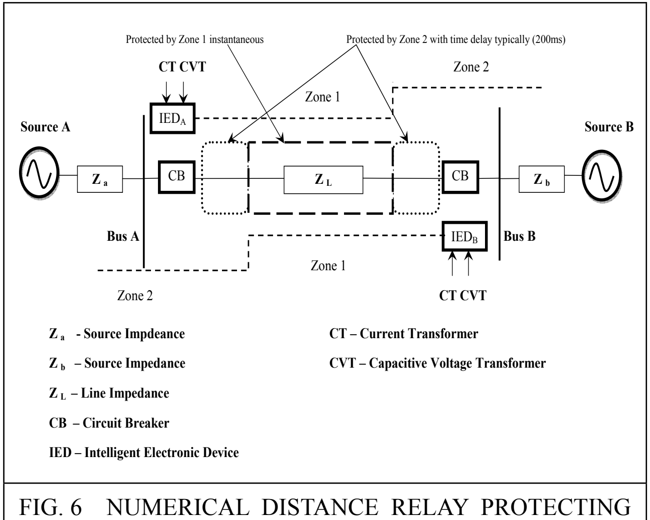

FIG. 6 NUMERICAL DISTANCE RELAY PROTECTING TRANSMISSION LINE HAVING TWO IN FEED

Over-reach due to distance relay occurs due to

- DC offset in current waveform
- Loading effect
- Capacitive voltage transformer transients
- High source-to-line impedance ratio

The developments that were made by relay manufacturers to overcome each of the above-mentioned over-reach problem are discussed in the following subsections.

3.3.1 Techniques to Overcome DC Offset in Current Waveform

DC offset in current waveform is well-understood from switching RL transient which is given mathematically by (3)

$$I(t)=I_m \sin(\omega t+\theta-\varphi) - I_m\, e^{-R/L\, t} \sin(\theta-\varphi) \quad (3)$$

where, R is resistance of protected transmission line, L is inductance of protected transmission line, θ is phase angle of voltage, ω is angular frequency in rad/sec, φ is power factor angle. Null DC offset occurs when $\theta-\varphi=n\pi$,

where n = 0,1,2,3,.....

$$I(t) = I_m \sin(\omega t) \quad (4)$$

maximum DC offset occurs when

$$\theta-\varphi=\frac{n\pi}{2},\ \text{where } n=1,2,3,....$$

$$I(t) = I_m \cos(\omega t)-I_m e^{-R/L\, t} \quad (5)$$

This DC offset results in over-reach phenomenon in ground elements because it uses (6) to estimate the impedance for a fault in 'a' phase.

$$Z_{L1}=\frac{V_a}{I_a - I_E K_E} \quad (6)$$

where

$$K_E=\frac{Z_{L0}-Z_{L1}}{3Z_{L1}} \quad (7)$$

Z_{L1} is positive sequence impedance of protected line;

Z_{L0} is zero sequence impedance of protected line;

V_a is phase 'a' voltage;

I_a is phase 'a' current

This problem can be mitigated using mimic filtering [13], which uses replica impedance in current transformer secondary as shown in Figure 7.

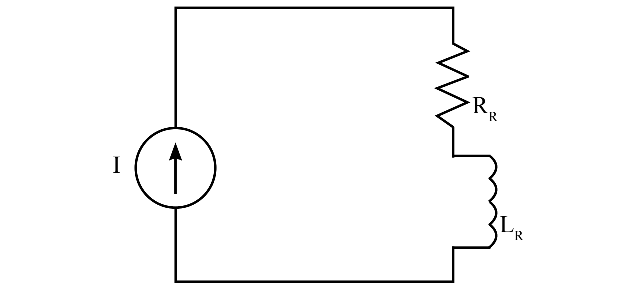

FIG. 7 REPLICA IMPEDANCE

$$V_r(t) = I_m[R_r \sin(\omega t + \theta-\varphi)+L_r\omega \cos(\omega t + \theta-\varphi)] + I_m \sin(\theta-\varphi)\, e^{-\frac{R}{L}t}\left(\frac{RL_r}{L}-R_r\right) \quad (8)$$

where $V_r(t)$ is the voltage across the replica impedance.

In (8), the decaying term vanishes when secondary impedance is replicated $\frac{L_r}{R_r}=\frac{L}{R}$. Figure 8 shows the impact of replica impedance, which clearly

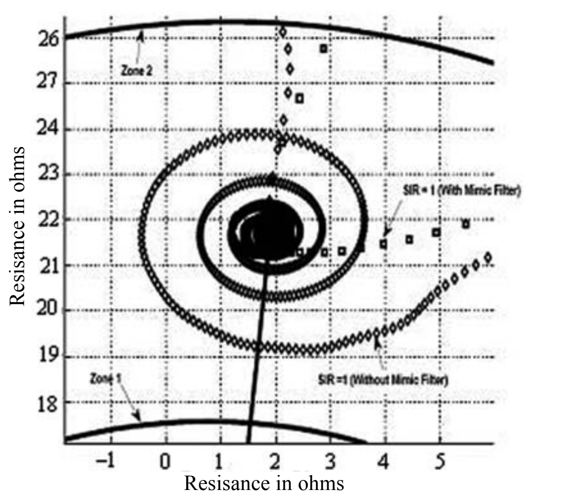

FIG. 8 REDUCTION IN OVER-REACH DUE TO MIMIC FILTERING

shows that the over-reach drastically reduces if mimic filtering was incorporated.

3.3.2 Loading Effect

This has a double impact in Numerical Distance Protection. Firstly, the estimated impedance may penetrate into relay characteristic during heavily loaded condition and may lead to tripping even though there is no physical fault [14]. Major blackouts which were triggered by relay maloperation due to load encroachment are listed in Table 1. Reference [3] has suggested techniques as mentioned below to overcome the relay maloperation due to load encroachment:

- lens characteristic
- tilting mho characteristic
- blinder characteristic
- load encroachment characteristic [15]

TABLE 1

MAJOR BLACKOUT DUE TO RELAY MALOPERATION

Date	Initial cause
9 Nov 1965 [16]	230 kV Niagara Toronto Line tripped by Zone 3 due to Overload.
12 Mar 1996 [17]	Due to fault
2 July 1996 [17]	345 kV Idaho Line tripped due to fault
14 Aug 2003 [18]	345 kV Chamberlin-Harding tripped due to fault
4 Nov 2006 [19]	280 kV Conneforde-Diele Line

Secondly, loading effect causes relay at one end of the line to over-reach and other end of the line to under-reach as shown in Figure 9 [5]. The amount of over-reach or under reach depends upon the pre-fault loading condition. This can be overcome by using adaptive tilting angle [20] characteristic, which is currently available in all quadrilateral numerical distance relay.

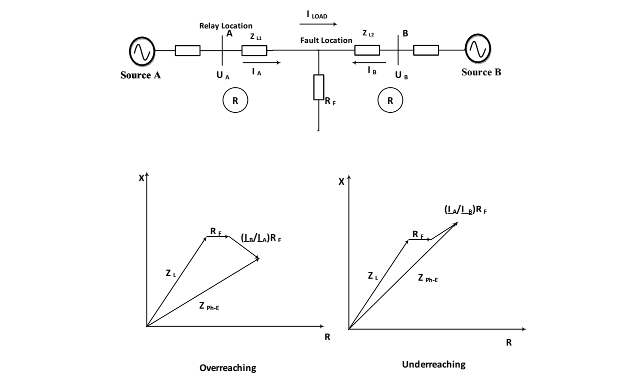

FIG. 9 OVERREACH AND UNDER REACH DUE TO LOADING EFFECT

3.3.3 Capacitor Voltage Transformer Transients

Capacitor Voltage Transformers are very popular for measuring voltages at extra high-voltage level because of economic reasons. Numerical Distance relays, on the other hand, offer high tripping speeds in the range of sub-half cycle to one full cycle. In order to achieve speed and selectivity, distance relay requires the exact replication of both primary voltage and primary current in the first post fault cycle; but transients which are generated with oscillation frequency close to fundamental frequency in capacitor voltage transformer secondary cause the high-speed relay to over-reach. Figure 10 shows the possibility of over-reach in distance protection due to CVT transients.

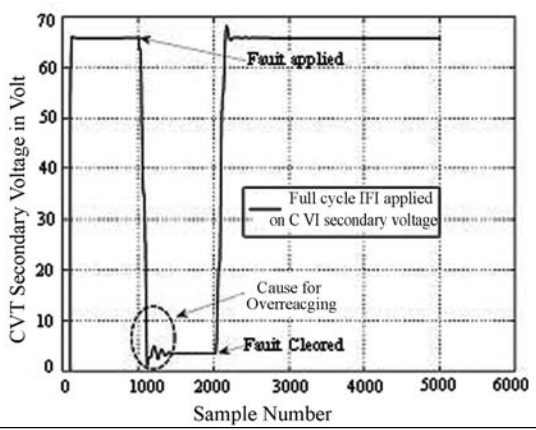

FIG. 10 OVERREACH DUE TO CAPACITOR VOLTAGE TRANSFORMER TRANSIENTS

3.3.4 High Source-to-Line Impedance Ratio

High SIR causes a drastic change in primary voltage signal immediately after the fault, which results in high transients in CVT secondary output and as a result of high transients, relay over-reaches [21]. Figure 11 shows how the high SIR results in relay maloperation even though fault are not within protected zone 1 area.

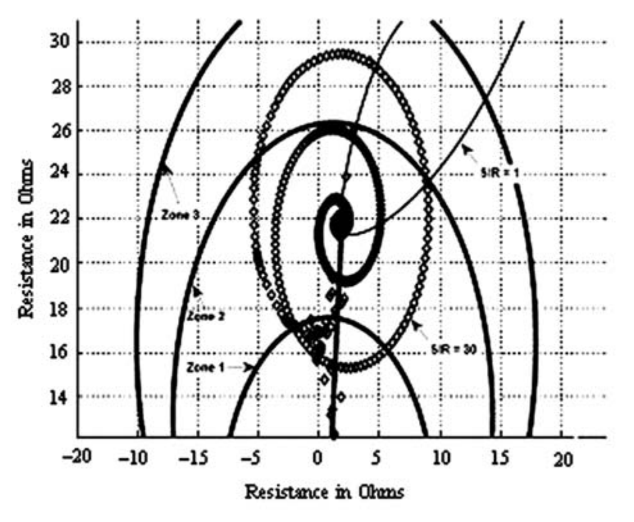

FIG. 11 OVER-REACH DUE TO HIGH SIR

As over-reach cannot be avoided completely, relay manufacturers have developed their own technique to handle this problem. Some of the most famous techniques are listed in Table 2.

TABLE 2

TECHNIQUES USED BY RELAY MANUFACTURERS

GE [22]	Double zone 1 is used
SEL [23]	Tracks SIR and adapts reach setting for zone 1
ABB [1]	Reduced zone 1 reach
SIEMENS [2]	
Alstom [10]	Loss of load accelerated tripping

3.3 Fault Resistance and Fault Location

This plays a very important role for reach setting calculations and the conventional way is to use Warrington formula; but reference [24] has discussed some important points which should be taken into account as the fault level has gone up. Even in today's situation, protection engineer handles this issue by Warrington formula to estimate the worst case reach setting, but unfortunately fault location plays a dominant role in impedance estimation because the effective resistance increases as the fault point moves towards station B as shown in Figure 12.

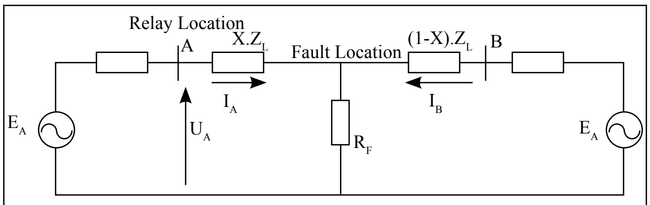

FIG. 12 SYSTEM WITH TWO INFEEDS

Figure 13 shows how the estimated impedance varies from the actual value for a particular value of fault resistance and load angle when fault location moves towards station B.

Researchers are working in an innovative way to tackle this issue as the fault resistance is not deterministic.

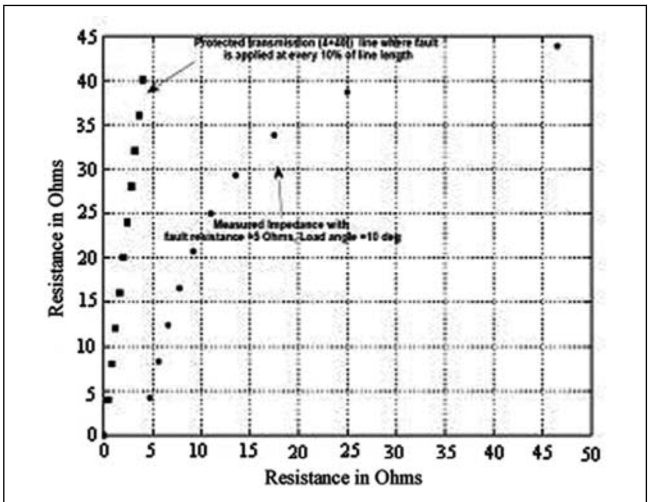

FIG. 13 EFFECT OF FAULT LOCATION ON IMPEDANCE ESTIMATION

3.4 Power Swings

Power swings may result in relay maloperation because there is a possibility that the estimated impedance may enter the zone characteristic causing the relay to trip the line. However, the traditional way is to block the tripping by using power swing blocking function which detects the power swing condition by monitoring the rate of change of impedance, which will be high during fault and small during power swing. The rate of change of impedance is monitored by using outer and inner blinder, in which the time for an estimated impedance to cross the blinders will be monitored to detect the swing and block relay operation. Although the scheme is capable of detecting swings, the performance of this scheme depends upon the distance setting between the outer and inner blinder that needs exhaustive stability studies with different network and operating conditions to arrive at the worst case, so that the relay should not operate for stable power swings. In addition to this problem, the swing locus varies as shown in Figure 14, depending upon the ratio of sending and receiving end voltage magnitude. Reference [25] has discussed the challenges in conventional power swing blocking function and how it can be overcome by using swing center voltage. The main advantage of this technique (swing center voltage) is that it requires zero setting from the user for power swing blocking.

The other challenge which is of current interest with power swing out of step blocking protection is the location of relay, so that optimal is landing i.e. minimal generation and load mismatch will be achieved in each area after segregating the unstable areas.

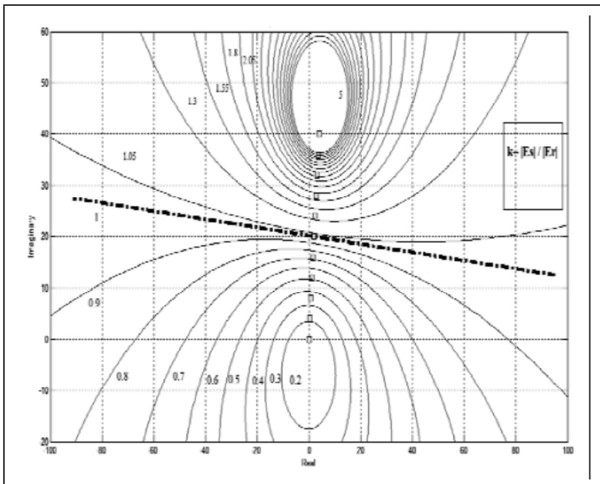

FIG. 14 SWING LOCUS FOR DIFFERENT SENDING AND RECEIVING END VOLTAGE MAGNITUDES

4.0 CONCLUSION

It was inferred that though researchers have provided solution to some key issues, the ever-growing complex power system demands further developments in areas like reduction of tripping time, optimal islanding during power swings, which are currently focused on with a completely different mathematical way like wavelet transform and new measurement technique using phasor measurement units.

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