Transmission Line Trip Region for Single Line to Ground Fault in Various System Configuration and Operating Condition

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***Abstract* - The distance relays installed at substations continuously monitor the impedance. This impedance is called apparent impedance. During fault, the transmission line impedance restrict fault current, thus apparent impedance becomes transmission line impedance. This apparent impedance is significantly affected by fault resistance (tower footing resistance for SLG), prefault system conditions (i.e. load flow & voltage level), prefault system configuration (i.e. source impedance, in-feeds), shunt capacitance and mutual coupling of parallel lines. In this paper, the effects of all mentioned parameters are studied.**

I. INTRODUCTION

Distance protection is commonly used for protection of transmission lines. Out of various possible faults, the occurrence of single line to ground fault is very high. Till now, we have studied SLG fault under unloaded condition. However, ground fault resistance, remote end in feed, sources' impedance, system configuration, & present operating condition (Load flow) etc affect the reach accuracy of relay. Moreover, line capacitance and mutual coupling also affect reach accuracy of relay.

For a simple two source equivalent system (Fig.1.1), the apparent impedance for SLG in phase A can be given by
- $Za=xZL+(1+IMF/INF).R_F$

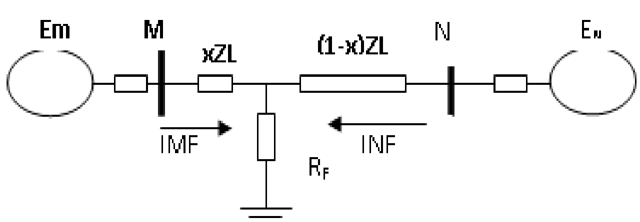


Fig 1 Two source equivalent system

Hence, apparent impedance is not only dependent on fault location x but also remote end in feed along with fault resistance R_F. R_F is dependent on tower footing resistance which may vary up to 200Ω depending upon country soil characteristics. These parameters remain unknown though system operating condition i.e. remote end equivalent voltage and source impedance can be estimated with breaker status and made available to substation using SCADA. If system characteristic is fixed, Rf and x are only variables; then a trip region (Fig1.2) can be prepared.

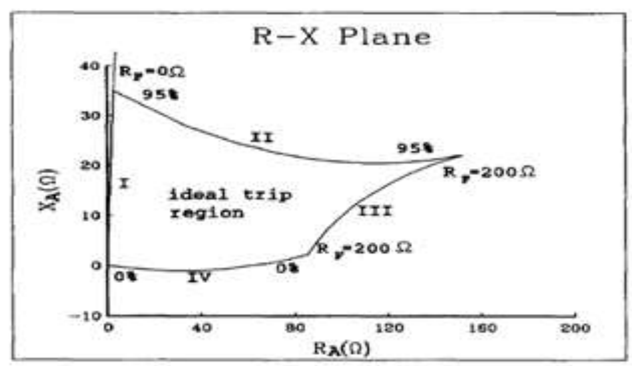


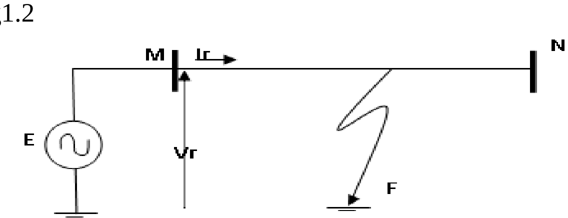
Fig 1.1 TRIP REGION

1. Distance Relay

Over-current relays are very cheap and considerably reliable. Hence, they constitute very significant portion of LV industrial protection system. However, they suffer some major drawbacks. It is very difficult to implement coordination, selectivity [1]. The reach of over-currents relay is heavily depending upon the type of fault and source impedance. The source impedance is changing with switching on/off of lines. Hence, relay may overreach or under reach with change in system configuration and fault resistance.

1.1 Distance Relay Fundamentals

Let us consider a single phase line MN, having a stiff source at location M and no source at location N. For simplicity line is modeled as R-L series circuit (i.e short line) as shown in Fig1.2



If line MN is subjected to a ground metallic (zero fault resistance) fault, then fault current will be limited by impedance of line from point M to F. The ratio of voltage and current at location M shall give the line impedance value up to fault point. Hence, ratio Vr/Ir will give the apparent impedance as seen by relay at location M. therefore, trip criteria $if\ Zr < Zset, then\ trip$ can be set for operation.

1.2 Apparent impedance seen by relay

The above discussion is valid for single phase line. In practice EHV lines are three phase. The load flow is expected to balance largely. There are ten different types of fault possible on a three phase line. Any types of fault will disturbance balance system. The analysis of unbalanced system is done with help of symmetrical components which introduces three types of sequence impedances. Out of given three sequence impedances; the positive sequence is present during all faults as shown in table 1.1. Hence, it will be prudent to measure, the positive sequence only.

Fault	Positive Sequence	Negative Sequence	Zero Sequence
PH-G	Yes	Yes	Yes
PH-PH	Yes	Yes	No
Ph-PH-G	Yes	Yes	Yes
Three Phase	Yes	No	No

Table 1.1 Presence of positive sequence in various faults

There are many elements (i.e. transformers, O/H lines, generators etc) in power system. As per statistics given in [2], the probability of fault in O/H transmission lines are very high (50%) and out of these probability of occurrence of SLG fault is quite high (85%).

In SLG fault all sequence component comes in series as shown in Fig 1.3. The apparent impedance seen by the relay is given by $Zr = {Va}\Big/\left(Ia + \frac{Z_0 - Z_1}{3Z_1}\ Ires\right)$ where $Ires$ is the zero sequence current at relay location. The component $\frac{Z_0 - Z_1}{3Z_1}$ is also called residual current compensation factor. It is because of zero sequence current present in relay.

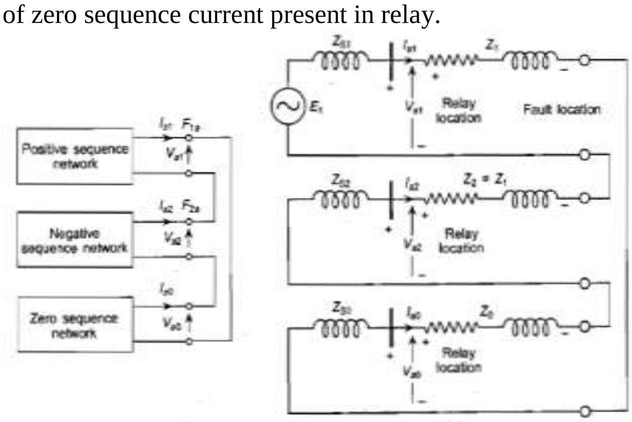


Fig. 1.3 Sequence Network for SLG fault (a-g), source(2)

Thus the apparent impedance seen by relay is given as $Zr = {Va}/{(Ia + K\ Ires)}$ where $K = \frac{Z_0 - Z_1}{3Z_1}$.

A three phase system applicable for fig 1.1 is suitable for radial system. EHV lines are part of system and must have sources at both ends.

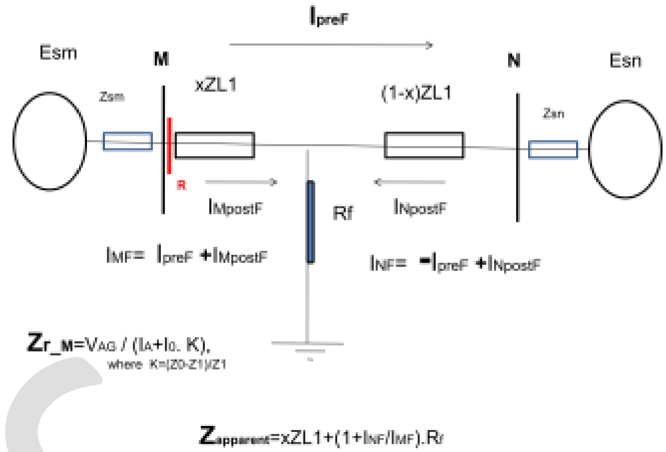


Fig. 1.4: Two Source Equivalent System

A two source equivalent system, which can be closer to power system, can be given by Fig 1.4. In fig1.4 , the system conditions external to protected line is included in equivalent source impedances(Zsm & Zsn) and voltage equivalents(Esm & Esn). The lumped external impedance Zsm and Zsn can be updated from local circuit impedance, breaker status information and online measurements of system load. Local computers make this feasible and linking to the remote computers provides more accurate updating [7].

1.2.1 Effect of fault resistance on apparent Impedance

The fault resistanceis an operational problem and depends upon various factors, such as voltage level, tower footing resistance, soil resistivity, etc. In given case, the apparent impedance can be expressed as$Z_{apparent} = xZ_L + (1 + \frac{I_{NF}}{I_{MF}})R_f$. The effect of fault resistance, remote end in-feed, load flow etc can be very well understood by expression.

Suppose, the remote end equivalent source impedance Zsn is large enough to contribute any fault current, then apparent impedance seen by relay on R-X plane is shown as fig 1.5

1.2.2 Effect of In-feed on apparent Impedance

If the effect of load flow is not included and remote end also contribute to the current flowing in to fault resistance, then its' effect would just as to increase the fault resistance (if fault current due to local source & remote source are in phase). Remote end in-feed would not have any effect on metallic faults, however, presence of fault resistance and strength of remote end. The same is shown in Fig 1.6.

1.2.3 Effect of Load Flow on apparent Impedance

For considering the effect of load flow, the second term i.e $(1+\frac{I_{NF}}{I_{MF}})R_f$ will have both real and imaginary part. Its' effect can be additive or subtractive. It depends upon loading i.e. angular separation and voltage magnitude. Greater angular separation or say greater loading will move apparent impedance towards R-axis. The increase in difference of voltage magnitude will move apparent impedance upward direction.

In a nutshell increase in loading will reduce apparent impedance and increase in difference of voltage magnitude will increase apparent impedance. Fig 1.7 summarizes effect of load flow. Load flow would not have any effect on metallic faults. Detailed effect of load flow on apparent impedance is given in [4] &[7].

1.2.4 Effect of mutual coupling on apparent Impedance

The impact of mutual coupling comes into existence in double line configuration. Mutual coupling only appears when zero sequence current flows during a fault (supposing that transposition eliminates the positive and negative mutual coupling). If faults affecting only one circuit of the line are considered, only ground faults and so only ground units are affected by mutual coupling.

The measured impedance seen by the relay may cause overreach or under reach depending on the mutual impedance whose polarity is decided by the relative direction of the currents in parallel lines. Relay may under reach in case of the same direction of currents and overreach in case of the opposite direction of currents in parallel lines. The overreach or under reach caused by the mutual coupling effect can be compensated by selecting the proper boundary conditions of the relay settings (i.e. compensation factor K) . The apparent impedance for double line configuration is given by$Zr = V_{ar}/(I_{ar}+K_0 I_{0L1}+K_{0mu} I_{0L2})$

where$K_0 = {(Z_{0L1}-Z_{1L1})}/{3Z_{0L1}}$ and $K_{0mu} = \frac{Z_{0mu}}{Z_{1L1}}$

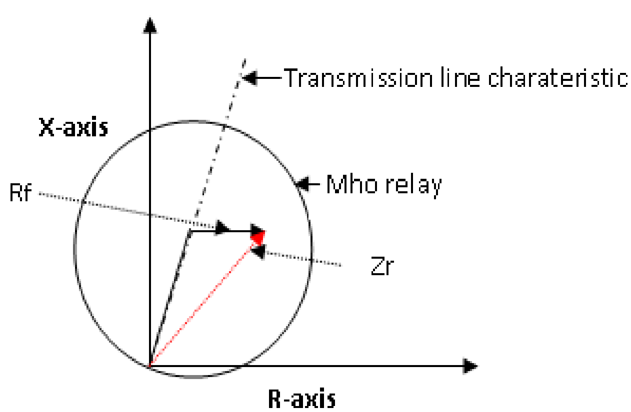


Fig. 1.5 Effect of fault resistance

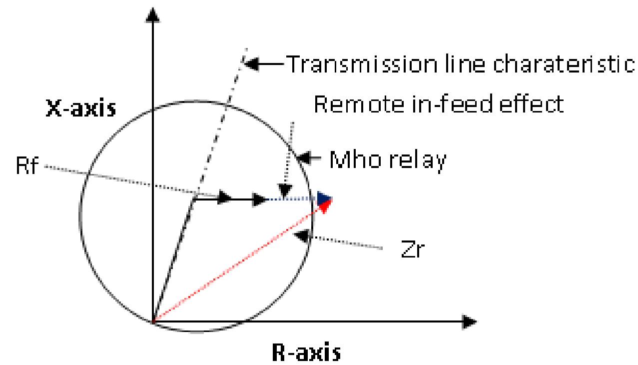


Fig. 1.6 Effect of remote in-feed

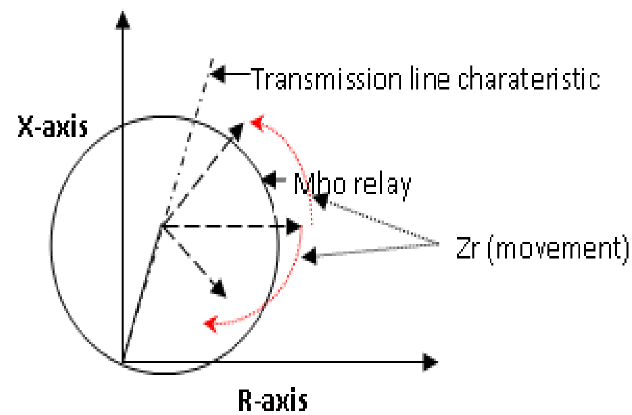


Fig. 1.7 : Effect of Load Flow

1.2.5 Effect of Source impedance on apparent Impedance

The relative strength of source equivalent (ratio of zero sequence impedance source equivalents) has more effect on flow of zero sequence current. This significantly affects the apparent impedance in double line configuration. Let us say that direction of load flow is from strong source to weak source and fault is seen by relay at strong source end, then there is chance of under reach (apparent impedance more than actual one) after a particular length of line. The effect will be vice-versa for weak end i.e. overreach (apparent impedance less than actual one). This particular length is governed by relative zero sequence impedance strength at both direction and is called "immunity distance" $\boldsymbol{p_i = Z_{sm0}/(Z_{sm0}+Z_{sn0})}$by [16]. The effect of source impedance, system heterogeneity and load flow as given in [16] is summarizes in Table 1.2

Cause of error	Effect
Source Impedance Modules at both end	Increases apparent resistance
System heterogeneity	Shift apparent resistance
Previous Load flow	Shift apparent resistance

Table 1.2 Causes of errors, source [16]

1.3 Trip region for SLG fault

Considering above mentioned impact the apparent impedance for single line configuration two source equivalent systems can be given by $Z_r = x.Z_L + \Delta Z$, where $\Delta Z = f(R_f, \delta, V, Z_s, Z_0\ etc)$. The detailed analysis of given expression is done in [7]. The fault can occur anywhere along the length of line with variable fault resistances. If system operating condition and configuration is held constant, then all these apparent impedances can be covered by making a suitable envelop cover in R-X plane by four boundaries as given below(given in [7]):-

Line I: solid faults at different locations;
Line II: faults at a relay-reach end (80% of line length) with different fault resistance up to 200Ω
Line III: faults at different points with a 200Ω fault resistance;
Line IV: faults at the relaying point with different fault resistance up to 200Ω;

The four lines and the included area constitute what may be designated an ideal trip region under the prevailing system conditions as given in Fig.1.8

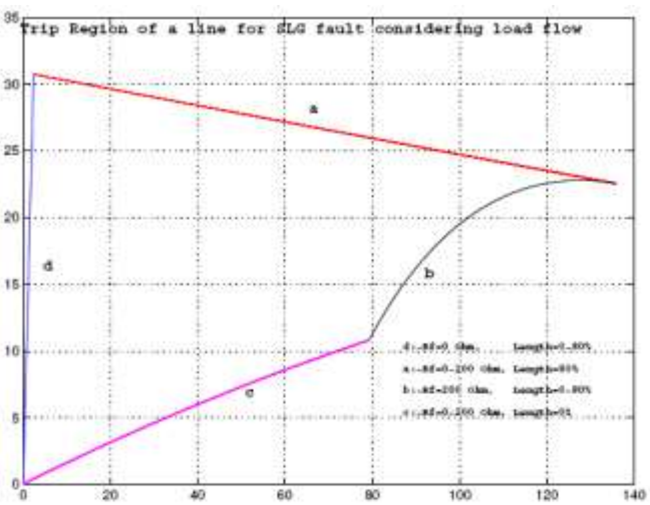


Fig 1.8 Trip region

1.4 Effect of active and reactive Power flow

The active power flow between buses is significantly affected by difference in angular separation whereas reactive power flow is affected by voltage magnitude difference. The effect of load flow on trip region is extensively discussed in [8] and it is concluded that "the main factor affecting the ideal operating region of a digital distance relay is the active and reactive power flow in the line." The effect of change in system configuration is within tolerable range and main function is not affected significantly even under a major change in system configuration. The effect of load flow and change in active & reactive power is shown in following figures:-

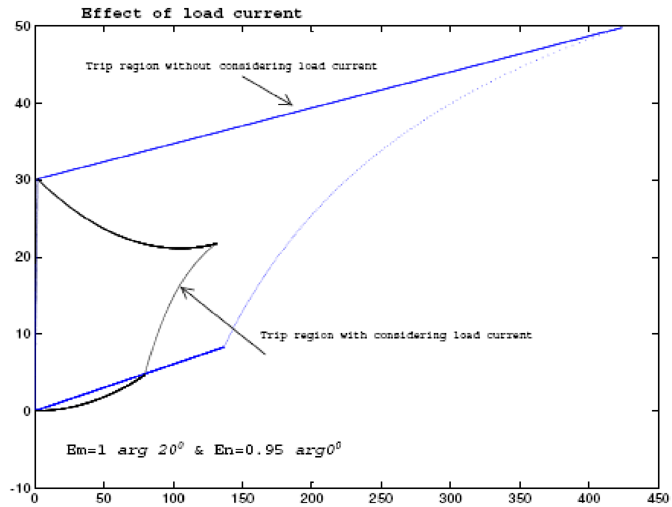


Fig 1.9 Effect of load current on trip region

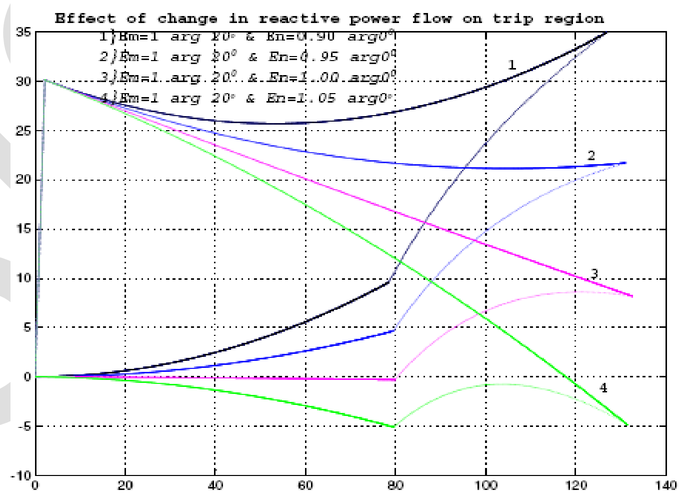


Fig 1.10 Effect of reactive power flow on trip region

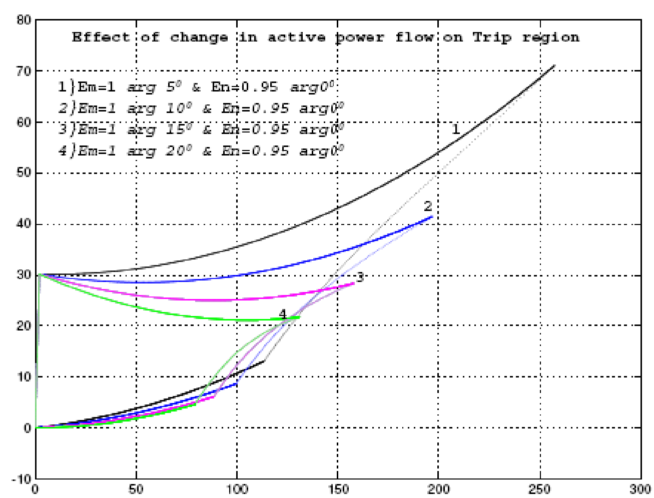


Fig 1.11 Effect of active power flow on trip region

1.5 Effect of shunt capacitance

Till now the effect of shunt capacitance is not considered. High-voltage transmission lines have significant shunt capacitance. The inclusion of shunt capacitance is analyzed in [7] and it is concluded that "Substantial errors in measurement can result from ignoring the capacitance influence especially for high resistance faults." A fault in two sources equivalent system having substantial shunt capacitance can be modeled as per fig1.12

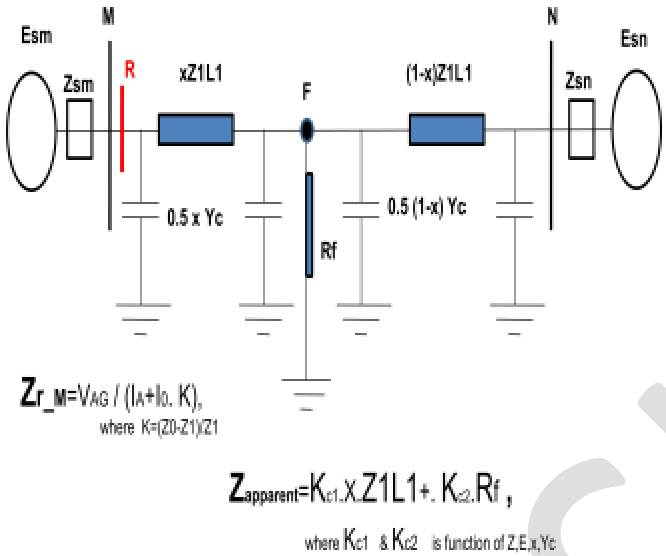


Fig 1.12 Two sources equivalent system with shunt capacitance

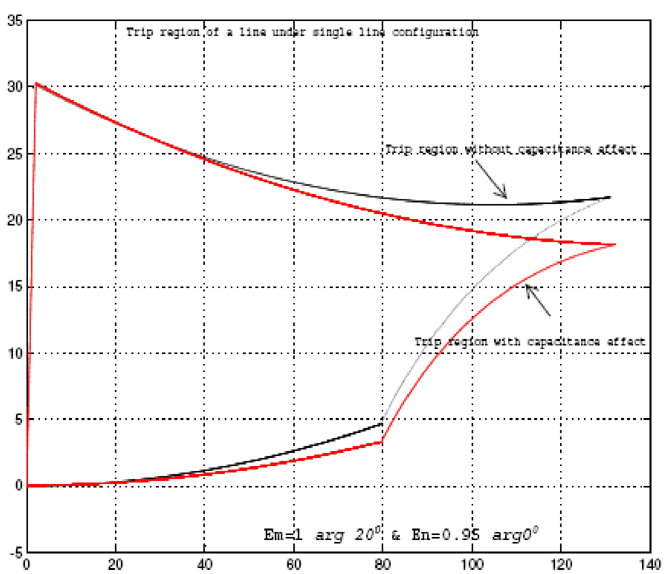


Fig.1.13 Trip region with shunt capacitance effect

It is evident from trip region that shunt capacitance effect is more prominent at high fault resistance and at longer fault distance.

1.6 Result validation with simulation

In order to validate the finding of trip region a simulation was performed in matlab 2009a. The results are found satisfactory.

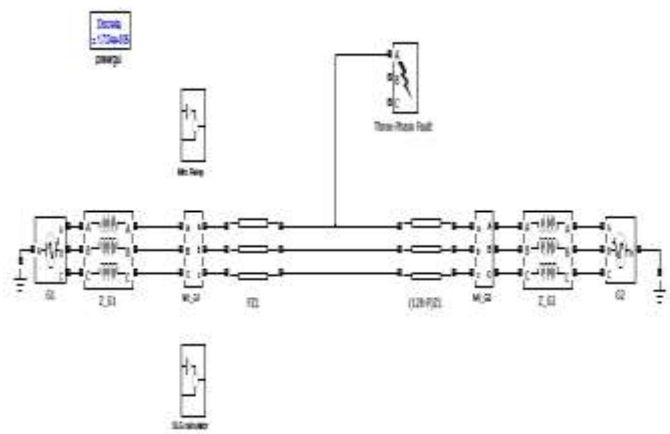


Fig 1.14 Simulation diagram for two sources equivalent system with shunt capacitance

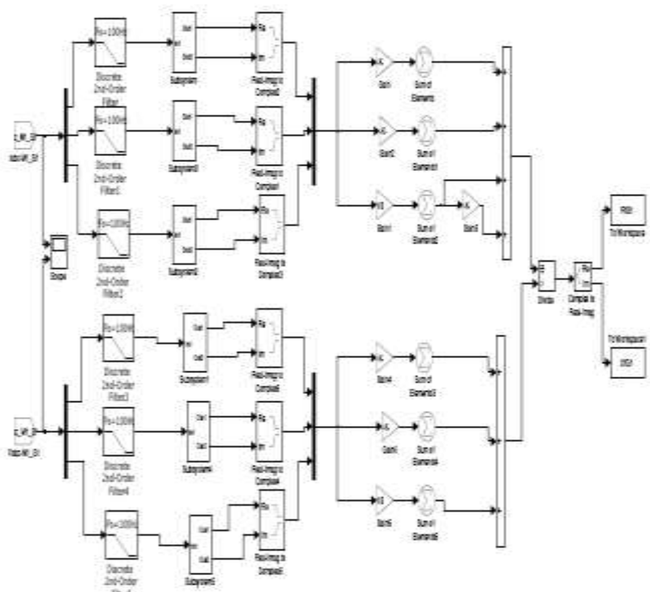


Fig 1.15 Relay for SLG fault

Fig 1.16 shows the superimposed results of simulation and program and they clearly validate the error introduced by shunt capacitance. One cannot be sure about fault trajectory shown in fig **1.16** as it depends upon DFT used for sampling and relay decision. DFT model given in Matlab is used in relay referred above .Many papers have been published for faster DFT estimation. It is seen that though fault trajectory differ, the final settle value is same.

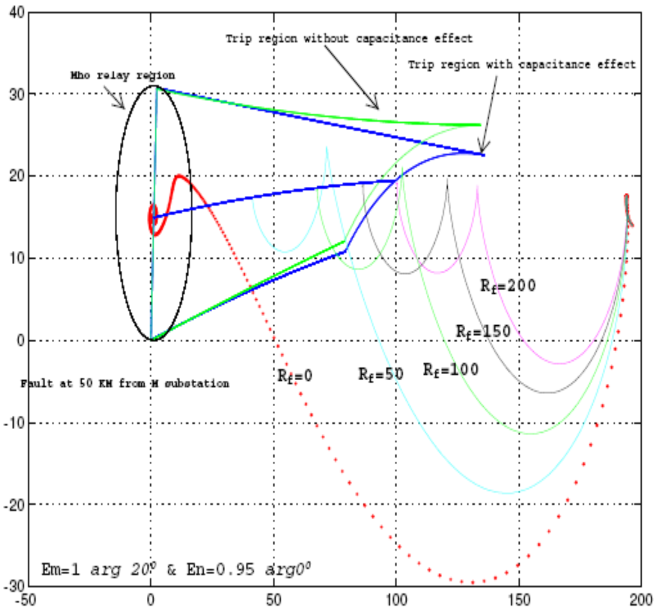


Fig 1.16 Superimposed results of simulation & program

1.7 Two sources equivalent system with Double line

The circuit model for two sources equivalent system with double lines configuration having shunt capacitance and mutual coupling can be expressed as fig 3.9

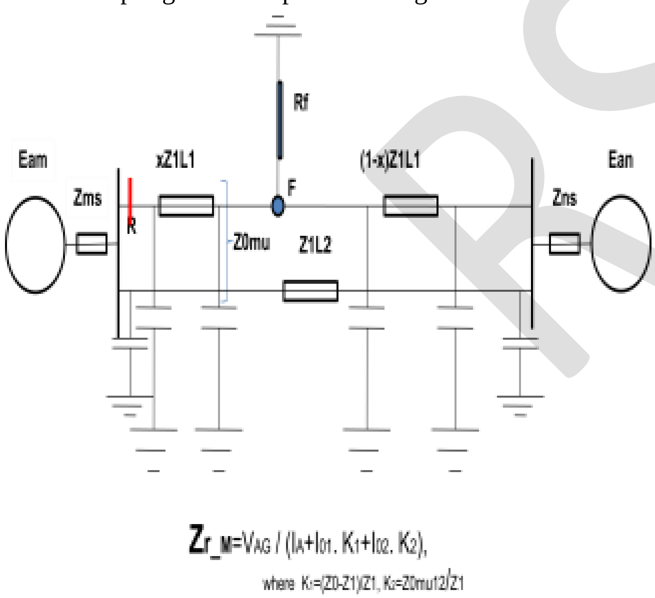


Fig 1.17 Circuit model for two sources equivalent double line configuration

1.8 Effect of shunt capacitance & mutual coupling

As it is assumed that lines are fully transposed, the mutual coupling effect on positive and negative sequence impedances will be around 2% of sequence impedances [12], whereas on zero sequence impedance it will be around 60%-70%[12],[10] of zero sequence impedance, hence, cannot be neglected. The zero sequence network can be modeled as fig 1.18 [12]& [13].

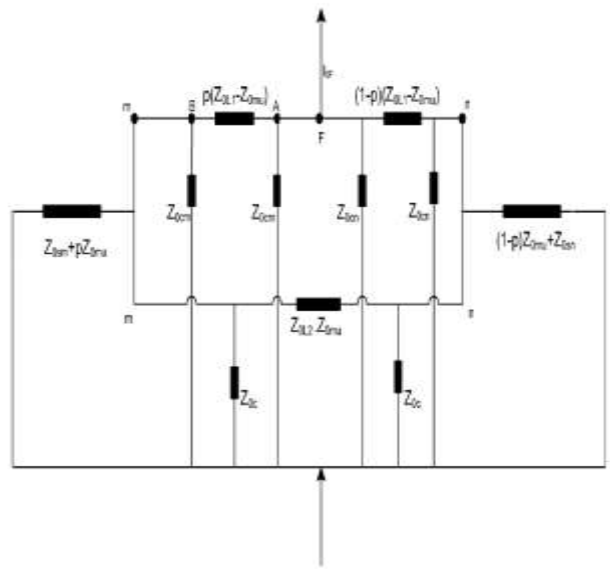


Fig 1.18 Modified Zero sequence Network, source [13]

It is to be noted that in apparent impedance calculation the zero sequence current of healthy line is also given to relay, failing which relay may under reach or over reach depending upon situation as explained in 1.2.4 & 1.2.5. The trip region is given in fig 1.19. The results validation was also done with matlab simulation. The table 1.2 shows the comparison results obtained from program and simulation and they are matching significantly.

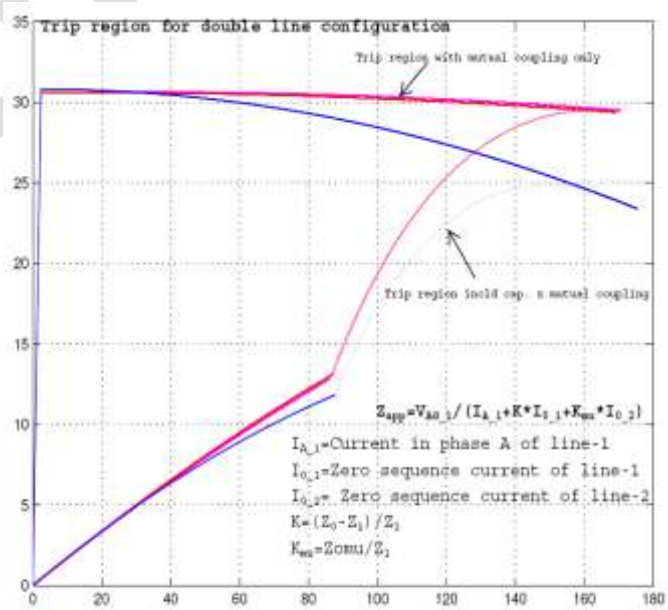


Fig 1.19 Trip region for mutually coupled lines with shunt capacitance

1.9 Comparison

If we compare trip region of system configuration given by fig 1.4 & fig 1.9, we will see that shape is same but trip region for system given by fig 1.9 is larger. The same is shown in fig 1.20

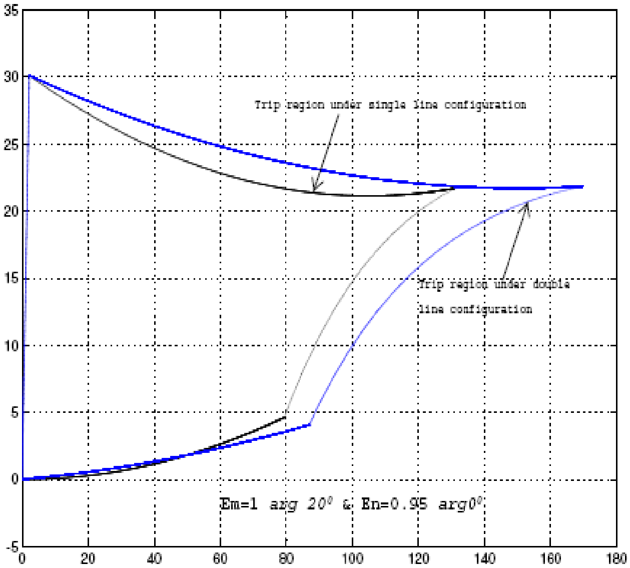


Table 1.20 Trip region comparison

1.10 Three source equivalent system (LILO configuration)

Three source equivalent system forms majority part of our power system. Whenever a new substation or power plant is added, the preferred modification is done by making LILO of two sources equivalent system with double lines configuration as given in fig 1.21

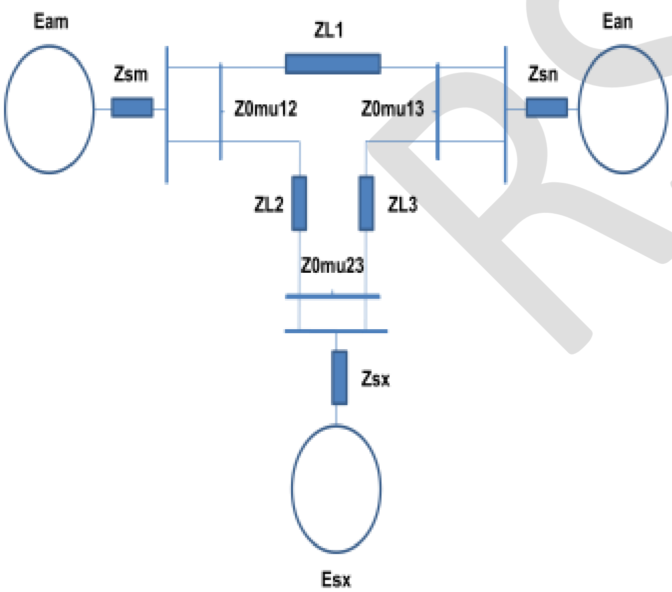


Fig 1.21 Three source equivalent system

Here, the shunt capacitance is not shown for sake of simplicity. The fault model with shunt capacitance can be done as per fig 1.4 or fig 1.9. Here, mutual coupling can be neglected if lines don't run on same tower as may be possible for 765KV system. For 400KV or 220KV system, the mutual coupling effect is prominent, hence, cannot be neglected. The modeling of zero sequence network can be done as per fig 1.22 [12].

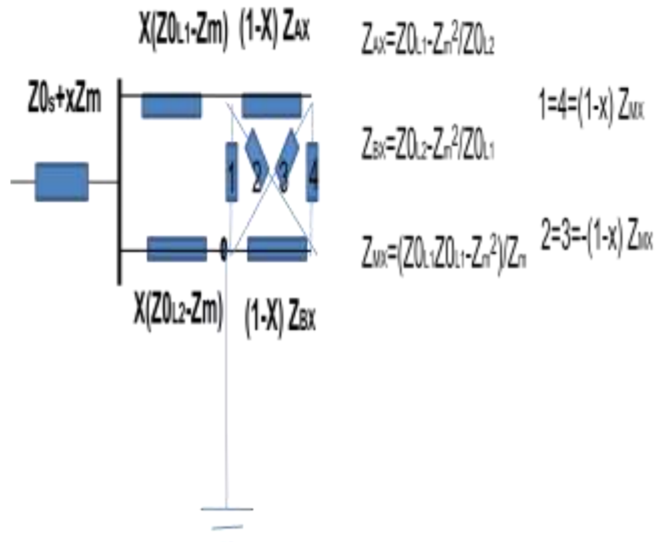


Fig 1.22 Zero sequence network for three sources equivalent system

The trip region is given in fig 1.23 & 1.24.

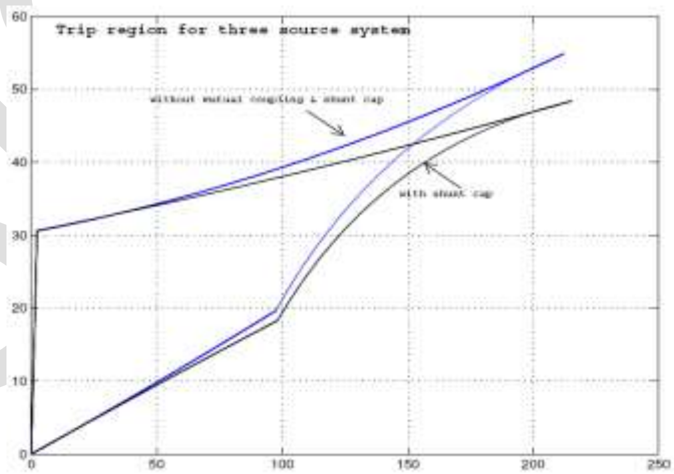


Fig 1.23 Trip region of a line for three source equivalent system under ideal condition & with shunt capacitance

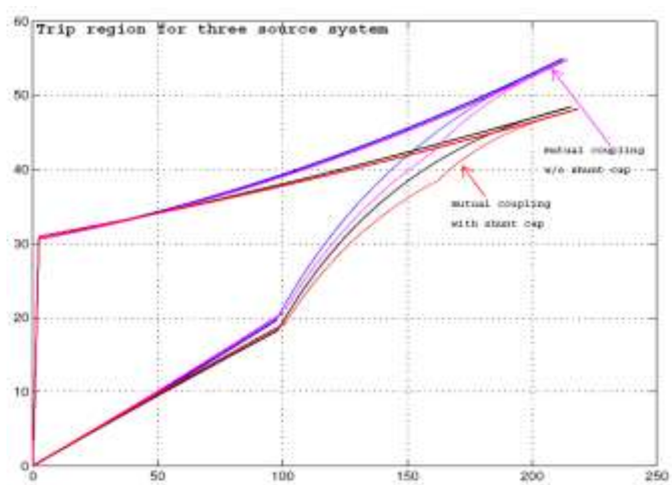


Fig 1.24 Trip region of a line for three source equivalent with shunt capacitance & mutual coupling

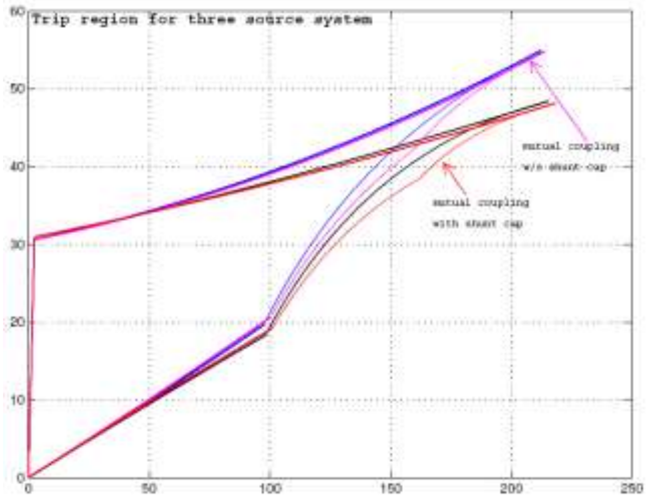


Fig 1.25 Trip region of a line for three source equivalent system under ideal condition & with shunt capacitance

II. TRIP REGION ANALYSIS AND ADAPTIVE SETTING

2.1 Trip region analysis

During normal operation, the operating condition of the line could not be constant; it will change from one condition to the other. The main factors which affect the ideal distance relay operating region are active and reactive power flow in the line. The relay boundary setting should be made adaptive by considering the effects of load flow, shunt capacitance and mutual coupling. This would help to solve the problems in the development of an intelligent adaptive digital distance relay which does not need communication links from the remote end of the line or the system control centre.

2.2 Neural network for adaptive relaying

The artificial neural network (ANN) can be used in power system protection as it is able to perform parallel data processing with high accuracy and fast response. By adapting the relay settings, the adaptive protection is applied to compensate for the influence of various power system operating conditions and this can be done without requirement of separate high speed communication channel for data transmission.

Adaptive protection requires an estimate of the actual power system condition before the fault. To incorporate the effect of prefault active and reactive power flows on the relay trip region, the change in active and reactive power flows with respect to a constant reference values is used as the one of the input parameters to train [9],[10],[13].

Authors have used BPNN (back propagation neural network) [13] and RBFNN (radial basis function neural networks)[10] for training & prediction of results. The performance of both in terms of prediction for unseen data is good. In proposed study, RBFNN has been used.

2.3 Training of neural network with RBNN

For this, the trip region may be divided into four region i.e.a,b,c&d as described in fig 1.3. To train the ANN for adapting to boundary "a", the three input parameters taken as $\Delta P, \Delta Q$and the various values of resistance $R_a$along the boundary "a" with $X_a$as the corresponding output parameter O. Similarly, the three input parameters $\Delta P, \Delta Q,$, and the various values of reactanceX_b along the boundary "b" are considered to train the ANN used to adapt to the boundary "b" with $R_b$taken as the corresponding output parameter. The procedure used to train the ANN, which adapts to the boundary "c", is the same as the procedure of boundary '"a" with corresponding and parameters, whereas training the ANN which adapts to the boundary "d," the input and output parameters are the same as those of the ANN for boundary "b" but with corresponding and values. The aforementioned four different RBNNs were trained individually and the corresponding outputs of trained RBNNs are used together to estimate the trip region for a given prefault load condition.

The network will stop learning when the mean square error (MSE) or number of epochs reached a predetermined target value. In this study, the MSE was set to 0.00001, and the maximum number of epoch for training was set to 300.

The system data [13] is given below:-

$$
\begin{aligned}
&Z_{1L1} = 37.75\angle 86^\circ, \quad Z_{0L1} = 134.5\angle 81.3^\circ,\\
&Z_{1L2} = 37.75\angle 86^\circ, \quad Z_{0L2} = 134.5\angle 81.3^\circ,\\
&Z_{0mu} = 87.425\angle 81.3^\circ,\\
&Z_{1sm} = 20\angle 85^\circ, \quad Z_{0sm} = 30\angle 85^\circ,\\
&Z_{1sn} = 10\angle 85^\circ, \quad Z_{0sn} = 20\angle 85^\circ,\\
&y_{sh1} = (0.00 + j * 0.10371) * 10^{-2}/km(p.u),\\
&y_{sh0} = (0.00 + j * 0.07083) * 10^{-2}/km(p.u).
\end{aligned}
$$

2.4 Testing and prediction of trip region for system under 2.1 & 2.2

For testing/ validation the accuracy of the neural network adaptability, two test cases[13] having different values of active and reactive power flows from training set but within the range of the training set are used. The same are listed in Table 4.2.

Ems(real)	Ems(img)	Ens(real)	Ens(img)	P	Q
1.00926	-0.03877	0.94314	-0.18439	650	175
1.01931	-0.03738	0.94064	-0.19183	700	225

Table 2.2 Testing data set, source [13]

It is seen from Fig. 2.1, 2.2, 2.3 & 2.4 that testing results of the RBNN-based network are able to give a successful prediction for system represented by fig 2.4 & 1.9 i.e two sources equivalent system with single line and double lines with shunt capacitance & mutual coupling as applicable.

Hence, the trained neural networks adapt to the new operating conditions quite accurately. So based on the operating condition and the variation in the value of the proposed measured impedance considering the mutual coupling and shunt capacitance effects, the adaptive relay will be able to take more appropriate trip (or no-trip) action as demanded under a particular operating condition.

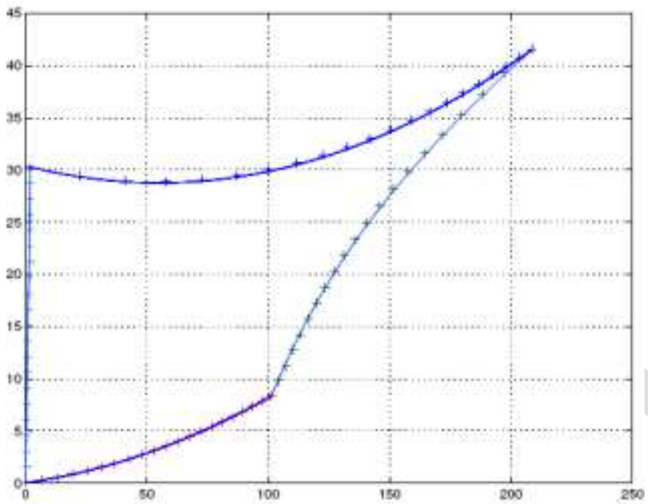


Fig 2.1 Predicted (+) vs actual (─) trip region for two sources equivalent single line system for test data 1

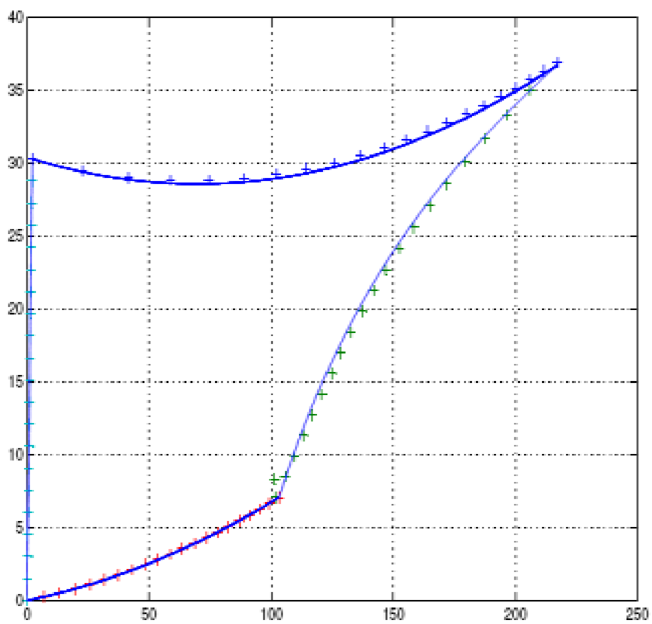


Fig 2.2 Predicted (+) vs actual (─) trip region for two sources equivalent single line system for test data 2

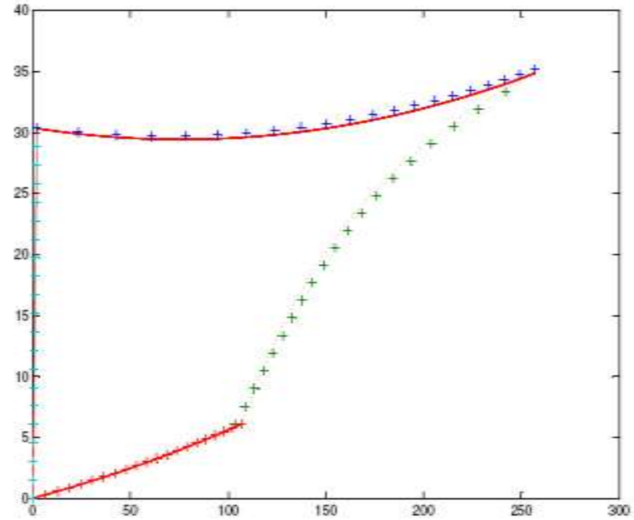


Fig 2.3 Predicted (+) vs actual (─) trip region for two sources equivalent double line system for test data 1

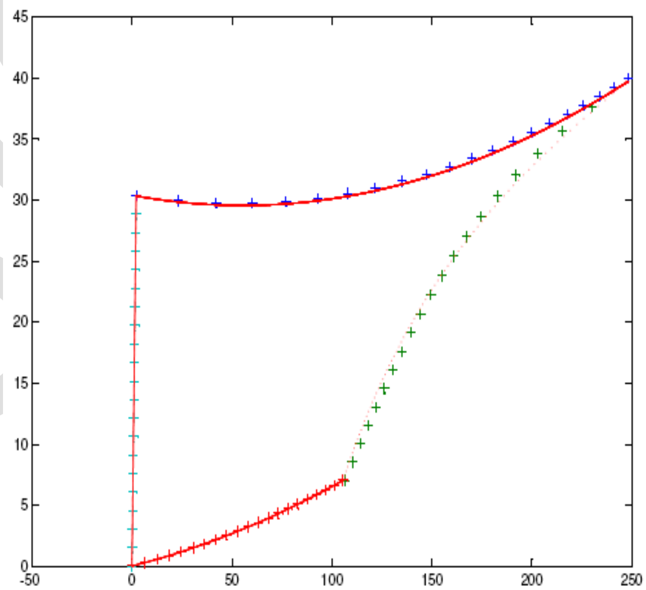


Fig 2.4 Predicted (+) vs actual (─) trip region for two sources equivalent double line system for test data 2

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