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Study and Analysis of the Offset Mho Characteristics for the Loss of Excitation Protection of an Alternator

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Abstract - *Loss of Excitation threatens the generator and power system stability. Several criteria have been proposed for loss of excitation detection and some of them are field under voltage/current criterion, impedance criterion, reverse reactive power criterion etc. Among them impedance boundary of steady state stability limit (SSSL) is widely used. But this criterion is sensitive to the variation of output active power of synchronous generator and may mal-operate in external faults, power swings and other non-LOE condition. In this study a Novel adaptive protection criterion with an offset mho element based on SSSL is used to distinguish LOE from non-LOE condition. This adaptive criterion could automatically adapt to the system operating modes and correctly operate in LOE condition. The impedance boundary circle of the steady state stability limit can adaptively fit for operating modes. The simulation results show that the adaptive impedance criterion is better for reliable protection against LOE and non-LOE condition.*

Key Words*- Adaptive criterion, External faults, Generator protection, Loss of Excitation (LOE), Power swings, Synchronous generator, Steady state stability limit.*

I. INTRODUCTION

In power generating plants Loss of Excitation (LOE) is a critical fault condition caused due to the accidental tripping of a field breaker, AVR system failure, field open short circuit (flashover of the slip rings), or even generator protection mis-operation. With the development of power system network Loss of Excitation protection of synchronous generators is becoming more and more important for the reliability of the system [1].

Generator may completely or partly lose its field excitation. Complete loss of excitation means the generator field voltage is reduced to zero. The partial loss of excitation means only part of field winding is excited by the voltage. Loss of Excitation causes the generator to absorb large amount of reactive power from the grid. This condition causes the machine speed to go above the synchronous speed, and the machine starts operating like an induction generator. So, the machine draws a large amount of reactive power from the power system [2][3].

Reasons for loss of excitation:

Generator may fail to have its field supply due to various causes. Generally, the generator may completely or partially lose its excitation depending upon the cause. Some of the reasons for occurring of the loss of excitation condition are,

- Field winding open circuit.
- Field winding short circuit.
- Flash over occur at brushes or slip rings.
- Loss of supply to the main exciter.
- Accidental field breaker tripping.
- AVR control circuit failure.

II. LOE PROTECTION BASED ON IMPEDANCE METHODS

Mho distance relays are widely used within the industry to provide high – speed LOE detection. Currently, the most accepted methods for LOE protection are the Berdy and Two zone positive Offset approaches. Both are impedance – based methods with a negative offset Mho and Two zone positive offset Mho with directional unit supervision [4][5].

2.1 Berdy or negative offset Mho relay characteristics:

Negative Mho offset relay is a single-phase single element high speed distance relay. It is arranged to operate from the voltage between two phases, and the difference between the currents of the two phases, at the terminals of the generator to be protected. The operating characteristic plotted on an R-X diagram. The centre of the circle is on the –X axis. The Offset is approximately equal to half of the direct – axis transient reactance of the generator and diameter is approximately its direct --axis synchronous reactance. The relay will operate to close its contacts for any impedance vector such as Z, which terminates within the circular operating characteristic shown in figure 1[6].

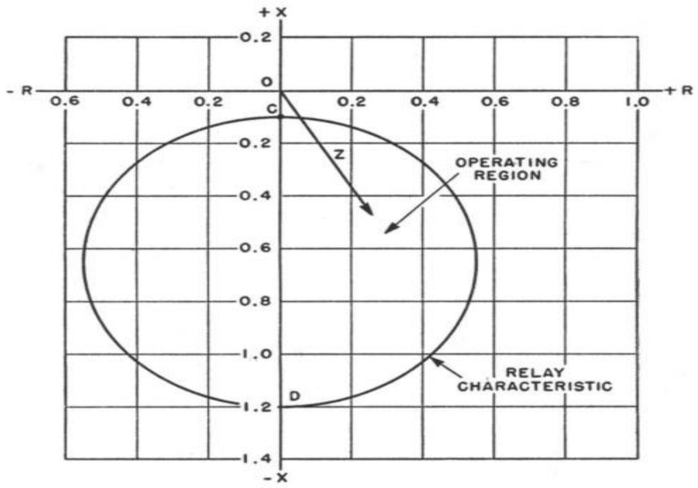

Figure 1. Operating characteristics of negative offset mho relay

2.2 Two zone positive Mho offset with directional unit:

Two zone positive offset contains two circle zones shown in figure 2. One is outer circle called as zone-2 and the inner circle is called as zone-1. Zone-2 reach diameter is equal to 110% of direct axis reactance (X_d) plus system reactance (Xs) with an offset which is equal to the system reactance (Xs). Generally, the system reactance (Xs) is considered as both the transformer reactance (X_t) plus transmission line system reactance. But in this proposed scheme only transmission line reactance (Xs) is considered and the transformer reactance is neglected. Here the system reactance (Xs) is referred as the transformer reactance (X_t) [7].

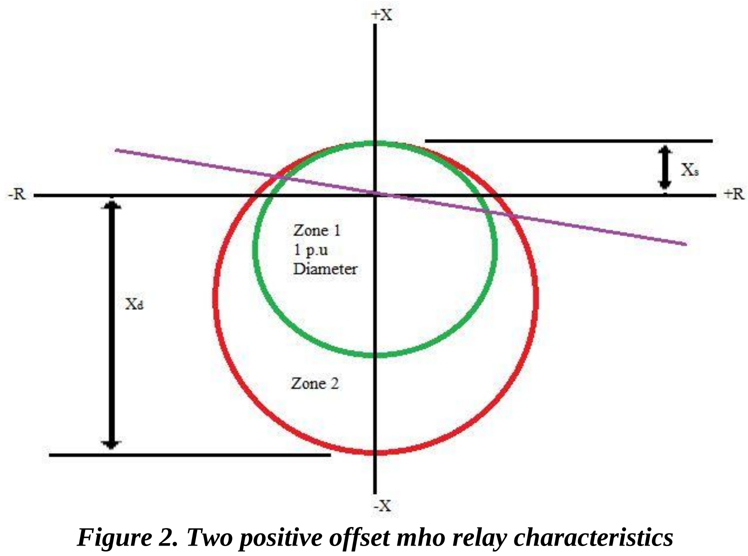

Figure 2. Two positive offset mho relay characteristics

III. STEADY STATE STABILITY LIMIT CIRCLE

The Impedance boundary criterion of steady state stability limit is commonly used for the detection of the Loss of Excitation (LOE). It is analyzed in a single-machine infinite bus system, as shown in the figure 3[1][6][8].

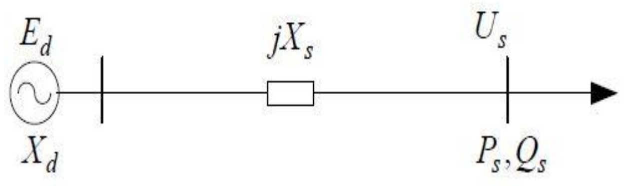

Figure 3. Single machine infinite bus system

As the system shown in Fig. 3, the active and reactive power of the synchronous generator can be expressed as follows:

$$P_s = \frac{U_s E_d}{X_d + X_s}$$

$$Q_s = \frac{-U_s^{\ 2}}{X_d + X_s}$$

Where,

- X_d is the synchronous reactance of a non-salient pole generator.
- E_d is the inner electric potential of the generator.
- X_s is the connecting system reactance.
- U_s is the voltage of infinite-bus system.
- P_s, Q_s is active and reactive power output to the system.

Then the impedance boundary of SSSL at the generator terminal is,

$$Z_{G.cr} = \frac{V_s^{\ 2}}{P_s - jQ_s} + jX_s$$

$$Z_{G.cr} = \frac{-j(X_d - X_s)}{2} + j\frac{(X_d + X_s)}{2} e^{j2\varphi})$$

Where $\varphi_s = \arctan\frac{Q_{s,cr}}{P} = \arctan\left[\frac{-U_s^{\ 2}}{(X_d + X_s)P}\right]$

IV. ADAPTIVE PROTECTION CRITERION FOR LOSS OF EXCITATION PROTECTION

From the beginning of Loss of Excitation to the boundary of Steady State Stability Limit (SSSL) and in normal operating conditions, slip is approximately equal to zero, and the excitation voltage U_L is equal to the electrical potential, E_d in per unit value.

Then the impedance boundary circle shown in figure 4 is as follows:

$$Z_{G.cr} = -j\frac{U_{lb}}{2P_s}\left(1 - e^{j2\varphi}\right) + jX_s$$

$$= \frac{-jU_{lb}}{2P_s} + j\frac{U_{lb}}{2P_s} e^{j2\varphi_s} + jX_s$$

From the above equations the center, C= $\left[0, \frac{-jU_{lb}}{2P_s}\right]$ and the radius will be as shown below, r = $\frac{U_{lb}}{2P_s}$, Where U_{lb} and X_s are the impedance boundary circle settings of the adaptive protection criterion.

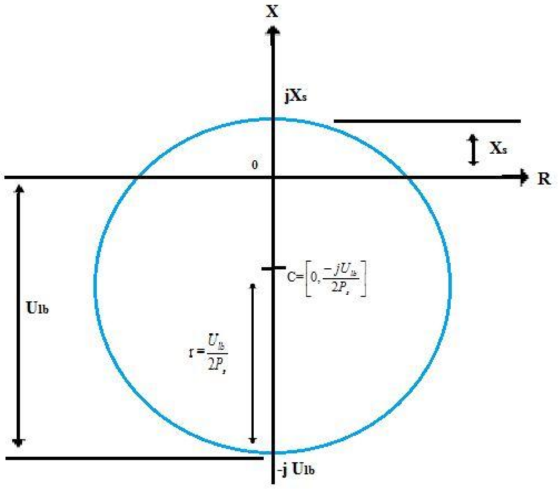

Figure 4. The impedance boundary circle of adaptive protection criterion

To develop a complete protection scheme, some methods to resolve the problems like external fault, power swings etc.
Method 1: External fault can be resolved by adding negative sequence current blocking unit for ground or arcing ground faults, and directional unit for symmetrical faults. A time delay unit can also resist external fault well.
Method 2: Power swing, time delay could be adopted to prevent mal-operation.
According to all the analysis above, a LOE protection scheme based on the adaptive criterion could be presented as shown in Figure 5.

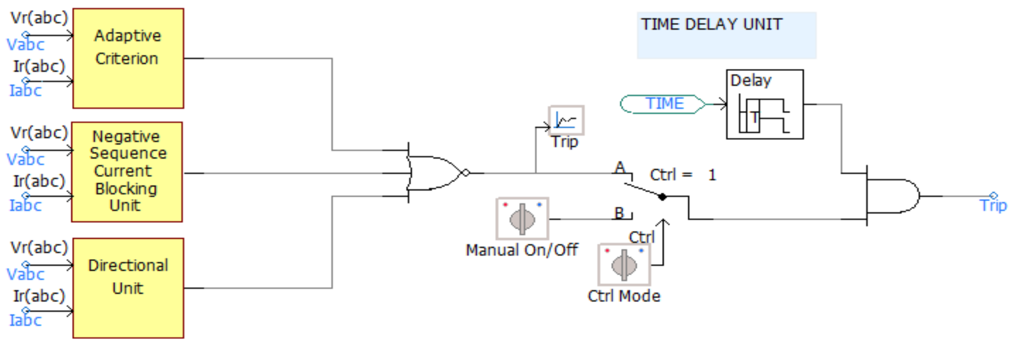

Figure 5. Adaptive loe protection scheme logic diagram

V. PROPOSED ALGORITHM ON PSCAD

The PSCAD model of test power system model is developed. Loss of Excitation is obtained by applying timed logic field voltage tripper. Protection algorithm is developed using Frequency Fourier Transform (FFT) blocks. These FFT blocks extract the phase voltages and the phase currents. The phase voltages and currents are converted into Positive, Negative and Zero sequence voltages and currents respectively by sequence filter blocks is in figure 6(a) and 6(b).

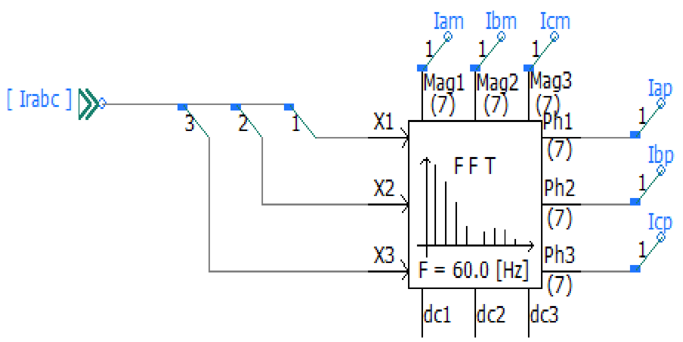

Figure 6(a). Frequency Fourier Transform (FFT) blocks for phase currents

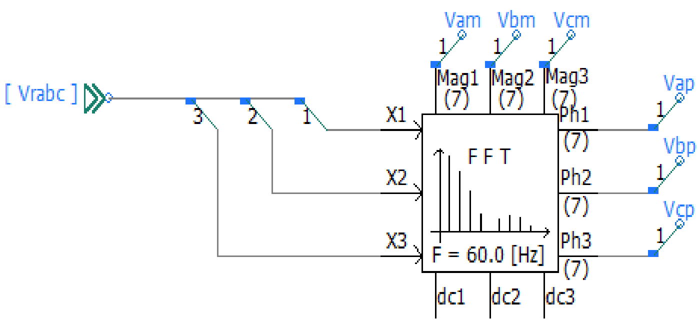

Figure 6(b). Frequency Fourier Transform (FFT) blocks for phase voltage

From the direct axis reactance and transient reactance parameters of the test system synchronous generator, the Zone1 and Zone2 circles radius and origins are calculated. These calculations are done using the subsystems shown in figure 7(a) and 7(b). These values are given to the Offset mho relay block and time delay block introduce to set relay intentional time delay for each zone. Finally, these two zones of relays are connected by OR gate and output of this gate create a relay trip signal.

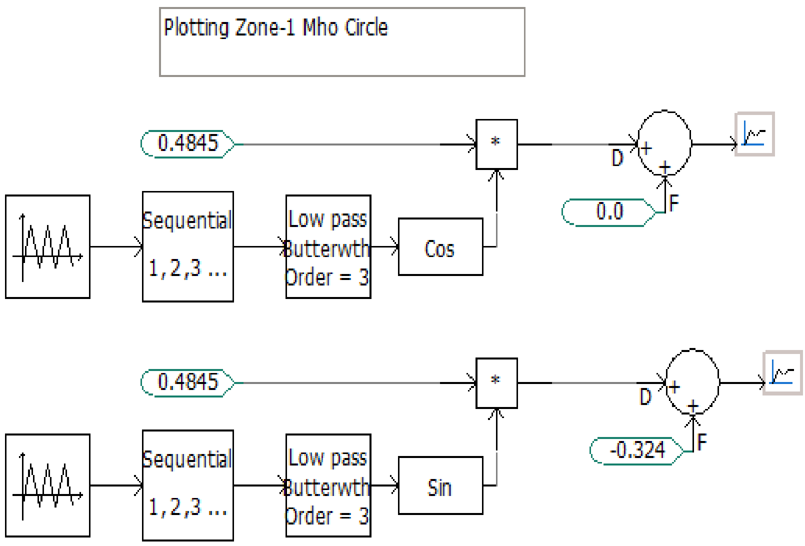

Figure 7(a). Algorithm to plot zone1 mho circle

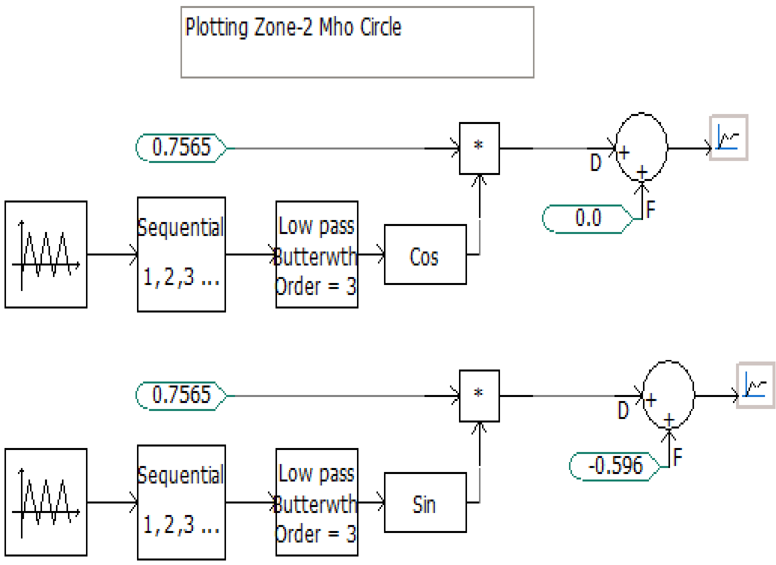

Figure 7(b). Algorithm to plot zone2 mho circle

VI. SIMULATION RESULTS OF THE ADAPTIVE LOE PROTECTION CRITERION

The simulation results were shown for the two different cases

5.1 LOE (During field fault condition):

From the Figures 8 and 9, it can be observed that in the case of without adaptive protection criterion the impedances trajectories took more time to enter in the impedance circles.

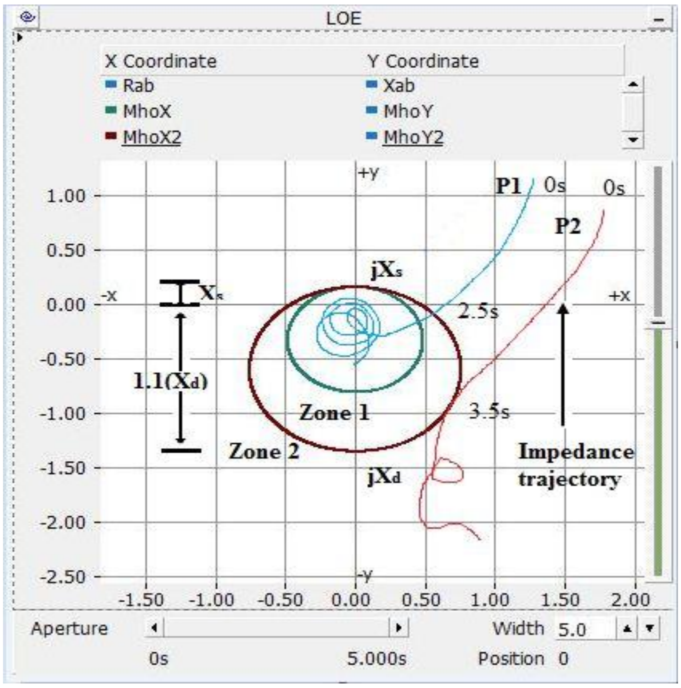

Figure 8. Impedance boundary circles and trajectory of loe without adaptive protection criterion in R-X plane

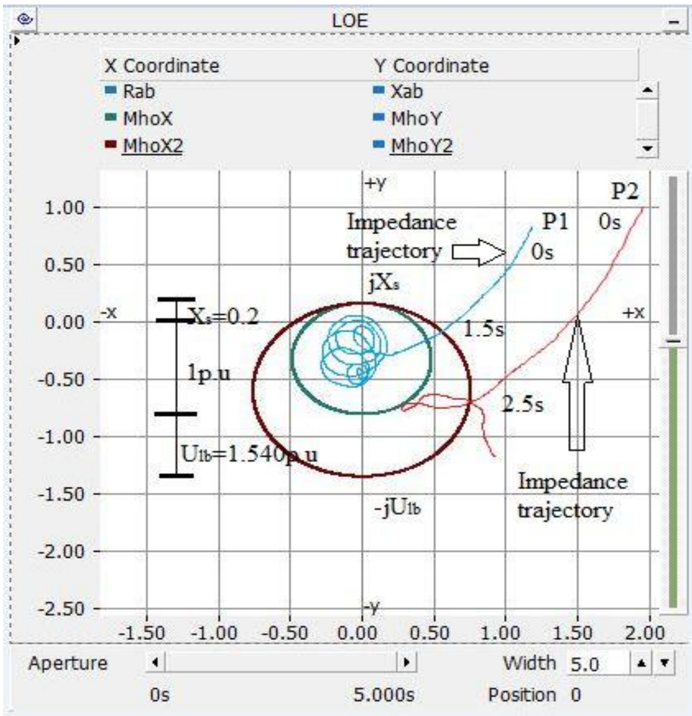

Figure 9. Impedance boundary circles and trajectory of loe with adaptive protection criterion in R-X plane

During light load condition even, trajectory didn't enter into the impedance circle. But with the case of adaptive protection criterion follows the change of the generator load, impedance trajectories took shorter time to enter into the circles to reliably trip rather than the traditional impedance criterion.

5.1 Non-LOE (External fault condition):

From the Figures 10 and 11, it can be observed that with adaptive protection criterion, the simulation results under single phase ground fault are verified the effectiveness of the blocking methods mentioned above.

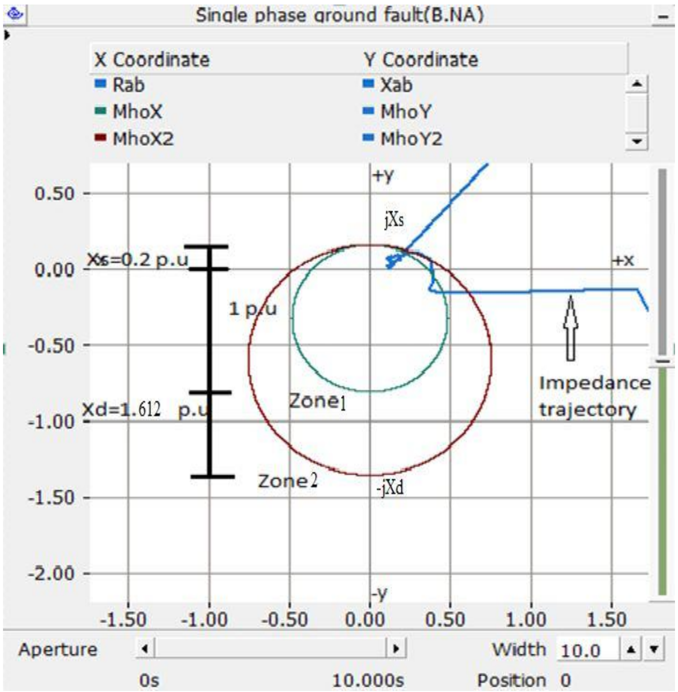

Figure 10. Impedance boundary circles and trajectory of single-phase ground fault without adaptive protection criterion in R-X plane

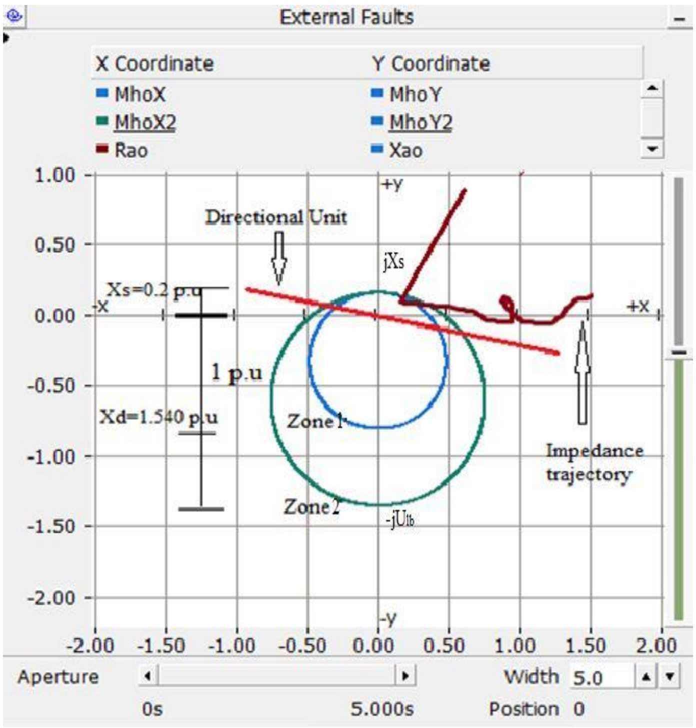

Figure 11. Impedance boundary circles and trajectory of single-phase ground fault with adaptive protection criterion in R-X plane

For the external faults the impedance trajectory is much faster than LOE, in order to avoid this the negative sequence current unit and directional and a time delay is used.

From the Figures 12 and 13, it can be concluded that the simulation results under the three-phase ground fault is verified with and without adaptive protection criterion and verified the effectiveness of the blocking methods.

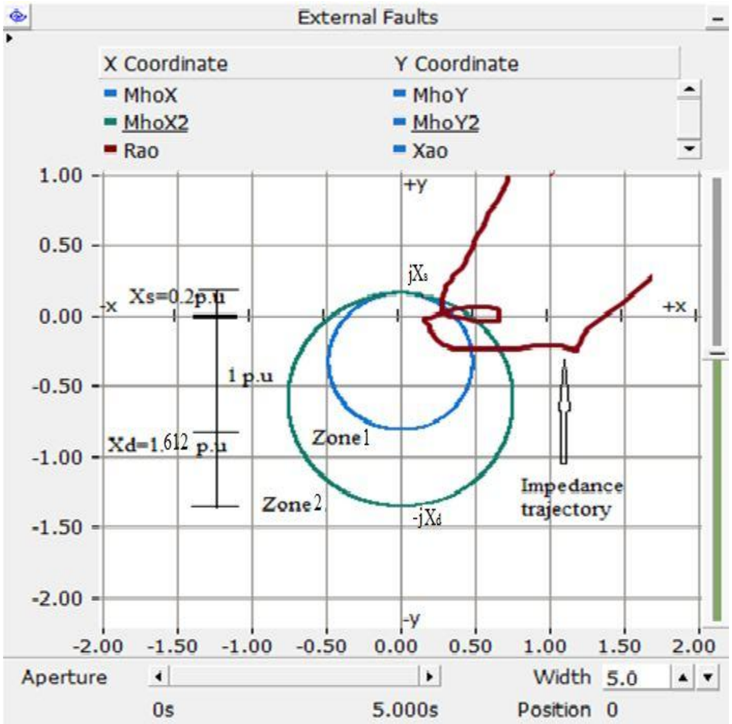

Figure 12. Impedance boundary circles and trajectory of three phase ground fault without adaptive protection criterion in R-X plane

The impedance trajectory of the three-phase fault is blocked by the blocking units like negative sequence current blocking unit and directional unit and time delay unit to resist the impedance trajectory, not to enter into the circles. This is how the relay mal operation is overcome during the non-LOE condition. By this the effectiveness of the relay will improve to operate at the different operating modes at different fault conditions, and reliability of the power system is improved.

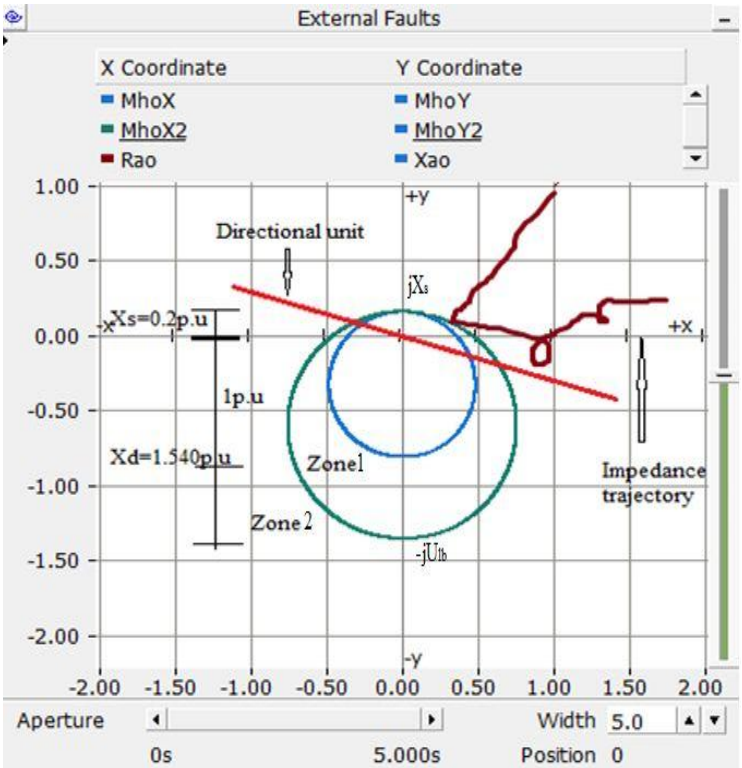

Figure 13. Impedance boundary circles and trajectory of three phase ground fault with adaptive protection criterion in R-X plane

VII. CONCLUSION

It is observed that the traditional impedance boundary criterion scheme fails to differentiate the LOE and non-LOE condition, but with the Adaptive protection scheme, it is able to detect and mitigate the mal-operation of relays during non-LOE conditions. Not only that, the traditional impedance scheme takes more time to give the trip initiation, when compared with the adaptive protection criterion with the positive offset mho element.

- With the help of Adaptive criterion, the reliability of the system at different operating conditions is improved and reduce mal-operation of LOE protection.

- Mal operation over the external faults is avoided by adding negative sequence current blocking unit and directional unit, which improved the reliability of the protection scheme.

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