Effect of Single Phase to Ground Fault with Arc Resistance on the Performance of Distance Relay

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Abstract—**Distance relay is the main protection of power transmission lines and make an important role in power system stabilization if it operates selective and instantaneous. In this paper, the trajectory of the fault impedance is determined. It is shown that in the end of the first zone or in the middle of the second zone, distance relay could not make a correct decision for operating if the fault occurs with arc. So to overcome this problem, in this paper a novel technique using total harmonic distortion (THD) is proposed. The proposed method makes the distance relay more selective and instantaneous.**

Keywords- Distance protection; Arcing faults; Total harmonic distortion; Fast Fourier analysis;

I. INTRODUCTION

Protection layer is defined as the calm layer of power system, because this layer should not operate in normal conditions and has an instantaneous and selective operation in fault conditions. Distance relay is a common protection device in line protection, which measures voltage and current samples to calculate the impedance [1-3]. If the calculated impedance is less than the adjusted setting of relay, and remains this condition for specific samples, the relay will send a command function to circuit breaker for operation, otherwise it should not operate. In normal condition, relay should not operate but in some cases named power swing [4-5], although there is no fault in the system, but relay makes a mistake and operates. This problem is solved by power swing blocking, which uses impedance variation rate for detecting this condition [6]. In fault condition, according to measured impedance, one of the relay zones will pick up. In this circumstance, if fault is taken placed at the first zone, it is expected that relay operates instantaneous and selective. If the fault is solid or with a fixed resistance, according to relay characteristic, it calculates the fault distance and operates according to related zone [7-8].

Based on the statistics data, about 70~80% of faults in power systems are single-phase to ground faults, and most of them are transient and occur with arc [9]. Arc has a variable resistive characteristic, which can affect the operation of distance relay. In this paper, the effect of arcing single phase to ground fault is simulated and shown if an arcing fault occurs at the end of the first zone or a little later, distance relay cannot detect it in a selective and instantaneous manner, although the fault is in the first zone. To distinguish arcing fault situation from a solid fault situation, it used total harmonic distortion factor and is shown it can help the relay to operate in a selective and instantaneous manner.

The organization of this paper is as follows: the dynamic arc characteristic is modeled in Section II. Section III explains the scheme of a digital distance relay. The simulation results presented in section IV and Section V provides conclusions regarding this work.

II. DYNAMIC CHARACTERISTIC OF FAULT ARCS

A. Arc model

Assume for any reason the insulation strength between one conductor of transmission line and tower that hold it is reduced. Because of this reason, a short circuit is happened and because of high voltage and low impedance, large quantity of current flows through this path. According to design of power system, the amplitude of this current will vary from 1400A to 24000A [10]. In short circuit condition the column of air ionized by arc length is fixed at the arc place, but with a large cross section to be suitable to able pass such a large flow from this path. Studies have shown that the voltage drop on the column of arc almost independent of amplitude of current and the physical profile curve only depends on weathers location of arc place. This voltage drop is constant and about 15 Volt per Centimeter. Different equations for arcing fault model are presented such as linear equations with constant coefficients, a piece wise of linear equations and differential equations. In this paper, differential equations are used for modeling arcing faults. Some studies show that the dynamic arc characteristics can be exactly simulated by the following arc equation [11].

$$\frac{dg_p}{dt} = \frac{1}{T_p}\left(G_p - g_p\right) \qquad (1)$$

In this equation g_p is the conductivity of arc, T_p is primary arc time constant and G_p is the conductivity of primary arc which can be evaluated by:

$$G_p = \frac{|i|}{V_p L_p} \qquad (2)$$

Where L_p is the length of arc, V_p is the average constant arc voltage gradient and be about 15 V/cm and i is current of

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primary arc. Time constant T_p is calculated using experimental curve and is shown with (3) [10].

$$T_p = \frac{\alpha I_p}{L_p} \quad (3)$$

where the coefficient α is about 2.85×10^{-5} for heavy current arcs, which is empirically obtained by fitting (1) with (2) and (3) to match the experimental cyclograms of the arc currents ranging from 1.4 kA to 24 kA. In this paper, to obtain the normalizing arc peak current I_p, it is used from this fact that, for heavy current primary arcs, the arc voltage drop will be very small. Consequently, in order to estimate I_p, the fault is assumed as a solid fault, and fault analysis is then carried out to determine the fault current I_p, for the latter condition.

B. Solving the arc model equation

For modeling the primary arc it should change the differential equation to difference equation as shown in (4).

$$\frac{dg_p}{dt} = \frac{1}{T_p}\left(G_p - g_p\right) \rightarrow \frac{\Delta g_p}{\Delta t} = \frac{1}{T_p}\left(G_p - g_p\right) \quad (4)$$

So by solving this equation it can find the conductivity of arc with an equation like (5).

$$g_{p1} = \left(g_{p0} + \frac{|i|\Delta t}{\alpha V_p I_p}\right)\left(1 + \frac{L_p \Delta t}{\alpha I_p}\right)^{-1} \quad (5)$$

g_{p0} is the initial value of arc conductivity and is changed in each iteration of solving this equation.

III. DIGITAL DISTANCE RELAY

A simple mho distance function, with a reach of Z ohms, is shown in Fig. 1. This diagram is exactly equal to an R-X diagram except that all the impedance vectors have been operated on by the current I. The mho function uses the current and voltage measured at the relay point to determine if the apparent impedance meet within the mho characteristic. To calculate impedance, relay uses voltage and current samples. At first, relay calculates amplitude and angle for fundamental harmonic component of voltage and current of each phase, then a block is used for estimating positive, negative and zero sequences of voltage and current.

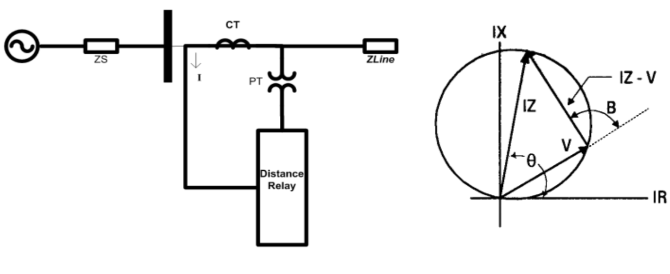


Fig. 1: Mho distance relay operation

Assuming the N samples are obtained for each period, and that discrete time signals are X(k) then sampled signals are given as in equation (6).

$$X(n) = \sum_{k=0}^{N-1} X(k).\, e^{-i\left(\frac{2\pi nk}{N}\right)} \quad (6)$$

$$X_1 = \frac{2}{\sqrt{2.N}} \sum_{k=0}^{N-1} X_k.\, e^{-i\left(\frac{2\pi k}{N}\right)} \quad (7)$$

where n is the order of the harmonics. The fundamental frequency signal is the one with n=1. N is the number of samples contained in the data window. In equation (7) all the N samples are used in the calculation of the fundamental frequency signal, resulting in a full cycle Discrete Fourier Transform (DFT).

The extraction of fundamental frequency component of voltage and current signals via discrete Fourier transformer is used and then for single phase to ground impedance calculation, zero sequence of voltage and current are needed. Resistance and reactance are then calculated from voltages and currents samples (k) at relaying point as in (8) and (9).

$$R_k = \mathrm{Real}\left(\frac{V_k}{I_k + (K_0).I_{0k}}\right) \quad (8)$$

$$X_k = \mathrm{Imag}\left(\frac{V_k}{I_k + (K_0).I_{0k}}\right) \quad (9)$$

where K_0 is the compensation factor and is calculated using (10) and I_{0k} is zero sequence of measured current, which is calculated using (11).

$$K_0 = \frac{z_0 - z_1}{z_0} \quad (10)$$

$$I_{ok} = \frac{I_{ak} + I_{bk} + I_{ck}}{3} \quad (11)$$

I_{ak}, I_{bk} and I_{ck} are currents of each phase measured at the relay point.

If the fault is two phase fault, measured impedance will be calculated using equations (12)-(14) which are not depend on zero sequence of measured current.

$$Z_{ab} = \left(\frac{V_a - V_b}{I_a - I_b}\right) \quad (12)$$

$$Z_{bc} = \left(\frac{V_b - V_c}{I_b - I_c}\right) \quad (13)$$

$$Z_{ca} = \left(\frac{V_c - V_a}{I_c - I_a}\right) \quad (14)$$

where V and I are voltage and current of each phase. R_k and X_k in two phase fault are real and imaginary part of equations (12)-(14).

IV. SIMULATION RESULTS

For analyzing the effects of arcing faults on the operation of distance relay, a simple power system is selected and its three phase diagram is shown in Fig. 2. It is assume that the direction of pre-fault power flow wasn't change during fault.

The system operates in 230kV, 60 Hz. The positive and zero sequence of the line parameters is shown in Table I.

Relay zones are defined as 80% of line 1 as zone 1, 100% of line 1 and 50% of line 2 as zone 2 and 100% of line 1 and 100% of line 2 and 20% of line 3 as zone 3. Setting of relay is done and assuming the fault is solid, so it means if a solid fault occurs in each zone, the relay can operate in a selective manner.

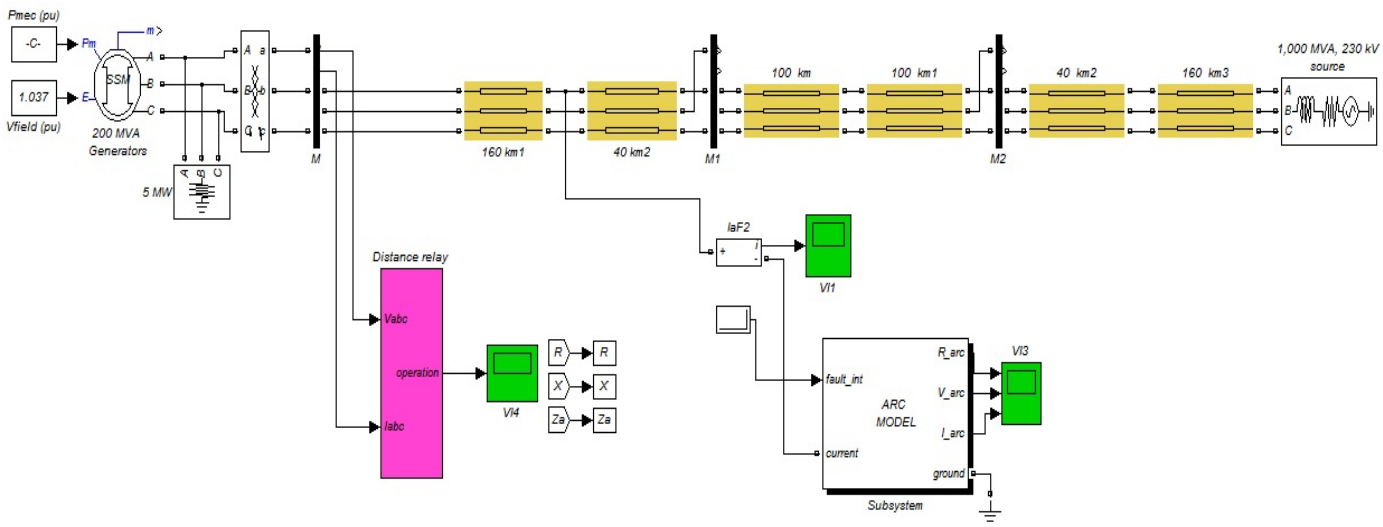


Fig. 2: Three phase diagram of the system under study

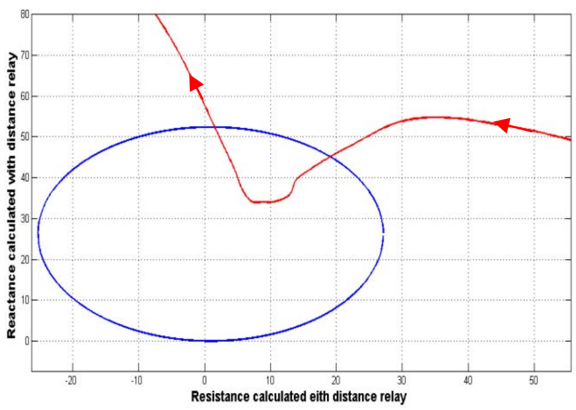
TABLE I. LINE DATA

	Positive Sequence	Zero Sequence
R(Ω/km)	***0.01165***	***0.2676***
L(mH/km)	***0.8679***	***3.008***
C(nf/km)	***13.41***	***8.57***

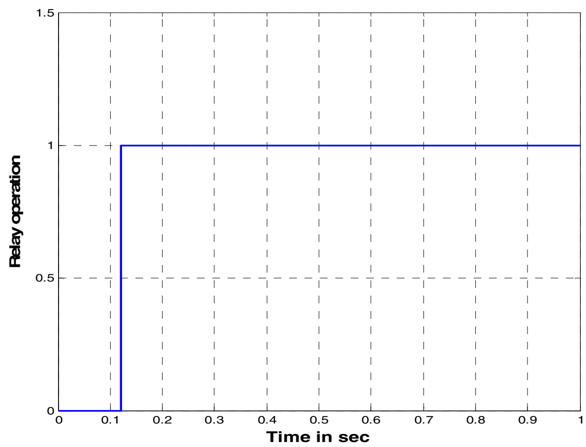
Operation of distance relay for a solid single phase to ground fault at the end of zone 1 is shown in Fig. 3 and it can see the trajectory of impedance is fall in the area of zone 1 and remain in it for specific samples so the relay picks it up and issues the operation function to the breaker and fault will clear in a selective and instant manner.

In this simulation, the sample time is taken to be 50 micro seconds, and a solid fault is occurred at 80% of the line 1 (zone 1).

Now assume an arcing fault occurs at 78% of line 1, which related to zone 1. The arc model is simulated in Matlab software. Arc parameters for this system are presented in Table II.



(a) Impedance trajectory



(b) Relay function

Fig. 3: Operation of distance relay with solid fault (it is detected in the first zone and clear it)

TABLE II. ARC CHARACTERISTIC DATA

V_p (V/cm)	***15***	α	***2.85*10⁻⁶***
I_p (A)	***3000***	Δt(sample time)	***50*10⁻⁶***
G_{p0} (1/Ω)	***0.05***	Fault time (sec)	***0.1***
L_p (cm)	***350***		

With these arc parameters, the operation of relay is going to study. First it should analyze the arc characteristic, so resistance, voltage and current of the arc at arc point is plotted in Fig. 4.

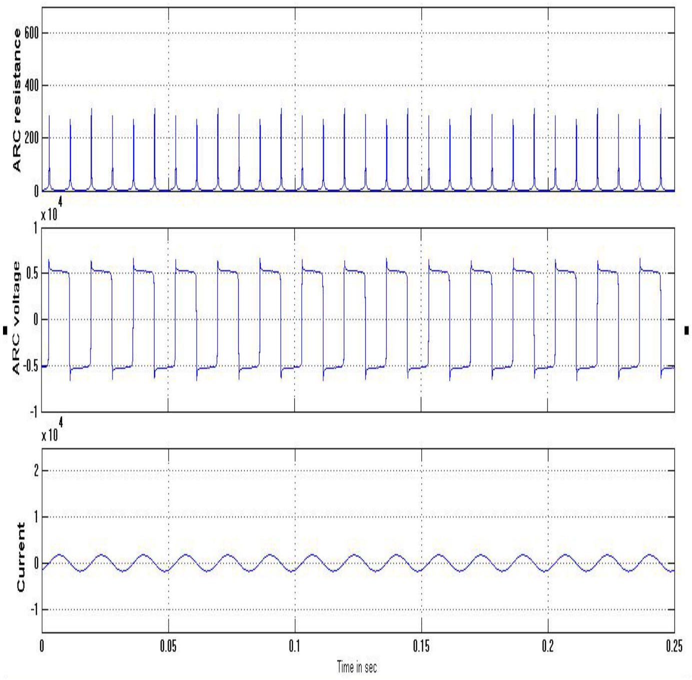
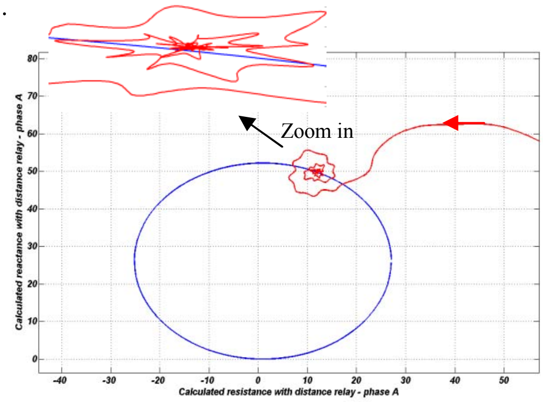
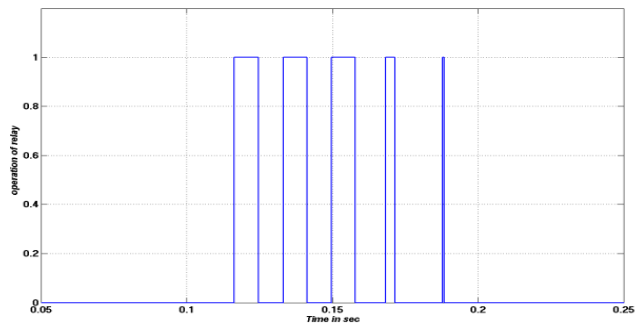


Fig. 4 : Arc characteristic; Resistance, voltage and current

So with this arc situation, the trajectory of impedance is plotted in Fig. 5(a). Also, the relay command is shown in Fig. 5(b).



(a) Impedance trajectory

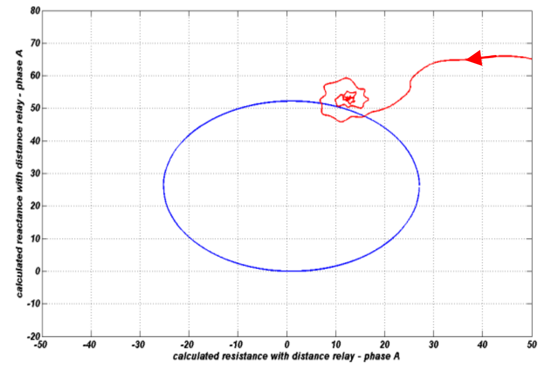


(b) Relay function

Fig .5 : Operation of distance relay with arcing fault

As shown in simulation, it can be seen that if an arcing fault occurs at the end of first zone or near it, relay cannot make a correct decision, and the fault is seen at the second zone. It means, for example, if an arcing fault occurs at 78% of line 1, which is in zone 1, it is seen in second zone and also with a time delay, because zone 2 is not instantaneous.

Let test arcing fault if it occurs at 85% of line 1, which pertain to zone 2 in setting. This situation is shown in fig. 6.



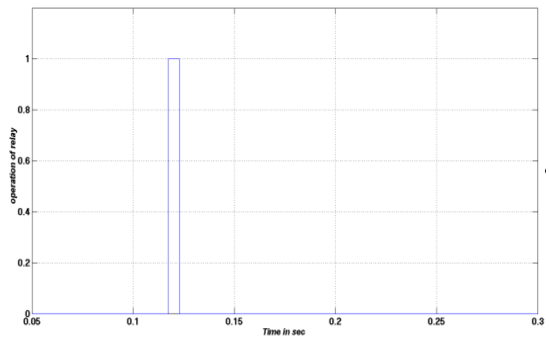


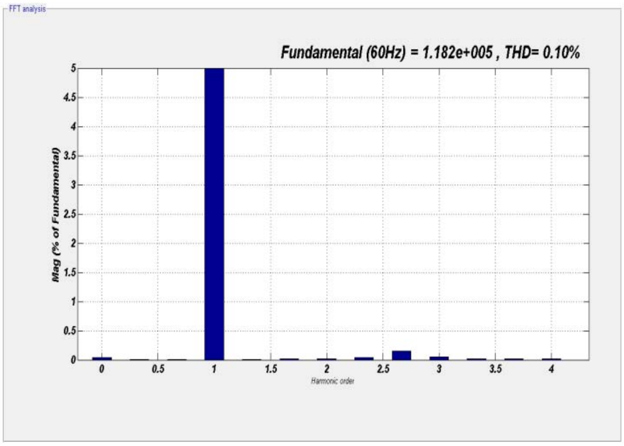
Fig. 6: Operation of distance relay with arcing fault at 85% of line 1

In this situation trajectory of impedance will fall in zone 1, but it converges at zone 2.

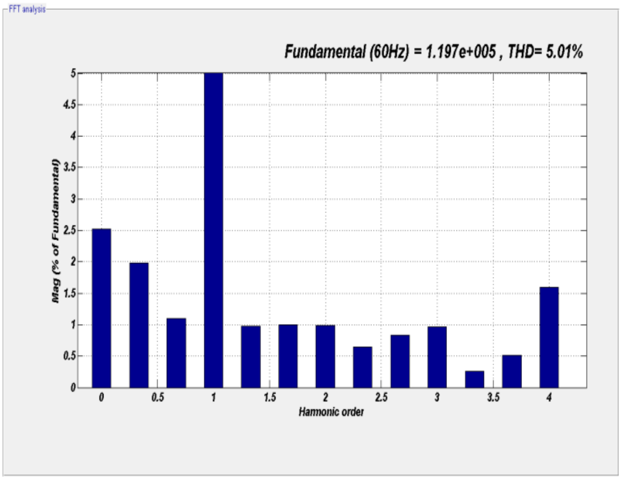
In order to improve the performance of distance relay in terms of arcing fault, an adaptive distance relay to detect this situation is presented. As arcing fault has a variable resistance as shown in fig. 4, the trajectory of impedance is lied in zone 1 and zone 2, so it wasn't still in one situation that relay picks it up and sends trip command, so the relay cannot make an correct and immediate decision. To improve distance relay sensitivity, it can use the harmonic information of fault characteristic for detecting the arcing fault condition. If a solid single phase to ground fault occurs, the voltage of faulty phase has only fundamental harmonic as shown in Fig. 7, but if an arcing fault occurs, the voltage of that phase has other harmonics too. So it is suggested to use total harmonic distortion (THD) factor to detect the arcing fault and make a correct decision. So, if an arcing fault occurs, it happened with much more THD factor, thus this factor can use to distinguish the arcing fault type and solid fault. So in arcing fault condition with improved relay, it can detect the arcing fault in a more selective and rapid manner. In this situation, the improved relay can set its zones according to arcing fault situation or solid fault condition. At solid fault conditions, the relay settings are defined as before mentioned and at arcing fault, we can define the zones as follows:

Zone 1= 90% of line 1
Zone 2= 100% of line 1 and 60% of line 2
Zone 3= 100% of line 1 and 100% of line 2 and 30% of line 3.

It should pay attention to this fact that the relay should detect and issue the operating command to a breaker at the maximum period of three to five cycles.



(a) solid fault



(b) arcing fault

Fig. 7 : Harmonic analysis of fault voltage

Table III shows the THD factor in arcing fault situation and solid fault situation, which are calculated with three cycle samples.

TABLE III. THD FACTOR

THD in arcing fault	***5.01%***
THD in solid fault	***0.1%***

So, the adaptive distance relay proposed in this paper can detect the fault situation and make a correct decision and have a better reach ability compare with the conventional distance relay.

V. CONCLUSION

In this paper, the operation of distance relay in arcing fault situation is analyzed. It shows that if an arcing fault occurs at the end of each zone, for example zone 1, the distance relay will mistake the fault location and see the impedance in the second zone, so the relay cannot operate in a selective and instantaneous manner. So an adaptive distance relay is proposed which uses THD factor to detect the arcing fault situations from solid fault, because the arc has variable resistance with a nonlinear characteristic. It can use three cycle data for calculating THD factor and takes a correct decision. The proposed adaptive relay has a better reach ability in arcing fault conditions that help relay to operate in a more selective and instantaneous manner.

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