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ADAPTIVE MHO DISTANCE RELAY FOR COMBINED TRANSMISSION LINE: AN OPTIMIZATION TECHNIQUE FOR CHARGING CURRENT COMPENSATION

J. Tavalaei, M. H. Habibuddin and A. A. Mohd Zin
Department of Electrical Power Engineering, Universiti Teknologi Malaysia, Johor, Malaysia
E-Mail: mhafiz@fke.utm.my

ABSTRACT

The combined transmission system is expanding due to beatification and safety considerations and enhanced reliability in the distribution and transmission systems. It is expected to improve distance relay operation in presence of combined transmission system. Distance relay with Mho characteristics is simulated to mitigate the charging current effect of combined system with significant part of underground cable. The combined system is modelled mathematically based on the equivalent pi model to increase the accuracy. The distance relay is simulated based on the mathematical equation. The rate of charging current is compensation is extracted for single line to ground, line to line to ground and three-phase faults. The charging current compensation rate is extracted by direct search and the feasible solution is extracted by Utopia point approach. The findings show the fault with high resistance faces distance relay to mal-operation. The compensation of charging current can significantly mitigate the mis-operation rate of Mho distance relay. Due to the zone characteristics is constant, the selected value of charging current compensation required to have minimum overreach and underreach rates. By injecting the optimal charging current compensation rate at the relay point, the operation of Mho relay bounces to more than 99.5% for combined transmission system.

Keywords: distance relay, Mho characteristics, optimal charging current compensation, direct search, combined transmission system.

1. INTRODUCTION

Power transmission system is protected with several relays to increase reliability. Underground cable is protected with differential relay, but the main protection device in overhead line is distance relay which is backup by an overcurrent relay. Moreover, distance relay is used to detect fault occurrence in transmission line and also to estimate fault location. Several studies were carried out to improve distance relay operation and fault location estimation to make distance relay adaptive with specific transmission system. On the other hand, mis-operation of protective devices will occur due to conventional transmission system analysis in lumped parameter. The well-known drawbacks of transmission line are fault resistance [1-4] and charging current [5-8] of transmission system. These two effects forced distance relay to mis-operate.

Several papers explain improving distance relay operation [9-11]. Fault resistance is calculated by Bergeron's equation to overcome overreach in distance relay due to fault resistance [12-14]. Furthermore, this technique is presented [9] to compensate capacitive effect of combined transmission line. A simple mathematical equation supports compensation technique on pre-fault power flow. This method omits negative effect of fault resistance [15-17] on distance relay by adaptive shift vector procedure [10]. Instantaneous active power is monitored at relay point to calculate fault resistance which is independent of transmission system length.

Overhead line characteristics are electrically different with underground cable even at the same voltage. In underground cable the conductors, X/R ratio of positive sequence, charging current and mutual coupling ratio are different with overhead line [5]. Zero sequence impedance of sheath, mutual impedance (between sheath and conductor) and different return path on fault condition are explained [7]. Induced voltage and current on sheath are neutralized by bonding methods. This technique improved distance relay by modelling a capacitor at relay point of conventional method [8]. The high voltage overhead transmission system is affected by distributed capacitance which forced distance relay to mal-operation. A mathematical formulation is suggested to overcome distributed capacitance [6]. The charging current in long transmission line makes slow operation of distance relay.

This study addresses a unique transmission system containing both overhead line and underground cable. Distance relay operation is influenced by mentioned puzzles which push distance to mis-operate. The distance relay is modelled using MATLAB software. Then, charging current effect of combined transmission system and mis-operation of distance relay during fault is presented. To mitigate the mis-operation, the charging current compensation technique is applied in addition with direct search to find the best compensation rate.

2. DISTANCE RELAY OPERATION

Distance relay divides voltage over current waveforms in order to obtain impedance of power system. This impedance value is proportional to transmission line length. The positive sequence impedance is used in protection scheme to reduce the number of phase and line distance relay.

2.1. Modal transform

Three phase components are converted to sequence components. This transformation is converting three-phase *ABC* to the symmetrical component *positive,*

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negative and zero. Modal transform is done by Fortescue transform. This transformation filters the integer coefficient of third harmonics inherently.

2.2. Sequence impedance

The calculated impedance is in sequence form. The desired power system is operated with positive sequence, hence negative and zero sequences are undesired [8]. Negative and zero sequences exist in real network because of network's inherent configuration and power system apparatus [18-20]. In this research, the positive sequence impedance is assumed to be extracted by dividing positive voltage over positive current. Hence, the voltage magnitude needs to be divided on current magnitude and the phase's differences. Finally, the resistance (real part of impedance) and reactance (imaginary part of calculated impedance) are extracted. Therefore, the variations in measured impedance reveals disturbance in power system.

Installed distance relay measure voltage and current of related phase and the cumulative impedance measured by distance relay for single line is:

$$Z^{Measured} = \frac{V_i}{I_i + kI^0} \tag{1}$$

and for double line is:

$$Z^{Measured} = \frac{V_i - V_j}{I_i - I_j} \tag{2}$$

Where '*i*' and '*j*' represent '*abc*' phase and '*k*' factor in equation (1) is a constant factor calculated by:

$$k = \frac{Z_l^0 - Z_l^1}{Z_l^1} \tag{3}$$

This factor represents the impact of zero sequence on measurement of phase impedance by distance relay.

2.3 Charging current compensation

To mathematically model the combined transmission system, the cable section needs to be analysed adequately. The lumped parameter model does not represent a long transmission line exactly due to non-uniform distributed line parameters. It is possible to find the equivalent circuit of long transmission accompanied by line accuracy. The series arm of equivalent lumped parameter and the shunt arms are represented by *Z'* and *Y'/2*, respectively. Hence, the normal lumped parameter equation will change to:

$$V_S = \left(\frac{Z'Y'}{2} + 1\right)V_R + Z'I_R \tag{4}$$

To obtain the value of equivalent lumped parameter model equal to distributed parameter, the coefficients of V_R and I_R must be identical. The distributed parameter coefficients are as follows:

$$Z' = Z\,\frac{\sinh \gamma l}{\gamma l} \tag{5}$$

$$\frac{Y'}{2} = \frac{Y}{2}\,\frac{\tanh(\gamma l/2)}{\gamma l/2} \tag{6}$$

where *Y* is equal to *yl*, the total shunt admittance of line. The correction factor is used to convert the nominal lumped parameter to equivalent lumped parameter.

The main problem of cable is the huge rate of charging current. The cable section of combined transmission line is modelled in Figure-1.

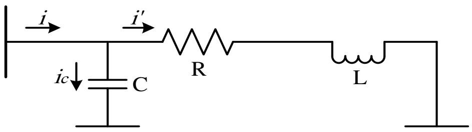

Figure-1. Modeling of charging current for cable section.

The i_c' and i represent capacitive current and cable current, respectively. The charging current compensation based on presented model is improved for equivalent lumped parameter model.

$$V = Ri' + L\frac{di'}{dt} \tag{7}$$

$$i' = i - i_C = i - \frac{Y}{2}\frac{dV}{dt} \tag{8}$$

The term *Y/2* in (8) represents half of the total capacitance of cable. Now, by using two times integration of (7) and (8):

$$\int_{t-T}^{t}\int_{t-T}^{t} V dt^2 = R\int_{t-T}^{t}\int_{t-T}^{t} i' dt^2 + L\int_{t-T}^{t} i' dt \tag{9}$$

$$\int_{t-T}^{t} i' dt = \int_{t-T}^{t} i dt - \frac{Y}{2}V \tag{10}$$

$$\int_{t-T}^{t}\int_{t-T}^{t} i' dt^2 = \int_{t-T}^{t}\int_{t-T}^{t} i dt^2 - \frac{Y}{2}\int_{t-T}^{t} V dt \tag{11}$$

and by substituting (10) and (11) in (9):

$$\int_{t-T}^{t}\int_{t-T}^{t} V dt^{2} = R\left[\int_{t-T}^{t}\int_{t-T}^{t} i dt^{2} - \frac{Y}{2}\int_{t-T}^{t} V\,dt\right] + L\left[\int_{t-T}^{t} i dt - \frac{Y}{2}V\right] \tag{12}$$

Now, by substituting the terms of equivalent lumped parameter into (12), the equation is as follows:

$$\int_{t-T}^{t}\int_{t-T}^{t} V dt^{2} = Rl\,\frac{\sinh \gamma l}{\gamma l}\left[\int_{t-T}^{t}\int_{t-T}^{t} i dt^{2} - \frac{Y}{2}\,\frac{\tanh(\gamma l/2)}{\gamma l/2}\int_{t-T}^{t} V\,dt\right] + Ll\left[\int_{t-T}^{t} i dt - \frac{Y}{2}\,\frac{\tanh(\gamma l/2)}{\gamma l/2}V\right] \tag{13}$$

The (13) covers the non-homogeneity and charging current compensation simultaneously.

2.4 Direct search

Direct Search (DS) Method is appropriate to solve problems that involved functions might not be differentiable or its derivatives have complex expressions or even cases where their analytical expressions cannot be determined. The DS only need information about the functions values. It advances towards an optimal solution based on the comparison of the functions values in several points.

2.5 Utopia point approach

The most feasible solution is calculated by (14) which measures the minimum distance with the feasible one as the best answer.

$$\sqrt{\sum_{i=1}^{N}(OF_i^{Cal} - OF_i^{\min})^2} \quad i = 1,...,N \tag{14}$$

The flowchart of the proposed method is illustrated in Figure-2. The sequence and the application of steps are explained precisely.

3. CASE STUDY

This network is a combined transmission system which is radial. An infinite bus is a model with a three-phase source. The short circuit capacity is 3000 MVA. The ratio of inductance to resistance of voltage source is 9.452 in 60 Hz [9]. To provide a return path, a generator winding is in star mode connection which solidly touches the ground. In load flow analysis, the generator bus is a swing bus to control the transfer power. The transmission system is designed to supply an industrial city. This load is 124 MVA at 0.92 lagged which received power in 63 kV. The simulated network is represented in Figure-3. Transmission system operates in 220 kV. This combined system contains 70 km of overhead line and 30 km of underground cable. Although the operating voltage of overhead line and underground cable is the same, the overhead line shows higher resistance and inductance than underground cable in positive sequence. However, the capacitive characteristic is significantly less than underground cable. The same condition is dominant on zero sequence of transmission sections. A step up transformer is installed at sending end to increase the transmission voltage. The short circuit capacity of transformers is 2100 MVA. Power system voltage and power are evaluated after a load flow in static mode. The main scope of power system is to keep voltage, power and frequency at in range. On the other hand, the full load condition is also in the range. In a steady state condition, the voltage of relay point exceeds 220 kV, while the angle is close to zero. The voltage of transmission system at the junction and receiving end is the same with different voltage angle. This feature causes transfer power in transmission line. However, the light load is the main problem of combined transmission line due to a high charging current.

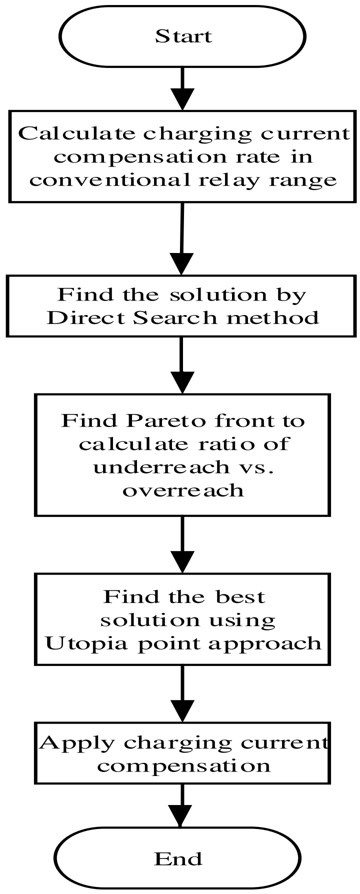

Figure-2. Flowchart of protective scheme.

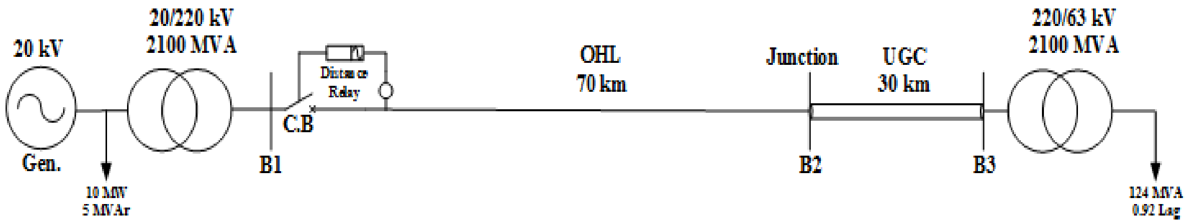

Figure-3. Single line diagram of combined transmission system.

The operation of distance relay is simulated for fault location from 0 km to 87 km in steps of 1 km (88 points) and fault resistance from 0 Ω to 100 Ω in 9 steps for single line to ground fault, line to line to ground fault and three-phase fault. Therefore, the total number of sample data is 2376 (88×9×3).

4. RESULT

Figure-4 portrays reactance of transmission line measured at relay point. The Z^{pos} shows positive sequence impedance of transmission line which is called the desired impedance. The discontinuity in first cycle is related to initial condition of apparatus.

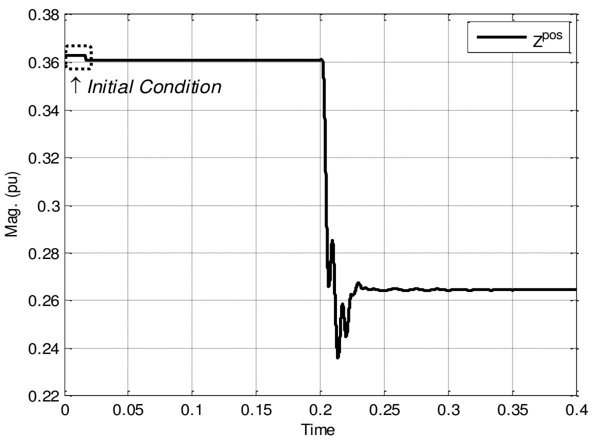

Figure-4. Positive sequence reactance of transmission system.

Distance relay operation is shown in Figure-5 for a different fault resistance at reach point of relay. In This discontinuity does not affect the remaining signal from the second cycle onward. The fault waveforms are highly distorted and contained harmonics of fault condition and resistance. Hence, a filtering on voltage and current waveform is vital. Distance relay is affected by fault resistance and fault location which can reduce fault trajectory on zone locus. Figure-5 (a), a line to line to ground fault is carried out at 80 km of distance relay location where fault resistance is changed from 0 Ω to 100 Ω. While the fault impedance increases the relay is unable to protect the transmission system and faced under reach. In Figure-5 (b), the Mho relay characteristics are tested for a three-phase fault. The fault happed at the reach point of the relay and the fault resistance varies up to 100 Ω. Again, the relay faced under reach in presence of high fault resistance. The Mho characteristics are faced-mal-operation with high fault resistance. On order to mitigate the undesired impact of charting current on Mho characteristics, an optimal compensation rate is calculated based on direct search. The extracted value is used for single line to ground, line to line to ground and three-phase fault compensation. Figure-5 illustrates the best CCC values. The Pareto front contains 16 acceptable solutions. These solutions are extracted from over 2700 generated results by charging current rate variation and by underreach and overreach rate calculation.

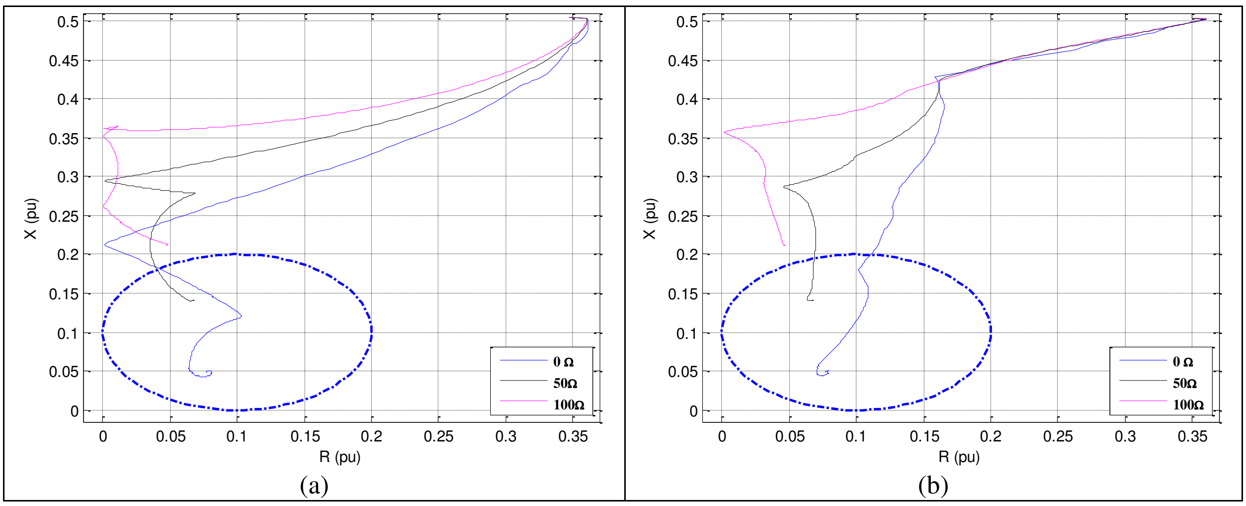

Figure-5. Fault impedance trajectory (a) Line to line to ground, (b) three-phase.

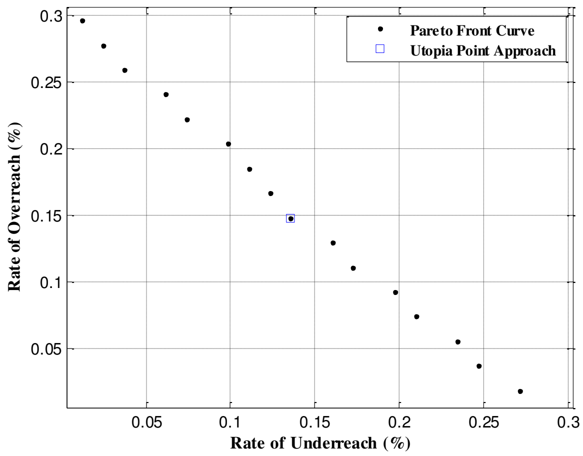

Figure-6. Pareto front of CCC rate.

The best results of Pareto front curve of DS extracted by Utopia point approach shows the best value of CCC is 1.5057 pu, which has minimum distance with feasible solution compared to other solutions. This solution causes 0.136% underreach as well as 0.148% overreach. Therefore, the selected charging current by utopia point approach will be optimized and subsequently the best results based on approaches are extracted from Pareto front curve.

The Figure-7 proves that the proposed method can effectively compensate the undesired effect of charging current. By this compensation the fault with high resistance is covered by Mho distance relay.

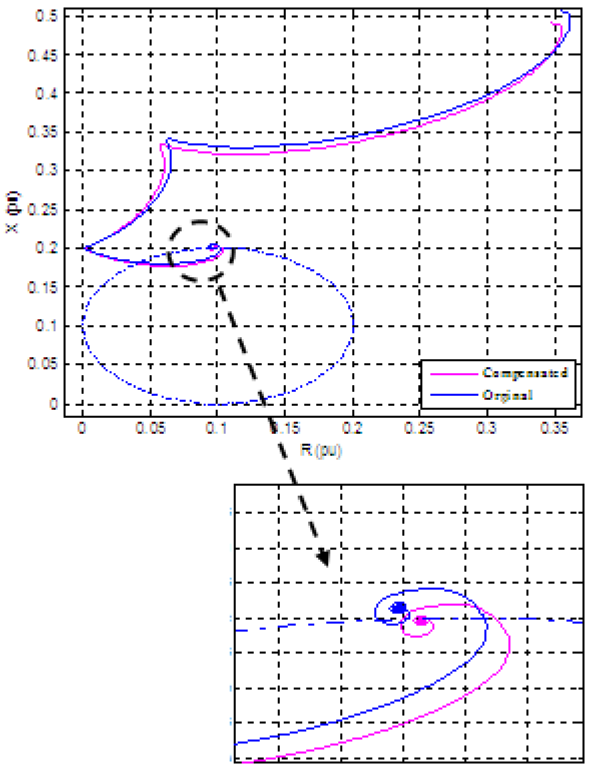

Figure-7. Compensated fault trajectory is inside the zone and protected by distance relay.

5. CONCLUSIONS

A distance relay operation is simulated in this paper by using MATLAB software. This model measures phase and line impedance of the case study. Simulated distance relay is applied to a combined transmission system with a significant section of the underground cable. The transmission line is modelled in equivalent lumped parameter to increase fault analysis accuracy compared with the conventional method. The positive sequence impedance is extracted to avoid mis-operation of distance relay during high resistance fault. Combined transmission system affects distance protection with a huge charging current due to cable operation in high voltage. Charging current and non-uniform electrical characteristics affects the distance relay operation. The Mho distance relay mal-operation is mitigated by applying charging current compensation along with direct search. The best solution is finally extracted by Utopia approach illustrates around 0.23% mal-operation after compensation.

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