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Original Article

Enhancing Distance Relay Performance against High Impedance Faults Using Artificial Neural Networks

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Abstract: *Conventional Mho relays for distance protection face several serious limitations especially in discriminating between HIF and heavy load situations in the transmission lines. Since the current in the case of HIF is extremely limited by the fault resistance, it usually bears similarities in electrical characteristics with heavy loading scenarios and thus leading to false tripping or relay underreach with serious consequences. In this paper, an advanced and very selective distance protection as well as fault location system for 100 kilometers long transmission line has been developed using the MATLAB/Simulink software. Specifically, the key innovation lies in the design of a sophisticated two-level supervisory discrimination algorithm that considers the measured phase impedance and the residual or ground current (Ig). In the event of balanced heavy load situation, even if the measured impedance becomes less than the zone setting of the relay (106.99 ohm), the residual current does not cross the critical value of 1.65 A and therefore prevents the relay from unnecessary operations. However, in case of real HIF scenario where the non-linear electric arc dynamic is assumed to be used to model the fault occurrence, the imbalance in the structure leads to the Ig exceeding 1.65 A and thus justifying the presence of fault and eventually activating the relay through AND gate logic design. Also, an artificial neural network has been incorporated into the system that estimates the autonomous fault location by using various transient waveforms of voltages and currents along the 100 km line.*

Keywords: *Power Systems Protection, Distance Relay, Mho Characteristics, High Impedance Fault (HIF), Loaded Conditions, Artificial Neural Networks (ANN).*

I. INTRODUCTION

It is essential to detect, classify, and locate faults as fast and accurately as possible, since their occurrence may seriously affect the performance of power transmission systems [1]. Transmission lines act as the basic components of power grids and run through large geographical distances while encountering numerous types of environmental threats. There are many protective devices used for the safety of transmission lines, but distance relays, especially based on the conventional Mho characteristic, are widely employed all over the world for protection of the transmission lines. The widespread usage in the industry of the distance relays is based on their unique ability to calculate independently the area of fault by observing the voltage/current ratio, which corresponds to the positive-sequence impedance between the point of relaying and the point of the fault [2]. Although conventional Mho distance relaying schemes show excellent results during operation with typical situations of bolted short circuits, they demonstrate poor results in terms of accuracy, sensitivity, and reliability when working with High-Impedance Faults (HIFs). High-Impedance Faults appear due to breakage of the overhead transmission line and falling of the conductor onto the very resistive ground, like asphalt, concrete, dry earth, gravel, or live vegetation in the close proximity of the conductor [3]. As the fault circuit is characterized by huge and rather unstable dynamic resistance, the fault current is heavily reduced. The fault currents reach extremely low values and are often not greater than, and sometimes less than, usual load currents [4]. In terms of impedance, this leads to shifting the impedance trajectory of the Mho relay far beyond the conventional Mho circle. This situation causes the severe underreaching of the distance relay that cannot recognize the active ground fault inside its protection zone.

A. Literature Review and Related Works)

The problem of safe isolation of high-impedance faults without triggering false trips due to non-fault events in power systems has been one of the most urgent tasks studied for many decades [1], [2]. The main difficulty in this regard is associated with abnormal loads and heavy overloads. As a result of the heavy loading of the transmission system, the dynamic properties of the load blocks considerably complicate the calculation of the parameters, and the impedance trajectory goes far down to the R-X plane, reaching the outer regions of the distance relays [10], [12]. Therefore, the major structural contradiction in this case becomes the need for high sensitivity to detect low current arcing HIFs and sufficient security of not being tripped in the case of heavy, low impedance symmetrical overloads [5], [8]. To overcome these limitations and diminish the underreaching effect caused by the resistance of the fault path, different compensation and analysis methods were developed [3], [11]. Classical ground distance elements usually suffer from structural unbalance or mutual infeed effects [7], [11]. To solve the problems connected with non-linearity of ground faults without costly implementation of communication facilities, modern science has turned towards using dynamic models of loads in distance protection algorithms [4]. The precision of phasor estimation during transients has been notably improved due to synchronization [6]. Besides that, data-based approaches and intelligent protection elements proved to be more effective in recognizing patterns and non-linear transformation under dynamic power system operation [9]. An ANN learns the electrical transients at the location of relaying and maps distorted post-fault voltage and current waves to the accurate fault coordinates without the need to have an analytical description of the electric arc in the form of mathematical formulas.

II. METHODOLOGY AND SYSTEM MODELING

A. Overall System Configuration

The above-described protection and fault location algorithm has been developed and analyzed with the help of the MATLAB / Simulink package. As can be seen from the above figure of the simulated power system (fig. 1), the network model used for the simulations is of a 100km three-phase power source network connected through a multi segment power transmission line.

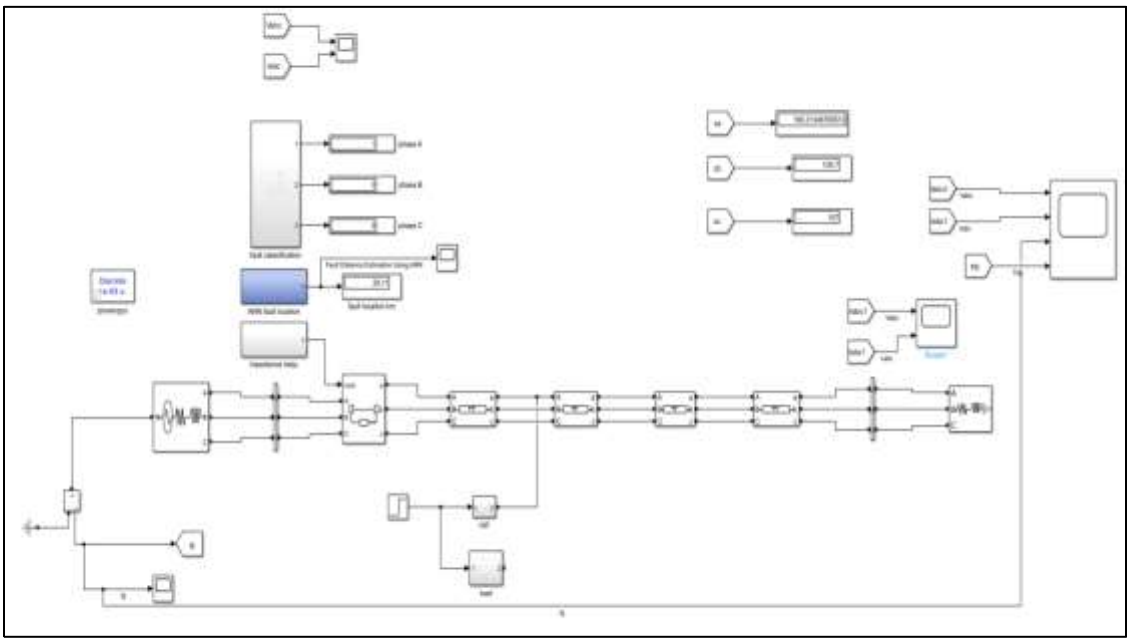

Figure 1: General Block Diagram of the Proposed Transmission Line Protection and ANN-Based Fault Location Simulation Network

The protection core consists of an ordinary distance/impedance relay block along with a sophisticated computational intelligent system. It comprises three unique modules namely:

- Module for Fault Classification: In charge of determining which phases are under fault (Phase A, B or C).
- Impedance Relay Block: Calculates the impedances of each phase (Za, Zb, Zc) based on the voltage and current readings (Vabc and Iabc) obtained at the point of relaying.
- ANN Fault Location Module: An Artificial Neural Network that uses the transient characteristics of voltage and current waveforms for predicting the precise fault location in kilo meters (km).

B. Modeling of high-Impedance Fault (HIF)

In order to determine the feasibility of the proposed protection scheme, a non-linear arcing fault model was developed by taking into consideration the model shown in (Fig. 2) which uses an anti-parallel diode. The non-linear nature of the arc is modeled by the use of two anti-parallel diodes with DC supply, resistor, and inductor.

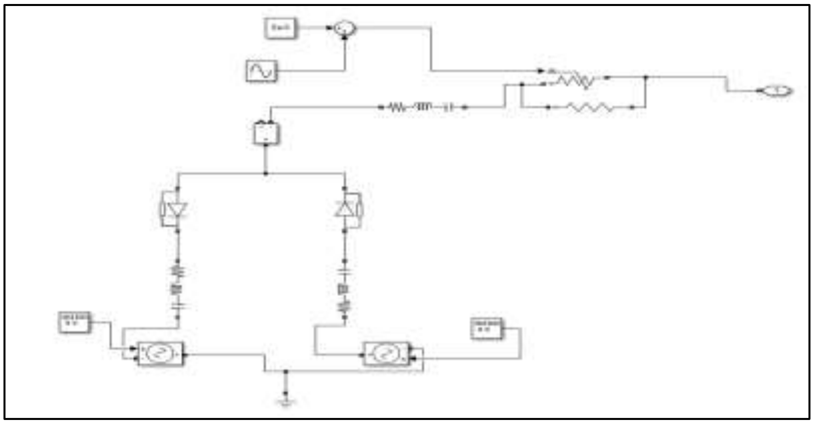

Figure 2: Simulation Model for the Non-Linear Arcing HIF Using MATLAB/Simulink Subsystem

Dynamic fault resistance (Rf) can be varied using a combination of time varying sinusoidal wave and dynamic offset magnitude of 5*10^3 ohm. The mathematical expression of voltage current relationship in arcing fault condition is given by:

$$v_{HIF}(t) = \begin{cases} V_p + R_f \cdot i_{HIF}(t), & \text{if } i_{HIF}(t) > 0 \\ -V_n + R_f \cdot i_{HIF}(t), & \text{if } i_{HIF}(t) < 0 \end{cases}$$

Where Vp and Vn indicate the positive and negative voltage characteristic thresholds of the arcing ground, respectively.

C. Distance Relay Circuit Design and Phase-A Component

Internal sub system of distance relay is designed in such a way that individual phase is analyzed individually as shown in Figure (Fig. 3). Distance protection unit constantly monitors the three phases voltage (Vabc) and current (Iabc) to compute positive sequence impedance.

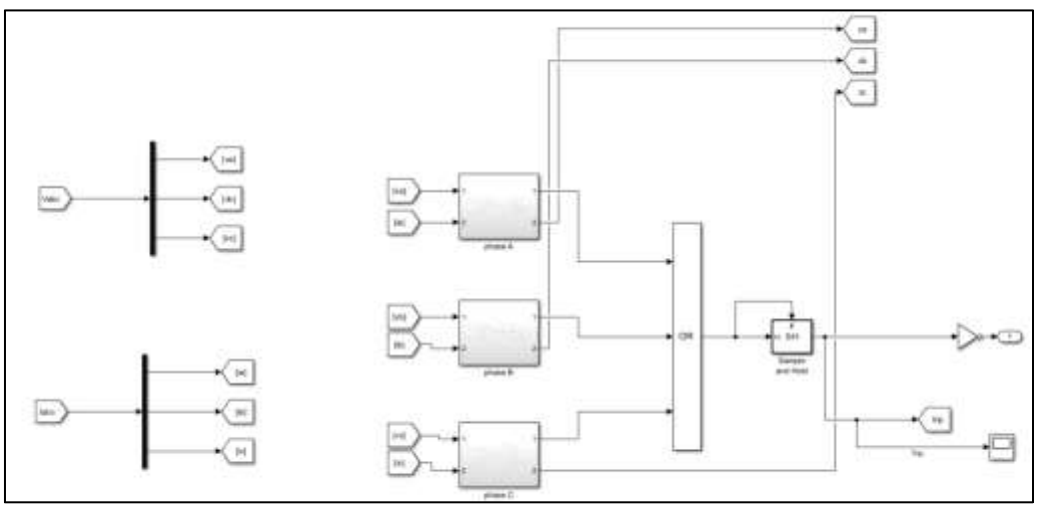

Figure 3: Block Diagram of the Distance Protection Relay Structure Showing Distinct Phase Evaluation Sub-Systems.

In respect to Phase-A internal circuit, the value and phase angle of calculated impedance are compared to the preset threshold value (Zset = 106.99 ohm). In accordance with normal operation limits, the tripping action takes place when the following condition holds true:

|Zmeasured| ≤ 106.99 ohm

D. Differentiation between Heavy Loads and High Impedance Fault Conditions

In order to avoid false operation under heavy load conditions, in which high currents cause excessive impedance drops and thereby deceive the conventional Mho characteristics, a new technique of discrimination is adopted through the ground or residual current (Ig). During regular heavy loads where the structure is balanced, there is no residual current (Ig). However, during actual high-impedance fault conditions, the balance in the structure is disrupted by generating a residual component. A threshold current is set as follows:

$$\textbf{Fault Condition Flag} = \begin{cases} \textbf{True}, & \textbf{if } I_g > 1.65\ \textbf{A} \\ \textbf{False}, & \textbf{if } I_g \leq 1.65\ \textbf{A} \end{cases}$$

The output of the Impedance Comparing (|Z| < 106.99 ohms) and the Residual Current Supervisor (Ig > 1.65A) is passed through a logic AND gate inside the Interlocking Supervisor block as shown in Fig.4. Therefore, in case where the heavy load reduces the impedance to below its value but still Ig < 1.65A, then the relay considers it as a non-fault condition.

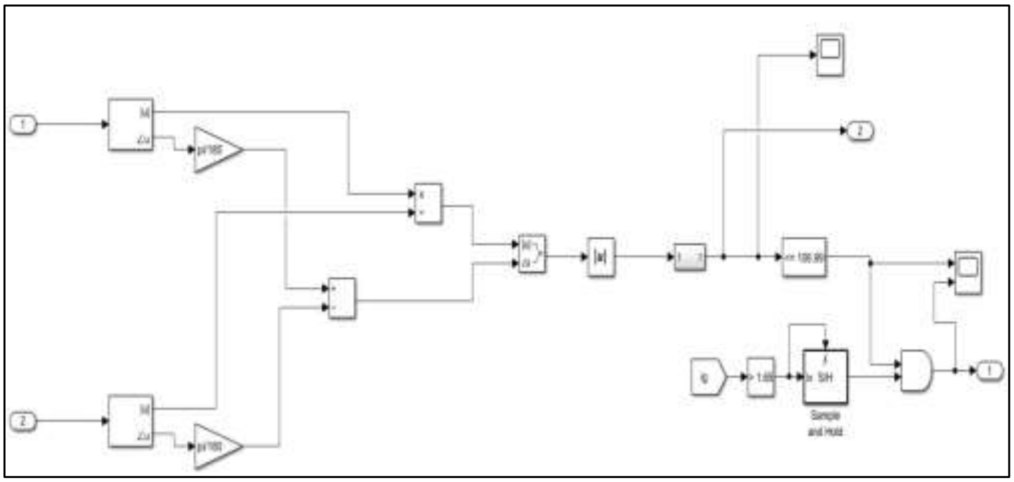

Figure 4: Block Diagram for Internal Logical Control and Threshold Verification for Phase-A Distance Relay through Ig Interlocking

A trip signal is allowed only when both conditions are fulfilled together:

Trip Signal = (|Zmeasured| ≤ 106.99 ohm) AND (Ig > 1.65 A).

E. ANN Fault Distance Estimation Scheme

In order to estimate the fault distance precisely during high impedance faults conditions, the Artificial Neural Network (ANN) algorithm is added to the protection scheme. The ANN algorithm is implemented based on the standard Neural Network Tool-set of MATLAB, using Multi-layer Feed-Forward Backpropagation type. Training data was created through performing simulation experiments for several different cases using the 100 km transmission line. Voltage (Vabc) and Current (Iabc) samples are acquired at the relaying point by changing the fault location from 0 km to 100 km, in addition to changing the fault angle and fault resistance. Network Inputs: Instantaneous values obtained from the three-phase voltage and current. Network Output: Precise value of the fault distance from the relaying point in kilometers (km).

III. RESULTS AND DISCUSSION

Verification of the performance of the proposed dual supervision protective scheme and ANN intelligent fault location was done under different operating conditions using MATLAB/Simulink software. The major concern of this analysis is the safety of the relay under heavy load condition compared to its reliability under actual 100 km line HIF condition.

A. Case A: Heavy Overload Operation

To generate a highly challenging scenario for the relay operation, a load block of high capacity was introduced in the 100km power system. It can be seen from the waveforms (Fig.5) that owing to the heavy current flow through the system, the impedance calculating blocks Za, Zb and Zc showed a highly decreased magnitude such that the impedance path crossed the 106.99 ohm reach limit. In a conventional setup, this case would immediately lead to a fault and hence a maloperation (trip). However, in the proposed setup, since the heavy load situation is a structurally balanced one, the magnitude of the ground current Ig is normal and stays well below the threshold value of 1.65 A. Thus the logical AND gate does not meet the criteria for input activation, leading to the output signal being zero.

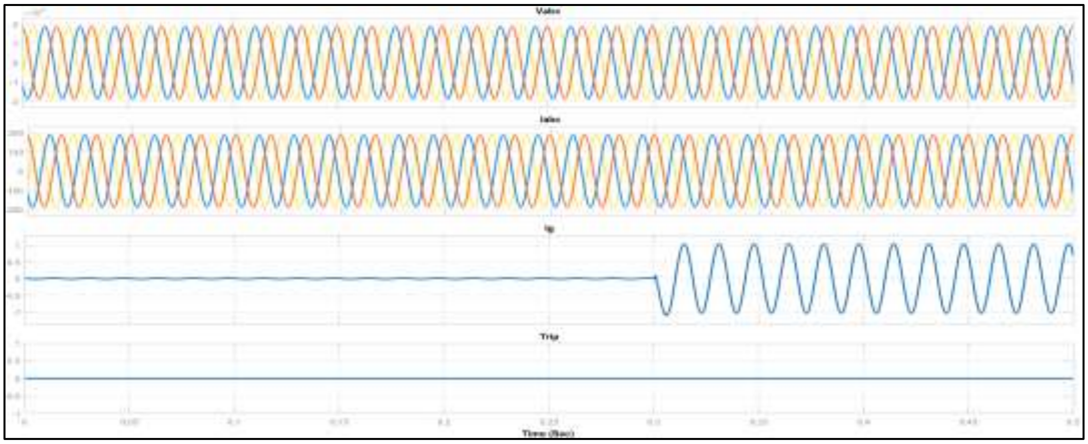

Figure 5: Wave Forms Simulation under Heavily Loaded Conditions: Balanced Phase Currents, Ground Current (Ig), and Non-Trip Logic Stability

B. Case B: High Impedance Arcing Fault (HIF)

A genuine HIF scenario was generated in the system through the use of the non-linear arcing fault model. The simulated response plots shown in Figure 6 demonstrate that even though the current value is relatively small, the phase imbalance results in a unique zero sequence current contribution. The supervisor recognizes that Ig has exceeded 1.65 A level, which satisfies the AND condition for Trip= 1 output.

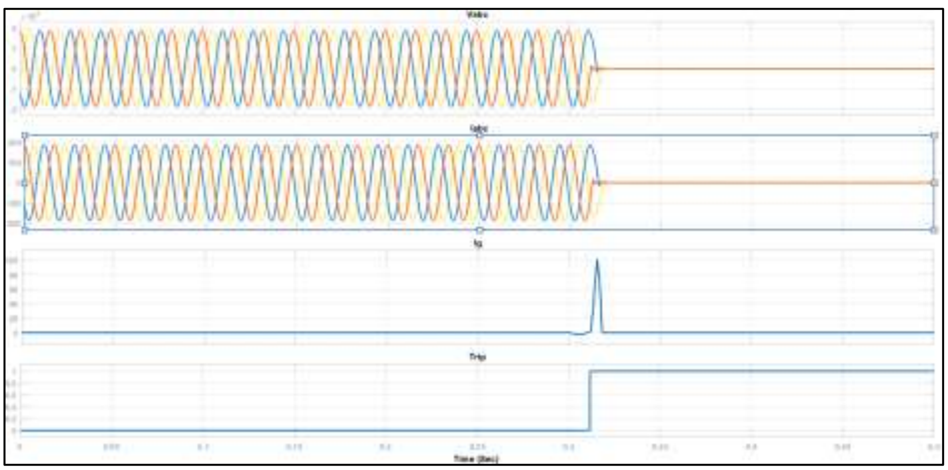

Figure 6: Transient Wave Form Simulation under Real High Impedance Arcing Fault Condition: Distorted Phase Current, Rise in Ground Current (Ig), and Instantaneous Tripping

C. Case C: Intelligent Fault Distance Estimation

The moment the fault classifier block identifies the phase under concern, both the transient voltage and current waveforms are input to the already trained Feed-Forward Backpropagation ANN block simultaneously. In order to demonstrate the intelligent tracking ability of the computational intelligence layer, a dynamic case study was carried out where an asymmetric HIF occurred in the first section of the 100 km transmission line at t = 0.31s.

According to the dynamic tracking response curve (Fig.7), before the occurrence of the fault (t < 0.31s), the network output strictly stays at zero which indicates the network is in the normal mode. After the fault occurs at t = 0.31s, the non-linear distortions of voltage and current due to the electric arc are detected through the network input. The output of the ANN shows the instant step response converges immediately after the fault occurrence, settling at the estimated value of the fault distance at 29.5 km.

In spite of the highly non-linear arcing resistance which usually forces the conventional analytical mathematical fault locator algorithms to under reach or fail, the proposed data-driven ANN approach can accurately capture the fault distance without any problem and can give a very accurate continuous distance estimation.

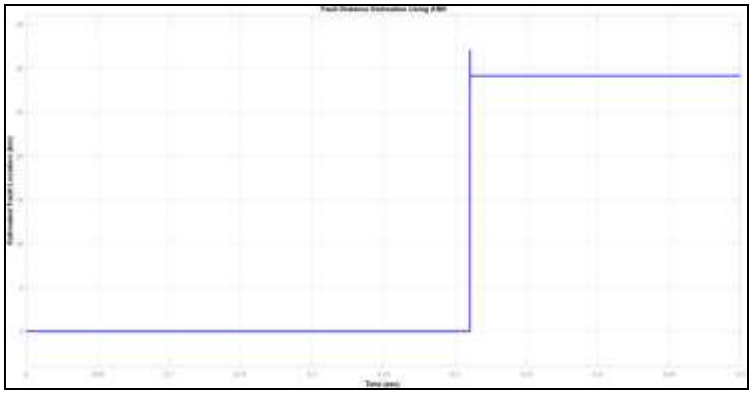

Figure 7: Transient Response and Settling Performance of the Proposed ANN Fault Locator for A High-Impedance Fault Initiated At T = 0.31s

IV. CONCLUSION

In this paper, a successful development of a novel distance protection method which was devised to solve the problems associated with classical distance protection methods such as Mho relays due to HIFs and heavy loading cases on a 100 km transmission line was made. It was shown that using only the impedance trajectory approach increases the vulnerability to tripping/failure of reaching faults. By employing the residual current supervisor (Ig), set to a specific threshold of 1.65 A, a fully selective operation is attained. The relay is able to withstand tripping during heavy load situations where the system is balanced without any faults. On the other hand, it is highly dependable since it trips in a very quick manner during actual nonlinear arc HIF cases when the criteria of impedance and ground currents are satisfied together. Moreover, the incorporation of an ANN based module helps in providing an additional intelligent block for the purpose of mapping the faulted waveforms to detect the faulty location within 100 km transmission line, achieving a quick settlement time of 29.5 km when a fault occurs at t=0.31s.

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