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Protective Relay Models for Electromagnetic Transient Simulation

Implementation of a PSCAD/EMTDC two-zone model for the study of distance relay with adaptation to MHO characteristics for Transmission Lines protection

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Abstract—85-87% of power system failures pertain to transmission lines, or more broadly to distribution systems, maloperation. Those failures can incur serious damage upon the faulted part, if protective actions have not been taken promptly. Distance relays are widely implemented to detect operational disturbances in long transmission lines. They are capable of providing multiple zones of protection coverage, along which the protected transmission line is 100% fault-detected. They are also characterised into a number of types, among which MHO type is most suitable protection method for long transmission lines. This paper aims at analysing a distance relay MHO type characteristic with a two-zone of protection coverage – primary zone and back-up zone. Analysis carried out through a PSCAD/EMTDC model. The transmission line under analysis has the parameters of 275 Km, 230 kV and 60 Hz. The developed model has evaluated the relaying system via two main case studies: (A) steady-state and (B) transient state "phase-to-phase fault" studies.

Index Terms—Transmission lines, Distance relay, MHO characteristics, R-X plane, Phase-to-phase fault

I. INTRODUCTION

I.I Overview

Electric power system is among the most complex, if not the furthermost, human-made systems whose complexity is growing, as a result of being relentlessly adapted to new technologies, and of which are renewable-based energies integration, equipment digitalisation and power storage adaptation [1]. Although the complexity drives the system towards optimisation "smart-oriented system", it becomes more prone and susceptible to different system failures – including over-load, over-voltage and over-frequency conditions [3]. Those failures pose a challenge upon maintaining power supply continuity and can incur serious damage on the part involved, if it is not promptly isolated and thereafter cleared out. Therefore, electric power system critically requires an auxiliary system that must take corrective actions on the occurrence of faults, namely protection system.

The philosophy of electric power protection ensures that, in the occurrence of fault, the faulted part must be disconnected from the system. This precludes further damage that is most of the power previously delivered to the load flows now into the fault path. Protection system is often designed in a way that electric power system is segmented into a number of zones, wherein no part of the system is left unprotected. Protection zones overlap around circuit breakers that perform system isolation from faulted parts. A circuit breaker is a fault-interrupting apparatus that solidly interposes flow of current to the faulted components [9]. The natural electromagnetic induction of circuit breakers entails an external circuit that enables energisation of their coils during which a tripping-signal applies to the circuit breaker indicating an abnormal operation.

Protective relays are the external circuits whose main objective is providing controllability of the circuit breakers' tripping-signals against faults [10]. Among the electric power systems, transmission lines are a critical component across which a large amount of power is transferred. They are generally 3ϕ conductive mediums span over long distances where susceptibility to being in contact to each other or to ground is high. In general, 85-87% of the power system failures are related to transmission lines, or more broadly to distribution systems, misoperation [11]. Thus, solid protection system is designed for transmission and distribution systems. It is the general practice for transmission lines protection system to employ high-speed primary techniques along with slower-speed backup techniques, where backup protection takes actions only if the primary protection fails in isolating faulted parts.

This paper is dedicated to analysing transmission line faults through observing a circuit breaker and protective relay actions. A Mho type distance relay characteristic is considered and simulated using PSCAD-EMTDC. It is clear from the literature that distance relays are set upon the basis of the positive-sequence impedance spanning from relay location along to a pre-determined point of the protected transmission line. It is the general practice that protection coverage of distance relays is made through three forward protection zones providing primary, backup and remote protection techniques. In this paper; however, instead of spreading the scope across three or four protection zones, a system configuration of a primary zone and another time-delayed back-up zone providing protection to a long transmission line is taken into account.

This is adequate to study, through a PSCAD-EMTDC model, the protected system stability under a steady-state and phase-to-phase transient conditions.

I.II Aims and Objectives

This paper aims:

- To investigate the significance of protection techniques in electric power system via emphasis lies upon distance relay MHO type characteristic principles and fault occurrence in long transmission lines.
- To model and simulate a distance relay system using PSCAD-EMTDC with a careful selection of reach-point settings and tripping time.
- To analyse and observe the developed model voltage and current stability throughout steady-state and phase-to-phase transient conditions.

I.III Background

AC transmission lines, also known as transmission feeders, are 3ϕ, conductive connections, at pre-defined voltage magnitudes, among substations, switchyards, and generating stations. Transmission lines are utilised to transmit large amounts of power across power systems [3]. Important characteristics are operating current and voltage, impedance and ampacity. They are terminated at circuit breakers and interconnected to form networks as illustrated in Fig. (1-a). They can be deigned as overhead or underground transmission lines. Fig (1-b) shows simplified illustration of overhead three-phase transmission line [5].

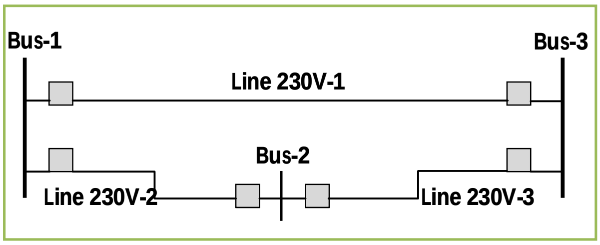

Figure (1-a) One-line diagram showing three buses, six circuit breakers, and three 230-KV transmission lines

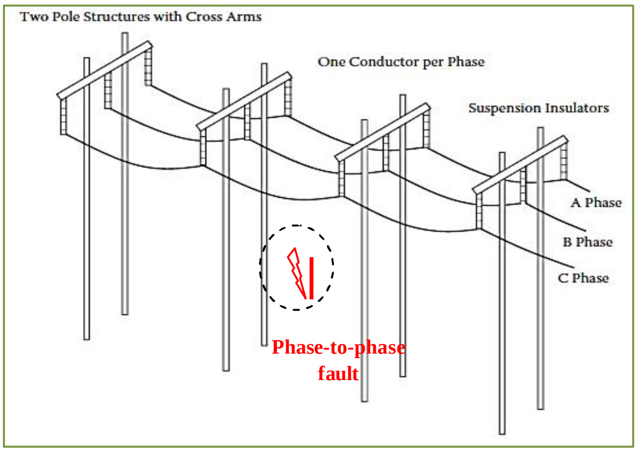

Fig (1-b) shows simplified illustration of overhead three-phase transmission line [5].

Transmission lines are often categorised by their length as illustrated in Fig. (2) and are modelled as lossless or lossy transmission lines [1].

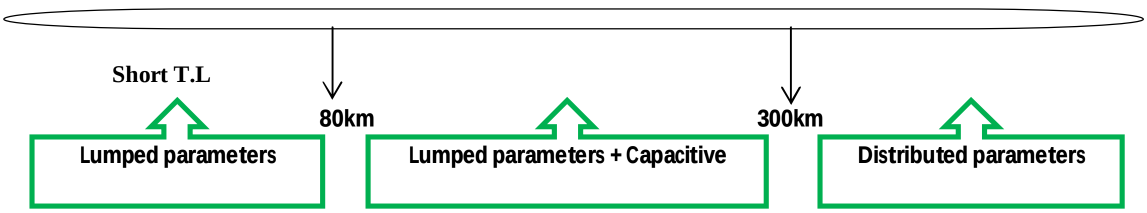

Figure (2) Trans Figure (2) Transmission line (T.L) physiognomies

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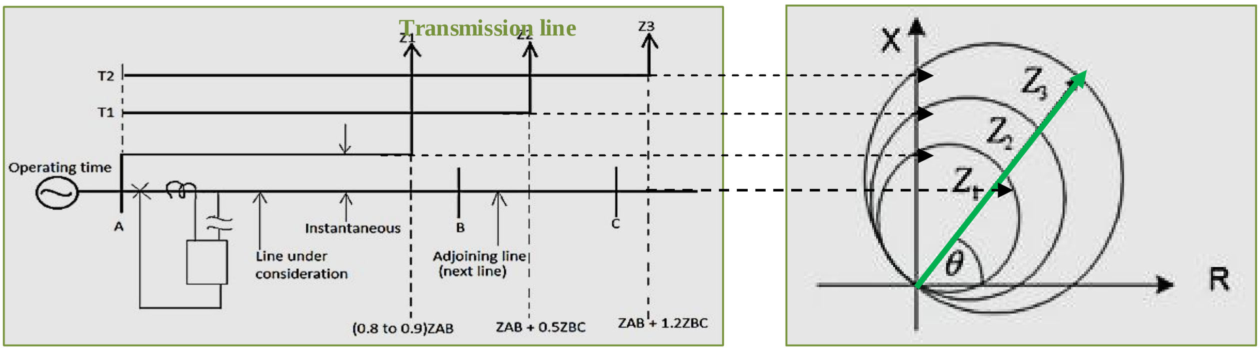
Lumped parameters (R, C, G, L) are used to represent transmission lines for transient studies while distributed parameters are used for long transmission lines as R and G cannot be ignored [7]. Transient studies on transmission lines are normally conducted to examine their behaviours against lightening and short-circuit faults. Surge arrestors are very effective and fast-to-respond protection method against lightening while circuit breakers can add more protection mechanism during short-circuit faults. Phase-to-phase fault is an example of a short-circuit between any pair of the three conductor lines as depicted in Fig (1-b). At the location of the phase-to-phase fault, the voltage on two of the three phases will be depressed and the current in the faulted phases will be higher than the current in the third phase [4].

Protective relays, by themselves, cannot drive a circuit breaker to open or close; instead, they complete the control circuit from a battery to a circuit breaker trip or close coil. When a circuit breaker tripping coil is energised, it releases energy from a hydraulic cylinder, a spring, a compressed gas cylinder, or some other energy storage sources that then open the prime contacts of the circuit breaker [11]. A wide variety of protective relays and protective relay functions are currently available from which the selection can be critical. However, they all continuously monitor power system conditions and when a protective relay detects a short circuit or other abnormal conditions, the output contacts change their state from open to closed. Thus, a "tripping-signal" sends out to the appropriate circuit breaker [8]. The operation during which a relay changes its state is where the relays distinctively differ. Among the most widely used relays are distance relays, differential relays and directional relays. Distance relays, also referred to as impedance relays, are common form of protection on high voltage transmission systems due to their suitability, simplicity and least likely to require additional systems or equipment. In addition, selectivity and remote back-up protection are natural benefits of this type of protection [9].

Distance relays use voltages and currents acquired at the relay location to calculate the apparent impedance of the protected line [7]. The calculated apparent impedance is compared with a pre-determined impedance that is called reach of the relay. During normal operation, the apparent impedance must be larger than the impedance-reach of the relay. If the apparent impedance is less than the impedance-reach, then a fault has occurred; as such, the relay energises the circuit to trip the appropriate circuit breakers in order to isolate faulted line from the rest of the system [7]. Distance relays can have different characteristics – including MHO, quadrilateral and reactance characteristics. The MHO type characteristic is optimal for phase-fault relaying for long transmission lines, and mainly where severe synchronising-power surges may occur [9]. The typical practice in applying the R-X plane of MHO characteristic relaying is to install multiple sets of impedance relays at each relaying point, creating corresponding multiple zones as shown in Fig. (5). The operating zones are defined such that whenever the ratio of V/I falls inside a circle, the relay unit operates. R and X represent the resistive and reactive parts of the monitored impedance, and can be in per-unit or ohms [6].



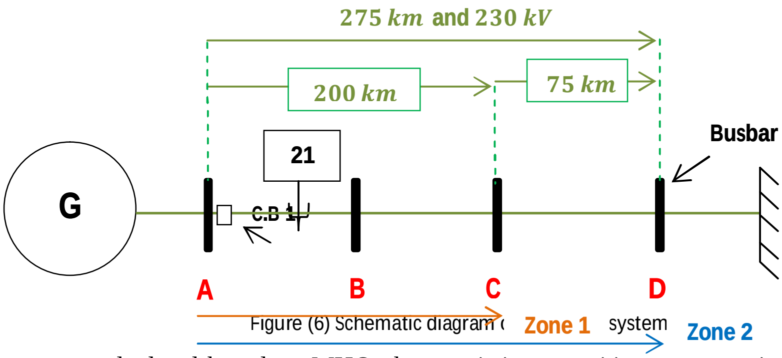
(b) Figure (5), (a) Distance relay protection zones (b) MHO characteristics for three zones of protection

In the majority of cases, the reach-point settings of the three main protection zones is made in accordance with the following criteria:

- *Zone-1* is set to cover between 80 and 85% of the length of the protected line with instant operating time $t_1 = 0$.
- *Zone-2* is set to expand over zone-1 plus 20-50% of the shortest next line with operating time delayed by 0.25 sec to 0.4 sec.
- *Zone-3* is set to expand along zone-1 and zone-2 plus 25% of the shortest next line with operating time delayed by 0.6 sec to 1.0 sec.

II. METHODOLOGY

In this paper, a transmission line with the parameters of $275\,Km$, $230\,kV$ and $60\,Hz$ along with its protection system – circuit breakers and distance relays – is modelled with the aid of PSCAD/EMTDC. The protection system consists of two operational relaying zones: Zone-1 performs primary protection, and Zone-2 performs back-up, or remote-trip, protection as depicted in Fig. (6).



The reach-point settings were calculated based on MHO characteristics – positive sequence impedance $(1.36 + 26.3j)\ \Omega/km$ and zero sequence impedance $(28.02 + 92.45j)\ \Omega/km$. It is established that a distance relay is located between (Busbar A) and (Busbar B) during which time a tripping-signal propagates to C.B1 in occurrence of faults. Therefore,

$$Zone_1 impedance = 200\ km \times (0.1236 + j0.5084)\ \Omega$$

Where $(0.1236 + j0.5084)\ \Omega$ is the normal protection setting for $Zone_1$.

$$Zone_1 = 24.7265 + j101.6826\ \Omega$$

$$= 104.6458 \angle 1.3323\ \Omega \xrightarrow{yields} 104.6458 \angle 76.33\,°$$

Zone setting for MHO characteristic at C.B1.

$$Zone_1\ reach\ setting = 80\%\ of\ the\ protected\ T.L$$

Thus,

$$Zone_1\ reach\ setting = 0.8 \times 104.6458 \angle 1.3323\ \Omega \xrightarrow{yields} 83.7167 \angle 1.3323\ \Omega/phase$$

Set radius of MHO circle for zone-1 can now be determined.

$$Zone_1\ MHO\ circle\ radius = \frac{83.7167}{zone\ number} = \frac{83.7167}{2} = 41.858\ \Omega$$

Zone-2 is set in such that it covers Zone-1 unit (A-B and B-C) plus the remaining 20% (C-D). Therefore,

$$Zone_2\ reach\ setting = Zone_1\ reach - point + 20\%\ of\ the\ protected\ T.L$$

$$Zone_2\ reach\ setting = [1 \times (104.6458 \angle 1.3323)] + [0.2 \times (104.6458 \angle 1.3323)] \xrightarrow{yields} 125.57 \angle 1.3323\ \Omega/phase$$

Set radius of MHO circle for zone-2 can now be determined.

$$Zone_2\ MHO\ circle\ radius = \frac{125.57}{2} = 62.785\ \Omega$$

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The Fast Fourier Transform (FFT) can now be employed. FFT is a fast algorithm for efficient computation of Discrete Fourier transform. FFT reduces the number of arithmetic operations and memory required to compute the Discrete Fourier transform [6]. The developed relay modelling algorithm, which utilises FFT block in PSCAD/EMTDC for extracting the fundamental component, is depicted in Fig (7).

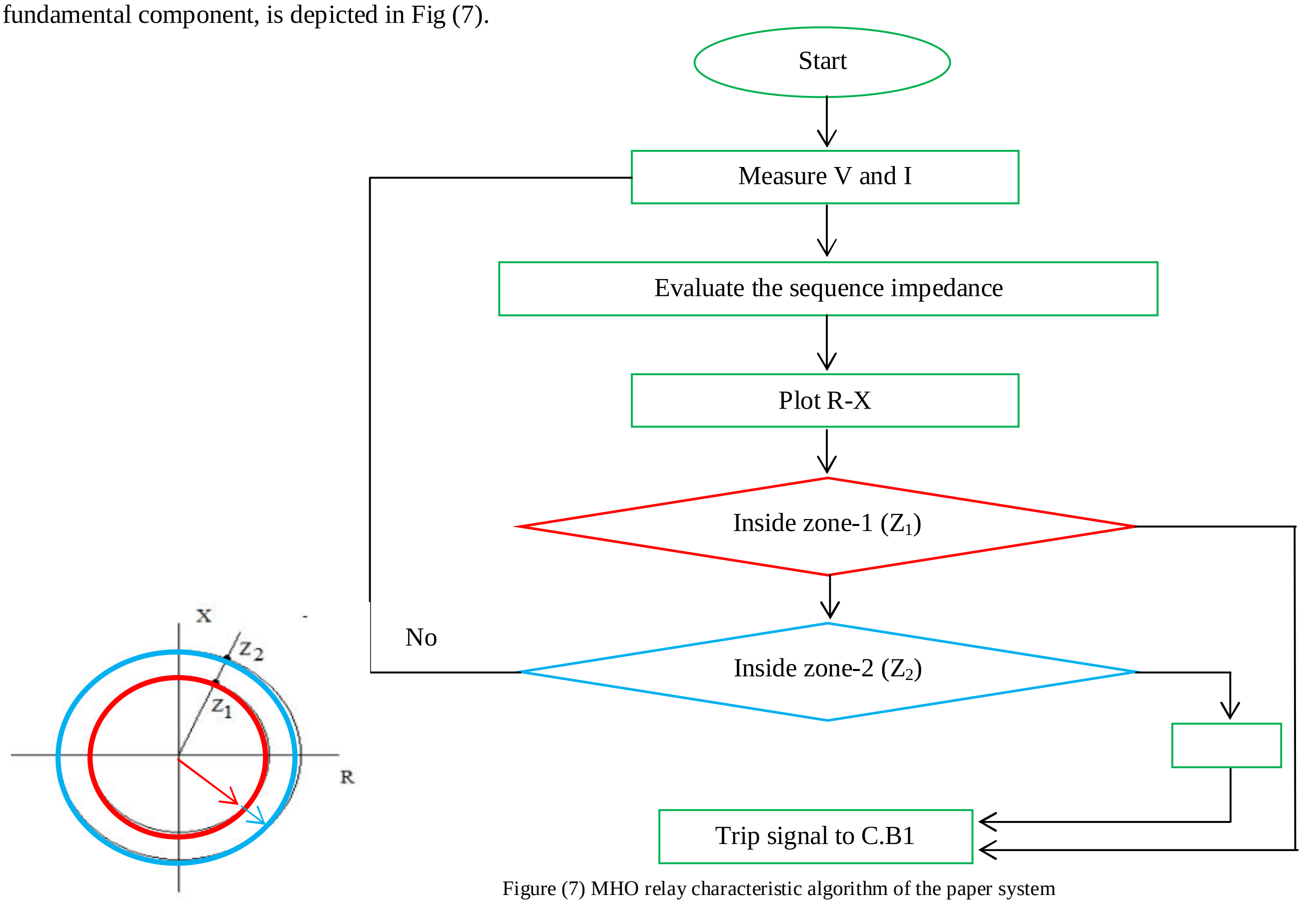


Figure (7) MHO relay characteristic algorithm of the paper system

The algorithm flow operates as follows:

- Voltage and current are input signals fed into FFT to evaluate the sequence impedance, mainly the positive sequence.
- MHO R-X plane is plotted.
- If the calculated impedance (V/I ratio) is inside zone-1, the relay sends a tripping-signal to C.B1, and if it is not then the R-X plot will pass along to zone-2.
- If the calculated impedance (V/I ratio) is inside zone-2, the relay sends a tripping-signal to C.B1 after a delay time of 0.3 sec. The delay time is set to avoid incorrect coordination.
- If the calculated impedance (V/I ratio) is neither inside zone-1 nor zone-2 then the system is not suffering from abnormal operations and the algorithm flow starts again.

The developed model is tested under two operational conditions: (A) steady-state condition (power flow) and (B) transient state condition (phase-to-phase fault). The fault is occurred at (Busbar B) as shown in Fig. (8).

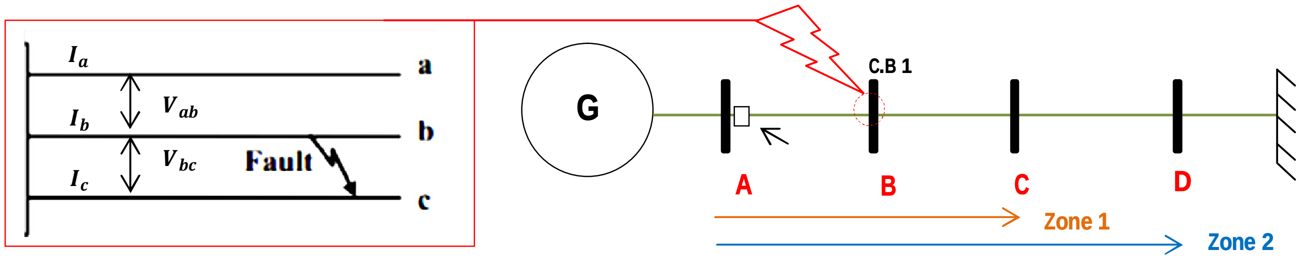


Figure (8) Schematic diagram illustrating the paper system during transient condition

At the fault,

$$V_b = V_c, I_a = 0, I_b = -I_c$$

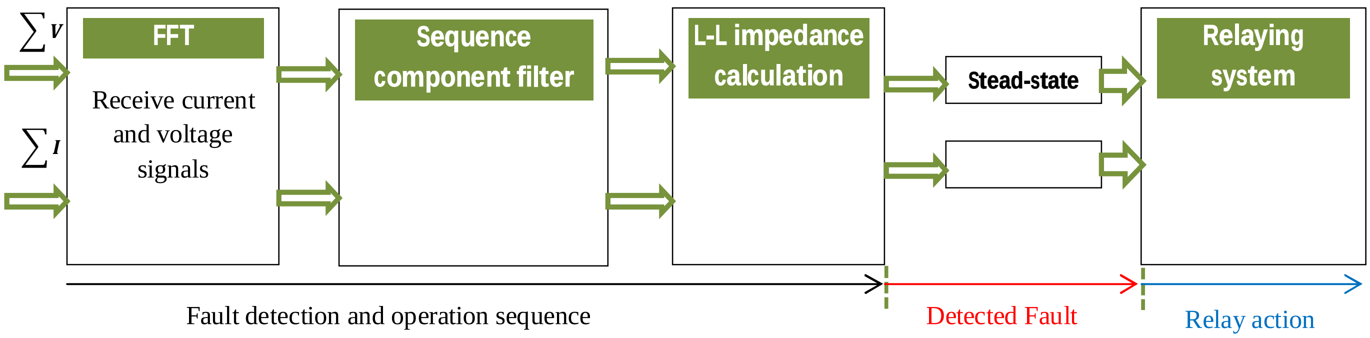
Phase (a) and phase (b) are considered as symmetrical components to minimise the calculation complexity for which the symmetrical component matrix becomes as follows:

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a = 0 \\ I_b \\ I_b = -I_c \end{bmatrix}$$

The fault current then can be expressed as

$$I_f = I_b = -I_c = (a^2 - a)\, I_{a1} - j\sqrt{3}\, I_{a1}$$

The configured PSCAD/EMTDC model performs the blocks shown in Fig. (9) using the pre-programmed master library component. The simulated waveforms are discussed hereinafter.



III. SIMULATION RESULTS AND DISCUSSION

The behaviour of the developed PSCAD model is studied through two different operational conditions. The conditions are comitted to checking the performance of the distance relay during normal operation and transient phase-to-phase short circuit operation. Emphesis placed upon the shape or pattern of the obtained voltage and current waveforms along with the developed R-X impedance trajectrory for both conditions.

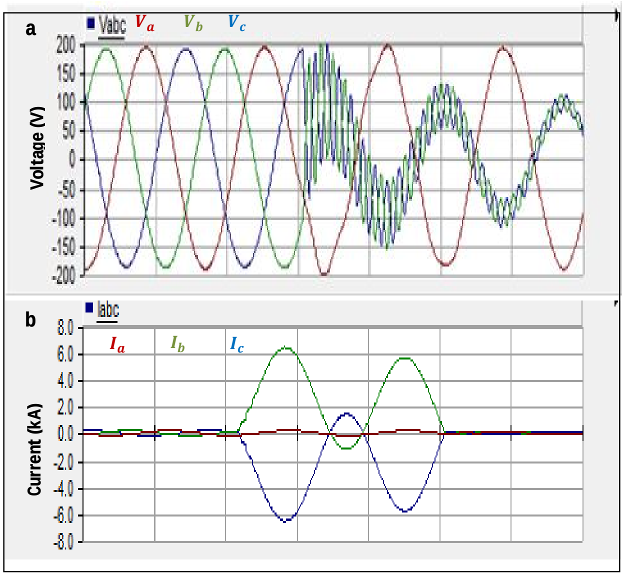


Figure (11) Simulation results for transient-state condition (a) 3Φ Voltage waveforms, (b) 3Φ current waveforms

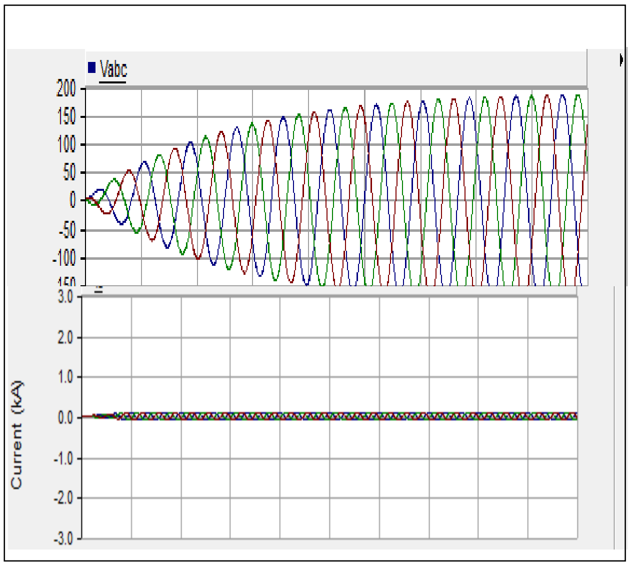


Figure (10) Simulation results for steady-state condition (a) 3Φ Voltage waveforms, (b) 3Φ current waveforms

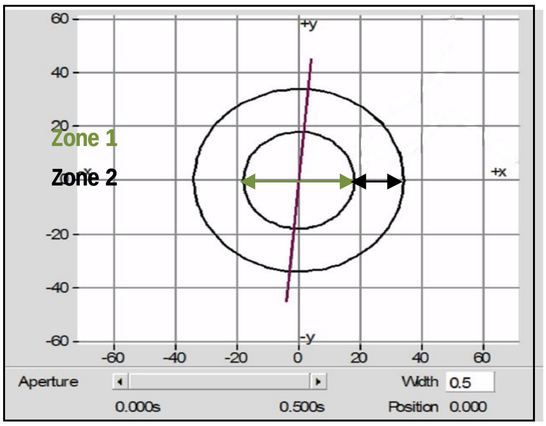


Figure (12) R-X impedance trajectory steady-state condition

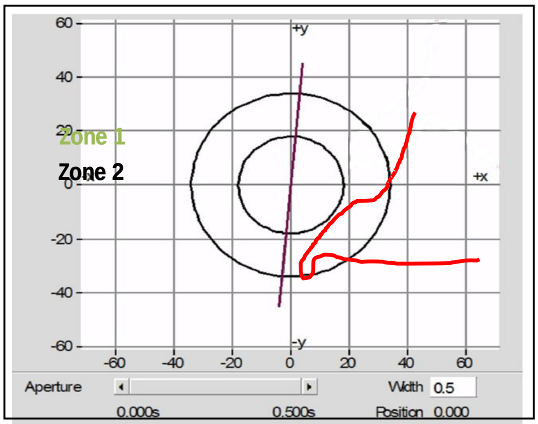


Figure (13) R-X impedance trajectory transient condition

From the simulation results, it is clear that the developed system is acting in the abnormal operation condition differently to the normal operational condition, which then validates it. Furthermore, the simulation results are in agreement to the theoretical waveforms. The transmission line under study had the same parameters during both conditions: $275\ Km$, $230\ kV$ and $60\ Hz$. The distance relay is placed nearby (Busbar B) in where the fault took place.

A. Steady-state Condition

This condition is carried out to exhibit the power flow of the model during normal operation. The stability of the system model is superior as shown in Fig. (10). The voltage waveforms for the three phases are stable and in $120\,°$ sinusoidal form, ensuring balanced system. Likewise, the current waveforms are stable, minimal and constant, ensuring no over-current occurrence.

In this case, the apparent impedance is larger than the impedance-reach of the used relay. As a result, the impedance relay does not detect disturbance on the transmission line; as such, no tripping-signal generated to the circuit breaker, which remained accordingly closed. This is proved by the fact that the R-X plane was cleared as shown in Fig. (12).

B. Transient Condition

In this condition, phase-to-phase fault is applied nearby (Busbar B), where the fault is a short-circuit between phase (b) and phase (c). The simulation results in Fig. (11) clearly show how the fault reflected on their behaviours. The voltage simulation shows critical drop in the contacted phases; (b) and (c). This ensures Eq. 5 that $V_b = V_c$, where they shrunk equally in their magnitudes at the same time. Although V_a seems constant during the fault, its magnitude slightly swings and this is inductive of an unbalanced system. The voltage drop mainly emanates from the excessive current flow towards the fault point. The current waveform shows zero value of phase (a) current, but excessively ramps up to $\pm 6\ kA$ for phase (b) and phase (c). It is evident how phase (b) and phase (c) current waveforms are mirror-image of each other with phase shift of $180\,°$. This validates Eqs. 6 and 7 that $I_a = 0$ and $I_b = -I_c$. The fault is set at a point spanning $125\ km$ from the circuit breaker C.B1, which is within zone-1 reach-point unit. The fault is detected by the system upon which R-X plane generated. It is clear from the R-X plane that the fault fell in zone-1 converge area, which then verifies that the relay model is capable of indicating the appropriate zone of operation. The fault is set at $0.28\ sec$ and a tripping-signal propagated to complete the circuit for the C.B1 opening. The tripping signal is shown in Fig (14).

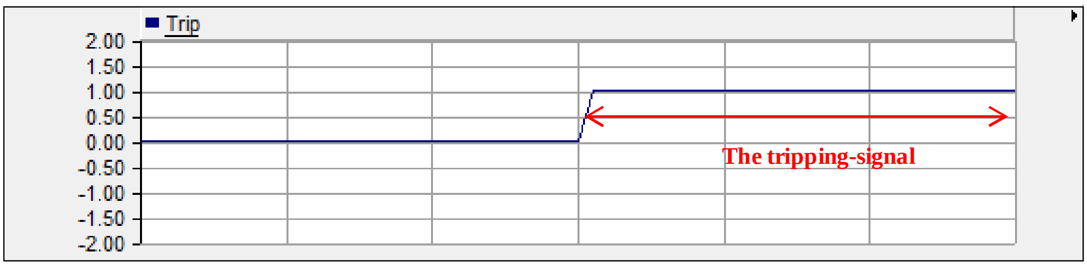


Figure (14) The tripping-signal generated upon fault detection

When the tripping-signal arrived at C.B1, an opening action took place immediately, during which active power fell to zero as shown in Fig (15).

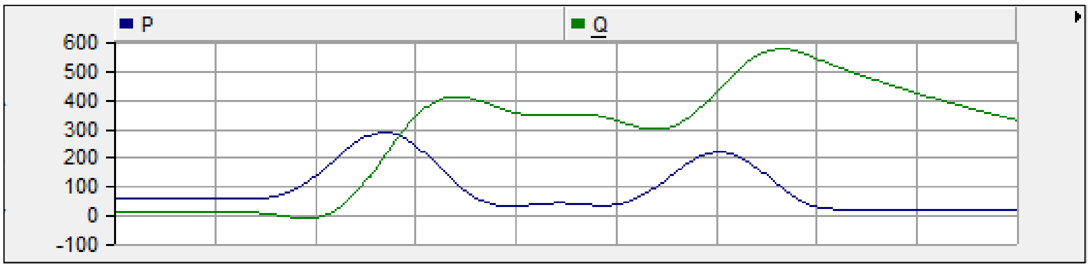


Figure (15) Real and reactive power waveforms after fault occurrence

IV. CONCLUSION

This paper is dedicated to examining transient measures and their effects in transmission lines and, in general, the overall stability of the power system. The study has demonstrated a PSCAD/EMTDC model that was successfully used to simulate a distance relay and to construct its algorithm. Two different operational studies were set to corroborate the consistency of the developed model. The performance of MHO characteristics was schematically evaluated during phase-to-phase fault. It is apparent how an extreme over-current transient presented over the occurrence of the fault during which time the distance relay was acting promptly as the fault was inside zone-1 circle. Concluded remarks:

- Transmission lines are essential media in power systems and normally transmit electric power at high voltages above $110kV$. Their widespread utilisation and natural operation increase their vulnerability to abnormal operations – such as short-circuit in two phases, all phases or phase to ground. This paper shows how distance relays are effective protection methods for long transmission lines.
- Distance relays are available in a plethora of types, where MHO type characteristic is most widely adapted to high voltage stationary systems – including transmission lines. This project indicates theoretically and schematically how a MOH characteristic distance relay plays a major role in transmission lines' protection.

- PSCAD/EMTDC is a powerful tool to examine transient studies as shown in the project analysis. The developed model successfully evaluated two operational conditions: (A) steady-state condition and (B) transient condition.

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