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INTELLIGENT TECHNIQUE FOR STABILIZING THE RESPONSE TIME OF TRANSMISSION LINE PROTECTION RELAY

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Abstract

It is impossible to develop a fault free system, regardless of how perfect the design might be, as time improves the system reliability and mean time to failure comes into place. This is not an exception for the new heaven transmission system. Delay in the relay response time is one of the factors identified as a challenge in the system and this affect power stability. This work presents the stabilizing response time of the transmission line protection relay using an intelligent based system. This will be achieved by the remodelling of the conventional relay employed in the existing system and optimize the operational efficiency using the singular value decomposition method. The methodology applied for the implementation of this study involves data acquisition from Enugu to Onitsha 330KV New Heaven transmission line which was done to study the conventional relay response time, considering some parameters such as the transmission capacity, line impedance, relay operating zones, transmission line distance, transformer ratings, actual relay time and nominal frequency. This methodology will enhance the operational speed and triggering time of the relays used for protection of the transmission line irrespective of the zones. The work will be implemented using Simulink and performance evaluation will be compared with the existing system and discussed. The relays in zone one are designed to trigger instantaneously. The relay in zone two are set to delay for 450ms before triggering while the relay in zone three are set to 750ms before it triggers. The result sows that the gap between the setting time and the triggering time of the relay is between (0.04 to 0.06ms).

Keywords: Power; Fault Detection; Relay; Transmission Line; Transformer; 330KV, Zones

1. INTRODUCTION

Transmission line faults have to be confirmed and located quickly and accurately in order to restore power delivery as quickly as possible. Historical events show that most of the large scale blackouts occurred due to a series of transmission lines experiencing disturbances leading to relay miss-operations (Kezunovic et al, 2014). When a transmission line is tripped due to the operation of protective relays, an accurate fault analysis can verify whether the operation of relay was correct. Incorrect and unwanted relay trips of healthy lines are called relay miss-operations (Kezunovic and Perunicic, 1999). Distance relay miss-operation can happen due to incorrect first zone setting, false trip of the second zone, false trip of the third zone after a power swing in the network, etc. Moreover, in the case of fault, it can provide the operator with an accurate estimation of the fault location to facilitate the restoration process. The confirmation and isolation of the faulted sections by the operator, as well as evaluating the relay operation by protection engineer is also possible by utilizing such fault analysis tools (Esmaeilianet al., 2015).

Different fault analysis methods have been proposed in the literature either as a separate fault detection, classification, and location functions or as a complete fault analysis tool (Propovic and Kezunovic, 1999). A group of methods are developed, considering line impedance calculation, while several others are based on high-frequency transients, travelling waves, and wavelet-based methods (Gonzalez-Sanchez et al., 2021).

Regardless of different schemes presented in these works, majority of them currently employed are distance protection, over current protection, differential protection etc. Distance protection being the predominant suffers from inaccuracy due to restraints of relays on protection schemes i.e reach settings. The relay cannot fully adapt to fluctuations in power system conditions especially in parallel lines as well as distinguish between transient and permanent fault following a short circuit (Upender et al., 2011).

In today’s Nigerian unbundled electricity industry, with its complex and weak electric power grid system, comes with its challenges of time synchronization of control and protection system. The demand for constant power supply is ever increasing; however the demand is met with lots of constraint. One of them being system faults. Faults on transmission line in particular is of great interest to the transmission company of Nigeria as more investment is put into restructuring the current infrastructure and also expanding existing ones (Awosopeet al., 2014).

The power sector of Nigeria is subdivided into policy, regulations, customers, operations. The operations division brings to light the activities of the transmission company of Nigeria that controls the high voltage delivery of power from generating plants to the substations for transmission to distribution stations. T.C.N handles a 330kv system capacity of 6870MW over a total distance of 5650Km their focus is to maintain power system stability, reliability and sustainability (Awosope et al., 2014). There is no fault-free system and it is neither practical nor economical to build a fault-free system. The various cases of abnormal circumstances such as natural events, physical accidents, equipment failure, and disoperation generate faults in the power system. The consequences of faults are traumatic amplification of current flow, increasing heat produced in the conductors leading to the major cause of damage (Yadav and Dash, 2024).

The actual magnitude of fault depends on resistance to flow and varied impedance between the fault and the source of power supply. Total impedance comprises of fault resistance, resistance and reactance of line conductors, impedance of transformer, reactance of the circuit, and impedance of generating station (Alam et al., 2014). The conventional distance relay settings are based on a predetermined network configuration with worst fault outcomes. Replacing these relays with solid state type will be time consuming and also will introduce harmonics into the transmission system, hence there is need to remodel the conventional system design to make it more intelligent and also to improve the triggering speed.

2. METHODOLOGY

The methodology applied for the implementation of this study involves data acquisition from Enugu to Onitsha 330KV New Heaven transmission line which was done to study the conventional relay response time, considering some parameters such as the transmission capacity, line impedance, relay operating zones, transmission line distance in KM, transformer ratings, actual relay time and nominal frequency. The data was acquired from the New-Haven substation, Protection Control and Metering Department. Then, the relay response time characteristics are modelled using the data acquired; the load flow along the 33kV transmission line will also be modelled. The models presented are simulated using MATLAB development environment. Finally, the simulation results are used to evaluate the performance of the model presented in the study.

2.1 Data Collection

Table 1presents the transmission line parameters with their respective capacities, the transmission line runs on a single circuit with conductor size of 381.7mm^{2}, conductor type is Bison Twin, line impedance of 0.039 (see table 2), line capacity of 1360A, and total line length of 106.2KM and 237 towers with the span of 450meters each.

Table 1: 330kv transmission lines parametric data

S/N	CIRCUIT	Year of installation	REG	NO OF CIRCUITS	TRANSMISSION LINE CAPACITY
1	Onitsha - New haven	1982	Enugu	1	1360
2	New Haven - Ugwuaji	2013	Enugu	2	1360
3	Ugwuaji - Markudi	2015	Enugu	2	1360
4	IkotEkpene - Ugwuaji 1	2016	Enugu	2	1360
5	IkotEkpene - Ugwuaji 2	2016	Enugu	2	1360
6	IkotEkpene - Ugwuaji 3	2016	Enugu	2	1360
7	IkotEkpene - Ugwuaji 4	2016	Enugu	2	1360

Table 2: 330KV Empirical parametric data

length of line (KM)	Conductor Size (mm2)	Conductor Type	Fro. Terminal	To. Terminal	Line Impedance
106.2	381.7	Bison Twin	T1	T237	0.039
7	381.7	Bison Twin	T1	T18	0.039
203.18	381.7	Bison Twin	T1	T475	0.039
162	381.7	Bison Twin	T1	T405	0.039
162	381.7	Bison Twin	T1	T405	0.039
162	381.7	Bison Twin	T1	T407	0.039
162	381.7	Bison Twin	T1	T407	0.039

2.2 330KV Transmission line Distance Relay Tripping Report

The operation of protective relay scheme requires extensive analysis in order to determine its performance. Therefore, it is important in this research work to study and present the performance of existing distance relay in the 330KV substation. This is done through distance relay trip report presented in table 3. This gives report of fault location, actual relay time set and time response of relay during fault occurrence. From the relay trip report of table 3, fault report shows that fault occurred at 40.7km which is in zone 1. This is right as zone 1 which is set to be 80% of the line. Also, from trip report 7 and 12 fault occurred at 27.00km and 69.8km and relay indicated zone 1 with response time of 0.00ms which is correct. Trip report number 2, 4, 5, 9, 13 and 14 shows that fault occurred at 70.5km, 80.3km, 78.5km, 79.6km, 78.8km and 81.0km respectively, and the relay indicated zone 2 with response time of 473ms, 480ms, 485ms, 530ms, 520ms and 515ms respectively which is wrong because the relay was set to response at 450ms. Also, Trip report number 3, 6, 8, 10, 11, and 15 shows that fault occurred at 90.1km, 84.7km, 90.1km, 93.0km, 93.8km and 96.7km and relay indicated zone 3 with response time of 778ms, 780ms, 785ms, 810ms, 800ms and 820ms respectively which is also wrong because the relay was set to response at 750ms. These are clear indications that the relaying scheme in New-Haven substation lacks the quality of timing at zone 2 and 3. It could not operate at time of reach because high fault resistance present on the line causing the distance relay to under reach.

Table 3: New Haven 330KV line Distance relay tripping report

S/N	Date	Fault location (km)	Actual relay time set (ms)	Time of response (ms)
1	4/01/2019	40.7	0	0
2	12/12/2018	75.0	450	473
3	2/10/2018	90.1	750	778
4	26/8/2018	80.3	450	480
5	10/07/2018	78.5	450	485
6	6/06/2018	84.7	750	780
7	18/04/2018	27.0	0	0
8	2/02/2018	90.1	750	785
9	29/12/2017	79.6	450	530
10	6/08/2017	93.0	750	810
11	18/07/2017	93.8	750	800
12	20/03/2017	69.8	0	0
13	2/01/2017	78.8	450	520
14	13/12/2017	88.6	450	515
15	5/10/2016	96.7	750	820

3. MODELLING OF THE RELAY RESPONSE TIME CHARACTERISTICS

The data in table 3 presented in the system analysis of the case of study (New Heaven station); it was observed that the mechanical relay employed has very high response time and triggering time delay varies between (20ms to 80ms which is also not acceptable to rely upon for transmission line protection (Ademola et al., 2016). To solve this problem we would have adopted a solid-state relay for the design due their faster response time, however they induce harmonics and will take more time to implement in the conventional system, hence we enhanced the design of the conventional mechanical relay in use, adopting the singular value decomposition method which will intelligently enhance the response time of this relay to at most 0.1ms. This is achieved using the following steps according to (Feng-Jih et al., 2012);

Step 1: Find the estimated operating time on the relay characteristic curve corresponding to a specific multiple of tap value current M as in equation (1). Repeat this process to the right with incremental step ΔM to form the sample sequence I_j, k=1,2, 3,……… ,where :

$$M = M_{min} - \Delta M \tag{1}$$

$M_{min:}$ minimum multipleof tap value current; ΔM: incremental sampling step

Step 2: Use t_k, k =1,2,3,……to form the Hankel matrices H(0)and H(1) in equation 1 as follow;

$$H(0) = \begin{bmatrix} t_1 & t_2 & \cdots & t_h \\ t_2 & t_3 & \cdots & t_{h+1} \\ \vdots & \vdots & \ddots & \vdots \\ t_h & t_{h+1} & \cdots & t_{2h-1} \end{bmatrix}_{h\times h},$$

$$H(1) = \begin{bmatrix} t_2 & t_3 & \cdots & t_{h+1} \\ t_3 & t_4 & \cdots & t_{h+2} \\ \vdots & \vdots & \ddots & \vdots \\ t_{h+1} & t_{h+2} & \cdots & t_{2h} \end{bmatrix}_{h\times h}. \tag{2}$$

Step 3: Apply SVD to the Hankel matrix H(0) to obtain matrices R, £, and S in (3)

$$H(0) = R£S^T \tag{3}$$

Step 4: Determine the proper dimension for the modal coordination system in (3) and obtain matrices R, £, and S in (4), where n is also the number of fitting waveform components and its range is form 1 to the rank of £

$$R\Sigma S^T = \begin{bmatrix} R_n & R_0 \end{bmatrix} \begin{bmatrix} \Sigma_n & \underline{0} \\ \underline{0} & \Sigma_0 \end{bmatrix} \begin{bmatrix} S_n^T \\ S_0^T \end{bmatrix} \tag{4}$$

Step 5: Calculate the matrices A,B,C which are the estimates of the matrices Am, Bm and Cm in the state space system (5) (6) and (7) as show (Jokojeje et al, 2015);

$$M(k = 1) = AM\,(k) + Bu(k)k = 0,1,2\ \ldots$$

$$t(k) = CM(k) + Du(k) \tag{5}$$

$$\hat{A} = (\Sigma_n)^{-1/2} R_n^T H(1) S_n (\Sigma_n)^{-1/2} \tag{6}$$

$$\begin{aligned} B &= (\Sigma_n)^{1/2} S_n^T E_v \\ C &= E_1^T R_n (\Sigma_n)^{1/2} \end{aligned} \tag{7}$$

Where E_1^T is shown as (8)

$$E_1^T = [1\ 0 \ldots 0] \qquad 8$$

And the system matrix D is as shown in (9)

$$D = t_0. \qquad 9$$

Step 6: Transform the state space equation (5) into modal coordinate system to determine Am, Bm, and Cm as in equation (10) (12) (13) and (14) shows (Jokojeje et al, 2015)

$$M_m(k+1) = AM_m(k) + B_m u(k), k = 0,1,2,\ldots \qquad 10$$

Where $M_m(k)$ is shown in (11)

$$M_m(k) = \varphi^{-1}x(k) \qquad 11$$

$$\Lambda = \varphi^{-1}\underset{\cdot}{\hat{A}}\varphi = \begin{bmatrix} \lambda_1 & \cdots & \varrho \\ \vdots & \ddots & \vdots \\ \varrho & \cdots & \lambda_n \end{bmatrix} \qquad 12$$

$$B_m = \varphi^{-1}B \qquad 13$$

$$C_m = C\varphi \qquad 14$$

Where $\lambda_i$is eigenvalue of Ậ, i = 1, 2, …, n. φ: matrix whose columns are the eigenvectors of Ậ.

Step 7: Obtain the unit impulse response sequence from (10), the state space equations under modal coordinates as known system Markov parameters in (15) below:

$$\begin{aligned} t(k) &= t_0, k = 0 \\ &= CA^{k-1}B = C_m A^{k-1}B_m \;\; k = 1,2,3,\ldots, \qquad 15 \\ &= \textstyle\sum_{i=1}^{n} c_i\lambda_i^{k-1}b_i \end{aligned}$$

Step 8: Derive the equation of the fitted relay characteristic curve by transforming back to continuous M-domain system (16) (Jokojeje et al., 2015).

$$t(M) = \textstyle\sum_{i=1}^{n_i} C_i e^{-a,(M-M^i)}$$

$$+2\textstyle\sum_{i=1}^{n_2} K_i A_{r_i}^{-f(M-M^i)}\cos(2\pi f_i(M-M^i)+\varphi_i) \qquad 16$$

$$+\textstyle\sum_{i=(n_2+1)}^{n_3} K_i A_{r_i}^{-f,(M-M^i)}\cos(2\pi f_i(M-M^i)+\varphi_i) \qquad 17$$

Where t is the operating time with M as its variable, n_1 is the number of the smooth waveform components, n_2 is the number of the paired oscillation waveform components (thus the coefficient 2), n_3 is the number of the independent oscillation components. (n_3- n_2) number of the unpaired oscillation waveform components Ci, α_1, K_1 and A_{ri}, are the constants. F_1 is the oscillation frequency, in Hertz. $_\varphi 1$ is the oscillation phase shift, in radian.

3.1 Protective Relay Performance

Modelling of relays is important for the protection because it allows the users to observe the internal performance of relays during normal operating states of the power system as well as during system disturbances. Relay models are used in a variety of processes, such as designing new prototypes and selecting appropriate protection algorithms, setting relay parameters, and training personnel (Nagesh and Puttaswanmy, 2013).

3.2 Phasor Estimation Algorithms

The estimated phasors of voltages and currents are used in the implementation of protection algorithms in relays. The ratio of appropriate voltages and currents then provide the impedance to the fault. The performance of all of these algorithms is dependent on obtaining accurate estimate of the fundamental frequency component of a signal from a few samples. The algorithms are classified according to the approach used to calculate the impedance based on the voltage and current measurements. A phasor is a representation of a sinusoidal voltage or current of the nominal frequency, *f* and its positive going zero crossing is radians ahead of the time equal to zero. The mathematical representation of a phasor is as follows (Izuegbunam et al., 2012).

$$V = |V| e^{j\theta} = |V|(\cos\theta + j\sin\theta) \qquad 17$$

The real and imaginary parts of the phasor are expressed as follows.

$$\mathrm{Re}(V) = |V|.\cos\theta \qquad 18$$

$$\mathrm{Im}(V) = |V|.\sin\theta \qquad 19$$

The magnitude and phase of the phasor can be calculated using the real and the imaginary parts of the phasor as follows (Izuegbunam et al., 2012).

$$|V| = \sqrt{\mathrm{Re}(V)^2 + \mathrm{Im}(V)^2} \qquad 20$$

$$\theta = \tan^{-1}\left(\frac{\mathrm{Im}(V)}{\mathrm{Re}(V)}\right) \qquad 21$$

Discrete Fourier transform (DFT) is generally used to calculate the phasor of the fundamental frequency component in digital protective relays.

4. MODELLING OF THE LOAD FLOW ALONG THE 33KV TRANSMISSION LINE

This model is design to understand the load flow analysis in the 33Kv transmission line. Considering an n- bus power system shown in figure 1; the transmission lines are shown by their equivalent π model with the impedances converted to per unit admittance on a common MVA buses (Omoroguiwa and Emmanuel, 2012)

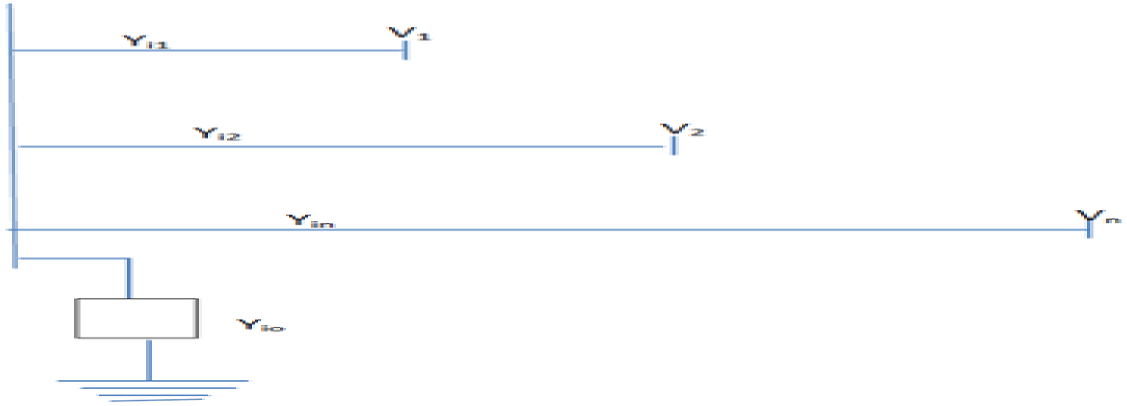


Figure 1: a typical bus of the power system

By applying the Kirchoff's current law (KCL) to bus i, we obtain the equation 22; (Omoroguiwa and Emmanuel, 2012)

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j, \quad j \neq i. \qquad 22$$

Where Y are the reference bus sign, V = voltage;

Given that the real and reactive power at the bus i are presented as (Omoroguiwa and Emmanuel 2012)

$$S_i = P_i + jQ_i = V_i \, I_i^* \qquad 23$$

Thus

$$I_i = \frac{P_i - jQ_i}{V_i^*} \qquad 24$$

Substituting for I_i in eqn. 24 yields the non linear equation for the transmission system

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j, \; j \neq i. \qquad 25$$

The above mathematical formulation for load flow problems results in a system of nonlinear algebraic equations which must be solved by iterative methods. The commonly used methods for solving load flow problems are Gauss-Seidel, Newton-Raphson and Fast Decoupled techniques. In this research work, Newton-Raphson techniques is used because of its quadratic convergence property and ability to handle large power network which are of paramount importance in solving nonlinear equations of power flow problems calling back equation 24 in admittance matrix as (Nagesh and Puttaswanmy, 2013);

$$I_i = \sum_{j=1}^{n} y_{ij} V_j. \qquad 26$$

In the above equations, j includes bus i. expressing this equation in polar form, we have

$$I_i = \sum_{j=1}^{n} |Y_{ij}| |V_j| \angle \theta_{ij} + \delta_j. \qquad 27$$

The complex power at bus i is determined by substituting (22) into (27)

5. SIMULATION OF THE MODEL

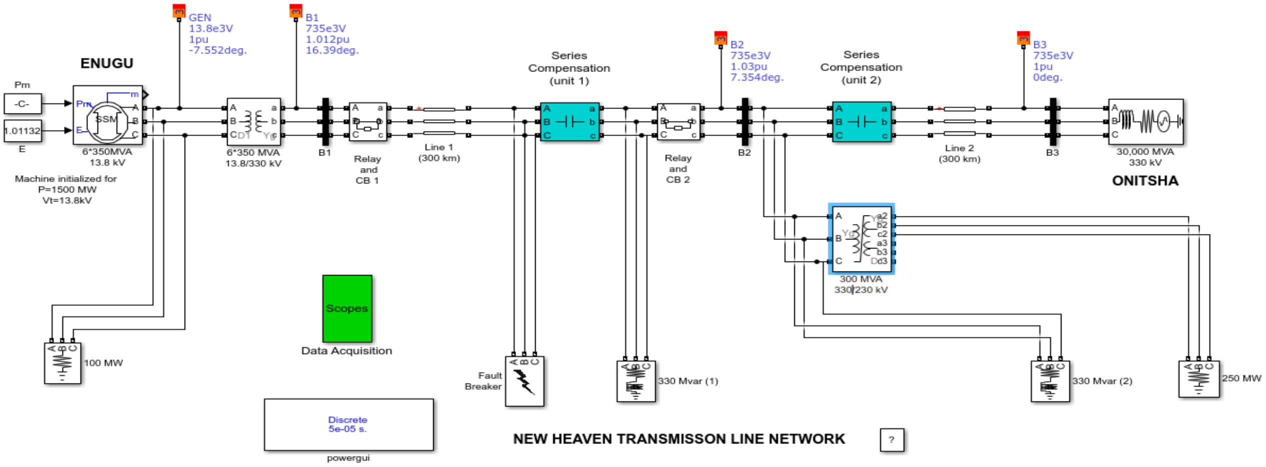
Since we have successfully developed an enhanced model for the protection relay time response and also the transmission line and load flow analysis, we have to implement the model using Simulink to evaluate the performance of the relay response in time of fault.

Table 4: The simulation parameters

Frequency	50Hz
Number of Buses	3

Generator capacity	350MVA
Transformer rating	230MVA
Number of Zones	2
Transmission Line distance per Bus	198Km
Number of relays	2
Relay Maximum triggering time	0.1ms

The simulation model in figure 2; presents a three phase 50Hz, 330KV power system transmitting power from new heaven to an equivalent Onitsha network through a 198km transmission line. The transmission line is split into two zones of 300km each serially compensated by a shunt reactance and connected between B1, B2 and B3. Each of the zone is protected with a relay-controlled circuit breaker which is expected to trigger the circuit breaker in less than 0.1ms when the threshold energy level of induced three phase to ground fault increases above 30MJ. The transfer function is presented in figure 3modelled considering the propagation time delay from the substation to the receiving end of the transmission bus.



2: Simulation model of the transmission line network

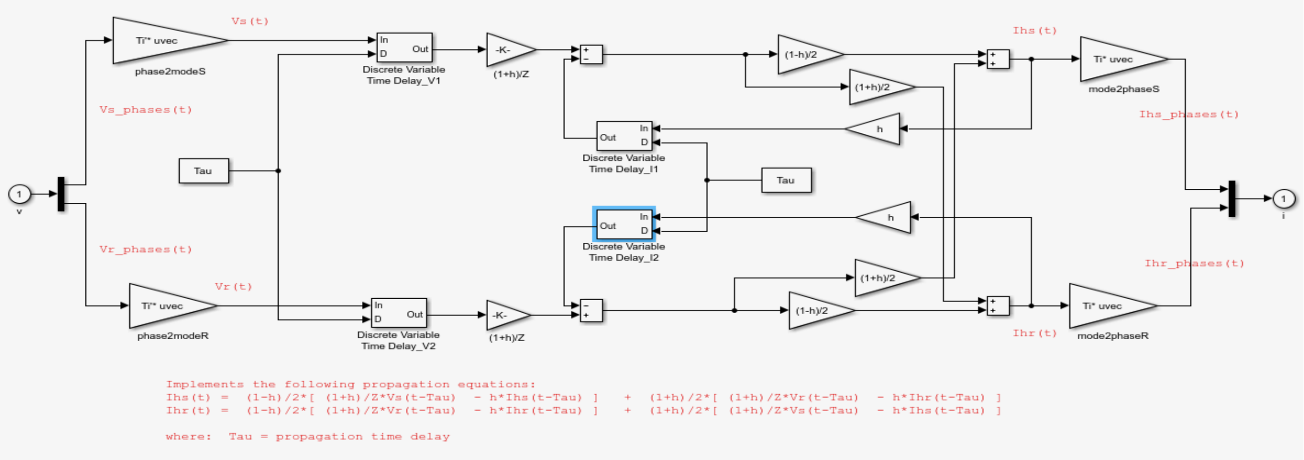


Figure 3: transfer function of the transmission line network

The power line is designed with an intelligent protective relay (see figure 4) using the singular value decomposition method as shown in equation 16. The implication is to intelligently improve the response time and triggering speed of the relay-controlled circuit breaker. To justify this claim, a fault breaker as shown in figure 4 is induced to introduce line to ground fault in zone 1 and three phase to ground fault in zone 2, these faults types have certain energy threshold levels which is expected to be detected by the relay and then act on it. The performance evaluation and result discussion will be evaluated using the instrumentation model presented in figure 6 and the results will be presented in the next chapter of this thesis.

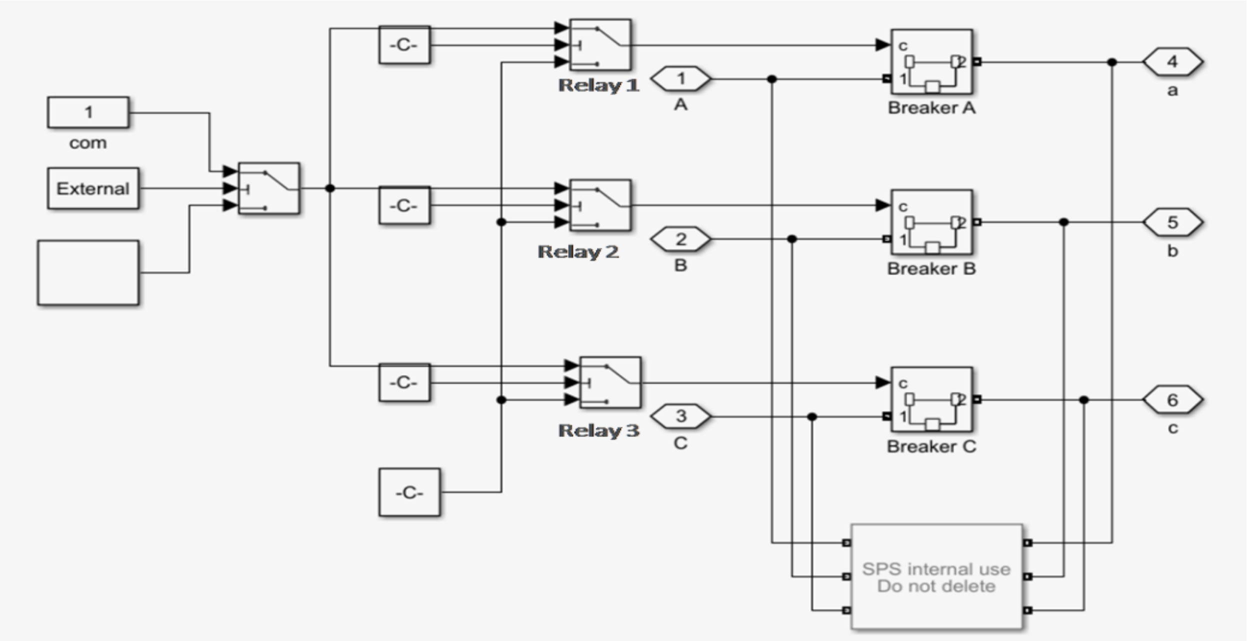


Figure 3: model of the protection chamber with the relays

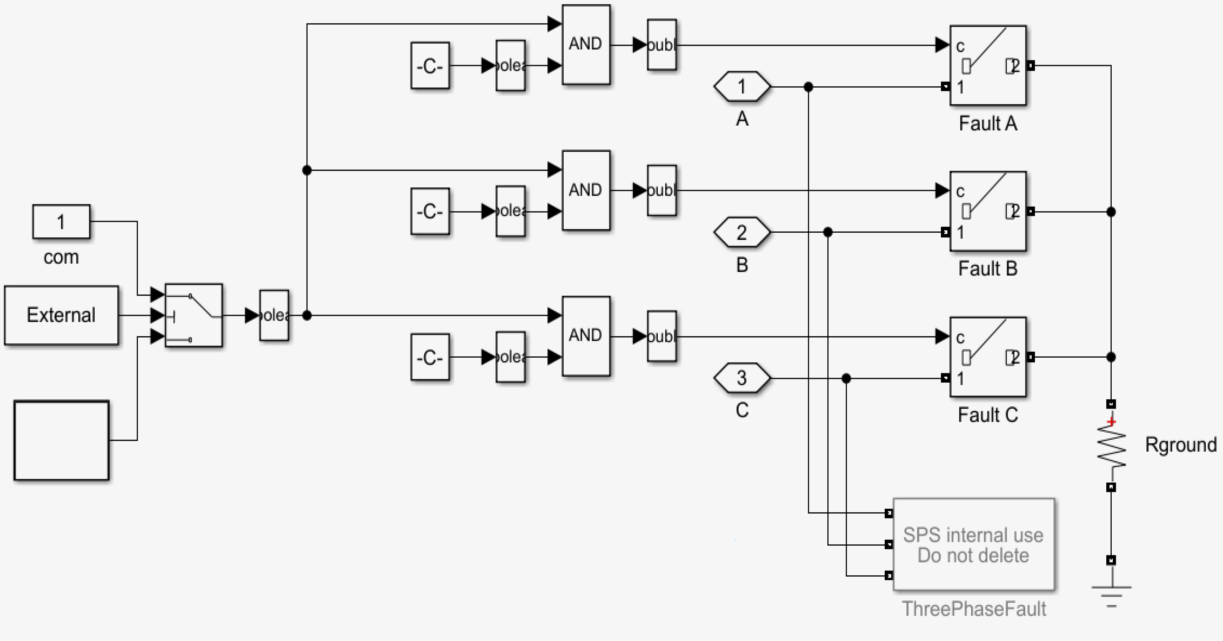


Figure 4: three phase to ground fault

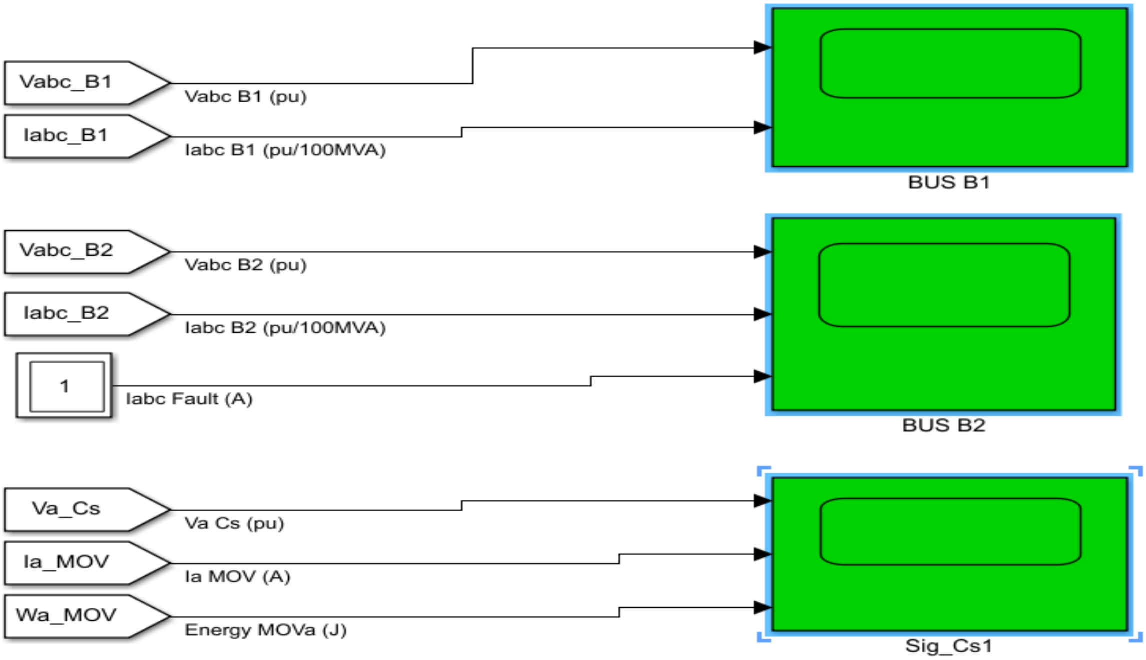


Figure 5: Model of instrumentation tool for analysis of relay response per bus

6. SYSTEM RESULTS

The power system transmission line is designed with the relay protection scheme as shown in table 1 and figure 1; the zone 1 relays are always instantaneous at 0ms, while a certain margin of delay is induced in zone 2 (450ms), this is to give time for the fault to clear by the relay action from zone 1; however, if that’s not the case the relay in zone two triggers. There is another protection relay with 750ms time delay in zone 3 to act if zone 2 relay could not respond.

Table 4: Actual setting for the relays

Fault	**Zones**	**Setting relay response time (ms)**
No fault	1	0
Single phase to ground	2	450
Three phase to ground	3	750

Evaluating the performance of the relays and transient stability of this simulation model when a line to ground and three phase to ground fault are applied on the line 1. Before the inducement of faults in the transmission line, the relays are inactive (closed), then line to ground fault is applied on the line 1 (yellow phase) at t =0.01ms with the two relays sensing the faults and open at t=0.05ms, simulating a fault detection and opening time of 0.04ms the relay triggers the circuit breaker at t=0.09ms to eliminate the fault. Thus the response time delay is 0.05ms, adding to the delay time 450ms gives 450.05ms (triggering time and delays time).

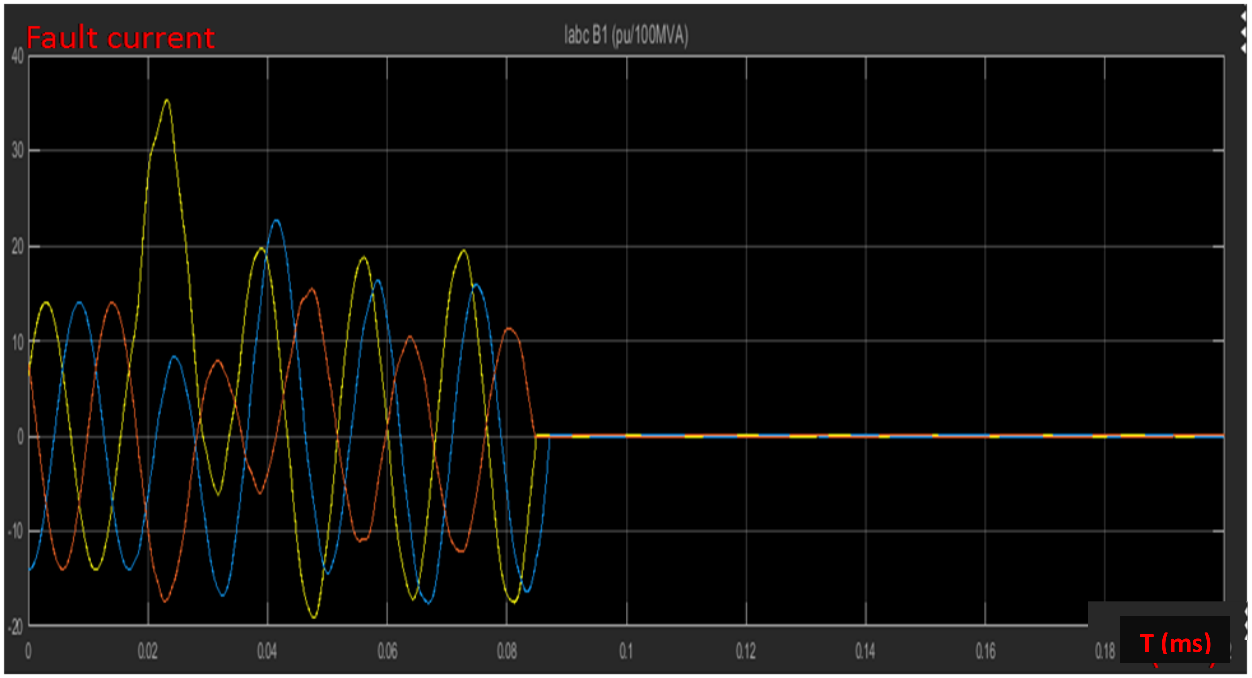


Figure 6: line to ground fault analysis

The line fault is characterized with an energy threshold of 10MJ of which the fault type is limited only to zone two and hence we cannot determine the response time delay for relay three in bus 2 at this moment. However, the implication of this result is to demonstrate the effectiveness of the enhanced algorithm we used to improve the sensing ability of the relays. The simulation result is fully presented in figure 7; showing the transient stability at bus 1 and the analysis of fault current neutralization respectively.

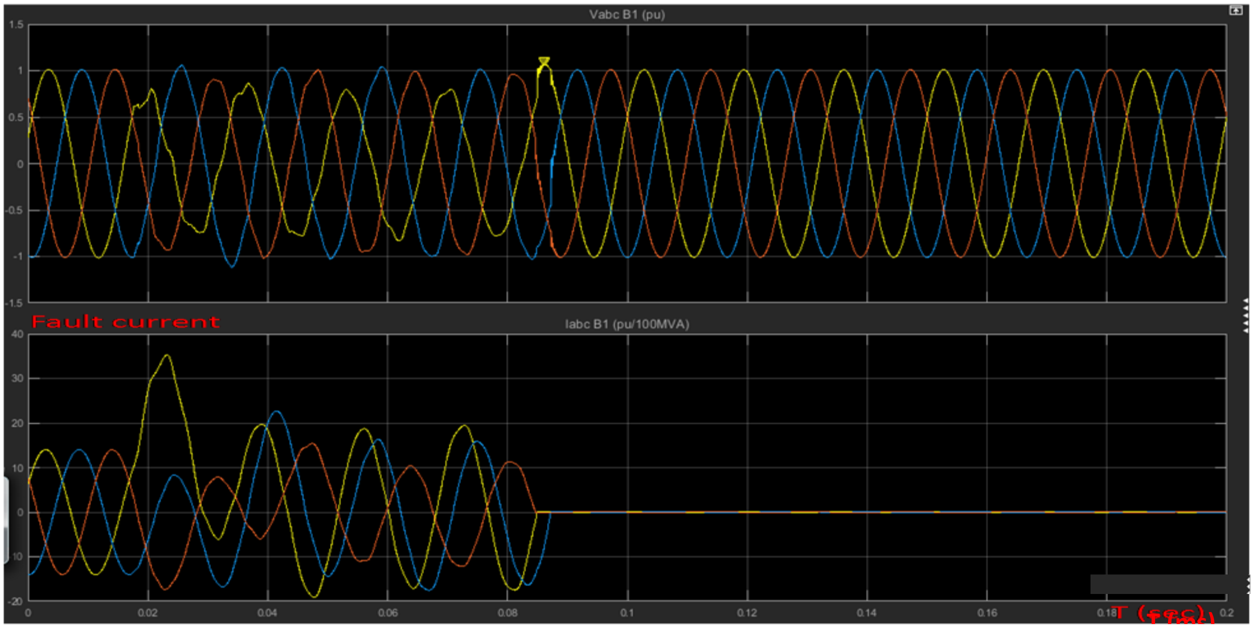


Figure 7: transient stability and relay response in zone (Bus) 1

To analyze the relay delay response time in zone 3, a three phase to ground fault is introduced to the system with varying threshold energy as shown in figure 8;

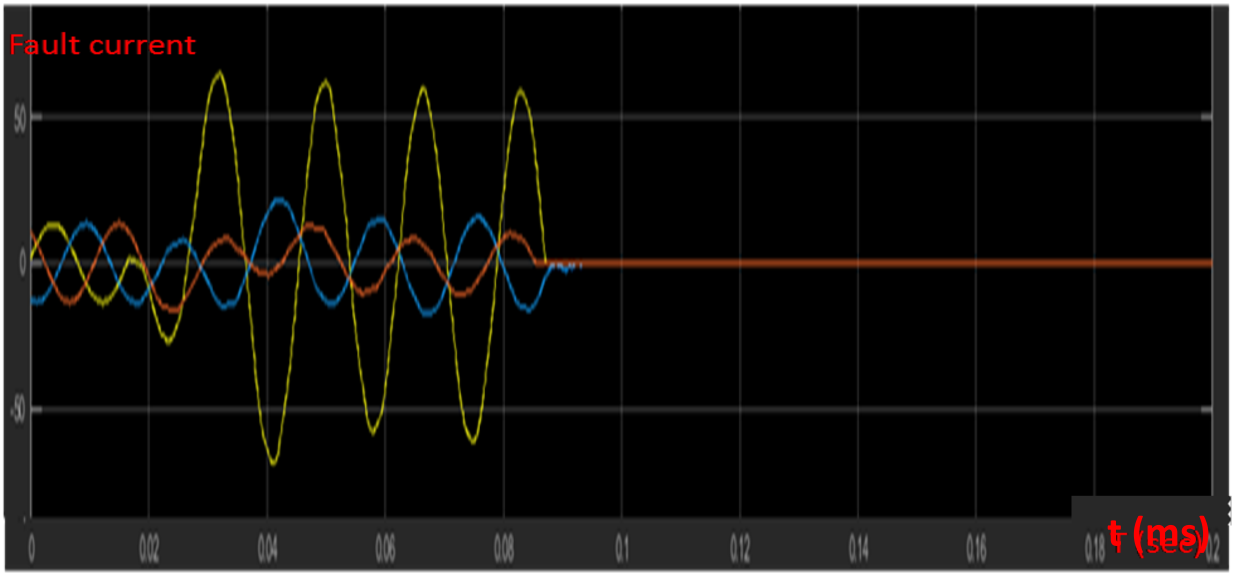


Figure 8: three phase to ground fault

From the result presented in the figure 8; the three phase to ground fault is induced into the transmission line from zone 2, and the relays are open at t=0.01ms, with the two relays sensing the faults and open at t=0.02ms, simulating a fault detection and opening time of 0.01ms the zone 1 relay triggers the circuit breaker at t=0.03ms to eliminate the fault. However this eliminates the fault only in line one. The implication is that the relay only controls the fault in line one, thus to control the fault in the other lines, the other zone 3 relay is triggered at t=0.09ms and hence the fault current is neutralized. The relay response time delay between zone 2 and zone 3 is 0.04ms which is much more improved response time result compared to the original system.

6.1 Discussions

This discussion is summarized using the table 5; this indicates the setting for the relays and the response time they actually achieved. The relays in zone one are designed to trigger instantaneously. The relay in zone two are set to delay for 450ms before triggering while the relay in zone three are set to 750ms before it triggers. The result sows that the gap between the setting time and the triggering time of the relay is between (0.04 to 0.06ms).

The simulation results presented have demonstrated the improved protection capacity for the remodelled relay, with the capacity to intelligently detect both single line to ground faults and three phase to ground fault. Secondly, the triggering delay response time between the two relays is at t=0.04ms which is a very reliable and effective means to protect the transmission line. Compared to the characterized system still currently from New heaven transmission station with triggering delay response time of 20ms to 85ms.

Table 4.2: Summary of response time results in both relays

Fault	**Zones**	**Setting relay response time (ms)**	**Actual relay response time (ms)**

No fault	1	0	0
Single phase to ground	2	450	450.05
Three phase to ground	3	750	750.04

7. CONCLUSION

Modelling of protective relays is economical and feasible alternative to investigate the performance of relays and protection systems. This study presents a new approach in the modelling design of the conventional relay using the Singular Value Decomposition Method (SVDM) method in MATLAB based on Hankel matrices which can estimate exact magnitude of DC offset component and completely eliminates it from operating quantities during faults and also makes use of smoothing window to filter out noise if any. The proposed method is evaluated using MATLAB to models a power transmission system and simulates many fault conditions on a selected transmission line such as line to ground fault and three phase to ground fault. This wok thus remodelled the conventional mechanical relay currently in use to respond faster and more intelligently using the singular value decomposition method (SVDM) to enhance the steady state response time at 0.04ms compared to the characterized relay at over 80ms delay.

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