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Adaptive Settings of Distance Relays in the Presence of Flexible Alternating Current Transmission System (FACTS) Devices in the Nigeria Transmission Network

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Abstract
The Flexible Alternating Current Transmission System (FACTS) devices affect the performance of the pre-existing protective distance relay on the transmission line. These devices would affect both the steady state and transient trajectory of the apparent impedance seen by distance relays due to the fast response time of the FACTS controllers with respect to that of the protective devices. The simulation model of the Thyristor Controlled Series Capacitor (TCSC), a series FACTS device was simulated in the Nigeria power system using MATLAB/ Simulink software. The apparent impedance of the Nigeria 330kv transmission network was calculated based on the method of symmetrical components of voltage and current. This ultimately set the trip boundaries of a mho-type distance relay. The results from the case study for a single line to ground fault at various locations were generated from system modelling and simulations for conditions without TCSC, with TCSC and with Metal Oxide Varistor (MOV) protection. The proposed adaptive relay algorithm was used in adjusting the settings of the relay to accurately trip with respect to the location and direction of faults in the Nigeria power system.

Keywords: Protection, Faults, Relay, Metal oxide varistor, FACTS

1. Introduction

The presence of a FACTS device in the faulted loop of a transmission line introduces changes to the line parameters seen by the distance relay. The FACTS device would affect both the steady state and transient trajectory of the apparent impedance seen by distance relays due to the fast response time of FACTS controllers with respect to that of the protective devices. During system faults, high fault currents through the series capacitor cause voltage to rise across the series capacitor bank, which in turn causes overvoltage that may damage the compensation devices (Biswal, Pati, & Pradhan 2013). In Hemasundar, Thakre, and Kale (2014), detailed modelling of distance relay and STATCOM were presented using Power System Computer Aided Design (PSCAD/EMTDC). Different fault types and location were simulated with different operation mode of STATCOM. The simulation results showed the under-reach and over- reach problems resulted from injected reactive power to the system. The distance relay detects a fault in the transmission line depending on the line impedance which is a function of the length of the transmission line or power system cable (Jagdale & Validya 2013).

Metal-oxide-varistor (MOV) devices, connected in parallel have been used to protect the series compensation against overvoltage during faults (Sivov, Abdelsalam & Makram 2015). The MOV-protected series compensation increases the complexity of fault analysis and device protection (Jamali & Shateri 2010). According to Benmouyal & Mahseredjian (2001), the equivalent MOV/capacitor per phase impedances were used to compute the new sequence impedances of the transmission line impedance matrix. This method ultimately sets the trip boundaries of a quadrilateral-type distance relay. This method was developed for a medium length transmission line neglecting the line's distributed parameters. In Khederzadeh, Ghorbani, and Salemnia (2012), a detailed model of SSSC and its control were presented. Analytical study based on voltages and currents symmetrical components for single phase to ground fault to show the impact of SSSC on distance relay performance was investigated. New equivalent symmetrical components of a 48-pulse SSSC and apparent impedance calculations for phase to ground and phase to phase fault were presented in Shojaei and Madani (2010). The simulation results showed the apparent resistance and reactance values were increased in both capacitive and inductive compensation mode due to the effect of coupling transformer leakage impedance.

During fault conditions, FACTS devices greatly impact on the trip boundaries of distance protection relays. These fault conditions if not interrupted promptly and accurately will lead to the power system being stressed (Nayak, Pradhan & Bajpai 2015), (Kundu & Pradhan 2014). Hence the performance evaluation of distance protection scheme in the presence of FACTS controllers which affect the apparent calculations at relay is very essential so as to develop a new setting for zones for distance relay on a transmission line (Mrehel, Elfetori, & Hawal 2013). The use phasor-measurement units (PMUs) at both ends of the line with a dedicated communication channel to compute the compensation level during a fault and adapt relay setting accordingly (Bhalja & Maheshwari 2008). Jyoti & Reshmita (2017) presented an adaptive zone selection algorithm for the transmission line with mid-point connected STATCOM. The impact of STATCOM on distance protection was investigated for different fault types, fault resistances and load angles. This method concluded that the proposed adaptive technique was effective for accurate zone tripping thereby mitigating both the under reach and overreach effects of STATCOM. According to Kumar, Chowdary and Babu (2013), Artificial Neural Network can be used to test for the effects of series compensated transmission line on distance protection under various fault conditions. The result indicated that the presence of a series compensator TCSC changed the impedance measured by the relay used by the protection system which causes mal-operation of protective and also shows wrong distance measurement. The application of Modified Optimization (MPSO) technique for optimal settings zones for Mho distance relay protected 400kV single transmission line of Eastern Algerian Transmission network compensated by TCSC connected at midpoint was studied in Zellagui & Chaghi (2013). The findings demonstrated the outstanding performance of the proposed MPSO over analytical method in terms of computation speed, rate of convergence and feasibility. Song, Johns and Xuan (2016), used the classification technique based on Artificial Neural Network (ANN) examine the effect of series compensation on distance relay used to protect transmission line. However the method involves a lot of empirical risk minimization and suffers from drawbacks. Also the classification scheme based on wavelet transformation was suggested in Megahed, Monem and Bayoumy (2006); the proposed technique was validated only for limited cases and involved a lot of assumptions especially on the compensation level.

Yusuf & Nwohu (2015) studied the effects of Unified Power Flow Controller (UPFC) on distance relay in the Nigeria 330kV (North Central) network. This work concluded that the UPFC during fault conditions greatly impact on the trip boundaries of distance protection relays. However, the effects of distributed parameters were neglected as the method was only applied to a medium length line of just about 120km. The presence of protective MOV operation during high fault conditions was not considered and the work did not proffer any solution to these identified effects of UPFC in the Nigeria power system. Dash, Pradhan, & Panda (2001) analysed the effects of series compensation on distance protection relay and presented a method using differential relays in adapting relay reach setting. This method neglected the effects of MOV action on the equivalent MOV/FACTS impedance and made assumption about the presence or absence of FACTS and the amount of compensation provided to the relay. Also the method was applied only on a medium length line neglecting distributed parameters. In Kazemi, Jamali, and Shateri (2008), the mal-operation of distance relay in the presence of series synchronous compensator using voltage and current symmetrical components was evaluated. However, this method did not consider the action of MOV protection on the SSSC during fault conditions and distributed parameters of the transmission line were neglected. Solutions were not provided to alleviate the identified problems in the work. With increasing research works proposing for FACTS devices to be incorporated into the Nigeria power system, the cumulative effect of these devices with MOV operation during fault conditions had not been hitherto articulated. This paper tends to bridge these identified gaps and particularly develop an adaptive algorithm that will adjust the distance relay settings during fault condition in the presence of FACTS device, considering MOV operation and distributed parameters in the Nigeria 330kV transmission system

2.0 Material and methods

The TCSC is a series FACTS compensator which consist of a capacitance (C) connected in parallel with an inductance (L) controlled by a valve mounted in anti-parallel conventional thyristors T_1 and T_2 and controlled by an extinction angle (α) which varied between 90^0 and 180^0. This compensator can be modelled as a variable reactance (X_{TCSC}) and the apparent reactance of the TCSC injected on transmission line is defined by the following equations 1 and 5.

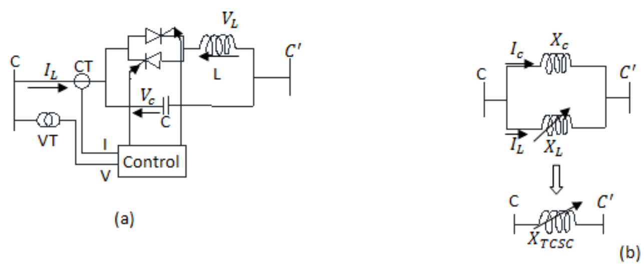

Figure 1: Transmission Line with TCSC System a) System Configuration (b) Apparent Reactance

$$X_{TCSC(\alpha)} = X_{L(\alpha)} // X_C = \frac{X_{L(\alpha)} X_C}{X_{L(\alpha)} + X_C} \quad (1)$$

The reactance of the variable inductance $X_{L(\alpha)}$ controlled by the thyristor is defined by equation

$$X_{L(\alpha)} = X_{Lmax} \left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right] \quad (2)$$

where $X_{Lmax} = L\omega$ (3)

The capacitance is defined by

$$X_c = \frac{-1}{J\omega C} \quad (4)$$

From equation (2) and (4), the final equation (1) becomes

$$X_{TCSC(\alpha)} = \left[\frac{L\omega.\left[\frac{\pi}{\pi - 2\alpha - \sin 2\alpha}\right].\frac{1}{\omega C}}{L\omega\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right] + \frac{1}{\omega C}}\right]$$

Or

$$X_{TCSC(\alpha)} = \frac{X_C X_{Lmax}\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right]}{X_c + X_{Lmax}\left[\frac{\pi}{\pi - 2\alpha - \sin(2\alpha)}\right]} \quad (5)$$

The active power (P) and reactive power (Q) on transmission line with TCSC were defined by following equations

$$P(\delta) = \frac{V_A . V_B}{Z_{AB} + X_{TCSC(\alpha)}} \sin\delta \quad (6)$$

$$Q(\delta) = \frac{V_B^2}{Z_{AB} + X_{TCSR}} - \frac{V_A V_B}{Z_{AB} + X_{TCSC}} \cos\delta \quad (7)$$

where, Z_{AB} was impedance of transmission line, δ was line angle, V_A *and* V_B voltages on extremity of transmission line.

2.1 Apparent Impedance Analysis.

The protection of a transmission line was zoned with each zone protected by a relay having different reach and operating time (Mrehel, Elfetori, & Hawal 2013). Due to the inaccuracies of current transformers and voltage transformers, distance protection zones are not set to be on the boundaries of the transmission line (Verma & Sharma 2017). The setting zones for protected electrical transmission line without TCSC were shown in figure 2.

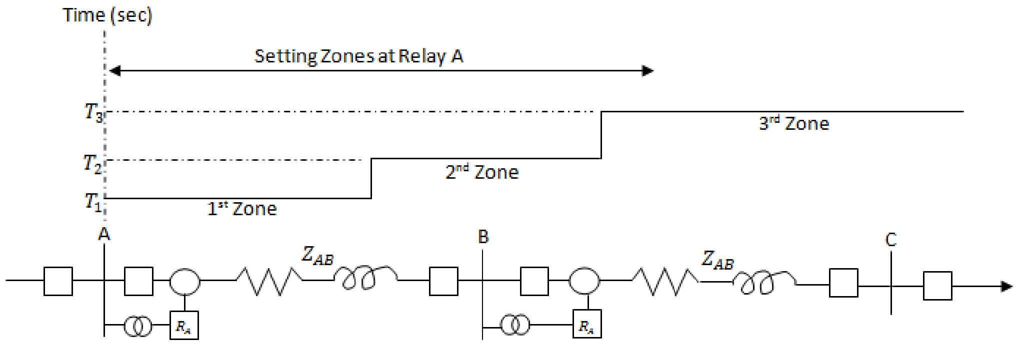

Figure 2: Zones of Protection

$$Z_1 = 80\% \ of \ Z_{AB} = 0.8(R_{AB} + jX_{AB}) \quad (8)$$
$$Z_2 = R_{AB} + jX_{AB} + 0.2(R_{BC} + jX_{BC}) \quad (9)$$
$$Z_3 = R_{AB} + jX_{AB} + 0.4(R_{BC} + jX_{BC}) \quad (10)$$

The total impedance of electrical transmission line AB measured by distance relay without fault is (Chauhan, Tripathy & Maheshwari 2014):

$$Z_{seen} = \left({K_{VT}}/{K_{CT}}\right).Z_{AB} \quad (11)$$

where

$$K_{VT} = {V_{prim}}/{V_{sec}} \quad (12)$$

And

$$K_{CT} = {I_{prim}}/{I_{sec}} \quad (13)$$

Where Z_{AB} was the real total impedance of the protected transmission line AB. K_{VT} and K_{CT} were the ratio of voltage to current transformer respectively. Z_1, Z_2, Z_3 were protection zone 1, zone 2 and zone 3 respectively, R_{AB}, X_{AB} were the line resistance and reactance respectively, Z_{seen} was the impedance measured by the relay, V_{prim} was the primary voltage, V_{sec} the secondary voltage of the voltage transformer, I_{prim} the primary current and I_{sec} the secondary current of the current transformer (Srivani & Vittal 2010). The presence of the TCSC with its reactor (X_{TCSC}) had a direct influence on the total impedance Z_{AB} of the line protected by the distance relay but no influence on the resistance. The new setting zones for a protected line with TCSC connected at midline were:

$$Z_1 = 0.8[R_{AB} + jX_{AB} + jX_{TCSC}(\alpha)] \quad (14)$$
$$Z_2 = R_{AB} + jX_{AB} + jX_{TCSC}(\alpha) + 0.2(R_{BC} + jX_{BC}) \quad (15)$$
$$Z_3 = R_{AB} + jX_{AB} + jX_{TCSC}(\alpha) + 0.4(R_{BC} + jX_{BC}) \quad (16)$$

2.1.1 Modelling of MOV/TCSC Equivalent Impedance

Series-connected controllers are designed to ride through contingency and dynamic overloads, and ride through or bypass short circuit current. They can be protected by metal-oxide varistor (MOV) arresters or temporarily bypassed by solid-state devices when the fault current is too high, but they have to be rated to handle dynamic and contingency overload (Sarangi & Pradhan 2011), (Nayak, Pradhan & Bajpai 2015). The linearized model shows an important result that even though the TCSC was connected in parallel with a highly non-linear device, the resulting total current through the combination remains sinusoidal and the MOV/TCSC circuit under fault can be approximated by a reduced single phase circuit of Figure 3(c).

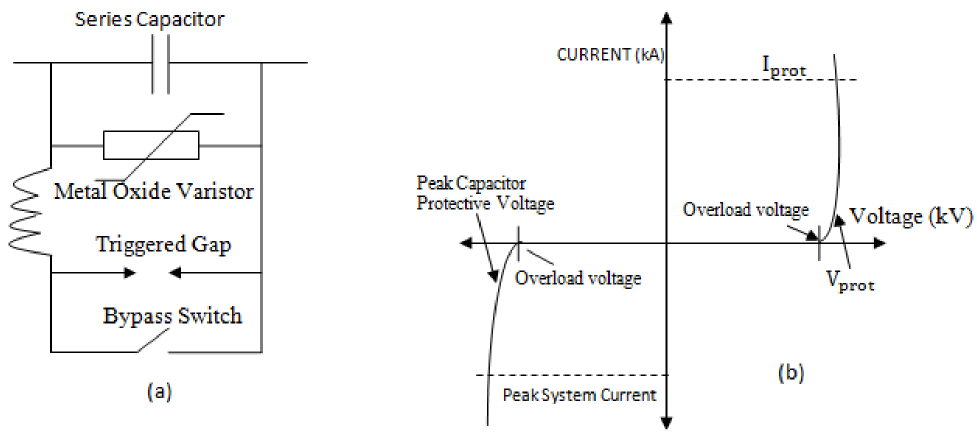

Figure 3 (a) MOV typical overvoltage protection scheme, and (b) V-I characteristics

This result is important for determining total line impedance and for distance protection.

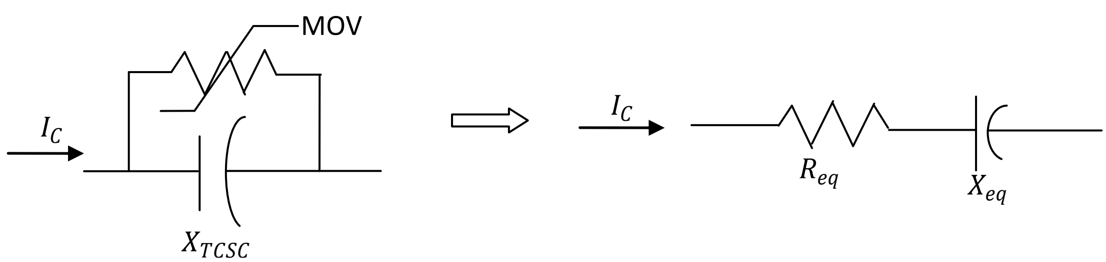

Figure 3(c): Modelling MOV/TCSC as equivalent impedance during system fault

The linearized model was developed by varying the capacitance, capacitor protective voltage level, system voltage, system impedance, MOV voltage-current characteristics, and other system parameters (Zellagui & Chaghi 2012), (Zigler 2008).

$$Z_{eq} = R_{eq} + X_{eq} \quad (17)$$

Where Z_{eq} was the equivalent impedance which comprised of the TCSC capacitive reactance, MOV resistance and transmission line impedance.

2.1.2 Simulink model of the Benin to Ikeja West transmission line

Figure 4 showed the whole modelling of distance relay on the Benin to Ikeja West transmission line in the Nigeria power system using MATLAB/Simulink and the Simpower tool. The input of the distance relay were phase voltages and currents, and the outputs were fault types indicators, zone indicator, the values of the transmission line resistance and reactance used for impedance trajectory and tripping signal. Each subsystem was established and modelled separately, then connected together to compose the larger power transmission system. The subsystems used were based on the main function of a typical digital distance relay. These include: Fault detection and classification subsystem, apparent impedance measurement, zone detection and tripping signal subsystem.

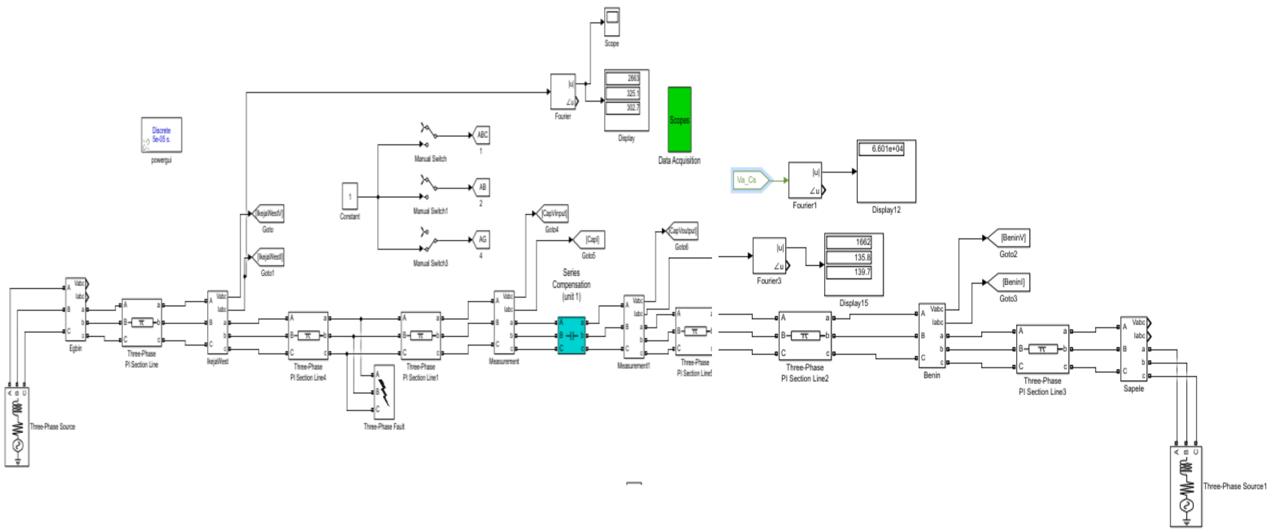

Figure 4: Simulink model of the Benin to Ikeja West transmission line

Source data: Phase-to-Phase voltage (V) = 330 kV, Positive sequence source resistance = 0.8929 ohms, Positive sequence inductance = 16.58 mH, Base voltage (V_{rms}) phase to phase = 415kV, Power system frequency = 50Hz. **Transmission line data:** System Voltage = 330kV, System Frequency =50Hz, Transmission line length = 280km, Positive sequence; R = 0.0368 Ω/km, L = 0.55 mH/km, C = 0.028μF; Zero sequence= R = 0.0328 Ω/km, L=1.7722 mH/km,C = 0.024μF.**TCSC & MOV data:**TCSC;Q_{max}=42MVAR,C = 306μF, L = 4.4Mh, V_{ref} =330kV,I_{ref}= 1000A.

3.0 Results and Discussions

3.1 Case Study of Different Fault types without FACTS compensation

Figure 5 to figure 10 showed the case study where the transmission line was simulated under different fault conditions without FACTS device. This was done using Matlab/Simulink and it showed the Mho characteristics and zone trajectory of the relays.

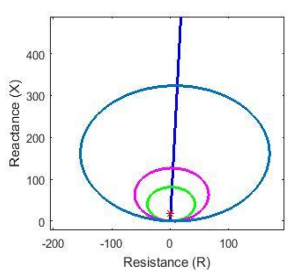

Figure 5: Mho characteristics of Relay A for single line to ground fault at 50Km

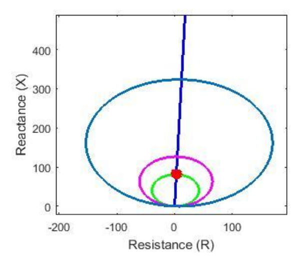

Figure 6: Mho characteristics of Relay B for single line to ground fault at 50Km

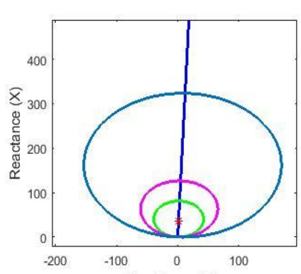

Figure 7: Mho characteristics of Relay A for single line to ground fault at 100Km

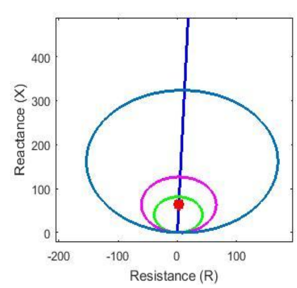

Figure 8: Mho characteristics of Relay B for single line to ground fault at 100Km

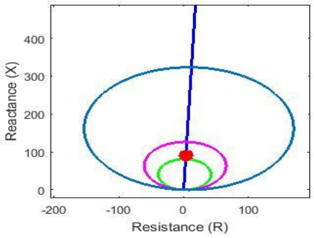

Figure 9: Mho characteristics of Relay A for single line to ground fault at 250Km

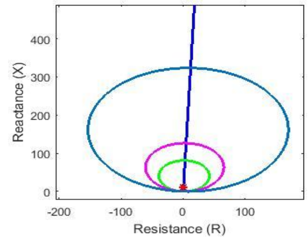

Figure 10: Mho characteristics of Relay B for single line to ground fault at 250Km

3.2 A Case of Different Fault Types with 40% TCSC compensation (Considering MOV protection)

The Mho characteristics of the relays in the presence of TCSC considering MOV protection for a single line to ground faults are shown in figure 11 – figure 16.

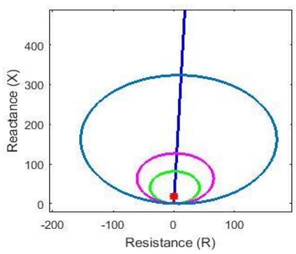

Figure 11: Mho characteristics of Relay A for single line to ground fault at 50Km in the presence TCSC considering MOV protection

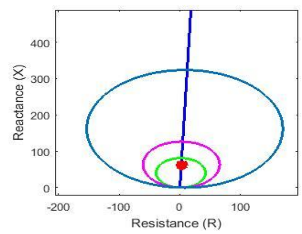

Figure 12: Mho characteristics of Relay B for single line to ground fault at 50Km in the presence TCSC considering MOV protection

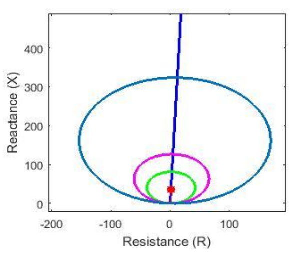

Figure 13: Mho characteristics of Relay A for single line to ground fault at 100Km in the presence TCSC considering MOV protection

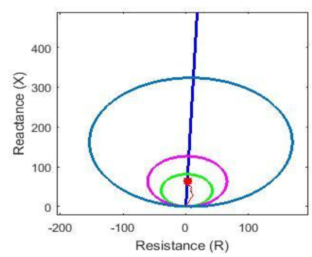

Figure 14: Mho characteristics of Relay B for single line to ground fault at 100Km in the presence TCSC considering MOV protection

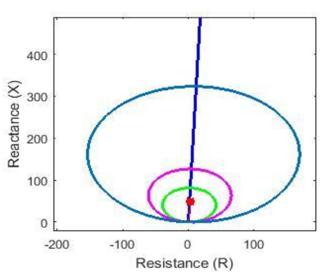

Figure 15: Mho characteristics of Relay A for single line to ground fault at 250Km in the presence TCSC considering MOV protection

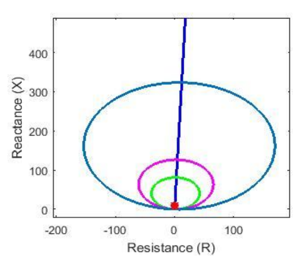

Figure 16: Mho characteristics of Relay B for single line to ground fault at 250Km in the presence TCSC considering MOV protection

3.3 Proposed Distance Relay Settings Adjustment Method

To mitigate the effects of TCSC placement and the cumulative action of the protective MOV to the distance relaying scheme, this paper proposed an adaptive setting of the distance relay. In this method, the relay setting was adjusted whenever the TCSC was located within a fault loop. Figure 17 showed the schematic diagram of the Benin to Ikeja west transmission line in the Nigeria power system while figure 18 showed the flow chart of the distance relay adaptive setting algorithm for mitigating the effects FACTS compensation and MOV protection as proposed in this paper.

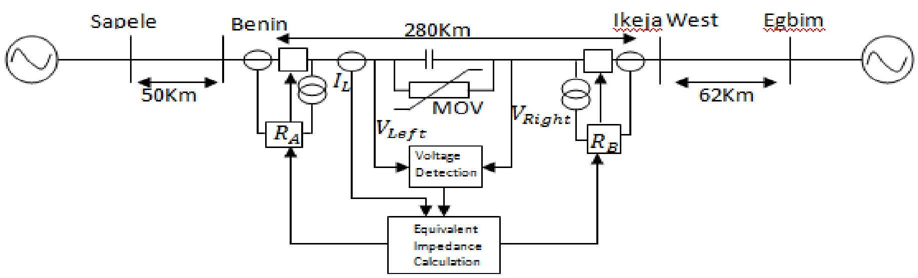

Figure 17: Schematic diagram of the proposed adaptive setting of mho relay for series compensation on the Benin to Ikeja West Transmission line

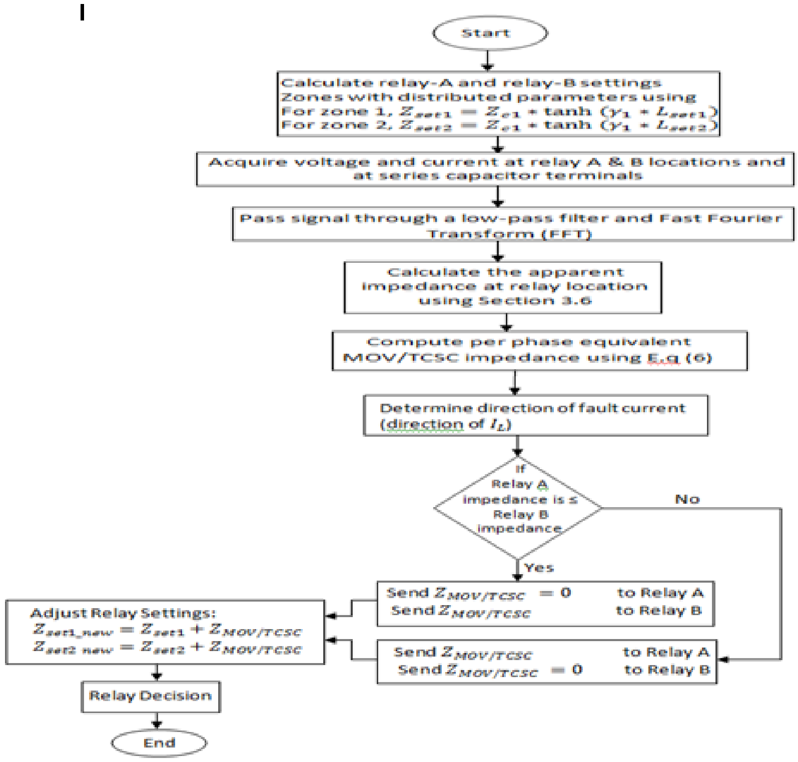

Figure 18: Flow chart of the proposed adaptive settings algorithm of mho relay for series compensation with MOV protection

3.4 The Adaptive Relay Setting Results in the Presence of TCSC Compensation (Considering MOV Action).

The adaptive setting algorithm above was applied on the Benin to Ikeja West transmission line so as to alleviate the effects of TCSC compensation and MOV action. The simulations were run for 40% compensation case for a single line to ground fault along the line. Figures 19 – figure 24 showed the relay settings and fault trajectories.

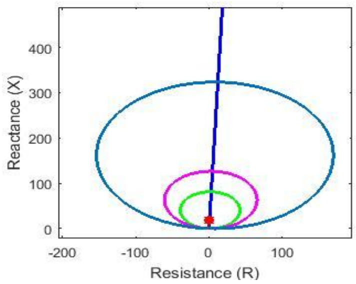

Figure 19: Relay A adaptive Setting for single line to ground fault at 50Km in the presence of TCSC considering MOV protection

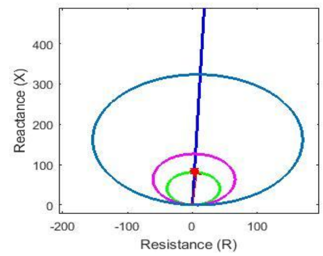

Figure 20: Relay B adaptive Setting for single line to ground fault at 50Km in the presence TCSC considering MOV protection

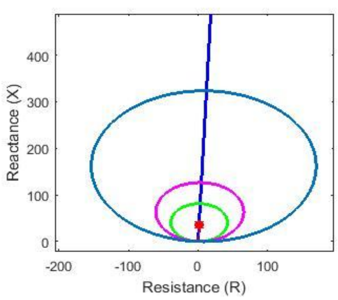

Figure 21: Relay A adaptive Setting for single line to ground fault at 100Km in the presence TCSC considering MOV protection

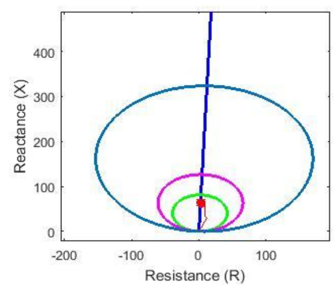

Figure 22: Relay B adaptive Setting for single line to ground fault at 100Km in the presence TCSC considering MOV protection

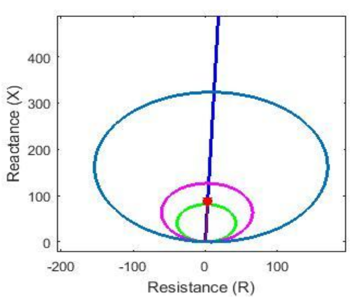

Figure 23: Relay A adaptive Setting for single line to ground fault at 250Km in the presence TCSC considering MOV protection

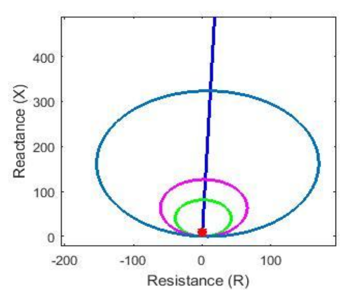

Figure 24: Relay B adaptive Setting for single line to ground fault at 250Km in the presence TCSC considering MOV protection

4.0. Discussion

In the base case study system, simulation of the Benin to Ikeja West transmission line (280km, 330kv) without TCSC device was done. It can be seen from figures 5 – figure 10 that the distance relays operated accurately and correctly in accordance to the relay zones coordination. For this case system without TCSC, the relay tripped a

50km fault at 50.03km for relay A and 229.47km for relay B indicating zone 1 and zone 2 protection zone respectively. For a 100km fault, the relay tripped at 100.1km for relay A and 181.9km for relay B indicating zone 1protection for both relays. Also for a 250km fault, the relay tripped the fault at 250.17km for relay A and 29.15km for relay B indicating zone 2 and zone 1 protection zone respectively. This base case system without TCSC indicated that the distance relay operated accurately and tripped the fault at the correct protection zones. The MOV is usually used to protect the FACTS device from very high fault current. Figure 11 – figure 16 show examples of the effect of MOV action for different fault locations on a TCSC compensated transmission line. For 40% compensation on the Benin to Ikeja West transmission line, the relay overreached its protection zone; for a 50km fault, the relay tripped the fault at 51.15km for relay A and 117.6km for relay B indicating both relays tripping in protection zone 1. For a 100km fault, the relay tripped at 100.1km for relay A and 67.46km for relay B. Also for a 250km fault, relay A tripped at 138.2km and relay B tripped at 30.02km indicating both relays tripping in zone 1. These tripping zones for MOV/TCSC incorporation showed inaccurate relay zone coordination. In figure 19 – figure 24, the proposed adaptive relay algorithm was implemented in the system. It could be seen that a 50km fault tripped correctly at 50.01km for relay A and 229.77km for relay B, 100km fault tripped at 100.1km for relay A and 180.01km for relay B also a 250km fault tripped at 250.10km for relay A and 29.50 for relay B. These indicated correct and accurate protection zone tripping. Thus, the proposed adaptive relay algorithm proved very effective in adjusting the settings of the relay to accurately trip with respect to the location and direction of faults in the Nigeria power system.

5.0 Conclusion

The results from the case study system showed faults at various locations and were generated from system modelling and simulations for conditions without TCSC, with TCSC and MOV protection. For the case system without TCSC, it was affirmed that the distance relay operated accurately in accordance to the zones coordination. When TCSC with MOV protection was incorporated in the system under fault conditions, the relay under reached its protection zone. The adaptive relay algorithm proposed in this paper was used to adjust the settings of the relay during TCSC compensation with respect to the location and direction of faults on the transmission line. The results from the implementation of this algorithm proved very effective for alleviating the effects of TCSC and MOV allocation on the relay protection zone coordination by adjusting the relay settings so that the relay tripped accurately and correctly at all system conditions.

6.0 Recommendation

This paper used the Mho type relay in studying the protection zone coordination of distance relays but other relays, such as the quadrilateral type, maybe used to study the effect of FACTS devices and different types of faults with arc resistance. The use of Phasor Measurement Unit (PMU) maybe considered for a coordinated adaptive setting involving multiple MOV protected lines.

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