Mansoura Engineering Journal

Volume 43 | Issue 4 Article 1

6-14-2020

Distance Relay-Based Phasor Measurements for Protection of Transmission Lines with UPFC.

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Recommended Citation
Mansy, Ibrahim and Dwidar, Mohamed (2020) "Distance Relay-Based Phasor Measurements for Protection of Transmission Lines with UPFC.," *Mansoura Engineering Journal*: Vol. 43 : Iss. 4 , Article 1.
Available at: https://doi.org/10.21608/bfemu.2020.95705

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Distance relay-based phasor measurements for protection of transmission lines with UPFC

متمم مسافي مؤسس على قياسات الوجه لحماية خطوط النقل مع أجهزة التحكم في سريان الطاقة الموحدة

I. I. I. Mansy and M. Y. Dwidar

KEYWORDS:
Distance Relay, Flexible AC Transmission System (FACTS), phasor measurement unit (PMU), Adaptive Rela

الملخص العربي:- **تُستخدم أجهزة نقل التيار المتناوب المرنة (FACTS) في نظم الطاقة الكهربائية الحديثة وذلك لزيادة سعة خطوط النقل وكذلك تحسين حدود الاستقرار الديناميكي والعابر. وبالرغم من ذلك فإن استخدام أجهزة نقل التيار المتناوب المرنة تؤثر بالسلب على متممات الوقاية المسافية المستخدمة. لذلك، فانه يجب تعديل مخططات متممات الوقاية المسافية المستخدمة لحماية خطوط النقل لتحقق الأمان والتكامل للشبكة الكهربية. يقدم هذا البحث دراسة لتأثير عملية تعويض الطاقة الغير فعالة على أداء المتممات المسافية (Mho relay) المستخدمة لحماية خطوط النقل. ويتناول تأثير اجهزة التحكم في سريان الطاقة الموحدة (Unified Power Flow Controller (UPFC على متمم الوقاية المسافي باستخدام التحليل الرياضي والمحاكاة. ثم يتم استخدام وحدات قياس الوجه (Phasor measurement units (PMUs لتطوير متمم مسافي متكيف (ذكي) في بيئة المحاكاة MATLAB/SIMULINK. حيث يعمل المرحل المتكيف على التخلص من تأثير اجهزة التحكم في سريان الطاقة الموحد. ويتم مقارنة النتائج مع متمم الوقاية المسافي التقليدي. واثبتت النتائج جدوى وفاعلية الحل المقترح في هذا البحث.**

Abstract—The Flexible AC Transmission System (FACTS) devices are used in modern electric power system to increase the capacity of the transmission lines and dynamic/transient stability limits. However, the FACTS devices cause mal-operation of the protective relays. So, the protective relaying schemes of transmission lines must be modified for achieving grid security and integrity. This paper studies the influence of the reactive power compensation on the performance of the Mho distance relays used to protect transmission lines. It deals with UPFC impact on the Mho distance relay using analytical and simulation techniques. Then, an adaptive Mho relay is developed in MATLAB/Simulink environment based on Phasor Measurement Units (PMUs). The developed Mho relay is used to exclude the effect of the UPFC in the fault loop. The performance of the adaptive relay is compared with the conventional Mho relay. The results prove the reliability and viability of the proposed adaptive relay.

Received: (23 October, 2018) - Revised: (4 December, 2018) - Accepted: (24 December, 2018)

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I. Introduction

The protection system is responsible for detecting power system component's problems and isolating these components. In most cases of power system's large-scale blackouts, the main reason is the failure of the protection system. Accurate, fast and reliable protection system is required for developing a stable operation of power system and reducing the probability of load shedding and blackouts. So, it is vital to analyze the performance of the protection system under various operating conditions and system arrangement [1, 2]. The distance relays are the main protection of transmission lines. They have a wide variety of characteristics, which make these devices selection is the most adequate for many applications. Moreover, they aren't influenced by the relative source impedances as the overcurrent relays [3].

Nowadays, the transmission capacity of the electric network should be developed to face the increasing demand in the electrical energy. Though the transmission capacity growth could be achieved by new transmission line structure, it cannot keep pace with the increasing in the power plants capacity and energy demand. This is because of minimizing capital costs and increasing problems in obtaining transmission rights of the way. Due to these difficulties, the system operators are interested in utilizing the recent power lines more efficiently. The efficient utilization of recent power lines is required to improve the dynamic and transient stability especially for long lines. This is because some power lines cannot be loaded near to their natural loading due to the relative low stability limits [4-5].

By considering the above-mentioned requirements, FACTS devices have been of worldwide concern for power system enhancement by increasing the transmitting capacity and provide the optimal operation of the power systems near to their limits [4-6]. Series connection, shunt connection or a combination of them are the various classification of FACTS in the electric power networks according to the application type. Although the use of FACTS devices has several merits, it provides an additional power system issues in the area of power system protection. These issues include quick changes in line impedance, power angle, load currents and the transients introduced by the fault incidence and control act of FACTS devices. So, the distance relay operation will be deteriorated, causing inaccurate estimation of faults location via under/over reach for several fault cases. The improper operation of the distance relay leads to improper tripping and not only minimize the reliability and security of system but also can start the cascaded tripping and blackouts [4-6].

The undesirable effects of using FACTS devices on transmission lines distance protection were studied in [7-13]. The shunt FACTS devices usually connected at the middle of the transmission line in order to keep the voltage of the mid-point around normal value and hence transmitting power will be increased. A fault in the first zone can't be detected accurately, so the distance relay mal-operate [7, 8]. The major problem grows when the fault occurs following FACTS device. The injected current significantly participates in fault current and an additional impedance will be added to the fault loop. This leads to the correct fault impedance can't be calculated by the relay and the relay will over or under-reach depending upon the compensation mode (inductive or capacitive). When fault takes place before the FACTS device, it has negligible participation in fault current [8, 9]. Static VAR compensator (SVC) impact are greater than the static synchronous compensator (STATCOM) on the conventional distance relay during various type of faults [10]. Using practical constrains in STATCOM control system will considerably reduce its impact on the measured impedance by distance relay [10, 11]. The major problems of protecting the transmission system employing UPFC using distance protection was investigated in [12] using analytical and simulation study. Apparent impedance's calculation technique for a system employing UPFC was presented during phase-to-ground fault. The performance of the conventional distance relay and pilot protection used to protect a multi-terminal transmission system equipped with UPFC was presented in [13] and the results were verified using real time digital simulator. The previous studies indicate that the conventional distance relay characteristic can't be achieved in the presence of FACTS devices.

Several researches have been introduced in [15-21] to solve the distance relay problems. The great development in communication technology and synchronized measurements have made the possibility of exchange data among different areas is possible. This led to the appearance of the Wide Area Measurement System (WAMS) concept [14]. The authors in [15-19] used the PMU to transfer the value of shunt injected current from the mid-point of line to the relay bus. Then these values are used to adapt the zone reach of the distance relay and hence overcome the mal-operation of distance relay in the existence of SVC and STATCOM. Ref. [20] presented apparent impedance calculations for shunt compensated transmission line and suggested an optimal Support Vector Machine (SVM) based on classifier for zonal (zone1 /zone2) discrimination. The SVM parameters were ascertained by Genetic Algorithm (GA). The operation of the power system can be provided online using WAMS in a very short time by a high-speed communication system [20]. Distance relay adaptive scheme was advised in [21] to protect the transmission line employing UPFC depended upon the PMU installed at the line terminals to transfer the data. It computed the UPFC control parameters online then the trip boundary was generated based on the calculated parameters. When series capacitor is used for transmission lines compensation, the current and voltage relation is affected. A statistical method was introduced in [22] for faulty phase detection by computing correlation factor for Series Capacitor Compensated Transmission Lines (SCCTLs). In [23] distance relay adaptive scheme was presented to protect the transmission line employing Static Synchronous Series Compensator (SSSC) based on the power system conditions. The SSSC structural and controlling parameters were determined in [23]. The digital distance relaying scheme provided an accurate protection to series-compensated double-circuit lines during a simultaneous open conductor and ground fault without using remote-end data or communication link [24]. Most solutions introduced to solve the distance relay problems caused by existence of FACTS devices on transmission system were adaptive distance protection. Where the power system parameters and FACTS control system are used to adapt the reach point of the distance relay.

In this paper, the impact of the UPFC on distance protection is investigated. Then a novel distance protection procedure is implemented to overcome the mal-operation and increase the accuracy, reliability and sensitivity of the conventional distance relay in presence of UPFC without compromising on its security.

This paper is organized as follows: a model of power system and UPFC device is introduced in section 2. UPFC impact on the measured fault impedance is introduced in section 3. In section 4, a description of the proposed scheme and how it's work will be introduced. The simulation results with and without FACTS devices using the conventional and proposed scheme are shown in section 5. Finally, the conclusion is presented in section 6.

II. Modelling of Power system and UPFC

A. System under study

A typical 500-kV, 60-Hz power system has been modeled with the ability to change system conditions, types of faults and their locations in this paper. The distributed parameter line model is used to model the transmission system. The Per-kilometer positive and negative sequence impedance of the transmission line is 0.0255 +j 0.3520 Ω/km, and the zero-sequence impedance is 0.3864 + j1.5556 Ω/km. The single line diagram of the system included UPFC is shown in Fig.1. The positive sequence memory polarized Mho relay [25] is installed at bus S and set to protect 80% of transmission line_1 length for zone 1. The distance relay measures the apparent impedance at the relay location during different types of faults. It consists of six measuring units required for protection against all the ten shunt faults types (AG, BG, CG, AB, BC, CA, ABG, BCG, CAG, and ABC). The magnitudes and phase angles of the current and voltage phasors at the fundamental frequency (50 HZ) are extracted using Fourier Transform (FT). Then, the extracted phasor values are used to estimate the apparent impedance which will be used for the analysis. A 100-MVAR UPFC is connected at the middle of the transmission line_1 (50 km from bus S). The PMU is connected to Bus-S and bus R using high speed communication channel for data transfer between them. Therefore, bus R data are available at relay location (bus S).

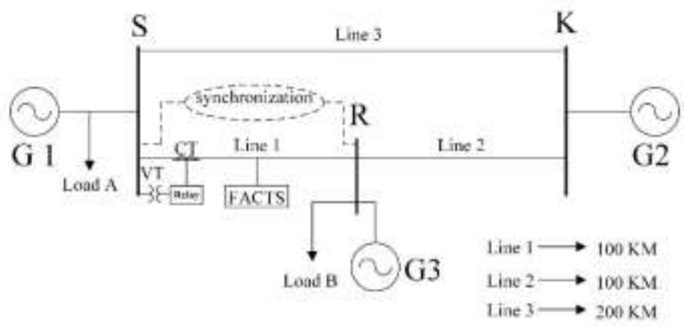

Fig. 1. Study system line diagram.

B. UPFC modeling

The UPFC is a combination of shunt and series compensation devices. Two voltage source converter (VSC) connected together through a common DC capacitor are the main component of UPFC. First converter is the STATCOM and connected in shunt with the transmission system through a 15/500 kV Δ/Y shunt transformer and the second one is SSSC connected in series with the line through a 12.5 kV/12.5 kV Y/Y series transformer [13]. The shunt converter regulates the voltage at the connecting point by injecting or consuming reactive power and provide the series converter with active power through the common dc capacitor. The primary function of the UPFC is achieved by the series converter which can inject a series voltage with variable magnitude and phase angle to regulate the power flow through the transmission line. The 100-MVA UPFC is connected at the midpoint of line_1 as shown in Fig. 2.

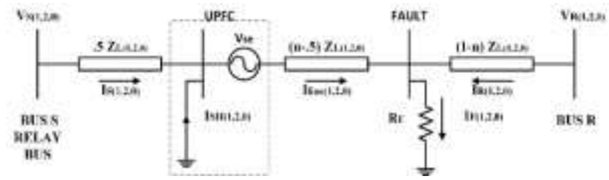

Fig. 2. The sequence network for a fault occurred at line 1

III. UPFC Impact on Distance Relay

As the positive sequence component is the only component exists during all types of faults, the conventional distance relay measures the positive sequence impedance from relay location to the fault point [1]. To protect the transmission line against all types of faults, six impedance measuring units consist of three grounds units and three-phases units are sufficient. In this section, the impact of the UPFC on the apparent impedance has been investigated. In general, the fault impedance seen by the conventional distance relay phase to ground element (Z_R) for single-phase-to-ground fault is calculated by:

$$Z_R = \frac{V_{relay}}{I_{relay}} = \frac{V_s}{I_s + mI_{S0}} \quad (1)$$

$$m = \frac{Z_{L0} - Z_{L1}}{Z_{L1}}$$

where I_s and V_s are the phase currents and voltages at relay location respectively, I_{S0} is the zero-sequence phase current, Z_{L1} and Z_{L0} are the line positive and zero sequence impedances respectively and m is the transmission line compensation factor. The fault impedance seen by the conventional distance relay phase to phase element (Z_R) can be calculated by:

$$Z_R = \frac{V_{relay}}{I_{relay}} = \frac{V_A - V_B}{I_A - I_B} = \frac{V_B - V_C}{I_B - I_C} = \frac{V_A - V_C}{I_A - I_C} \quad (2)$$

where V_A, V_B and V_C are the phase voltage at relay location respectively. I_A, I_B and I_C are the phase current at the relay location respectively. From figure (2), when a fault occurs at distance, n*L, from the relay installed at bus S, the UPFC is presented in the fault loop and the apparent impedance Z_R measured at bus S seen by relay is given by:

$$Z_R = nZ_{L1} + \frac{I_{sh}}{I_{relay}}(n - d)Z_{L1} + Z_{se} + R_f \frac{I_f}{I_{relay}} \quad (3)$$

where

$$Z_{se} = \frac{V_{se}}{I_{relay}}$$

The first term of (3) represents the positive sequence impedance from the relay point to the fault point. The second term represents the effect of shunt injected current from the UPFC shunt converter. The UPFC location in per-unit distance from the relaying point (d) equals to 0.5 as the UPFC is installed at the middle of the line. The third term represents the effect of the series injected voltage (V_{inj}) by the series converter of UPFC and the fourth term is the fault resistance effect. During a single-phase-to-ground fault condition, the zero sequence of the shunt injected current from the shunt converter will be trapped in delta connection of the coupling transformer winding. In this paper, it is assumed that the fault resistance has negligible value.

For the relay installed at bus R

The applied analysis at bus (S) can be applied at bus (R). for the same fault location, The UPFC doesn't exist in the fault loop for the measured impedance at bus R as shown in Fig. 2. By applying KVL, the voltage at bus R can be expressed as follow:

$$V_{1R} = I_{r1}\,(1-n)Z_{L1} + R_f\,I_{f1} \quad (4)$$

$$V_{2R} = I_{r2}\,(1-n)Z_{L1} + R_f\,I_{f2} \quad (5)$$

$$V_{0R} = I_{r0}\,(1-n)Z_{L0} + R_f\,I_{f0} \quad (6)$$

$$V_R = V_{1R} + V_{2R} + V_{0R} \quad (7)$$

$$I_R = I_{1R} + I_{2R} + I_{0R} \quad (8)$$

From the above equations, the voltage at bus R can be derived as:

$$V_{Relay} = I_R\,(1-n)Z_{L1} + (1-n)(Z_{L0} - Z_{L1})I_{0R} + R_f\,I_f \quad (9)$$

$$V_{Relay} = (1-n)Z_{L1}\left(I_R + I_{r0}\,\frac{(Z_{L0}-Z_{L1})}{Z_{L1}}\right) + R_f\,I_f \quad (10)$$

From equation (1), the apparent impedance seen by the distance relay at Bus-R can be written as:

$$Z_R = (1-n)Z_{L1} \quad (11)$$

where (1-n) Z_{L1} represents the positive sequence impedance from the relay location to the fault point. From (3) to (11), it's clear that:

- If the fault occurs at the left side of the UPFC, the measured impedance by distance relay at bus S depends only on the line positive sequence impedance (Z_{L1}) and the distance from the relay bus to fault incidence point (n) in per unit.
- If the fault occurs at the right side of the UPFC, the measured impedance by distance relay at bus S will be depended upon three items; the positive sequence impedance from the relay location to the fault location, the shunt converter injected current and the series converter injected voltage. The measured impedance at bus R will depends on the positive sequence impedance from relay location to the fault point.

IV. The proposed Mho Relay scheme

From the previous analysis, it's clear that the relay installed at bus R measured the correct fault impedance from the UPFC installation point to bus (R) when the relay at bus (S) miss. so, the proposed scheme divided the transmission line into two zones; first zone from the relay point to the UPFC installation point. In this zone the relay installed at bus (S) performs well. So, the conventional algorithm can be used to calculate the fault impedance. The second zone of the transmission line will be from the UPFC installation point to bus (R). in this zone the relay installed at bus (S) miss while the relay installed at bus (R) performs well and hence the measured impedance at bus (R) can be used to calculate the correct impedance at bus (S).

As shown in Fig 1, a precise time reference synchronized measurement of voltage and current occurs among bus (S) and Bus (R). So, the voltage and current signals from bus (R) will be available at the relay location. The Fourier transform will be used to extract the phasors of the relay bus voltage and current (V_S & I_S) and the phasors of the transmitted voltage and current from bus R (V_R & I_R). V_S and I_S will be used to calculate the impedance from the relay to the fault point Z_S using Eqs. (1 & 2) whereas V_R and I_R will be used to calculate the impedance from bus R to the fault point Z_r. If the measured impedance Z_S is smaller than d*Z_L, this means that the fault take place in the first zone of the proposed scheme. So, the fault impedance Z will equal to the measured impedance Z_S. else, the fault occurs in the second zone of the proposed scheme (between the UPFC connection point and bus R) and hence the fault impedance Z will equal the difference between the transmission line impedance and the measured impedance at bus R. The flowchart of the proposed relay scheme is shown in Fig. 3.

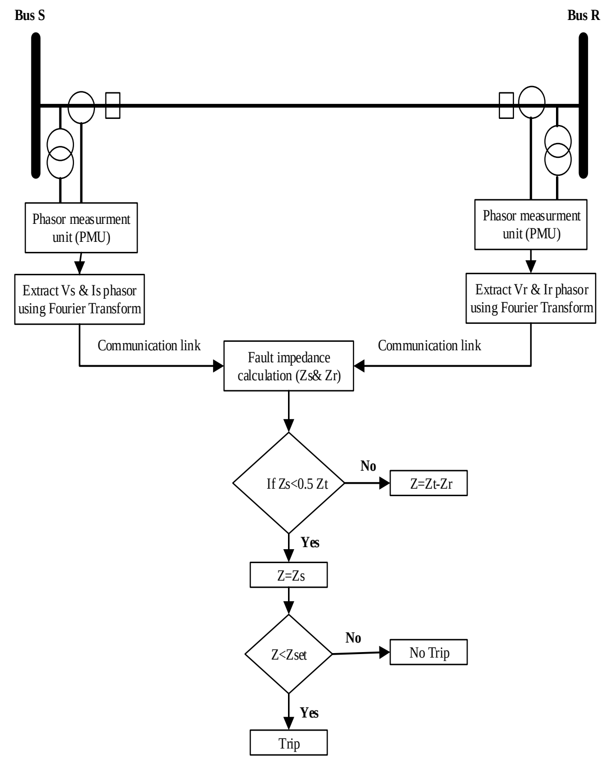

Fig .3. Proposed Algorithm of distance protection.

Finally, the measured impedance will be compared with the relay reach impedance (Z_{set}). If the measured impedance is smaller than the relay setting i.e. the fault is inside the reach, then a trip command will be sent, else the trip command will be prevented.

V. Results and Discussion

In this paper, the MATLAB environment is used to model the studied system shown in Fig.1. A 48-pulse VSC based UPFC is connected at the middle of transmission line_1 among bus S and bus R. First, the conventional distance relay characteristic will be evaluated with and without the UPFC. Then, the proposed distance relay scheme performance will be tested.

A. *Impact of UPFC on Distance Relay*

The UPFC reference values are set to be the same as the values before compensation for its different operational modes. The active and reactive power references for the UPFC (P_{REF}, Q_{REF}) are specified in MATLAB/Simulink. The reference values are (1348.51 MW, 55.47 MVAR) respectively. The effects off the UPFC on the apparent impedance seen by the relay during a single phase to ground and two-phase faults at Zone 1 reach point will be shown and compared with apparent impedance seen by the relay without the UPFC.

Case # 1 Single-phase to ground fault

A solid line-A to ground fault occurred at 80 kilometers from the relay installed at bus S (relay reach) i.e. the fault incidence point will be after the UPFC. The apparent impedance track measured by the Mho relay line-A to ground unit with and without connecting UPFC are shown in Fig. 4. Moreover, the apparent resistance and reactance as a function of time with and without connecting UPFC are shown Figs. 5 and 6 respectively. Figure 4 shows that, the apparent impedance seen by the relay R in the presence of the UPFC is greater than the apparent impedance without UPFC and the relay will under reach.

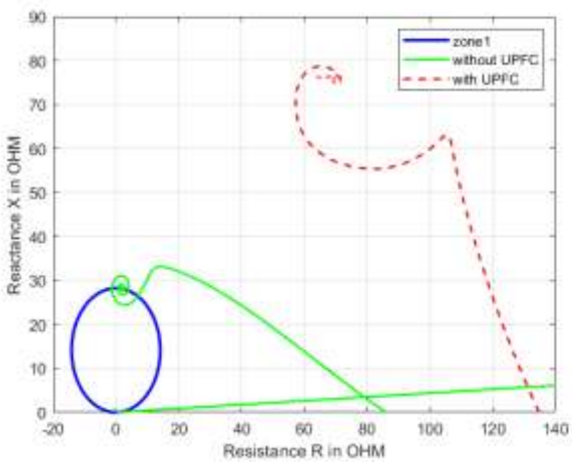

Fig.4 A-G fault apparent impedance track with and without connecting the UPFC.

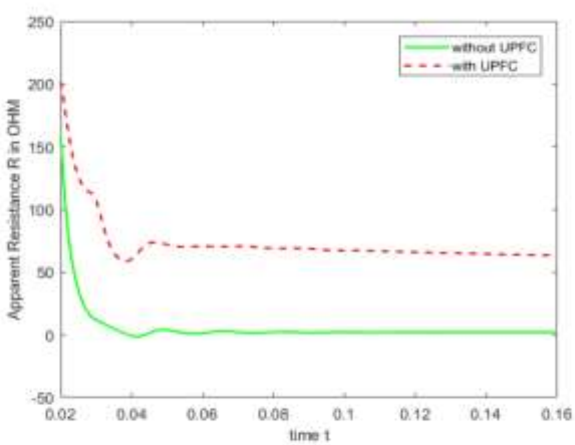

Fig.5 apparent resistance track with and without connecting the UPFC

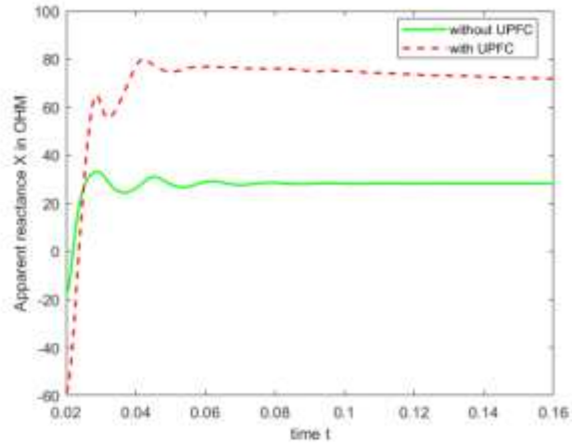

Fig.6 apparent reactance track with and without UPFC.

Figure 5 and 6 indicate the variations in both apparent resistance and reactance components with the time for an AG fault at Zone 1. It can be seen that the measured resistance and reactance components when the UPFC is present in the fault loop is greater than the measured resistance and reactance for system without the UPFC. The direct result of these increase is that the distance relay will under-reach.

To study the relay coverage, an AG fault at various locations has been studied and the measured impedance as a function of fault position in KM is shown in fig (7).

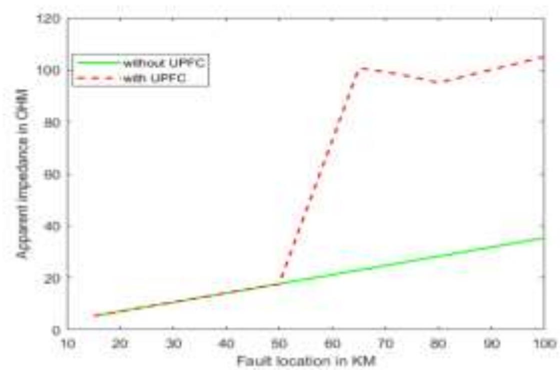

Fig (7) Measured impedance at different fault locations with and without UPFC for AG fault

Case # 2 Phase-to-Phase Fault

Also a line-A to Line-B fault occurred at 80 km from the relay installed at bus S i.e. the fault incidence point followed to the UPFC. The apparent impedance track measured by the Mho relay line-A to B unit with and without the UPFC is shown in Fig. 7, Moreover, the apparent resistance and reactance with time are shown in Figs. 8 and 9 respectively.

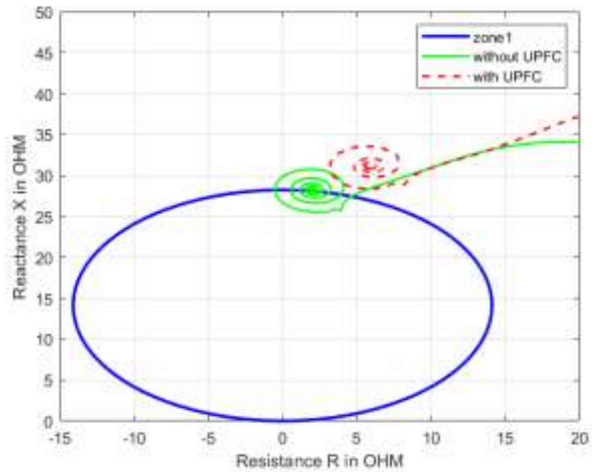

Fig. 8 A-B fault apparent impedance track with and without the UPFC.

Figures 9 and 10 show that, the apparent resistance and reactance are increased when the UPFC is presented in the fault loop like the single phase-to-ground fault. As a result, the distance relay sees this condition as an external fault and hence under-reach.

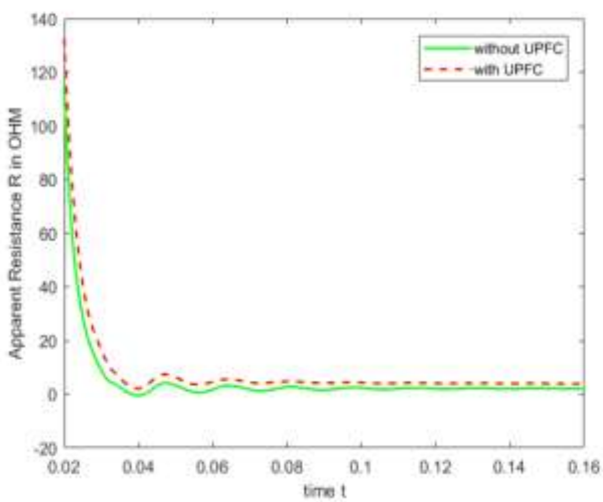

Fig. 9 apparent resistance track with and without the UPFC.

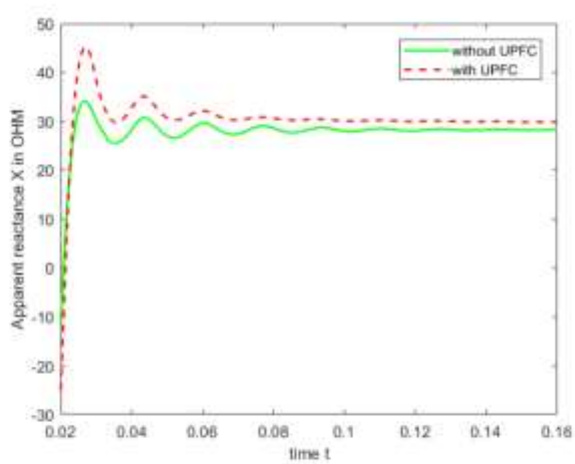

Fig. 10 apparent reactance track with and without the UPFC.

Also the relay coverage for an AB fault at various locations has been studied and the measured impedance as a function of fault position in KM is shown in fig (11).

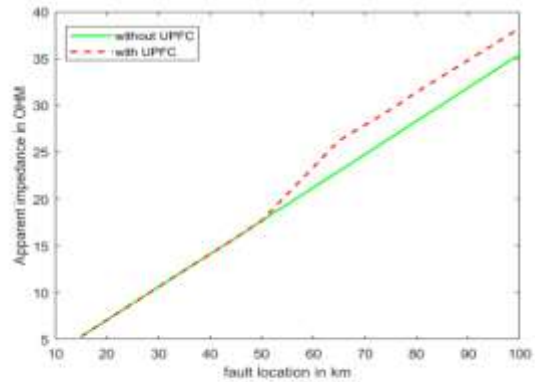

Fig (11) Measured impedance at different fault locations with and without UPFC for AB fault

Figures 4 to 11 demonstrate the distortion in the conventional distance relay performance for line to ground and line to line faults when the UPFC is present in the fault loop. The performance is far worse in the case of ground fault than the phase fault. This is due to the zero sequence of the injected voltage. Moreover, the difference between fault quantities are used for impedance calculations in two phase faults according to (2). Furthermore, the distance relay performance during two phases to ground faults is similar to the two phases faults so the results are not mentioned here.

Case# 3 Impact of UPFC location on the apparent impedance

In this paper, the impact of the UPFC location on the apparent impedance seen by the distance relay is also investigated. The UPFC location is specified by (n-D). This coefficient is related to the shunt part effect of the UPFC. On the other hand, the shunt part of the UPFC has a little effect on the impedance trajectory. the UPFC location only effects on one term of Eq. (3). So, it is expected that the UPFC location has a little effect on the apparent impedance seen by relay. Fig. 12, shows the apparent impedance track for A-G fault at zone 1 when the UPFC is installed at the beginning and at the middle of transmission line respectively. It's clear that, when the UPFC is installed at the beginning, the measured impedance will be slightly higher than the middle.

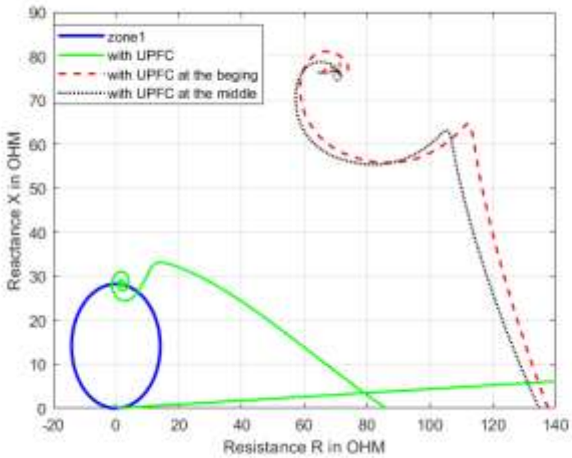

Fig 12. impact of various UPFC location on the apparent impedance during A-G fault

B. Performance Evaluation of the Proposed Distance Relay

In this section The performance of the Proposed scheme when used to protect a transmission line employing UPFC has been verified. the relay set to protect 80% of line_1 as a primary protection. Several faults scenarios are created at the relay reach to show the effectiveness of the proposed scheme.

An AG and AB faults occurred at 80 kilometers from the relay to verify the proposed scheme performance. The apparent impedance track measured by the proposed scheme line-A to ground element and line-A to line B element in the presence of UPFC together with the mho relay characteristic are shown in Fig. 13. Moreover, the apparent resistance and reactance track of A-G and A-B faults with time are shown in Figs. 12 and 13, respectively.

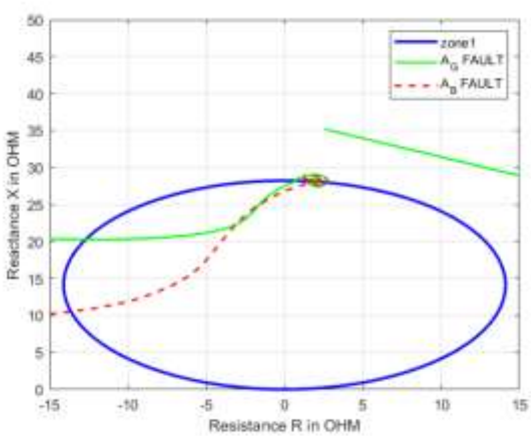

Fig.13 A-G and A-B faults apparent impedance track with UPFC.

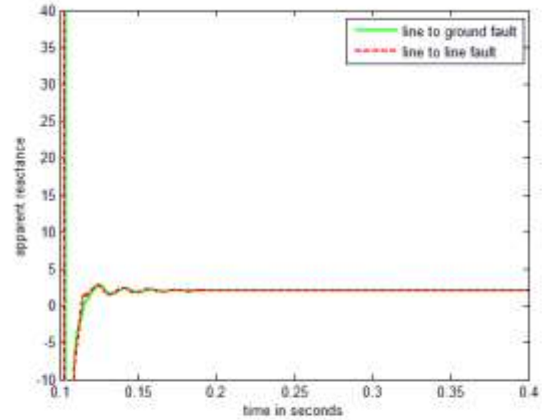

Fig.14 A-G and A-B faults apparent resistance track with UPFC.

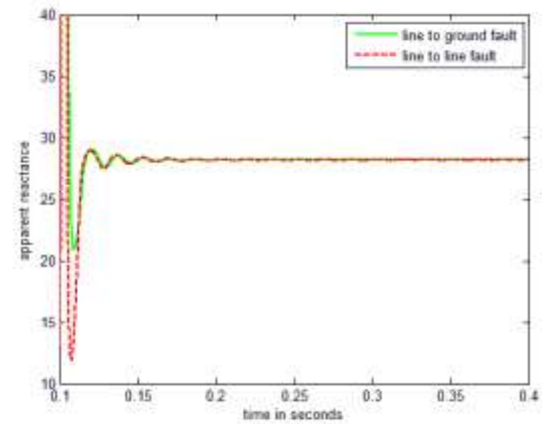

Fig.15 A-G and A-B faults apparent reactance track with time.

From Fig.14 and 15, it can be seen that the apparent resistance and reactance components when the UPFC is present in the fault loop are the same as when compared with system without the UPFC Figs (4-11).

VI. Conclusion

This paper studied the problems related with the conventional distance protection when used to protect a transmission system employed with UPFC device. A mathematical analysis was introduced to demonstrate the effect of the UPFC when installed at the mid-point of transmission line. The results are verified using the MATLAB simulation. The main outcomes can be written as follow:

1. The presence of the UPFC in the fault loop deteriorates the performance of the conventional distance relay for phase to ground and phase to phase faults.
2. The distortion is more severe in case of phase to ground fault than phase to phase fault because of the high value of zero sequence component in the injected voltage.
3. The UPFC location has no effect on the measured impedance.

Then a proposed Mho relay scheme using precise time synchronized measurement between the relaying bus and the receiving end bus is introduced to exclude the effect of the UPFC in the fault loop. The simulation results show that, the proposed scheme offers a promising solution for the transmission system protection in presence of UPFC, as it gives accurate results. Also, the simulation outcomes show the accuracy and strength of suggested distance protection scheme.

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