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Performance enhancement of distance relay in presence of unified power flow controller

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ABSTRACT

The characteristics of the distance relay are devised based on online and fault impedance. The relay uses fault information to react to the expected state; however, integrating the grid with a unified power flow controller (UPFC) might stop the relay from fault-triggered operations, requiring altered relay characteristics. Building relay tripping parameters are among the critical challenges that must be addressed for transmission line distance relays because current transmission networks face higher stress regarding power system operation. Furthermore, the use of flexible AC transmission systems (FACTS) instruments at the transmission level adversely affects distance relay performance due to impedance differences. The UPFC is among the essential FACTS instruments; it comprises shunt and series converters to alter the apparent relay impedance; hence, it was considered for this study, where a test system during fault was assessed to demonstrate the output of the distance relay before and after using the UPFC. MATLAB was used to build scenarios demonstrating the effect of a UPFC located in the transmission line's midsection or end or not using the UPFC. This research offers an analytical technique to determine the probable effects of UPFC on distance relay characteristics. The outcomes provide new relay characteristics for several fault resistances and locations for fault-specific impedance trajectory reactions.

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1. INTRODUCTION

The security and continuity of the electrical power system have been essential aspects for the past several years. Moreover, distance protection is among the indicators that require constant monitoring because it is crucial for protection mechanisms; however, it may be affected by several aspects that affect it adversely. Hence, researchers have gradually enhanced performance by improving response sensitivity and devising the distance relay to identify problems. Moreover, they have developed varying relay characteristics to adjust to the necessary system conditions [1]–[3].

Power electronics progressed quickly, allowing transmission networks to use high-power solid-state devices. Flexible AC transmission systems (FACTS) use solid-state power conversion technologies to regulate line power distribution. Various FACTS devices are used in power systems, such as series compensators, shunt compensators, and series-shunt compensators. The series-shunt compensator strongly influences the protection system, such as unified power flow controller (UPFC) [4]. Researchers are driven to stress the influence of UPFC on the protection system of transmission systems [5]. When put at the front of the line, voltage source converter-specific interphase power controllers (VSC-based IPC) have a more significant influence than unified (UIPC). FACTS regulators change apparent impedance for faults in the transmission line's first half comprising fault resistance issues [6], [7]. Admittance and impedance estimated for distance relay indicate that a static synchronous compensator with energy storage (STATCOM–ES) introduced into the system may significantly damage all distance protection relays. To decrease relay maloperation, an adaptive distance protection relay with different relay configurations based on STATCOM–ES operating features is needed [8].

Distance protection determines relay point impedance, and multiple factors affect relay point impedance for the first and other zones. Pre-fault power system characteristics may be divided into two categories. The first zone comprises the line’s structural aspects, designated by short circuit levels at the end of the transmission system. On the other hand, the second zone includes the pre-fault operational characteristics, indicated using the line-end-specific voltage magnitude fractions and line load angles. For the second zone, impedance assessment is based on two lines [9].

Conversely, the key benefits of utilizing FACTS devices are: i) Better use of existing transmission system assets; ii) More reliable and available transmission system; iii) More dynamic and transient grid stability; iv) Lower loop flows; and v) Better quality of supply for sensitive industries. These points facilitate enhanced FACTS use for power systems, including more significant challenges concerning distance relays to account for FACTS impact. The following paragraph provides a brief explanation and details the literature references that address this concern.

The work in [10]–[12] displayed the capacity to locate and classify all faults. The three zones' mho characteristics show STATCOM inclusion and exclusion impedance trajectories. STATCOM and fault locations greatly impact impedance estimates. Over- and under-reach issues precipitated by the several modes of STATCOM operation were determined and resolved in [13], [14]. Guan *et al.*, [15] performed advanced studies on STATCOM's RTDS-specific influence on feeder distance protection. Zhang *et al.* [16] and Zhang *et al.* [17] explained how STATCOM affects distance relay based on network settings, fault characteristics, and locations. The effects of SSSC on impedance measured at the relay location for several faulty points are specified in [18]. The literature lists novel methods to protect the transmission network, specifically compensated lines [19]. The literature has works concerning digital relay characteristics concerning UPFC-compensated transmission lines [20]. FACTS fundamentals and capacity to stabilize are very important and affected by different control techniques depend on this FACTS regulators were evaluated for execution [21]. The work in [22] identifies and categorizes faults with high accuracy to locate them. STATCOM inputs reactive power that impacts apparent impedance, causing distance delay under-reaching. However, STATCOM has no effect on the power system since relay failures because of the impedance setting. If the STATCOM is in the fault zone, the distance relay will maloperation due to higher impedance.

This work outlines computations and trajectories for apparent impedance and comprehensive simulation outcomes concerning distance relay approaches. One sample circuit comprises a UPFC connection. Several sets of device characteristics and locations are tested to ascertain the effects of apparent impedance and a new relay characteristic that provides a reach setting.

2. DISTANCE RELAY PROTECTION AND UPFC

A distance relay is a protective device typically used for protecting transmission lines. These devices determine impedance from the installation point to the fault and regulate the system based on the determined current-voltage ratio [23], [24]. Further, UPFC is a FACTS component having two converters, a shunt, and a series attached to the transmission line, it is employed to enhance power quality and system stability.

2.1. The distance relay and the characteristics that determine its tripping

Distance relay protects transmission networks. It measures current by dividing voltage at the relay location. This study used a distance relay type that may be defined as a function of impedance or its components utilizing rectangular coordinates (R and X) in a geometrical form, as shown in Figure 1(a). An admittance relay, where a circle crosses the R-X plane origin, uses admittance (inverse of impedance) to operate a mho distance relay. The relay's 3rd quadrant cannot detect bus-side problems. Figure 1(b) shows the mho relay operation [25], [26].

Operating duration and reach accuracy determine distance relay performance. Reach accuracy compares real-world ohmic reach to ohms. Distance relays have instantaneous directional zone-1 protection and one or more time-delayed zones. Zone-1 immediately trips and shields 80–85% of the line. The remainder provides safety for line impedance, V_T, and C_T computations. Zone-2 protects 15-20% of the line end in two seconds, while zone-3 provides backup in three seconds. Figure 2 shows the system [27].

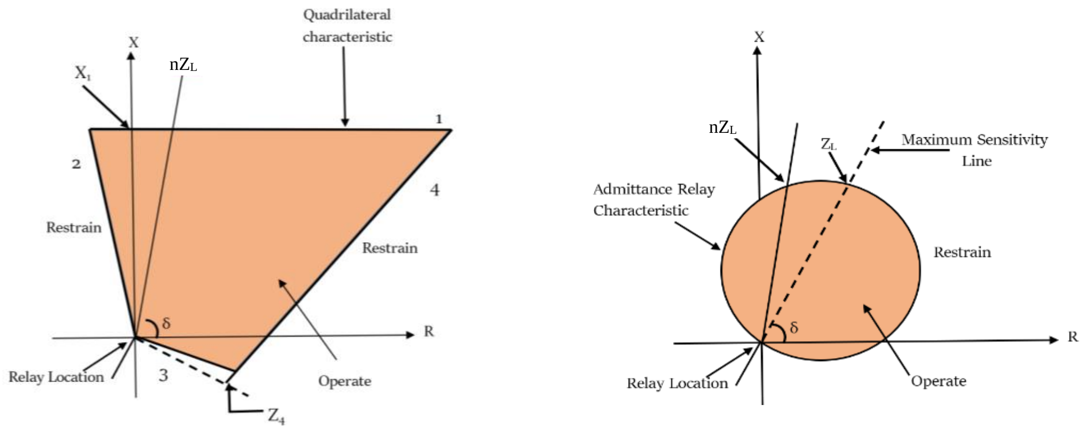


Figure 1. Operating generalized quadrilateral characteristics of distance relay (a) impedance characteristic and (b) mho characteristic

2.2. Calculation of apparent impedance while UPFC elements are present

Figure 3 depicts a double-circuit transmission network that links two sources and a UPFC at the center or relaying point in one line. Under a ground fault condition, the apparent impedance is available at the relay. Figure 4 depicts a UPFC devised have two voltage sources. The two converters (shunt and series) are linked using a DC capacitor that provides energy storage. The series converter helps create variable magnitude voltages having different phase angles, while the shunt balances the active power for the line and the series converter [28], [29].

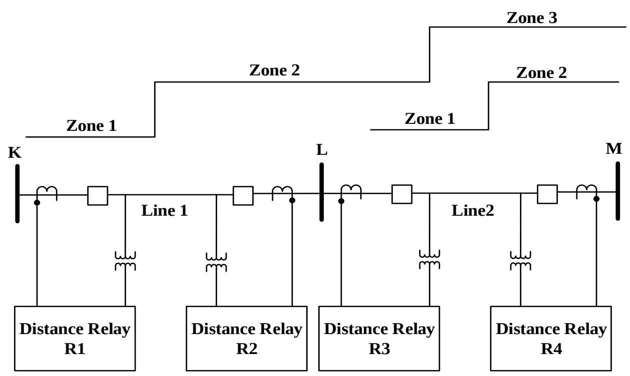


Figure 2. Distance relay operational zones characteristics

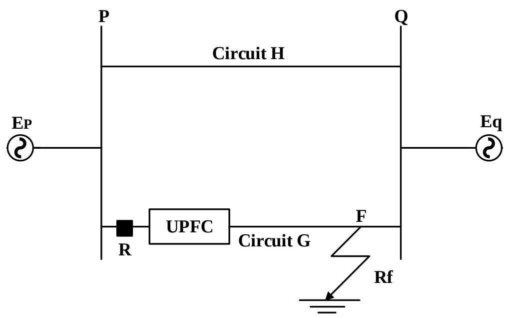


Figure 3. UPFC devise at the relaying point

The equivalent effective shunt and series voltage sources are represented by the phasors V_{sh} and V_{se}, respectively. The UPFC shunt and series impedances are designated as Z_{sh} and Z_{se}. V_i and V_j are the voltages at buses i and j, respectively. I_{sh} stands for the UPFC shunt converter's current. P_{sh} and Q_{sh} are the shunt active and reactive power flows. Power flow for P_{sh} and Q_{sh} comes from bus i. I_{ij} is the current passing via UPFC series converters. The active and reactive power flows from the UPFC series exiting bus i are designated as P_{ij} and Q_{ij}, respectively [30], [31]. The given equivalent circuit of UPFC is presented in Figure 4, the following equations can be written:

$$I_{sh} = \frac{V_i \angle\theta_i - V_{sh} \angle\theta_{sh}}{Z_{sh}} \tag{1}$$

$$I_{ij} = \frac{V_i \angle\theta_i - (V_{se} \angle\theta_{se} + V_j \angle\theta_j)}{Z_{se}} \tag{2}$$

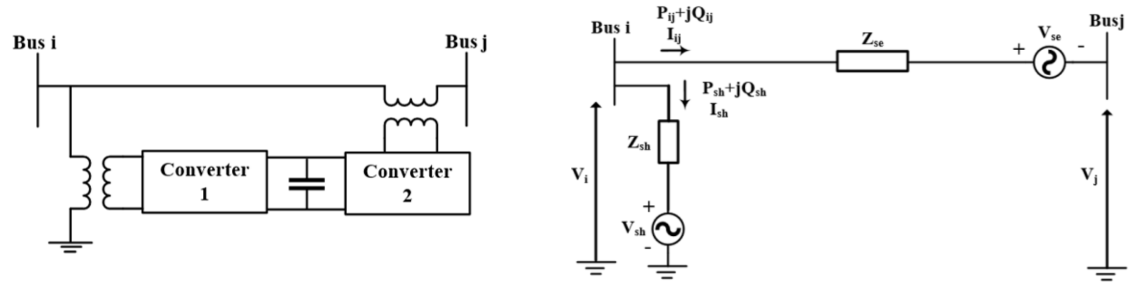
$$It = Ish + Iij \tag{3}$$

$$\Delta Pe = Pesh - Pese = 0 \tag{4}$$

Where I_t is the total current, ΔPe is the difference active power, $Pe_{sh} = Re\ (V_{sh} * I^*_{sh})$ and $Pe_{se} = Re\ (V_{se} * I^*_{ji})$ are active power exchanges between the shunt and series circuit via the DC bus. The above in (1)-(4) show that the presence of UPFC devices considerably influences the trip boundaries of a distance relay where the apparent impedance that calculates depend on the measured voltage and current will be changed due to the effect of currents and voltage i.e., I_{sh}, I_{ij}, V_{sh}, and V_{se}.

2.3. Unified power flow controller

UPFC comprises two converters (shunt and series) linked with the power system having a shared DC bus using a capacitor, as depicted in Figure 4(a). The shunt-linked converter is designated converter 1; it can regulate reactive power to give the necessary real power for converter 2 (series) that provides a variable voltage concerning its phase angle and value. The converters work independently from a reactive power standpoint; however, converter 1 regulates the active power available for converter 2, including the losses happening at the storage capacitor and the two converters. Figure 4(b) depicts the equivalent circuit representing UPFC. It has two branches – the shunt is associated with the 1st converter, represented using voltage source V_{sh} and impedance Z_{sh}. The series branch comprises the 2nd converter, described using voltage source V_{se} and impedance Z_{se} [32], [33].



(a) (b)

Figure 4. UPFC circuit (a) basic circuit and (b) equivalent voltage circuit

2.4. Controlling principle and available operation mode for the UPFC

UPFC is regarded as a commonly versatile member of FACTS devices, which employ power electronics to manage power flow on the grid. The UPFC includes a shunt controller (STATCOM) and a series controller (SSSC), which are interconnected via the shared DC bus, as explained in Figure 4. Voltage sourced converters (VSC) are employed by shunt and series converters, which are linked to the secondary coupled transformer. VSC functions to force the commutated power electronic devices (GTO, IGCT, or IGBT) to generate a voltage from the DC voltage source. The shared capacitor is a DC voltage source connected to the VSC's DC side [34]. The following paragraphs summarize the available mode of UPFC operation.

2.4.1. Shunt converter

UPFC has many likely modes of operation. Into the transmission line, the shunt converter injects a controllable current I_{sh}. To balance the series converter's active power, a single component of this current is chosen, while other reactive components are set to the reference level (capacitive or inductive). The controlling reactive power modes pertaining to this converter can be regarded as analogous to STATCOM and static VAR compensation; it has two control modes: i) VAR control mode: Regarding the reactive control mode, the reference input could either be capacitive or inductive VAR request; and ii) Automatic voltage control (AVC) mode: The shunt converter reactive current regulation is kept automatic to maintain a reference transmission line voltage at the contact point [35].

2.4.2. Series converter

The series inverter modifies the angle and strength of the series-injected voltage. This voltage injection is being used to modify the line's power flow. However, the UPFC's particular operating mode regulates the voltage. The precise value of the injected voltage can be ascertained using various techniques [36]. The actual value of the injected voltage can be found in several ways:

- Injection voltage mode: A voltage vector is made by this converter with the needed magnitude and phase angle via the reference input

– Phase shifter emulation mode: The reference angle here would be the shift in the phase between the receiving end voltage and the sending end voltage
– Line impedance emulation mode: The magnitude of the voltage vector is regulated by an impedance value, or reference input, which is entered in series with the line impedance this should be proportional to the line current's magnitude. The reference input determines the desired impedance and may be regarded as a complex impedance possessing reactive and resistive components of any polarity
– Automatic control for the power flow mode: To force this line current vector, controlling the injected voltage vector's magnitude and phase angle is essential, which can result in the required power flow. Regardless of changes in the system. Power flow scheduling and management capabilities can be achieved in this operation that is impossible with conventional compensation systems
– Independent shunt and sequential compensation mode: The two converters can be operated as separately from each other by UPFC circuit via disconnection of the shared DC terminals [37]

With regard to the last mode case, the series functions as a standalone SSSC, while the shunt functions as a standalone STATCOM. If one converter fails and the other can adapt to upcoming system changes, either converter can be used for series-only or shunt-only compensation within the UPFC architecture. Since the converter can neither absorb nor generate active power in the standalone mode, only in the reactive power domain can the operation continue. Because the injected voltage must be in quadrature with the line current, either reactive impedance emulation or controlled voltage compensation can be used to manage power flow.

3. METHOD

In a 500 kV transmission system, the power flow can be controlled by a UPFC. The UPFC is connected in 75 km line L2, between B1 and B2, which can be divided into four sections to carry out the results. 500 kV buses can control the reactive and active powers that flow through the line while managing the voltage at the connection point. The proposed UPFC includes two three-level, 100-MVA, 48-pulse GTO-based converters. A power exchange between the two converters can be achieved via a DC link. A maximum of 10% (28.87 kV) of nominal phase voltage in series with a power line can be injected by a series converter. Figure 5 presents the flowchart of the overall work steps, while Figure 6 presents the UPFC controllable region.

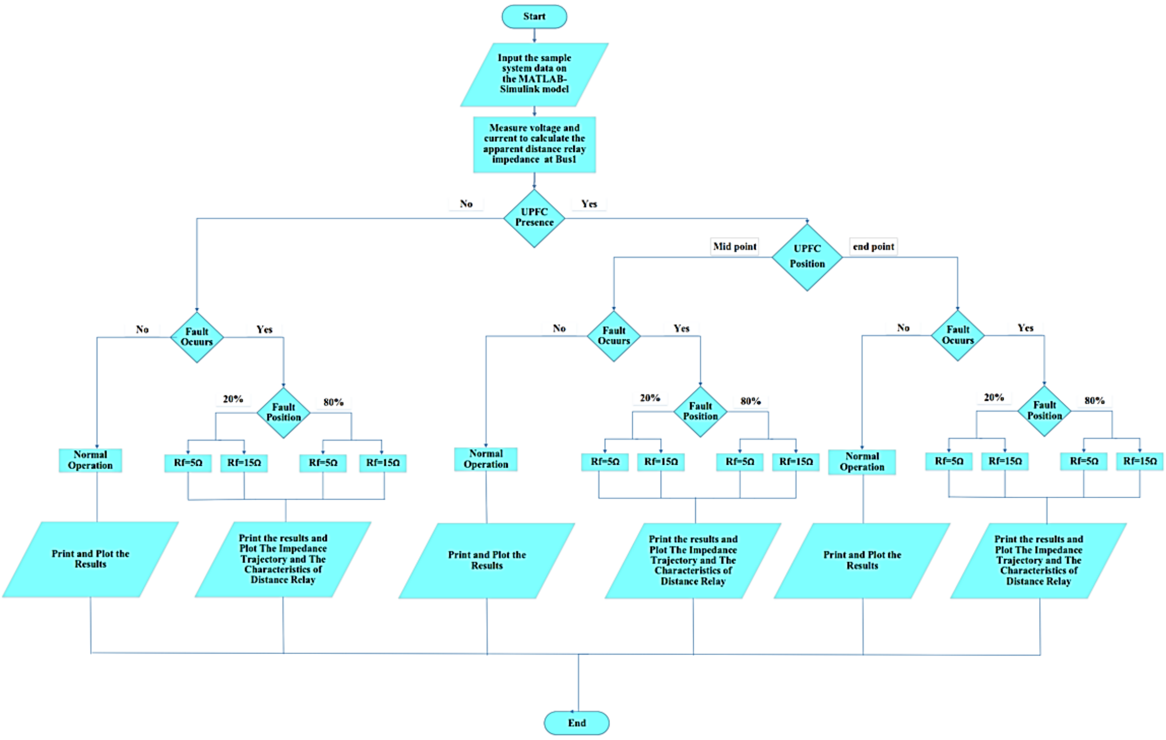


Figure 5. Overall flowchart for the proposed work

The proposed electric power system was modeled using MATLAB-Simulink. This paper's work is split into three parts as given in the following sections. Part I was modeled into three cases, the first one without using UPFC and other cases with different locations of the UPFC; Part II plotted the fault impedance trajectories, and part III operated the UPFC in different reference values to show the effect it on the distance relay apparent impedance.

3.1. Part I (Normal operation conditions)

This part comprises three cases: i) The first case: considers a system that does not employ UPFC (normal condition case), as demonstrated in Figure 7. The load flow studies determine the system's pre-fault conditions (voltage, currents) by employing measurement instrument tools; ii) The second case: UPFC is connected at the mid-point and end-point of the transmission line (L2) for the given sample system, and no fault was present (normal condition), as demonstrated in Figures 8 and 9; and iii) The third case: UPFC is connected after the end-point (after the load at B2), and also, no fault was present (normal condition), as demonstrated in Figure 10.

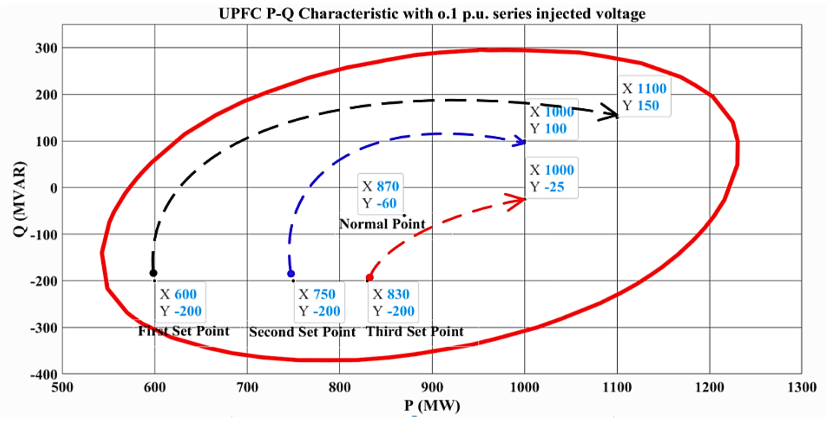


Figure 6. The proposed UPFC controllable region

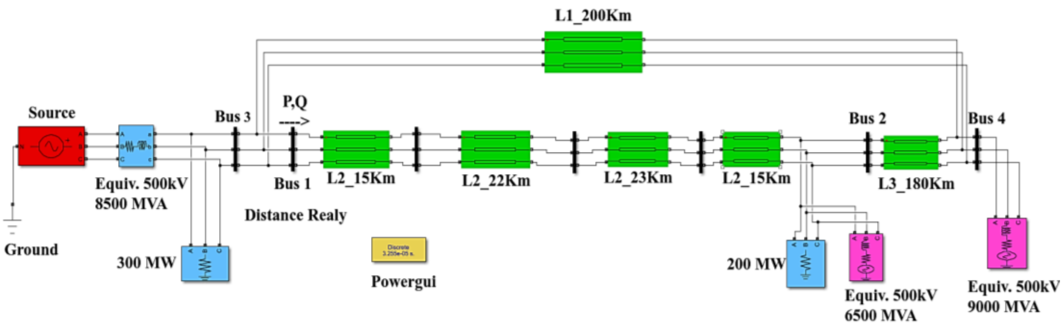


Figure 7. The proposed sample system using MATLAB-Simulink

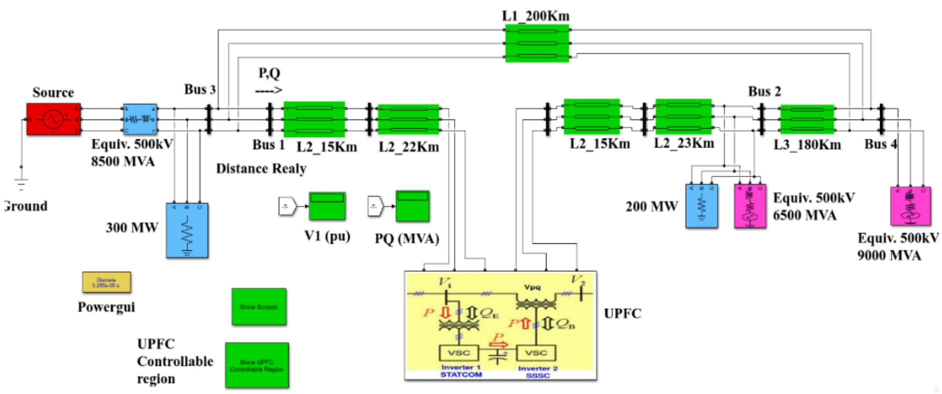


Figure 8. MATLAB-Simulink model for the sample system with UPFC location at mid-point

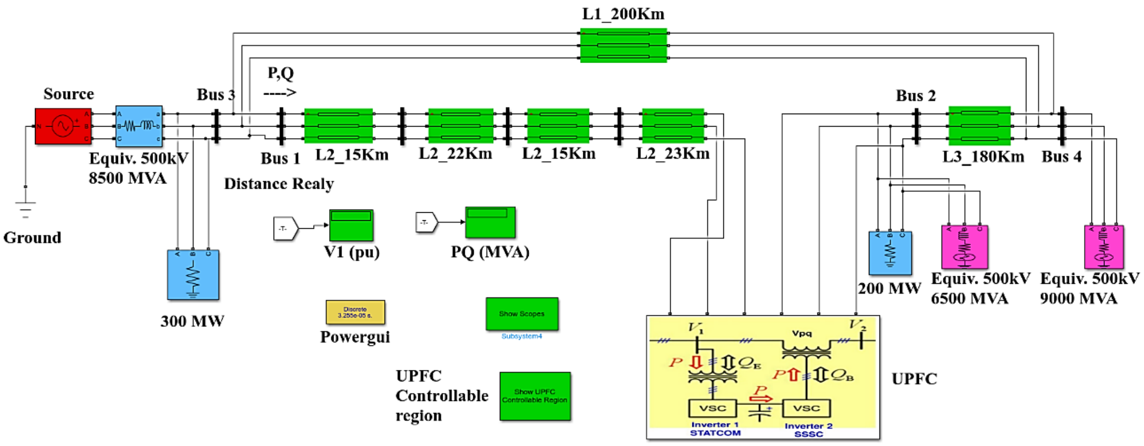


Figure 9. MATLAB-Simulink model for the sample system with UPFC location at the end-point before the load

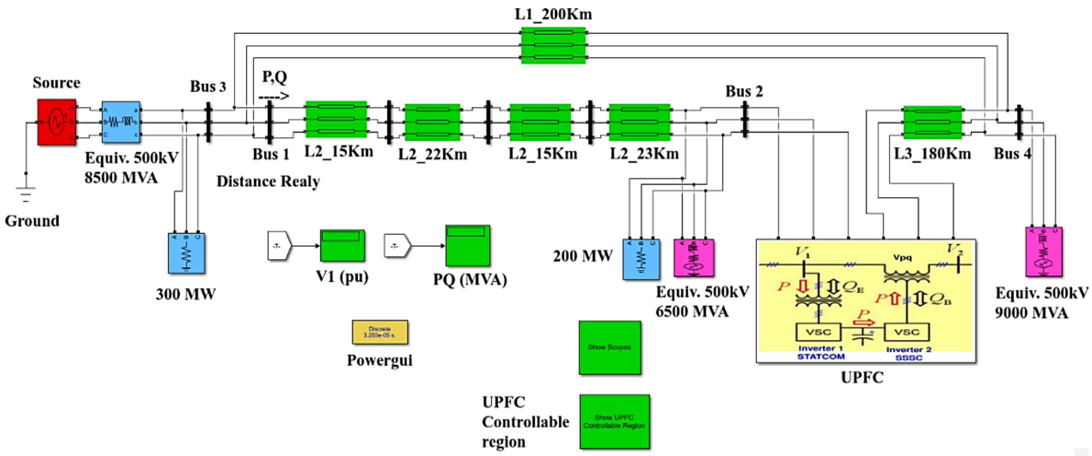


Figure 10. MATLAB-Simulink model for the power system with UPFC location at the end-point after the load

3.2. Part II (Plotting fault impedance trajectories)

In this part, for the three cases described in Part I, a three-phase to-ground fault has been used, which allows a chance to control the value of the fault resistance (Rf) to highlight the faults in various locations. Figure 11 demonstrates the put-forward method. The fault impedance locus is plotted without employing the UPFC for the variable fault resistance. It also includes bringing in the UPFC with identical values of fault resistance to determine the impact of compensation on the system.

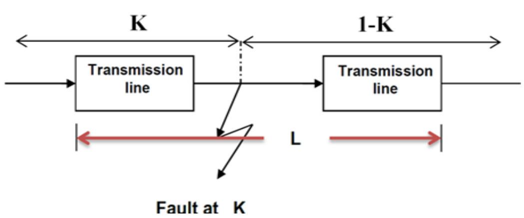


Figure 11. Faults in different locations

3.3. Part III (Operation UPFC in different reference values)

In this part, the operation of UPFC is analyzed and drawn by setting the per unit (p.u.) reference values based on three assumptions conditions, as provided in 1. Based on the initial and final reference set point conditions at a fixed step time, the UPFC will build its response. These conditions are demonstrated in the controllable region in Figure 6.

Table 1. UPFC reference values for three conditions

Conditions	P_{ref} Initial (p.u.)	P_{ref} Final (p.u.)	Q_{ref} Initial (p.u.)	Q_{ref} Final (p.u.)	Step Time (s)	Fault Time (s)
First	+6	+11	-2	+1.5	0.4	1.2
Second	+7.5	+10	-2	+1	0.4	1.2
Third	+8.3	+10	-2	-0.25	0.4	1.2

4. RESULTS AND DISCUSSION

The following Tables 2-5 give the proposed relay tripping parameters. The area boundary inside the rectangular coordinate is a tripping operation region that depends on the fault location (K), fault resistance (R_f), and system modification when adding UPFC. The normal start point has been drawn for the three cases described in part I. Then, three phases to ground fault in different locations and a variable fault resistance were integrated into the put-forward sample system. The impedance locus of the given sample system (part II) has been drawn for the three cases. As displayed in Figure 12(a) and Table 2, the first case excludes the involvement of UPFC. The impedance trajectory is seen to come under the operation characteristics pertaining to the distance relay; thus, the relay will send a trip signal independent of any defect. However, in the second case involving UPFC, the signal faces an under-reach state, so the characteristics of the put-forward relay must be changed to include the effects shown in Figures 12(b)-(d) and Tables 3, 4, and 5.

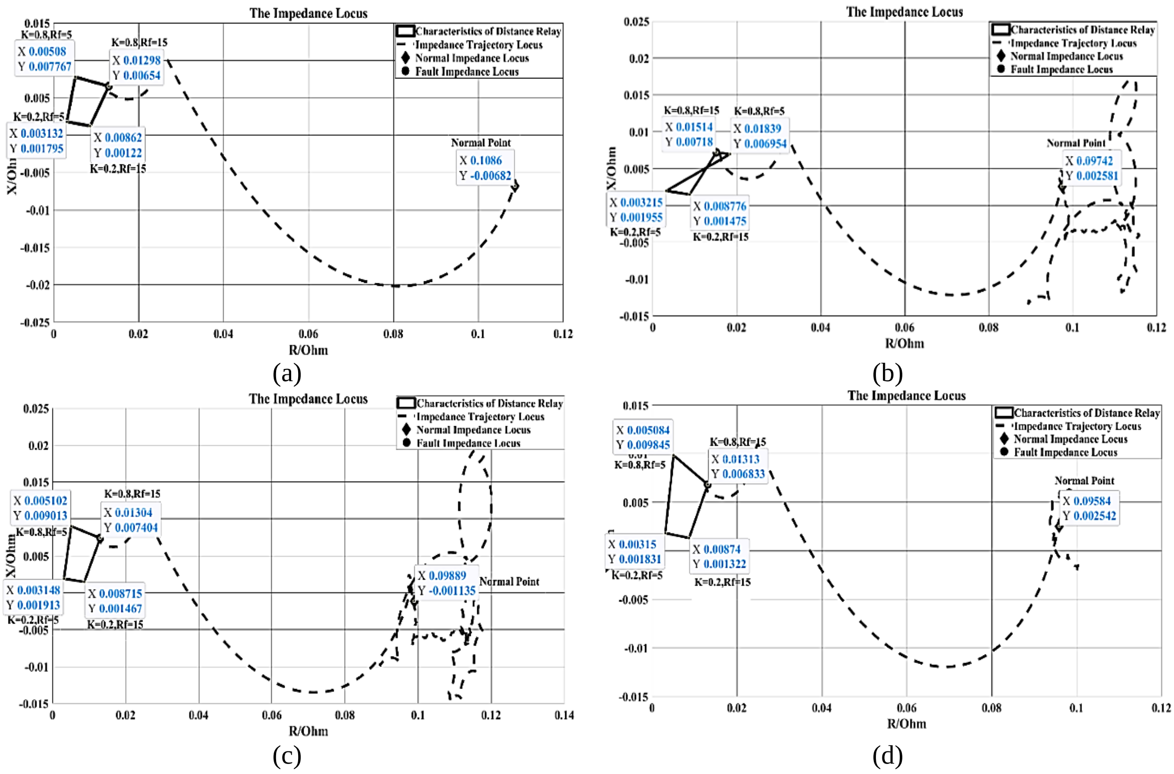


Figure 12. Impedance locus for the third case when UPFC at the end-point (third case after load location) where: (a) absence of UPFC, (b) UPFC at mid-point, (c) UPFC at end-point, and (d) UPFC at end-point after load location

Table 2. Resistance and reactance of the distance relay characteristic in the absence of the UPFC in the first case

K	R (ohm)	X (ohm)	R_f (ohm)
0	0.1086	-0.00682	0
0.2	0.003132	0.001795	5
0.8	0.00508	0.007767	5
0.8	0.01298	0.00654	15
0.2	0.00862	0.00122	15

Table 3. Resistance and reactance of the distance relay characteristic in the presence of the UPFC at mid-point for the second case

K	R (ohm)	X (ohm)	R_f (ohm)
0	0.09742	0.002581	0
0.2	0.003215	0.001955	5
0.8	0.01839	0.006954	5
0.8	0.01514	0.00718	15
0.2	0.008776	0.001475	15

Table 4. Resistance and reactance of the distance relay characteristic in the presence of the UPFC at the end-point for the second case

K	R (ohm)	X (ohm)	R_f (ohm)
0	0.09889	-0.001135	0
0.2	0.003148	0.001913	5
0.8	0.005102	0.009013	5
0.8	0.01304	0.007404	15
0.2	0.008715	0.001467	15

Table 5. Resistance and reactance of the distance relay characteristic in the presence of the UPFC at the end-point for the third case (after load)

K	R (ohm)	X (ohm)	R_f (ohm)
0	0.09584	0.002542	0
0.2	0.00315	0.001831	5
0.8	0.005084	0.009845	5
0.8	0.01313	0.006833	15
0.2	0.00874	0.001322	15

After observation and analysis of the sample system, data sets are collected and plotted by considering the presence and absence of UPFC as presented in Figure 13. The results demonstrate the impact of UPFC location (changing to different positions) on the transmission line of the sample system (B1-B2). The first put forward position is set on the mid-point, while the other is on end-point before and after the B2 load; the beginning position is overlooked since UPFC can be connected prior to the distance measuring points. As displayed in Figure 13, the overall results demonstrate these impacts on the distance relay characteristic and response, resulting in an over-reach or under-reach state should these impacts be overlooked.

Testing, plotting and analyzing an apparent impedance pertaining to the put forward relay for the sample system was done by introducing various operation conditions when the UPFC is functioning with three selected reference values set as provided in part III, Section 2.3. Figures 14-16 demonstrate the results, where (a) for the real power (Pref) response and (b) for the reactive power (Qref) response. Figure 14 displays the first reference value pertaining to the UPFC, while Figures 15 and 16 demonstrate the other possible causes. All Figures show the UPFC responses and the corresponding impedance distance relay.

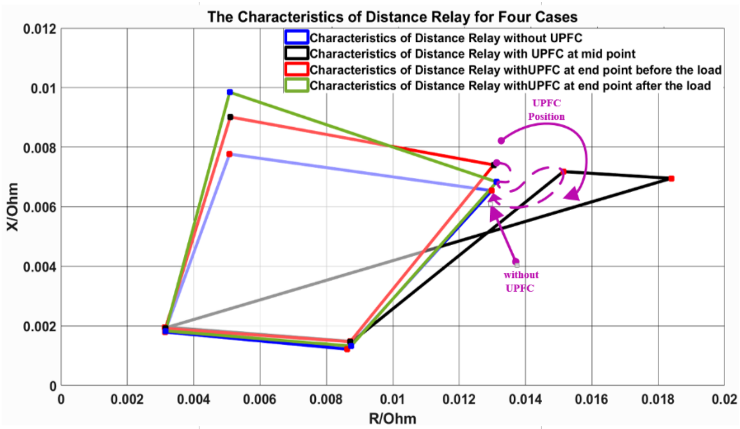
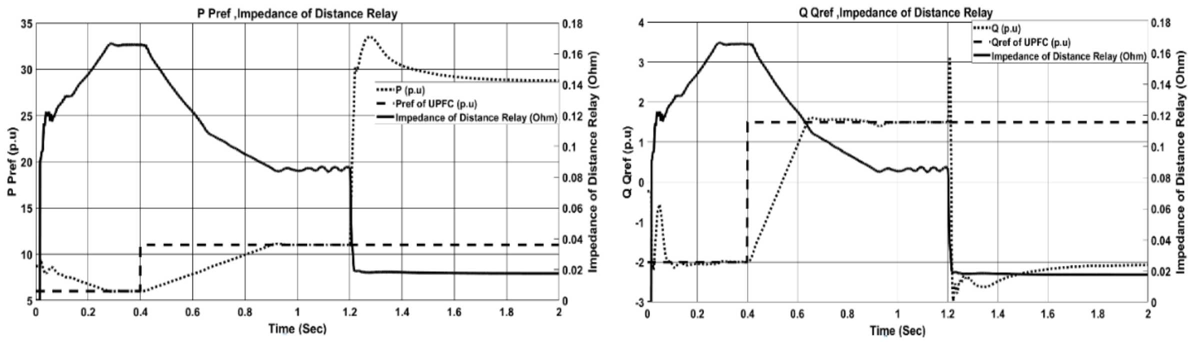
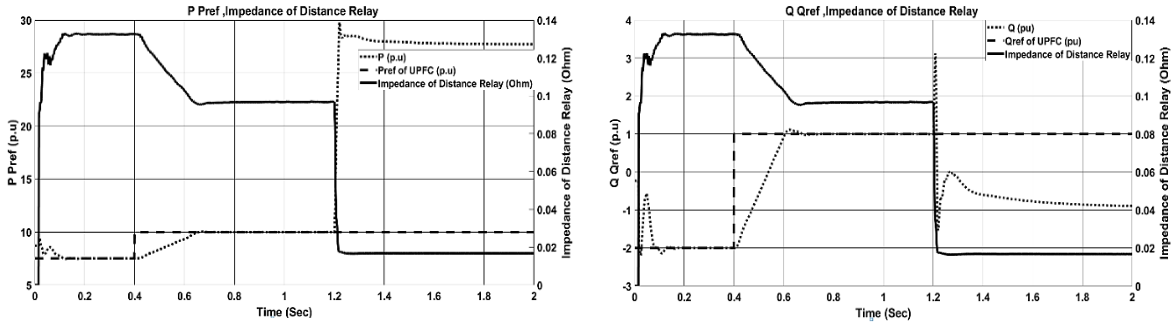


Figure 13. Characteristics of distance relay for all study cases



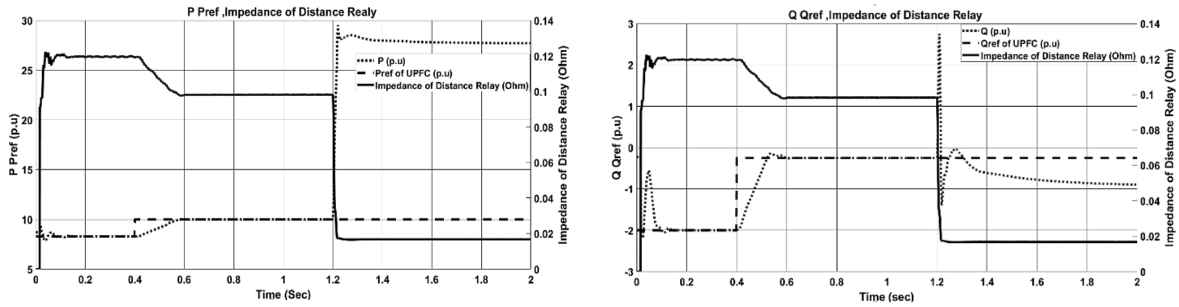
(a) (b)

Figure 14. Operation of the UPFC when the set reference values as in the first set point (a) P, Pref, and impedance of distance relay and (b) Q, Qref, and impedance of distance relay



(a) (b)

Figure 15. Operation of the UPFC when the set reference values as in the second set point (a) P, Pref, and impedance of distance relay and (b) Q, Qref, and impedance of distance relay



(a) (b)

Figure 16. Operation of the UPFC when the set reference values as in the third set point (a) P, Pref, and impedance of distance relay and (b) Q, Qref, and impedance of distance relay

5. CONCLUSION

The UPFC is regarded as one of the essential FACTS devices employed for increasing the quality and stability of the power system. A protective distance relay functions to protect a transmission line based on the apparent measured impedance. This paper assessed the impacts cast by UPFC operating region on the response characteristics of distance relay. Based on the simulation results, a distance relay may turn into over-reach or under-reach because of the adverse impact of the shunt controller (STATCOM) as well as the series controller (SSSC). The results demonstrate that the distance relay can be impacted by the phase angle of SSSC, Var control from STATCOM, and the direct voltage injection. These suggest an increase in the severity of the relay under-reach with the growing magnitude of SSSC injected voltage. In addition, the following points can be noted based on the simulation results: i) The compensation degree of UPFC relies on the following: an increase in fault resistance (Rf) could result in an increased compensation degree, while a decrease in fault resistance could result in decreased compensation degree; and increasing the distance of the fault (K) can lead to an increase in compensation degree, while the high line impedance determines the fault current; ii) UPFC has been employed to enhance the power system's quality and stability. The characteristics pertaining to the long-distance relay are affected by the UPFC, while the relay may suffer from an under-reach state in various degrees based on the location of the UPFC; iii) The under-reach state can occur when a UPFC is in the middle of a transmission line that is protected by a distance relay, which can also result in the most significant impact on the operational characteristics of the distance relay; iv) When the location of the fault is $1 > K > 0.5$, the effect is seen to be the largest. When a fault location is at $K = 0.2$, and the UPFC is located at the mid-point or end-point of the transmission line, a slight impact is cast on the distance relay's operational characteristics versus its presence before the fault location since the UPFC strays from the fault path; v) The new resultant characteristics of the distance relay show that UPFC at the mid-point is most effective compared to the end-point. The load impacts the relay characteristics and apparent impedance if UPFC at the end-point is connected after the B2 load; vi) Before and after adding UPFC, the old and the new lower edges rectangular coordinates of distance relay characteristics under $X = 0.002$ ohm are approximately not affected. vii) The measured apparent impedance (Z) from the relay point will decrease when Pref increases at constant Q = -2 p.u., where Z will change from 0.163 to 0.12 ohm when Pref varies from 6 to 8.3 p.u.; and viii) The measured apparent impedance (Z) from the relay point will be decreased when Qref decreases at constant P = 10 p.u., where Z will change from 0.1 to 0.096 ohm when Qref varies from 1 to -0.25 p.u.).

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