Impacts of a Distributed Power Flow Controller on the Performance of Distance Protection

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Abstract

In this paper, the performance of a distance protection relay is investigated in the presence of a Distributed Power Flow Controller (DPFC) in a transmission system. The DPFC, indeed, is derived from the Unified Power Flow Controller (UPFC). The differences are that the common DC-link has been eliminated and three-phase series converter has been divided to several single-phase series converters distributed through the transmission line. In order to analyze effects of DPFC on distance protection relays, different types of line faults are simulated at various locations by using the EMTDC/PSCAD® software and compare the measured impedance at the relaying point in the presence of DPFC with UPFC. The Simulation results show the effects of magnitude and phase angle of voltage injected by series converters on the performance of a distance relay. It is indicated that the under/over reaching of the distance relay is due to the zero sequence of voltage injected by series converters of DPFC. It has the most significant effect on the apparent impedance measured by phase to ground fault measuring unit. It is also illustrated that the fault resistance affects the measured impedance at relay point in the presence of DPFC.

Keywords: distance relay; Distributed Flexible Alternating Current Transmission System (D-FACTS); Distributed Power Flow Controller (DPFC); under/over reaching phenomena.

1. INTRODUCTION

Recently, in order to utilize the existing power system more efficiently, new types of Distributed FACTS (D-FACTS) devices have been situated in transmission lines. The D-FACTS devices have all benefits of FACTS devices, but at lower cost and higher controllability, reliability, and stability [1-6]. The DPFC is a member of the D-FACTS family with attractive features [5,6]. The DPFC has a similar configuration to the UPFC structure. As shown in Fig. 1, a single shunt converter and several independent series converters are the components of a DPFC. The series converters are used to balance the line parameters, such as line impedance, transmission angle, and bus voltage magnitude [5,6]. The same as the UPFC, the DPFC is able to control all system parameters. In the DPFC, the common DC-link between the shunt and series converters has been removed [5]. The active power exchange between the shunt and the series converter is carried through the transmission line at the third-harmonic frequency [5].

Depending on the particular problem occurring in a transmission system, FACTS devices can operate in either capacitive mode or inductive mode [7]. Subsequently, these devices affect the performance of distance relays which generally are used in transmission line protection. Several studies have been done to evaluate the performance of a distance relay in transmission systems equipped with FACTS controllers [8-31]. In particular, [8-16] have presented the influence of shunt FACTS devices on the performance of distance relays. The research described in [9] considers the performance of a distance relay in a transmission network equipped with a STATCOM for normal operating conditions and for fault conditions under different loading levels. The works in [17-23] present a study of the performance of distance protection relays when applied to protect series FACTS compensated transmission lines. The studies in [17] indicate a detailed evaluation of the effects of TCSC on the protection of compensated lines and show that not only does the TCSC influence the protection of its line, but also the protection of adjoining lines would get involved some problems. There has been a considerable work dealing with the FACTS devices which include both shunt and series sections [24-31]. In [24], the distance relay operation during power swing conditions for a transmission line with a UPFC is analyzed and the results are summarized graphically. In [24], studies also include the impact of different operation modes of UPFC on the apparent impedance seen by distance relay. The work in [25] shows that apparent impedance calculated by distance relays are affected by VSC-based FACTS controllers when controlling the power flow of transmission lines. The effects of a DPFC on other field of power systems have been considered. For example, in [32], the DPFC effect on sub-synchronous mitigation is investigated. However, the impact of DPFC on distance protection has not been evaluated significantly. This indicates the importance of this field to evaluate.

In this paper, analyzing the impacts of DPFC operating point on the distance relay behavior is the main area of concern. This effective issue should be considered in distance relay setting remarkably. In this research, the effects of DPFC parameters, i.e., angle and magnitude of voltage injected by series converters of DPFC on the distance relay behavior are investigated, separately. The effects of the shunt and series converters of a DPFC on the operation of a distance relay during various faults with and without resistance are also examined. Furthermore, a solution is provided to mitigate the effects of DPFC on the calculated impedance.

This paper is organized as follows. First, the DPFC operation principle is reviewed in the Section II. In the Section III, the control strategy of a DPFC is presented. The analytical investigation and the impedance calculation in the presence of a DPFC are described in the section IV. The performance of distance relays in the presence of a DPFC is illustrated and the measured impedances for DPFC and UPFC are compared in the Section V. Finally, the conclusions are given in the Section VI.

2. DPFC STRUCTURE

Comparing with UPFC, the basic ideas in the DPFC are DC-link elimination and utilization of 3rd harmonic current to exchange active power. The DPFC structure is described as follows:

2-1. DC-Link Elimination and Power Exchange

Within the DPFC, instead of using DC-link for power exchange between converters in the UPFC, the transmission line is used as a connection between shunt converter output and AC port of series converters in the DPFC (as shown in Fig. 1) [5]. The method of power exchange in the DPFC is based on theory of non-sinusoidal components [5]. Non-sinusoidal voltages and currents can be expressed as a sum of sinusoidal components at different frequencies. It is the main result of the Fourier analysis [25]. The product of voltage and current components defines the active power. Since the integral of some terms with different frequencies are zero [5], one can calculate the active power as follow:

$$p = \sum_{i=1}^{\infty} V_{si} I_{si} \cos \varphi_i \tag{1}$$

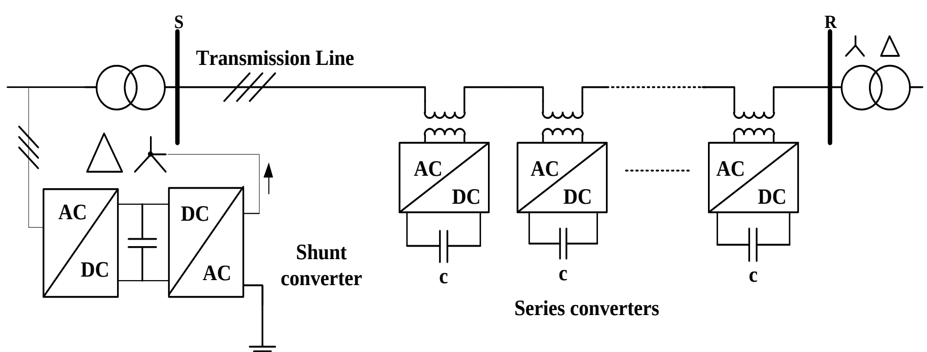


Fig. 1 DPFC structure

Where φ_i is the angle between V_{si} and I_{si}. Equation (1) expresses the active power components at different frequencies which are independent of each other. The converter can absorb the active power in one frequency and provides the output power in another frequency. Suppose that the DPFC is located in transmission line of a two-bus system; thus, the power supply generates and the shunt converter absorbs the active power in the fundamental frequency of current. Meanwhile, the third harmonic component is trapped in Y-Δ transformer [6]. Output terminal of the shunt converter injects the third harmonic current into the neutral of Δ-Y transformer. As a consequence, the third harmonic current flows through the transmission line. This harmonic current controls the DC voltage of series capacitors [6]. Fig. 2 indicates the active power exchange at fundamental and third harmonic frequency between the shunt and series converters in the DPFC.

3. DPFC CONTROL

The DPFC has three controllers: central controller, series controller and shunt controller, as shown in Fig. 3.

3-1. Central Controller

This controller tunes all of the series and shunt controllers' parameters and sends the reference signals to both of them.

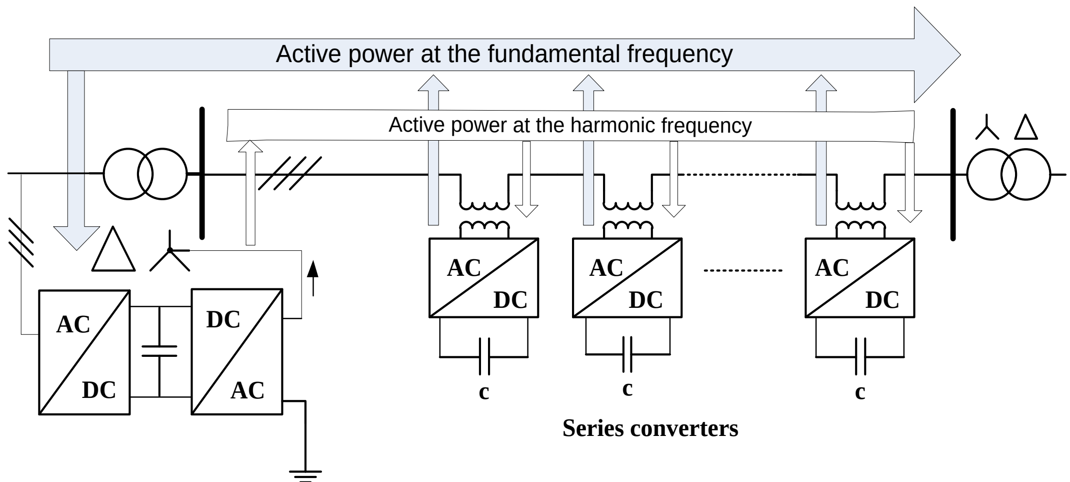


Fig. 2 Active power exchange between DPFC converters

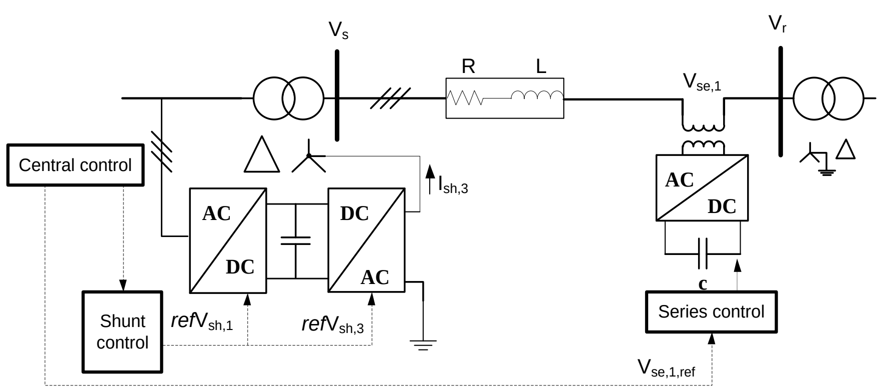


Fig. 3 DPFC control structure

3-2. Series Controller

Each single-phase converter through the line has a unique series controller. The inputs of this controller are series capacitor voltages, line current, and series voltage reference in *dq*-frame. Any series controller has one low-pass and one 3rd-pass filter to create fundamental and third harmonic of current, respectively. Two single-phase Phase Lock Loops (PLLs) are used to get frequency and phase information from the grid [33]. The block diagram of a series controller is shown in Fig. 4.

3-3. Shunt Controller

The shunt converter includes a three-phase converter that is linked to a single-phase converter. The three-phase converter absorbs active power from grid at the fundamental frequency and controls the DC voltage of the capacitor between this converter and single-phase one. The simulated diagram of shunt controller is shown in Fig. 5.

4. Apparent Impedance Analysis with DPFC

Apparent impedance calculation is carried out using power frequency components of voltage and current signals measured at the relay point [24]. The calculated impedance is profoundly affected by location and operating mode of FACTS devices during faults [16].

In this study, the DPFC is installed to be located near the relay. The shunt converter of DPFC is located at the beginning of the line, before the transformer, and the series converter of DPFC is installed at the mid-point of both line I and line II. Fig. 6 shows the simplified network of the system under study which contains two series 300km, 400kV transmission lines, and a fault at the second section of the compensated line I (i.e., after the location of DPFC series converter). Fig. 7 shows the positive, negative and zero sequence networks of the sample system for a fault at line I. A distance relay is installed at bus S to protect the associated transmission line I.

Voltage measured at the relay point at bus S is as follows:

$$V_{1s} = nI_{1s1}Z_{1L1} + V_{1F} + E_{1se1} + R_f\,(I_{1s1} + I_{1r1}) \tag{2}$$

$$V_{1s} = Z_{1L2}I_{1L2} + (1-n)Z_{1L1}I_{1r1} + R_f\,(I_{1s1} + I_{1r1}) + V_{1F} + E_{1se2} \tag{3}$$

Extracting V_{1F} from (3) and replacing it in (1):

$$I_{1L1} = \frac{n}{1-n}I_{1s1} + \frac{E_{1se1} - E_{1se2}}{(1-n)Z_{1L1}} - \frac{\sigma_1}{1-n}I_{1s2} \tag{4}$$

where:

$$\sigma_1 = Z_{1L2} / Z_{1L1} \tag{5}$$

Therefore, by using equations (3) and (4), the positive sequence of the voltage is given by:

$$V_{1s} = nI_{1s1}Z_{1L1} + V_{1F} + E_{1se1} + \frac{R_f}{1-n}(I_{1s1} + \frac{E_{1se1} - E_{1se2}}{Z_{1L1}} - \sigma_1 I_{1s2}) \tag{6}$$

Subsequently, the negative and zero sequence of the voltages are obtained from Fig. 7 similarly.

$$V_{2s} = nI_{2s1}Z_{1L1} + V_{2F} + E_{2se1} + \frac{R_f}{1-n}(I_{2s1} + \frac{E_{2se1} - E_{2se2}}{Z_{1L1}} - \sigma_1 I_{2s2}) \tag{7}$$

$$V_{0s} = nI_{0s1}Z_{0L1} + V_{0F} + E_{0se1} + \frac{R_f}{1-n}(I_{0s1} + \frac{E_{0se1} - E_{0se2}}{Z_{0L1}} - \sigma_0 I_{0s2}) \tag{8}$$

where:

$$\sigma_0 = Z_{0L2} / Z_{0L1} \tag{9}$$

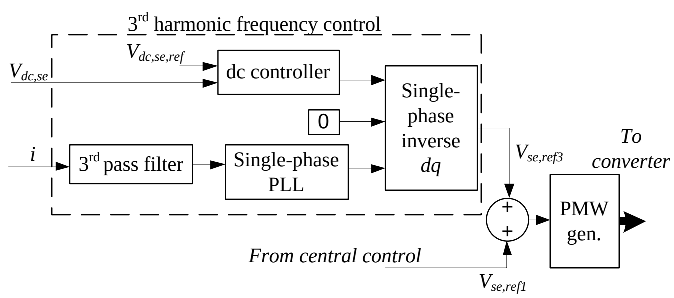


Fig. 4 Block diagram of the series converter control

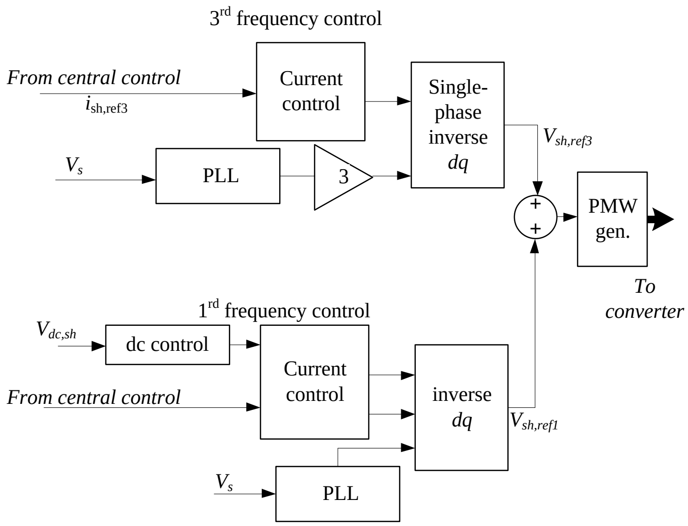


Fig. 5 Block diagram of the shunt converter control

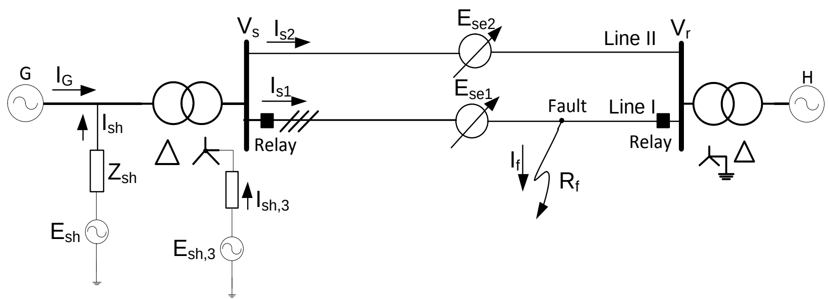


Fig. 6 Simplified faulted network for the study system with DPFC

4-1. Single phase to ground fault

The following equations can be utilized for a single phase to ground fault (*A*-*G*):

$$V_{0F} + V_{1F} + V_{2F} = 0 \tag{10}$$

By using equations (6)-(8) and (10), we have:

$$V_s = nI_{1s1}Z_{1L1} + n(Z_{0L1} - Z_{1L1})I_{0s1} + \frac{R_f}{1-n}[I_{s1} - \sigma_1 I_{s2} + (\sigma_1 - \sigma_0)I_{0s2}] + \Delta V_s \tag{11}$$

Where:

$$V_{0s} + V_{1s} + V_{2s} = V_s \tag{12}$$

$$I_{0s1} + I_{1s1} + I_{2s1} = I_{s1} \tag{13}$$

$$I_{0s2} + I_{1s2} + I_{2s2} = I_{s2} \tag{14}$$

$$E_{0se1} + E_{1se1} + E_{2se1} = E_{se1} \tag{15}$$

$$E_{0se2} + E_{1se2} + E_{2se2} = E_{se2} \tag{16}$$

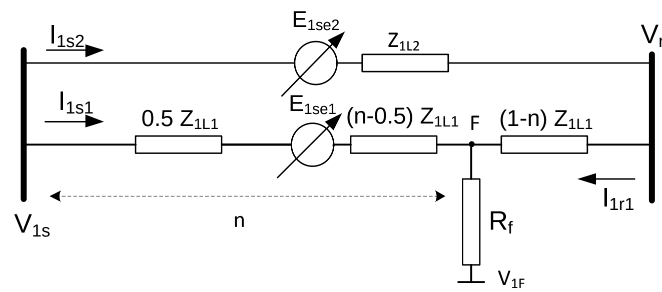
and

$$\Delta V_s = E_{se1} + \frac{R_f}{(1-n)}\left[\frac{E_{se1} - E_{se2}}{Z_{1L1}} + (E_{0se1} - E_{0se2})\left(\frac{1}{Z_{0L1}} - \frac{1}{Z_{1L1}}\right)\right] \tag{17}$$

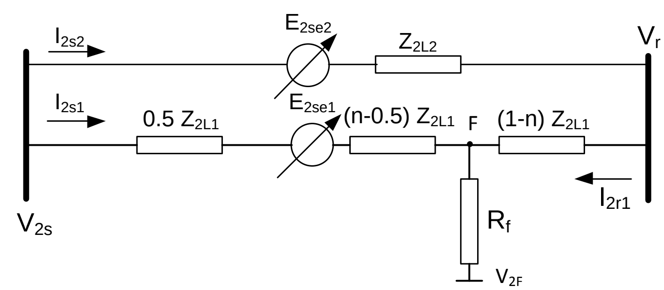
For single-line-to-ground faults, the apparent impedance calculated by the distance relay is made equal to the actual positive sequence impedance of the faulted portion of the line by introducing a zero sequence compensation factor [25]. Hence, if $R_f = 0$, the apparent impedance measured by a conventional distance relay, in absence of DPFC, is:

$$Z = \frac{V_s}{I_{s1} + \frac{Z_{0L1} - Z_{1L1}}{Z_{1L1}} I_{0s1}} = \frac{V_s}{I_{relay}} \tag{18}$$

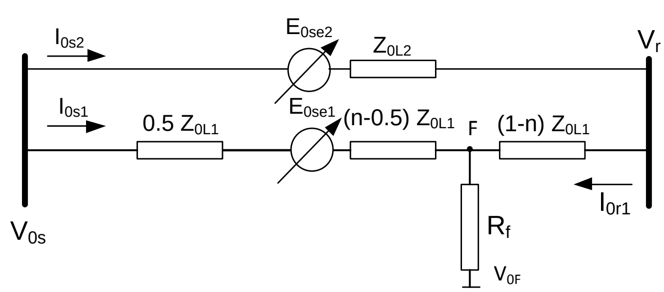
where, I_{relay} is the relaying current [34]. This shows an ideal relationship, where R_f is zero and also the shunt capacitances of the lines are neglected. When these factors are taken into consideration, the characteristics of conventional distance relays need to be modified in order to make sure that the dedicated



(a)



(b)



(c)

Fig. 7 Sequence networks of the system; (a) positive sequence network; (b) negative sequence network; and (c) zero sequence network

relay does not over-reach or under-reach. Therefore, using equations (11) and (18), the apparent impedance seen by the ground-fault indicator unit of a distance relay is given by:

$$Z = nZ_{1L1} + \frac{R_f}{(1-n)I_{relay}}(I_{s1} - \sigma_1 I_{s2} + (\sigma_1 - \sigma_0)I_{0s2}) + \Delta Z \tag{19}$$

Considering equation (19), the first term represents the line impedance to the fault point in the case of a solid fault with no mid-point series converter of DPFC. Therefore, the error in the apparent impedance (ΔZ) introduced as a result of the series voltage injection and the fault resistance is given as:

$$\Delta Z = \frac{E_{se1}}{I_{relay}} + \frac{R_f}{(1-n)I_{relay}}\left[\frac{E_{se1} - E_{se2}}{Z_{1L1}} + (E_{0se1} - E_{0se2})(\frac{1}{Z_{0L1}} - \frac{1}{Z_{1L1}})\right] \tag{20}$$

The first term in equation (20) represents the error in the apparent impedance measuring because of the series converter of DPFC in line I. The second term shows the error due to the fault current passing through the fault resistance; so that series converter in both lines would influence on the apparent impedance.

4-2. Phase to phase fault

For a phase to phase fault (*A*–*B*) we have:

$$V_{1s} = aV_{2s} \tag{21}$$

where:

$$a = -1/2 + j(\sqrt{3/2}) \tag{22}$$

From (6), (7), and (21) we have:

$$V_{1s} - aV_{2s} = nZ_{1L1}(I_{1s1} - aI_{2s1}) + (E_{1se1} - aE_{2se1}) + \frac{R_f}{(1-n)}((I_{1s1} - aI_{2s1}) + \frac{(E_{1se1} - aE_{2se1})}{Z_{1L1}} - \frac{(E_{1se2} - aE_{2se2})}{Z_{1L1}} - \sigma_1(I_{1s2} - aI_{2s2})) \tag{23}$$

Dividing Eq. (23) by I_{A-B}, we can obtain the apparent impedance for a phase to phase (*A*-*B*) fault:

$$Z_{A-B} = nZ_{1L1} + \frac{R_f}{(1-n)I_{A-B}}\left[(I_{1s1} - aI_{2s1}) - \sigma_1(I_{1s2} - aI_{2s2})\right] + \Delta Z_{A-B} \tag{24}$$

In equation (24) ΔZ_{A-B} depends on the presence of series compensator of DPFC and it is equal to:

$$\Delta Z_{A-B} = \frac{(E_{1se1} - aE_{2se1})}{I_{A-B}} + \frac{R_f}{(1-n)I_{A-B}}\left(\frac{(E_{1se1} - aE_{2se1})}{Z_{1L1}} - \frac{(E_{1se2} - aE_{2se2})}{Z_{1L1}}\right) \tag{25}$$

In equation (25), R_f is fault resistance between two phases. if $R_f = 0$, the series converter in line I can increase the error because of the differences between negative and positive voltage sequences. Moreover, if $R_f \neq 0$, not only does the series voltage injection of series converter in line I affect but also the series converter in line II influences on the fault current.

C. Three phase fault

Similarly, the apparent impedance measured by the relay for three phase fault can be derived and the final equations are given for brevity:

$$Z = nZ_{1L1} + \frac{R_f}{(1-n)I_{relay}}(I_{s1} - \sigma_1 I_{s2}) + \Delta Z \tag{26}$$

where I_{relay} is the corresponding line current.

$$\Delta Z = \frac{E_{se1}}{I_{relay}} + \frac{R_f}{(1-n)I_{relay}} \left[\frac{E_{se1} - E_{se2}}{Z_{1L1}} \right] \tag{27}$$

5. Simulation Results

A 400kV transmission system including a 160MVA DPFC is simulated in PSCAD/EMTDC environment. The Configuration of the under study consists two series 300km transmission lines. The other parameters of this system are as follows:

$Z_{1L1} = Z_{1L2} = 0.01133 + j0.3037 \ \ \Omega / km$

$Z_{0L1} = Z_{0L2} = 0.1535 + j1.1478 \ \ \Omega / km$

$Z_{1G} = 1.394 + j15.941 \ \ \Omega, \ Z_{1H} = 0.6971 + j7.9695 \ \ \Omega$

Load angle between sources: 15˚

The reach of the instantaneous Zone 1 is set at 80% (240 km) and Zone 2 set at 120% (360 km) with time delay of 20 power cycles.

5-1. Single Phase to ground Fault Effect on Distance Relay Performance

The DPFC influence on the apparent impedance measured by the relay is shown in Fig. 8. The figure compares the impact of DPFC on apparent impedance with and without the presence of the UPFC. The single phase to ground *(A-G)* fault is located at 230km from the beginning of the line I. In this case, the shunt converter of both DPFC and UPFC is set at 400 kV (1p.u) voltage level and series converters of DPFC and UPFC are set at 40 kV and 15˚. As can be seen from this figure, the distance relay does not see the fault at Zone 1 due to the series converters of DPFC effect. The DPFC impact on the measured impedance can be represented by Eq. (20). The zero sequence component of the voltage injected by the series converter of DPFC rises after occurrence of the fault. Therefore, the main component of E_{se1} is formed by E_{0se1} in Eq. (20). Furthermore comparing with UPFC, the effect of DPFC is less than the impact of UPFC. It is consequence of impact of shunt converter of UPFC.

The operating time of the distance relay is also influenced by the DPFC and UPFC. An example of delayed tripping is simulated with *A-G* fault at 190 km (Fig. 9). As can be seen from Fig. 9, relay takes 14 ms to trip on zone 1 in case of without any FACTS devices whereas it takes 72 ms for similar condition at DPFC compensated system. This represents about 4 to 6 cycles of relay operating time which is certainly unacceptable for zone 1. A similar case of delayed tripping of zone 1 for relay operation is shown in Fig. 9 for UPFC compensated system. It takes 74 ms to trip on zone 1.

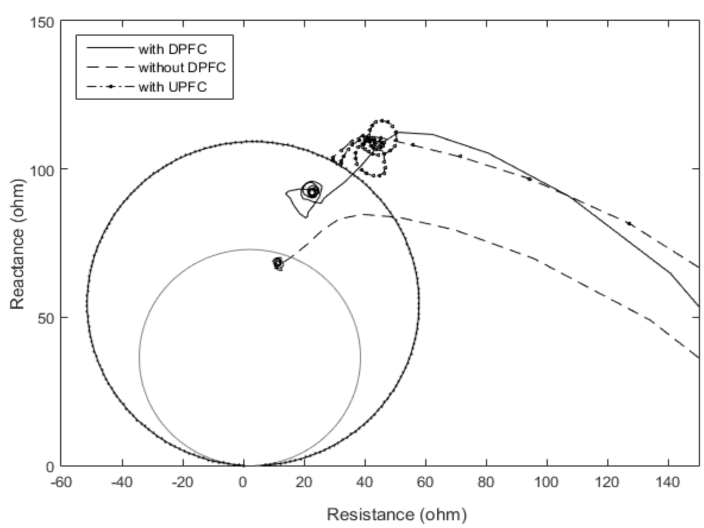


Fig. 8 DPFC and UPFC effects on the apparent impedance seen by the distance relay for an *A-G* fault

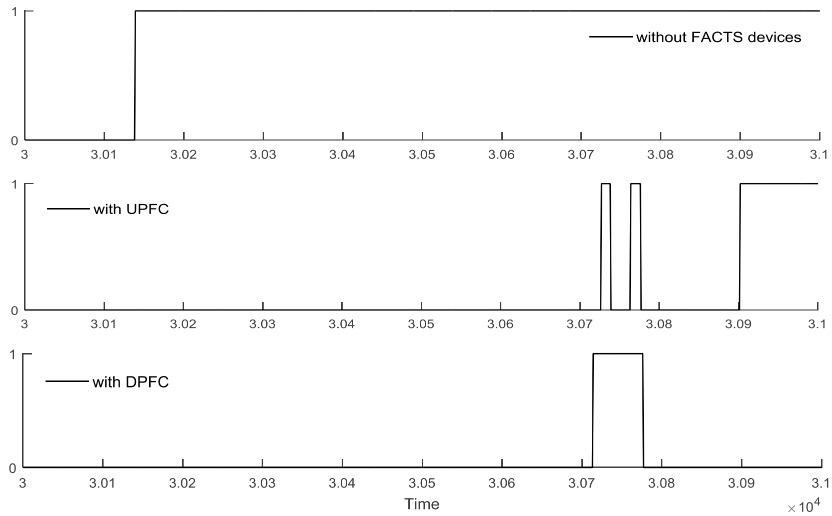


Fig. 9 Case of delayed tripping of zone 1 for a *A-G* fault at 190 km

5-2. Phase to Phase Fault Effect on Distance Relay Performance

Apparent resistance and reactance, as a function of time, are shown separately in Figs. 10 and 11, respectively. It is simulated for a phase to phase *(A-B)* fault at 230km with and without DPFC and UPFC. The DPFC has less impact in case of a phase to phase fault in compare to a single phase to ground fault. According to the simulations, amounts of positive and negative sequences of the voltage injected by the DPFC are lower in case of an *A–B* fault. Therefore, the region of under-reach for *A–B* faults is less than that one for *A-G* faults. In addition, the impedance measured by the phase to phase fault measuring unit is less affected by zero sequence of voltage injected by DPFC.

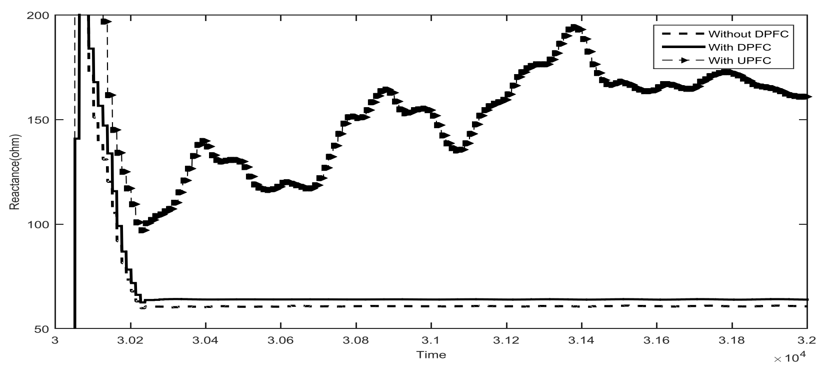


Fig. 10 Apparent resistance seen by the distance relay for an *A-B* fault occurred at 3s

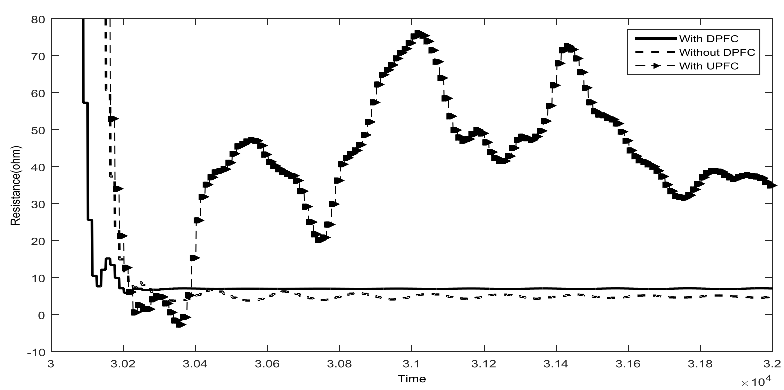


Fig. 11 Apparent reactance seen by the distance relay for an *A-B* fault occurred at 3s

5-3. Three Phase Fault Effect on Distance Relay Performance

In case of a three phase fault at 240km, the apparent impedance seen by the relay in the presence of DPFC and UPFC are shown in Fig. 12. The figure compares the impact of DPFC on apparent impedance in the same condition for single phase. It can be concluded from Eq. 27, the only effective part of DPFC on the apparent impedance is its series converter.

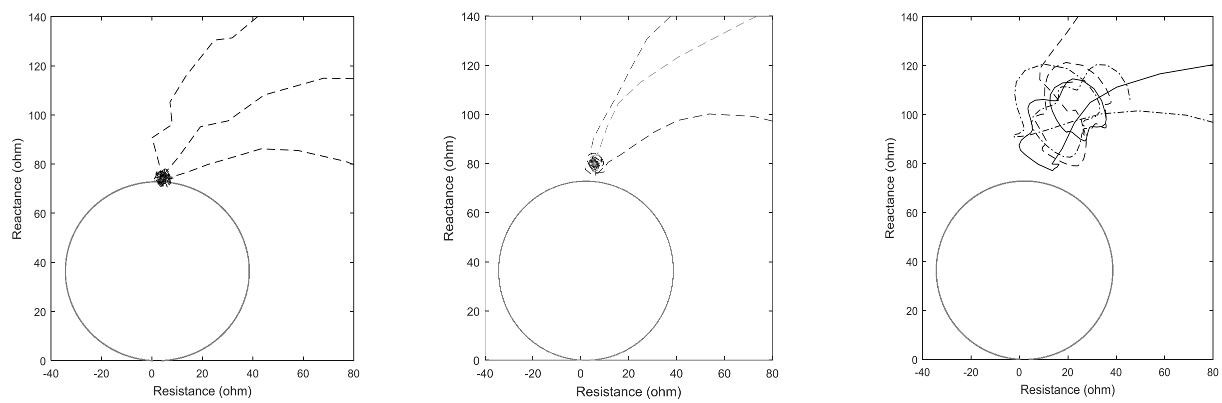
5-4. Phase Angle Voltage Control of Series Converters of DPFC Effect on Distance Relay Performance

The DPFC contains shunt and series converters. The line terminal voltage is controlled by shunt converter, while active and reactive power flow through the line are controlled by series converters. During faults, the phase angle of the voltage injected by series converters influences on the apparent impedance calculated by a distance relay. Therefore, the apparent impedance changes by varying phase angle of the DPFC operating point. In the simulation, various phase angle of the voltage injected by series converters are considered. In case of a single-phase fault at 240km, the apparent resistance, reactance and impedance for different phase angle (α) are shown in Figs. 13-15, respectively.

Figs. 13-15 indicate a change in apparent impedance seen by the distance relay for different α because of the active power exchange between the shunt and series converters of DPFC. In capacitive compensation mode, the DPFC causes a reduction in the calculated impedance and subsequently the relay will over-reach. In inductive compensation mode, on the contrary, the DPFC causes a rise in the calculated impedance and subsequently the relay will under-reach.

5-5. Amplitude Control of Series Converter of DPFC Voltage Effect on Distance Relay Performance

Obviously, the apparent impedance measured by the relay is affected by changing the magnitude of the voltage injected by series converters. As shown in Fig. 16, the apparent impedance increases by raising the series voltage magnitude of DPFC. This figure is for single phase fault at 240km and a constant phase angle.



(a) (b) (c)

Fig. 12 The apparent impedance seen by the distance relay for a three phase fault: a) without FACTS devices b) with DPFC and c) with UPFC

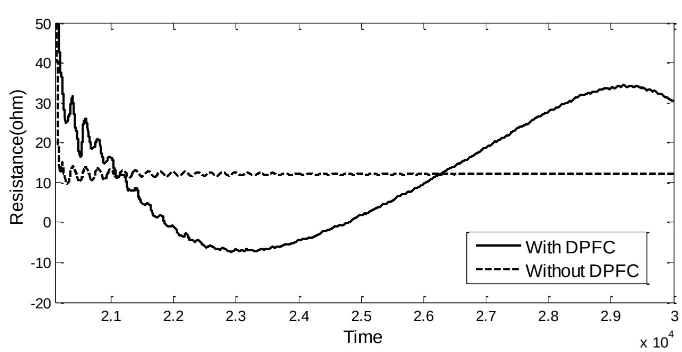


Fig. 13 Apparent resistance for different phase angle (α varies from 0° to 360°)

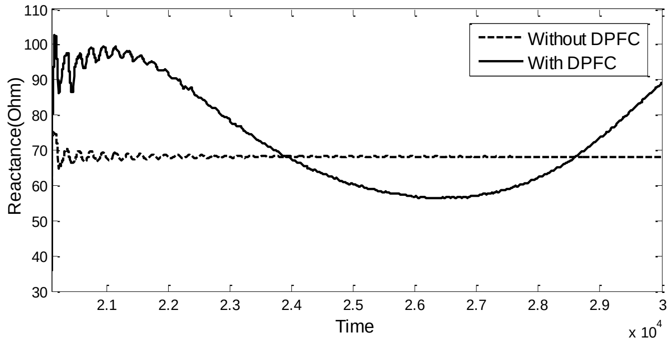


Fig. 14 Apparent reactance for different phase angle (α varies from 0° to 360°)

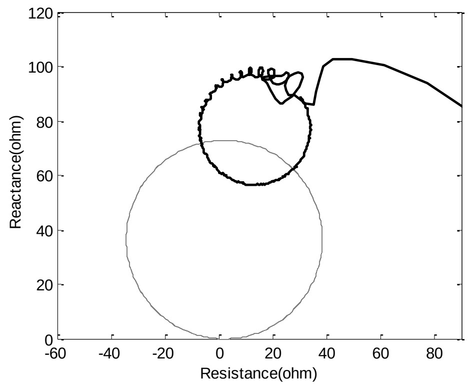


Fig. 15 Apparent impedance for different phase angle (α varies from 0° to 360°)

5-6. Effect of Fault Resistance

The performance of the distance relay in existence of DPFC and UPFC compensator is simulated in case of faults with resistance. There are two scenarios when the series converter of DPFC is installed at the mid-point. First, if a solid fault occurs between the relaying point and the mid-point, the DPFC is not included in the fault loop. Second, if the fault occurs at the same place with fault resistance, the DPFC would be included in the fault loop. When the DPFC is not included in the fault loop for solid faults, the measured impedance is equal to the actual impedance of the line section between the relay and fault points. In contrast, when the DPFC is included in the fault loop, even in the case of zero fault resistance, the measured impedance can be deviated from its actual value. In this analysis, the fault resistances are 0 and 40 ohm and a line-to-ground fault is applied at 30% from relay point (i.e., before location of DPFC series converter and within the zone 1). The performance of the distance relay is shown in Fig. 17 when the fault resistance is 0 ohm. The relay at the beginning of the compensated line I tripped on zone 1 for

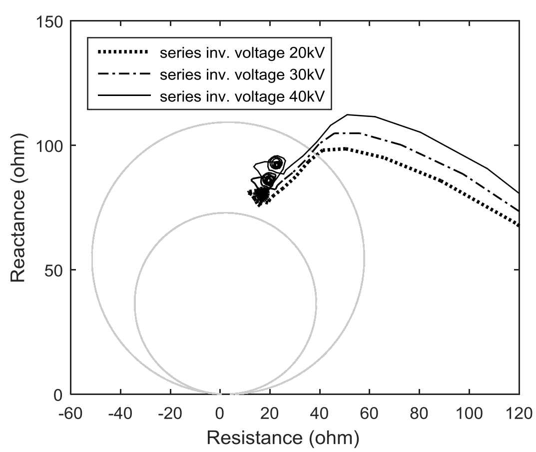


Fig. 16 Apparent impedance for different series injected voltage levels and a constant α

fault resistance 0 ohm, correctly. However, the series converter is connected in the mid-point; it is not present in the fault loop. Fig. 18 shows the result when the fault resistance is 40 ohm. The operation of the distance relay gets affected because of the voltage which is loaded on the fault resistance by the series converter of DPFC. Hence, the injected voltage results in under-reaching in where the relay either trip on the zone 2 or even fail to operate in case of faults with high resistance. In this case, the UPFC has impact on the apparent impedance when the UPFC includes in the fault loop. But this effect is more than the effect of DPFC (Fig. 18). It is because of the effect of shunt converter of UPFC on the apparent impedance.

6. CONCLUSIONS

This paper studies the impacts of DPFC on the performance of distance relay during three types of faults and compare with the effects of UPFC. The simulation results reveal the impacts of DPFC on the apparent impedance are less than the impacts of UPFC. This impedance depends on the controlling parameters of DPFC and UPFC, as well as the system operational and structural conditions. The simulations indicate the shunt converter of DPFC is ineffective on the apparent impedance seen by distance relay whereas the shunt converter of UPFC effects on the apparent impedance notably. The apparent impedance is influenced by the level of series voltage injected by the series converters of DPFC which installed at the mid-point. The distance relays are exposed to the malfunction, in the form of over-reaching or under-reaching. The simulation results also show that the region of under-reaching is reduced by decreasing the magnitude of the voltage injected by series converter of DPFC. It is shown that the series converter of DPFC phase angle, similar to voltage magnitude, has a noticeable impact on the distance relay. Furthermore, when the DPFC is included in the fault loop, even in case of a solid fault, the measured impedance would be deviated from its actual value. In this case, the effects of DPFC on the protective zones should be considered. An auxiliary component can be included in the distance relays to reduce the effects of DPFC on the measured impedance. This component should calculate the error in the apparent impedance ΔZ based on the output voltage of DPFC. Therefore, the actual impedance can be obtained by subtracting the calculated ΔZ from the measured impedance.

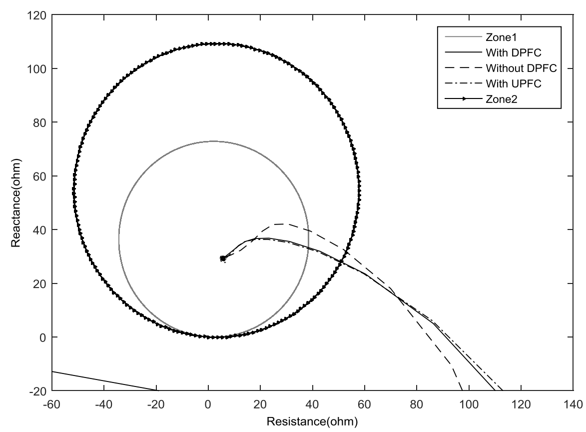


Fig. 17 Apparent impedance for an *A-G* fault is applied at 30% from relay point without fault resistance

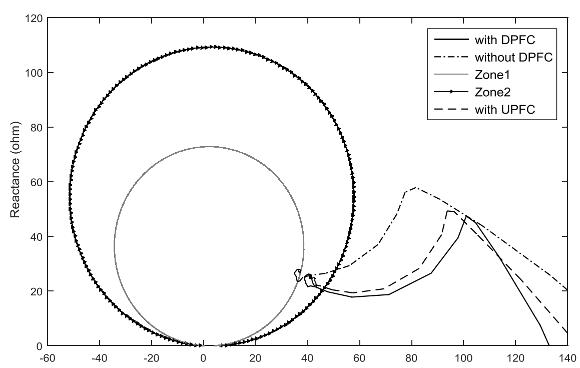


Fig. 18 Apparent impedance for an *A-G* fault is applied at 30% from relay point with fault resistance 40 ohm

7. SYMBOLS

V_{si}	voltage at bus S at the ith harmonic frequency
I_{si}	current at the ith harmonic frequency which passes over bus S
$cos\varphi_i$	power factor at the ith harmonic frequency
ΔZ	error in the apparent impedance
A	phase angle of the voltage injected by series converters of DPFC
V_{1s},V_{2s},V_{0s}	sequence of phase voltages at relay location at Bus S
$E_{1se1},E_{2se1},E_{0se1}$	sequence of phase voltages injected in line I by the series converter of DPFC
$E_{1se2},E_{2se2},E_{0se2}$	sequence of phase voltages injected in line II by the series converter of DPFC
V_{1F},V_{2F},V_{0F}	sequence of phase voltages at the fault location F
I_{1s1},I_{2s1},I_{0s1}	sequence of phase currents through line I at the relay location at Bus S
I_{1s2},I_{2s2},I_{0s2}	sequence of phase currents through line II at the relay location at Bus S
I_{1r1},I_{2r1},I_{0r1}	sequence of phase currents through line I at Bus R
Z_{1L1}, Z_{0L1}	sequence of impedances of the line I
Z_{1L2}, Z_{0L2}	sequence of impedances of the line II
Z_{1G}, Z_{1H}	positive sequence of impedance sources H and G
R_f	fault resistance
N	fault per-unit distance from the relay location

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