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A Study on Operation Zone of Distance Relay on Transmission Line Connected UPFC of KEPCO Systems

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ABSTRACT

This paper presents an apparent impedance calculation procedure for distance relaying of transmission line involving UPFC (Unified Power Flow Controller) devices between Kangjin and Jangheung of KEPCO (Korea Electric Power Cooperation) systems. The presence of UPFC significantly affects the trip boundaries that are also adversely affected by fault resistance combines with remote end infeed. Depending on the UPFC location, the trip boundary is influenced by the fault location, pre-fault condition, the arc fault resistance and the parameters of the UPFC itself (series voltage magnitude and phase angle). With the changes of these parameters, the measurement and protective range (trip boundaries) of the adaptive distance relay can also be changed. So, to analyze the operating characteristic of relaying in the power system is the most important part in the field of system protection.

This paper presents the apparent impedance calculations and the distance relay setting characteristics for faults involving the UPFC in the KEPCO systems.

1. INTRODUCTION

The use of power electronics devices to improve the power transfer capability of long transmission lines forms the basis of the concept of FACTS (Flexible AC Transmission System).

The UPFC (Unified Power Flow Controller) is a powerful device within FACTS devices, which consists of shunt and series converters. It was devised for the real-time control and dynamic compensation of AC transmission system, providing multifunctional flexibility required solving many of the problems facing the power delivery industry. As can be seen in Fig. 1, the series converter injects a series voltage of variable magnitude and phase. Besides, the shunt converter is operated so as to draw a controlled current from the transmission line. One component of this current is automatically determined by the requirement to balance the real power of the series converter. While the use of UPFC improves the power transfer capability and stability of a power system, certain other problems arise from the field of system protection in particular the transmission line.

The UPFC can be used to control the basic parameters of the transmission line, such as voltage, current, and phase angles etc. The presence of a UPFC in the fault loop affects both the steady state and transient components in the voltage and current. With the changes of these parameters, the measurement and protective range (trip boundaries) of the adaptive distance relay can also be changed. So, to analyze the operating characteristic of relaying in the power system is the most important part in the field of system protection. However, if the UPFC is not present in the system, the apparent impedance calculations of the fault are similar to the ordinary transmission line.

The 80 [MVA] UPFC is operated at the Kangjin S/S (substation) of KEPCO (Korea Electric Power Cooperation) systems, Korea, currently.

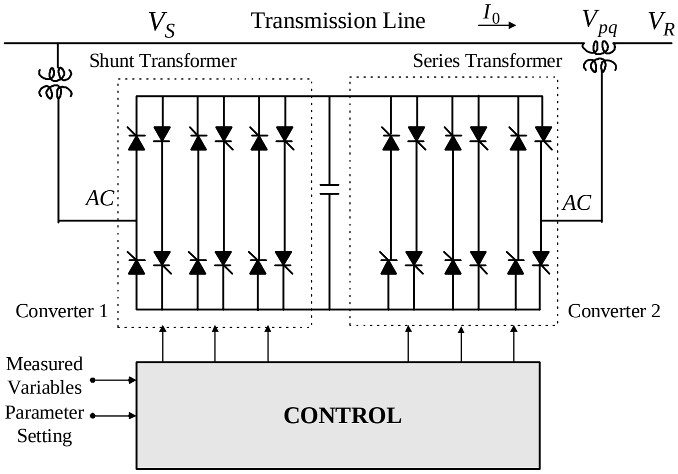

Fig. 1 System construction of UPFC

This paper presents the apparent impedance calculations and the distance relay setting characteristics for faults involving the UPFC in the KEPCO systems.

2. SYSTEM MODELING

2.1 Principles and Operating Characteristics of UPFC

The UPFC consists of two switching converters that are operated from a common DC-link provided by DC storage capacitor. In Fig. 1, Converter 2 provides the main function of UPFC by injecting an AC voltage of controllable magnitude and phase angle in series with the transmission line via a series transformer. Converter 1 is to generate or to absorb the real power demand by Converter 2 at the common DC-link [1-3].

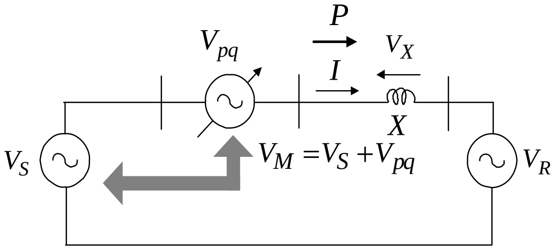

Fig. 2 Power system equivalent with UPFC

In order to investigate the capability of the UPFC to control real and reactive power flow in the transmission line, refer to Fig. 2. In this figure, V_{pq} denotes the injected compensating voltage, V_S the elementary two-bus system with sending-end voltage, V_R receiving-end voltage, δ transmission angle, and X line impedance. Fig. 3 shows vector diagram illustrating the relationship of those. Using this relation, the real and reactive power can be calculated as (1) [4-5].

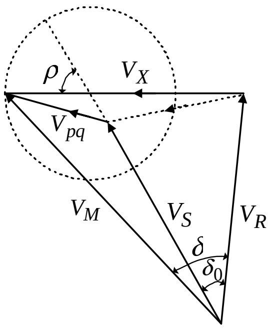

Fig. 3 Vector diagram of compensation with UPFC

$$
\begin{aligned}
P(\delta,\rho) &= \frac{V^2}{X}\sin(\delta) - \frac{V\cdot V_{pq\,max}}{X}\cos(\frac{\delta}{2}+\rho)\\
Q(\delta,\rho) &= -\frac{V^2}{X}(1-\cos(\delta)) - \frac{V\cdot V_{pq\,max}}{X}\sin(\frac{\delta}{2}+\rho)
\end{aligned}
\tag{1}
$$

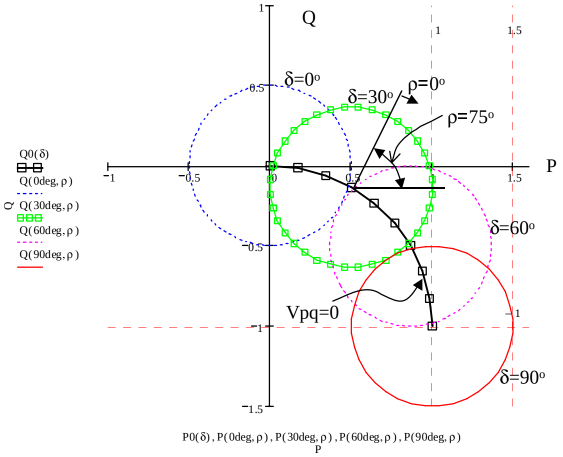

Fig. 4 Control range of UPFC

It follows from the above equations that this control region is a circle with a center defined by coordinates $P(\delta)$, $Q(\delta)$ and a radius of $V_R\cdot V_{pq}/X$. The boundary circle can be described by (2).

$$\{P(\delta,\rho)-P(\delta)\}^2+\{Q(\delta,\rho)-Q(\delta)\}^2=[\frac{V\cdot V_{pq\,max}}{X}]^2 \tag{2}$$

The circle around the origin of the $Q-P$ plane is the loci of the corresponding Q and P values, obtained as the voltage phasor V_{pq} is rotated a full revolution $(0\le\rho\le 360^o)$ with its maximum magnitude $V_{pq\,max}$ as Fig. 4 [6].

2.2 UPFC Model

An actual supply voltage in Fig. 2 is $V_s + V_{pq} = V_M$ because of the injected compensating voltage, V_{pq} of UPFC. Therefore, the voltage, V_X in line impedance X is as represent (3) [6].

$$V_X = V_S - V_R + V_{pq} = I \cdot X \tag{3}$$

In Figs. 2 and 4, the UPFC source model is obtained from (4).

$$V_{pq} = |r| \cdot e^{-j\rho} \tag{4}$$

where, r = magnitude of compensating voltage, and
ρ = phase angle of compensating voltage.

The magnitude of V_{pq} is controllable by UPFC and the angle ρ is controllable ranged from 0 to 2π. The next section will outline apparent impedance calculation procedure for KEPCO systems.

3. APPARENT IMPEDANCE CALCULATION IN TRANSMISSION LINE BETWEEN KANGJIN AND JANGHEUNG

Fig. 5 shows single equivalent diagram that involve UPFC device between Kangjin and Jangheung in KEPCO systems. The UPFC in Kangjin can be operated selective fifth mode as follows.

- Bus Voltage Control Mode by Shunt Compensator
- VAR Control Mode
- Injected Voltage Control Mode by Series Compensator
- Bus Voltage and Injected Voltage Control mode
- Real and Reactive Control Mode

Also, the following two assumptions have been taken as calculating apparent impedance seen by relay in this paper:

- UPFC is operated only by the mode of voltage compensation.
- The fault is considered A-phase line to ground (L-G) fault only.

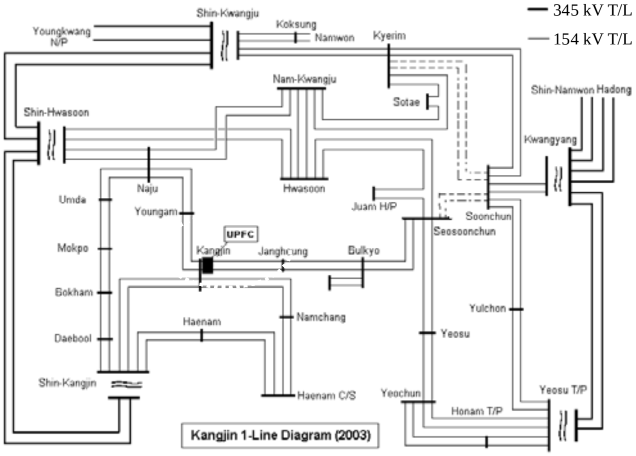

Fig. 5 The UPFC in Kangjin of KEPCO system

Distance relays are normally used to protect transmission lines. They respond to the impedance between the relay location and the fault location. However, when the faults occur, compensated voltages of UPFC change the apparent impedance seen by relay between Kangjin and Jangheung in KEPCO systems. Beside, the UPFC has series bypass circuit that consists of series CB and thyristor bypass switch in Real Time Control (RTC) board. If the faults occur in KEPCO systems, the bypass circuit must be operated for protecting the UPFC device. (See the Fig. 6)

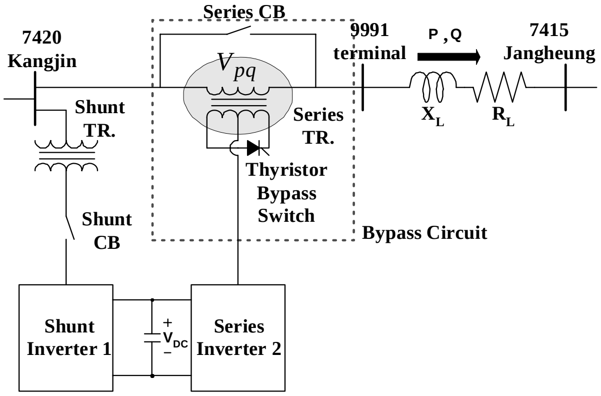

Fig. 6 Bypass circuit of UPFC system in Kangjin

Therefore, the apparent impedances seen by relay are calculated by two assumed cases in this paper. It is the first situation that the bypass circuit operates exactly for protecting UPFC when the faults occur, which are general operating situation. The second situation, that is the worst case, is that the series bypass circuit does not operate, when the faults occur, and then UPFC is operating continually. Nothing can be known how the distance relays on transmission line connected UPFC will operate, exactly.

System parameters for each case present in Fig. 7 and the Table 1. With these, apparent impedances from side A at the fault point are calculated with the two cases, respectively, where line impedance per km (Ω/km) of each transmission line between Kangjin and Jangheung is equal to each other.

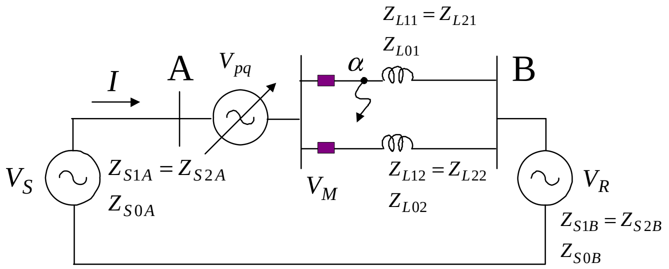

Fig. 7 UPFC system in Kangjin

Table 1 System Parameters

Z_{S1A} (Positive-sequence impedance of V_S)	1.7431+j19.424 [Ω]
Z_{S0A} (Zero-sequence impedance of V_S)	2.6147+j29.886 [Ω]
Z_{S1B} (Positive-sequence impedance of V_R)	1.7431+19.424 [Ω]
Z_{S0B} (Zero-sequence impedance of V_R)	2.6147+j29.886 [Ω]
Z_{L1} (Positive-sequence impedance of T/L)	0.03818+j0.3312 [Ω/km]
Z_{L0} (Zero-sequence impedance of T/L)	0.1604+j0.8670 [Ω/km]
α (Protection distance)	0.95 (95 %)
R_F (The fault resistance)	0~200 [Ω]
Transmission Line Length	20 [km]

3.1 Case 1 - Normal Action of Bypass Circuit in UPFC

Case 1 is the situation that the bypass circuit operates exactly for protecting UPFC for the fault, which means general operating situation. If the fault occurred at the upper transmission line (T/L) of Fig. 7, that T/L can be represented as Fig. 8 in this case [7-8].

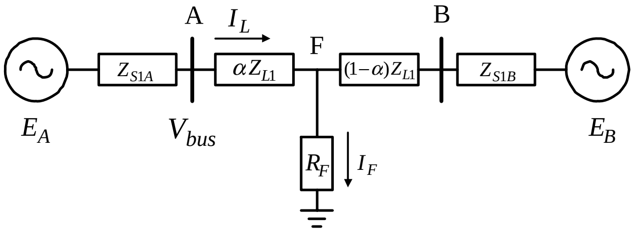

Fig. 8 Single phase-ground fault of circuit model

For an A-phase L-G fault, if the bypass circuit in RTC board of UPFC operates normally, the apparent impedance is calculated by traditional mathematical method [9].

As can be seen in Fig. 8, if the fault occurs at a point F, the apparent impedance seen by distance relay at A is obtained using (5). The apparent impedance in this case is considered line impedance in addition to leakage reactance of series transformer of UPFC.

$$Z_A = \frac{V_A}{I_A + k_0 \cdot 3I_0} \tag{5}$$

where, k_0 = $(Z_{L0} - Z_{L1}) / 3 \cdot Z_{L1}$,the zero-sequence compensating factor,
Z_A = line impedance at A-phase,
I_A = current of A-phase at the relay location,
V_A = voltage of A-phase at the relay location,
Z_{L0} = the zero-sequence impedance of T/L at the relay location, and
Z_{L1} = the positive-sequence impedance of T/L at the relay location.

The calculated results are shown Fig. 9 in this case. Zone 1 and 2 represent the conventional trip boundaries of relay in Fig. 9. Also, Optimal Zone 1 and 2 represent the calculated trip boundary using (5) that is considered leakage reactance of series transformer of UPFC.

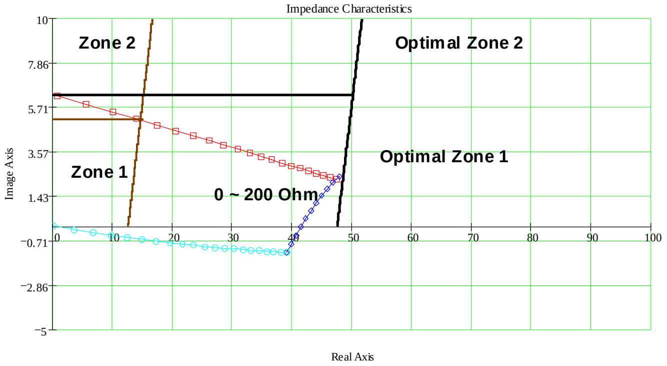

Fig. 9 Distance relay's trip boundary of A-phase ground fault

As can be seen result, the conventional installed relay's trip boundary, which set up conventional setting values, is over-reach. Therefore, it must be set up optimal zone 1 and 2 in this case.

3.2 Case 2 - Abnormal Action of Bypass Circuit in UPFC

Case 2 is the worst case, because if the series bypass circuit does not operate when the faults occur, then UPFC compensate continually in KEPCO systems. There is nothing to be known how the installed distance relays on transmission line connected UPFC will operate exactly. In this point of view, the apparent impedance seen by distance relay is studied on this case.

Parameters for calculation also are presented in the Table 1 and Fig. 7, where UPFC in KEPCO systems is located in front of terminal (9991) in Fig. 6. Therefore, the voltage of terminal (9991) is expressed as (6).

$$V_M = V_S + V_{pq} \tag{6}$$

The voltage phasor between terminal (9991) and Jangheung (7415) is expressed as (7), and phasor of correlation equation between Kangjin (7420) and Jangheung (7415) is presented in as (8).

$$H(h,\delta) = |h| \cdot e^{-j\delta} \tag{7}$$

$$V_R = [H(h,\delta)] \cdot V_M \tag{8}$$

The maximum voltage drop is 0.02 [PU], and angle difference is 30^o between Kangjin and Janghenug from EMS data of KEPCO, respectively. Therefore, h is calculated 0.98, and δ in (7). Also, the apparent impedance seen by relay in this case is calculated in case of an A-phase L-G fault of upper T/L by the above assumptions.

In the Fig. 7, if the fault occurs at a point , the positive- and negative-sequence impedance seen by relay at A (Kangjin) are obtained as (9).

$$\begin{aligned} Z_{1A}(\alpha) = Z_{2A}(\alpha) = Z_{S1A} + \alpha \cdot Z_{L1} \\ Z_{1B}(\alpha) = Z_{2B}(\alpha) = Z_{S1A} + (1-\alpha) \cdot Z_{L1} \end{aligned} \tag{9}$$

Current I_L, from Kangjin to Jangheung before the fault, is expressed as (10).

$$I_L = \frac{V_S - V_R}{Z_{1A}(\alpha) + Z_{1B}(\alpha)} \tag{10}$$

Also, load current in the upper T/L between terminal (9991) and Jangheung before the fault is calculated as (11).

$$I = \frac{V_M - V_R}{Z_{1A}(\alpha) + Z_{1B}(\alpha)} \tag{11}$$

Voltage at a point α before the fault is obtained as (12).

$$V_{AFD} = V_M - I \cdot Z_{1A}(\alpha) \tag{12}$$

The total sequence impedance before the fault is represented as follows:

$$Z_T = \frac{2 \cdot Z_{1A}(\alpha) \cdot Z_{1B}(\alpha)}{Z_{1A}(\alpha) + Z_{1B}(\alpha)} + \frac{Z_{0A}(\alpha) \cdot Z_{0B}(\alpha)}{Z_{0A}(\alpha) + Z_{0B}(\alpha)} \tag{13}$$

Therefore, the positive-sequence fault current at a point α calculated as (14), and the positive-, negative- and zero-sequence current from Kangjin to Jangheung at the fault are expressed as (15), respectively.

$$I_{1F} = \frac{V_{AFD}}{Z_T + 3 \cdot R_F} \tag{14}$$

$$\begin{aligned} I_{1A} &= I_{2A} = \frac{C_1(\alpha) \cdot V_{AFD}}{Z_T + 3 \cdot R_F} \\ I_{0A} &= \frac{C_0(\alpha) \cdot V_{AFD}}{Z_T + 3 \cdot R_F} \end{aligned} \tag{15}$$

where, $C_1(\alpha) = \dfrac{Z_{1B}(\alpha)}{Z_{1A}(\alpha) + Z_{1B}(\alpha)}$

$C_0(\alpha) = \dfrac{Z_{0B}(\alpha)}{Z_{0A}(\alpha) + Z_{0B}(\alpha)}$

Finally, the total fault current and voltage between Kangjin and Jangheung are obtained as (16) and (17), respectively.

$$I_{AB} = I + 2 \cdot I_{1A} + I_{0A} \tag{16}$$

$$\begin{aligned} V_{AB} = 3 \cdot I_{1F} \cdot R_F &+ \{(I + I_{1A}) \cdot Z_{L1}(\alpha) \\ &+ I_{2A} \cdot Z_{L1}(\alpha) + I_{0A} \cdot Z_{L0}(\alpha) \end{aligned} \tag{17}$$

The apparent impedance by seen distance relay of Kanjin side presents as (18).

$$Z_{AB} = \frac{V_{AB}}{I_{AB} + k_n \cdot 3 \cdot I_{0A}} \tag{18}$$

where, $k_n = \dfrac{Z_{L0} - Z_{L1}}{3 \cdot Z_{L1}}$ (the zero-sequence compensating factor).

Similarly, the apparent impedance seen by distance relay of Jangheung side is calculated using the same method described above.

4. SIMULATION RESULTS

Trip boundary of distance relay on transmission line connected UPFC in KEPCO systems at the fault is simulated using (18).

Fig. 10 shows the vector diagram about load currents variation vs. compensation of UPFC ($r = 0 \sim 0.5$ [PU]). If the angle of each bus is 30^o, angle of current can be changed from $+60^o$ to -60^o by UPFC as can be seen in Fig. 10. Therefore, these affect the distance relay, and then the relay will operates abnormally.

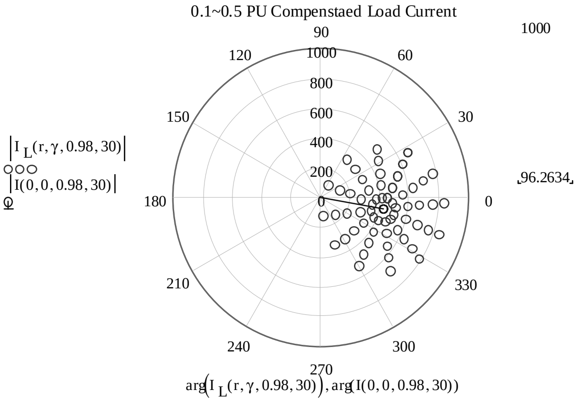

Fig. 10 Load current's variation from r=0.1 [PU] to r=0.5 [PU]

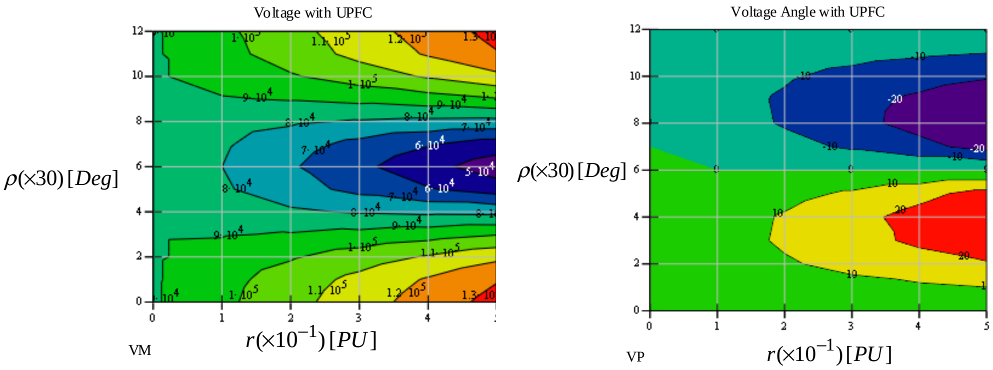

Fig. 11 Voltage's magnitude and angle after compensation

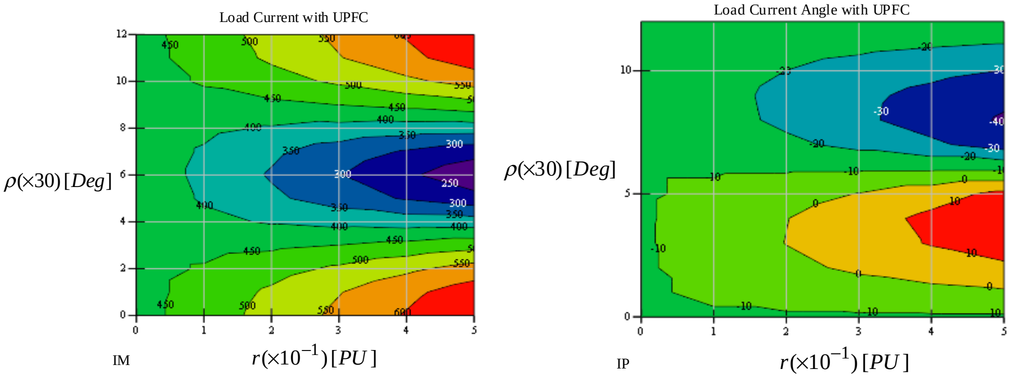

Fig. 12 Current's magnitude and angle after compensation

Similarly, Fig. 12 represents the magnitude and angle of load current after compensation, respectively. In the Fig. 12, the maximum load current is $\angle V_{pq} = 0^o$, and if the magnitude of compensating voltage is 240^o, the angle of load current is changed suddenly. Therefore, this situation affects operation of the distance relay.

Thereafter, the distance relay will over-reach or under-reach in this case. The calculated trip boundaries seen by the relay are shown from Fig. 13 to Fig. 16 about compensation of UPFC.

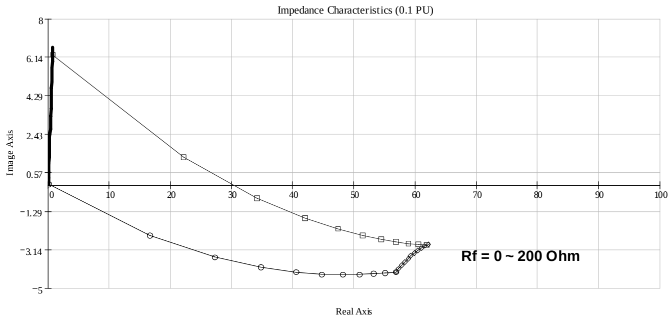

Fig. 13 Trip boundary at $r = 0.1, \rho = 0^o$

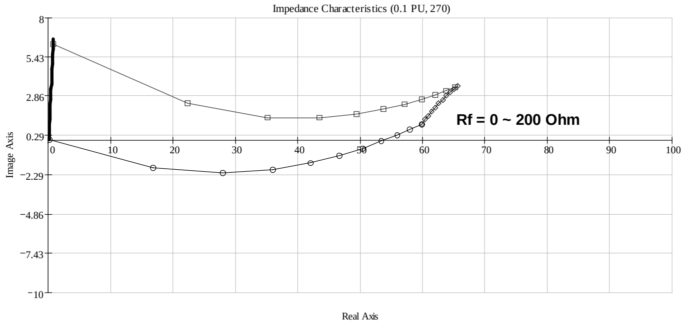

Fig. 14 Trip boundary at $r = 0.1, \rho = 270^o$

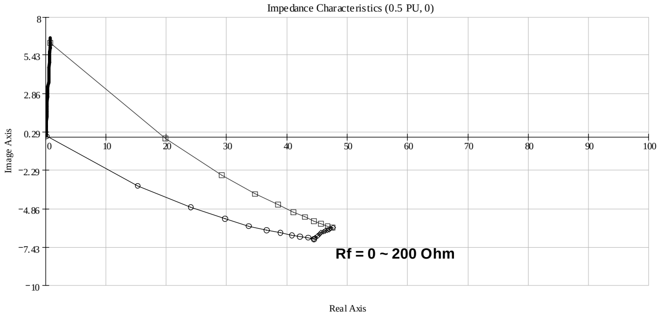

Fig. 15 Trip boundary at $r = 0.5, \rho = 0^o$

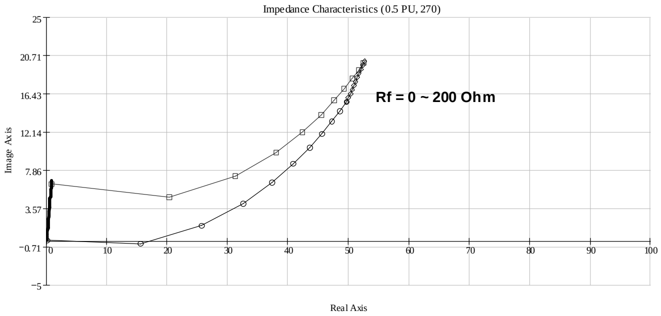

Fig. 16 Trip boundary at $r = 0.5$, $\rho = 270^{o}$

As can be seen in the above results, trip boundaries of the distance relay are changed by UPFC between Kangjin and Jangheung in KEPCO systems. The relay either over-reaches or under-reaches in accordance with the values of r and ρ of the UPFC, which are varied between 0~0.5 [PU], and $0 \sim 270^{o}$, respectively.

5. CONCLUSIONS

The apparent impedances seen by relay are calculated for two cases in this paper. The paper clearly shows that the UPFC parameters between Kangjin and Jangheung influence the trip boundaries significantly in addition to the fault resistance and hence the distance relay may be that the relay over-reaches or under-reaches, depending on the value of the fault impedance with compensation of the UPFC in KEPCO systems.

Therefore, adaptive setting of the distance relay is required for tripping boundaries on transmission line connected UPFC.

6. REFERENCES

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