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M. Tech
Project
Report

ADAPTIVE DISTANCE RELAY SETTING FOR TRANSMISSION LINES IN PRESENCE OF UPFC AND WIND FARMS

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Thesis submitted to

National Institute of Technology, Rourkela

For the award of the degree

Of

Master of Technology

In Electrical Engineering with Specialization

In “Power Control & Drives”

By

Rahul Kumar Dubey

DEPARTMENT OF ELECTRICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

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Thesis submitted in partial fulfillment of the requirements for the award of the Master of Technology in Electrical Engineering with Specialization in " Power Control and Drives"

By

Rahul Kumar Dubey

Roll No: 210EE2102

May-2012

Under the guidance of

Prof. B.Chitti Babu

Electrical Engineering

National Institute of Technology

Rourkela-769008

To my family & teachers

Department of Electrical Engineering
National Institute of Technology, Rourkela
Odisha, INDIA – 769 008

CERTIFICATE

This is to certify that the thesis titled "**Adaptive Distance Relay Setting For Transmission Lines in Presence Of UPFC and Wind Farms**", by Mr. Rahul Kumar Dubey, Roll No. 210EE2102 submitted to the National Institute of Technology, Rourkela for the degree of Master of Technology in Electrical Engineering with Specialization in " Power Control and Drives", is a record of bona fide research work, carried out by him in the department of Electrical Engineering under my supervision. I believe that the thesis fulfills part of the requirements for the award of degree of Master of Technology in Power Control and Drives.The results embodied in the thesis have not been submitted for award of any other degree.

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DECLARATION

I certify that

a. The work contained in this report is original and has been done by me under the guidance of my supervisor.

b. The work has not been submitted to any other Institute for any degree or diploma.

c. I have followed the guidelines provided by the Institute in preparing the report.

d. I have conformed to the norms and guidelines given in the Ethical Code of Conduct of the Institute.

e. Whenever I have used materials (data, theoretical analysis, figures, and text) from other sources, I have given due credit to them by citing them in the text of the report and giving their details in the references.

f. Whenever I have quoted written materials from other sources, I have put them under quotation marks and given due credit to the sources by citing them and giving required details in the references.

Signature of the Student

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RAHUL KUMAR DUBEY

CONTENT

ABBREVIATIONS

E_{aw}	Wind Source voltage
E_{an}	Grid voltage
V_{aw}	Voltage at bus 'w' where the relay is present
V_{an}	Voltage at bus 'n'
V_{as1} & V_{as2}	Voltage at two ends of UPFC i.e. at bus s1 & s2
E_{sh}	Shunt voltage of UPFC
$re^{j\theta}$	A factor for series voltage of UPFC
h_1	Voltage amplitude ratio.
δ_1	Power transfer angle.
K_0	Zero sequence compensating factor.
Z_{1sw}	Positive sequence source impedance of wind farm
Z_{0sw}	Zero sequence source impedance of wind farm
Z_{1sn}	Positive sequence source impedance of grid
Z_{0sn}	Zero sequence source impedance of grid
Z_{1wn}	Positive sequence impedance of line between bus w & n
Z_{0wn}	Zero sequence impedance of line between bus w & n
Z_{1ws1}	Positive sequence impedance of line between bus w & s1
Z_{0ws1}	Zero sequence impedance of line between bus w & s1
Z_{1ns1}	Positive sequence impedance of line between bus n & s1
Z_{0ns1}	Zero sequence impedance of line between bus n & s1
Z_{1wf}	Positive sequence impedance of line between bus w & fault point f
Z_{0wf}	Zero sequence impedance of line between bus w & fault point f
Z_{1nf}	Positive sequence impedance of line between bus n & fault point f
Z_{0nf}	Zero sequence impedance of line between bus n & fault point f
Z_{1s1f}	Positive sequence impedance of line between bus s1 & fault point f

Z_{0s1f}	Zero sequence impedance of line between bus s1 & fault point f
$Z_{\sum}$	Sum of total positive-, negative-, and zero-sequence impedances
A	Stands for a-phase as the calculations are for line-to-ground fault condition.
1	Stands for positive sequence.
0	Stands for zero sequence.

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Abstract

This thesis presents an adaptive distance relay setting for transmission lines with Unified Power Flow Controller (UPFC) and wind farms together. The ideal trip characteristics of distance relay is greatly affected in presence of UPFC in transmission lines as the apparent impedance is significantly affected. Similarly, the reach setting of the relay for the lines connecting wind farms is significantly affected as the relay end voltage fluctuates continuously. Thus, the proposed study focus on developing adaptive relay setting for transmission lines including both UPFC and wind farms considering variations in operating conditions of UPFC as well as wind farms together.

Chapter-1

Introduction

The introduction of Flexible AC Transmission System (FACTS) [1] controllers in the power system opens up new challenges to the line protection as they change the impedance of the lines dynamically. Consequently, distance relays, in the associated transmission system, will have an overreaching or under reaching effect depending on the control modes of the FACTS controllers. Hence, determining the boundaries of operation of a distance relay, adaptively in the presence of FACTS controllers, is a challenging task.

1.1 Research Motivation

There is a strong motivation to devise adaptive relay setting of the distance relay including UPFC and Wind Farms together. In the proposed study, the adaptive relay setting of the transmission line is developed and, the impacts of UPFC and wind farm on the same are considered. The proposed approach calculates the correct impedance to the fault point including wide variation in system parameters in UPFC such as degree of compensation, power transfer angle, fault resistance and fault location, at different wind penetration level with variation in different loading levels, source impedance, voltage amplitude, frequency . The method uses relaying end voltage and current information, and thus easier to implement. In current study, only Line-Ground fault is considered and the same can be extended for other types of fault situations as well.

1.2 Research Background

The operation of transmission lines including FACTs [1-2] devices such as UPFC [3-4] has attracted wide spread attraction as it improves the power transfer capability in long transmission lines. On the other hand, introduction of UPFC opens up new challenges as the apparent impedance of the lines is changed dynamically. Thus, the reach setting of the relay is significantly affected depending upon the modes of operation of the FACTs controller. Protection measures for transmission lines have been proposed including different FACTs controllers [5-8].The effect of UPFC location and fault resistance on the adaptive setting is

Clearly devised [5] for distance relay operation. A more extensive study has been carried out [7-8] considering a detailed model of UPFC.

P.K.Dash *et al.* [5] presented the apparent impedance calculations and the distance relay setting characteristics for faults involving the UPFC and the ones that exclude the UPFC. However, if the UPFC is located at the sending end of the line, the UPFC will be always present in the fault loop and will influence the relay-setting characteristic. The effects of the presence of the earth fault resistance, the UPFC control parameters, and the in feed from both the ends on the distance relay apparent impedance characteristics are also highlighted in this article. It is envisaged that these characteristics will be required to adapt the relay settings in the presence of UPFC for different made transmission line operating conditions.

In recent K. Seethalekshmi *et al.* [13] presented a scheme to predict the trip boundaries of a conventional distance relay in the presence of UPFC through the knowledge of the control parameters of the UPFC. It computes the series voltage and reactive current injection by the UPFC on-line with the help of synchronized phasor measurements [14] and these parameters are utilized in the adaptive trip boundary prediction. Additionally, the scheme also considers the fact that depending on the magnitude of the fault current, the UPFC may change its status to bypass operating mode [5], where series voltage injection is zero.

Similarly, the integration of wind farms in power system is increasing day by day to larger extent. The most difficult part in wind farm is the uncontrolled wind speed, leading to voltage and frequency fluctuation. Thus, the protection issues become critical as the transmission lines connecting wind farms are subjected to continuously changing environment. Adaptive protection schemes for distribution systems including wind source have been proposed in [10-11]. The adaptive relay setting for transmission lines including wind farm is proposed in [12] and the effect of variations in wind farm parameters on the reach setting is extensively studied. It is observed that the trip boundaries of the relay is significantly affected when the loading level, source impedance, voltage level, frequency etc. varies.

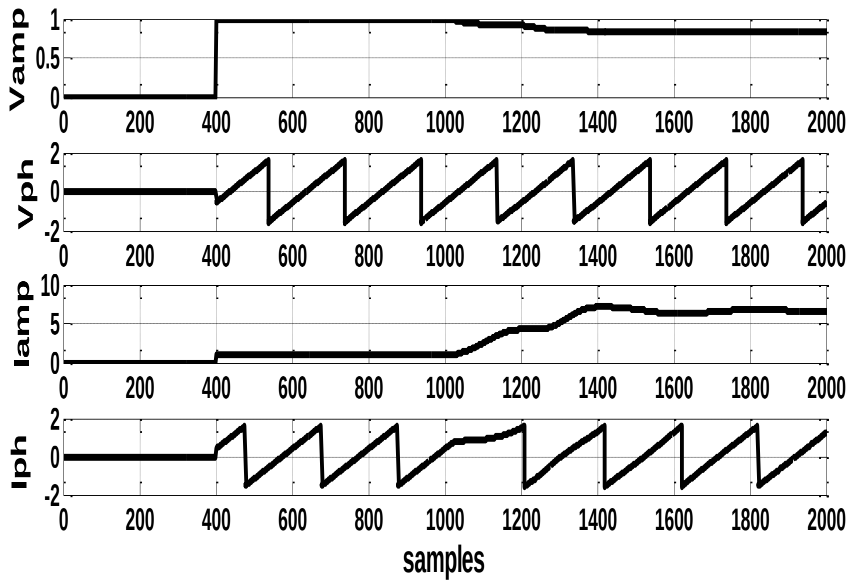

Fig.1.1 DFT based estimation of current and voltage of plane Transmission line including UPFC

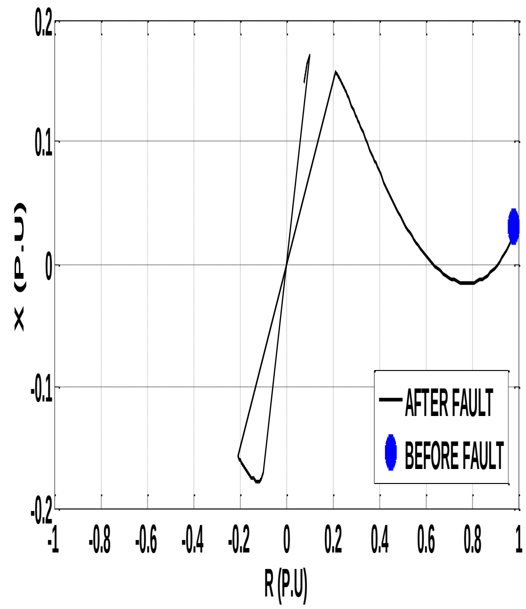

Fig.1.2 R-X trajectory for fault before UPFC.

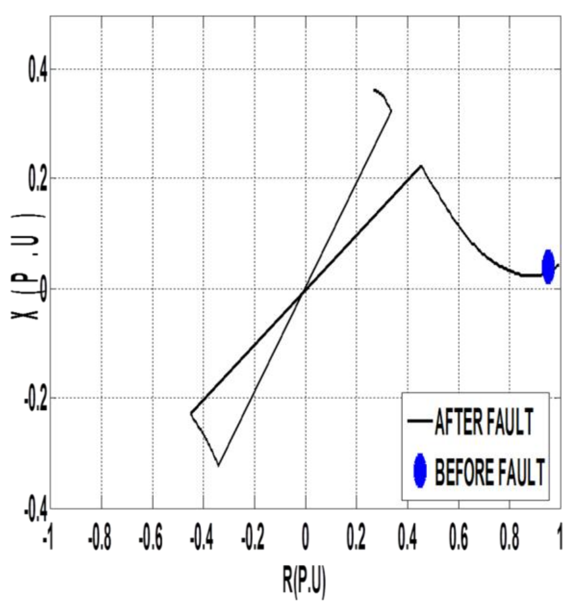

Fig.1.3 R-X trajectory for fault after UPFC.

1.3 Objectives of the Thesis

In the proposed study, the adaptive relay setting of the transmission line is developed and, the impacts of UPFC and wind farm on the same are considered. The proposed approach calculates the correct impedance to the fault point including wide variation in system parameters in UPFC such as degree of compensation, power transfer angle, fault resistance and fault location, at different wind penetration level with variation in different loading levels, source impedance, voltage amplitude, frequency.

The main objectives of the thesis are to:

1. System Studied and Apparent impedance calculation including wind farm and UPFC
2. Derivation of Apparent Impedance calculation for Fault before UPFC.
3. Derivation of Apparent Impedance calculation for Fault after UPFC.
4. Generating tripping boundaries for different condition using MATLAB coding & Simulink.
   (i) Variation in Wind farm parameters with no-effect of UPFC.
   (ii) Variation in UPFC parameters with Wind farm parameters kept unchanged
   (iii) Combined effect of Wind farm and UPFC

1.4 Thesis Organization

The thesis is organized as follows

Chapter-1

Chapter-1 gives a brief introduction of the problem associated with the adaptive distance relay setting for transmission lines, both in presence of UPFC and wind farms. The present status of available techniques and the limitations are discussed. The objectives and contributions of the thesis are highlighted.

Chapter-2

Chapter-2 focuses on system studied and apparent impedance calculation including wind farm and UPFC. The proposed research uses derivation of apparent impedance calculation for fault before UPFC and derivation of apparent impedance calculation for fault after UPFC.

Chapter-3

Chapter-3 focuses on results and analysis of the proposed research work.

Chapter-4

This chapter provides comprehensive summary and conclusions of proposed research work done.

Chapter-2

System studied and apparent impedance calculation including wind farm and UPFC

This chapter focuses on system studied and apparent impedance calculation including wind farm and UPFC. The proposed research uses derivation of apparent impedance calculation for fault before UPFC and derivation of apparent impedance calculation for fault after UPFC.

2.1 Schematic diagram of the system and corresponding equivalent model

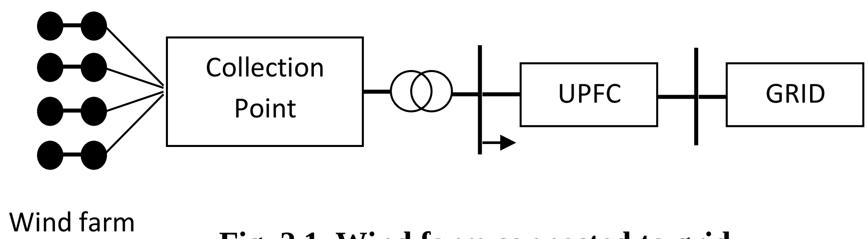

Fig. 2.1. Wind farm connected to grid

The system studied in the proposed application includes wind farms and UPFC both connected to the power transmission system. Numbers of wind generating units are connected together at one end of the transmission line as shown in Fig.2.1. At the same time the UPFC is place in between the transmission line. Line-ground fault is analyzed and corresponding apparent impedance is calculated for fault including UPFC (after UPFC) and not including UPFC (BEFORE UPFC) as follows. The equivalent circuit model is as shown in Fig. 2.2.

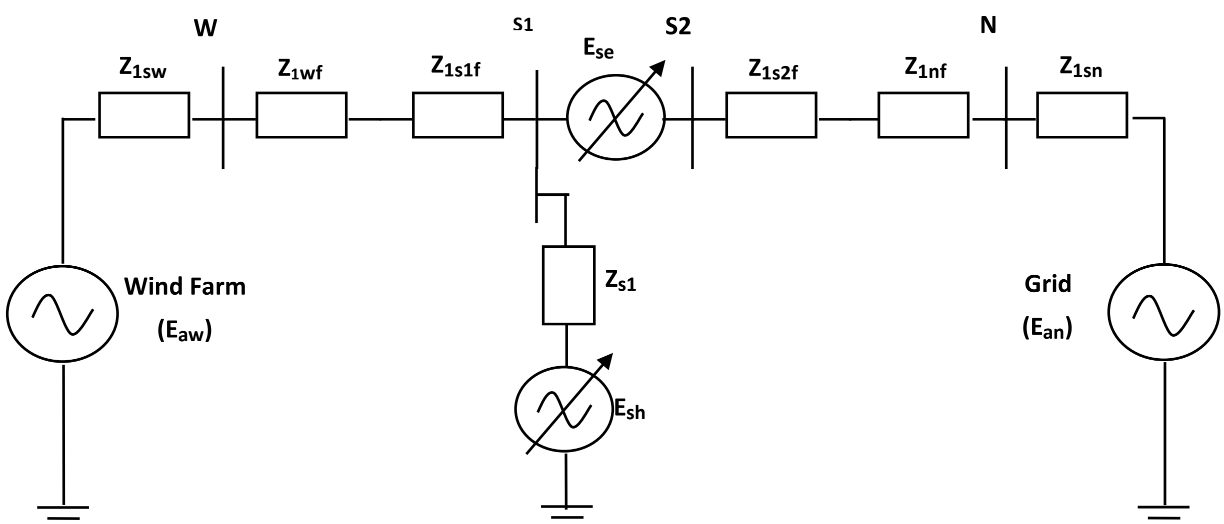

Fig. 2.2. Transmission system with Wind farm & UPFC

Considering the aforementioned transmission line network with UPFC and wind farm, the calculation for apparent impedance for fault before UPFC and after UPFC is carried out.

2.2. **Apparent impedance calculation for fault before UPFC**

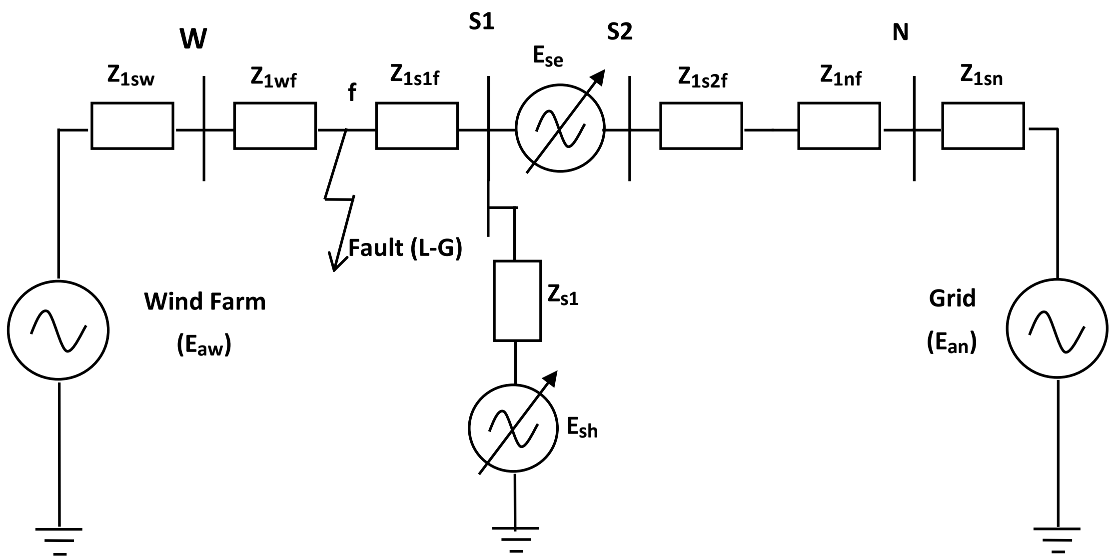

Fig. 2.3. System under study for fault before UPFC

The line diagram of the power system for line-ground fault before UPFC is considered at *f* through a fault resistance R_f shown in Fig. 2.3. The voltage and current information are retrieved at the relaying point at 'W '.

The apparent impedance measured at 'W' for fault occurring at 'f' (before UPFC) is obtained as

$$Z_{APP} = \frac{V_{aw}}{I_{aw} + K_0 I_{0w}}$$

$$= \frac{I_{1wf}Z_{1wf} + I_{2wf}Z_{2wf} + I_{0wf}Z_{0wf} + I_{ld}Z_{1wf} + 3R_f I_{0f}}{I_{1wf} + I_{2wf} + I_{0wf} + I_{ld} + K_0 I_{0wf}}$$

$$= Z_{1wf} + \frac{I_{0wf}Z_{0wf} + 3R_f I_{0f} - I_{0wf}Z_{1wf} - K_0 I_{0wf} Z_{1wf}}{I_{1wf} + I_{2wf} + I_{0wf} + I_{ld} + K_0 I_{0wf}} \text{.......(1)}$$

Where,

$$I_{1wf} = G_1 I_{0f} \text{.....(2)}$$

$$I_{2wf} = G_2 I_{0f} \text{.....(3)}$$

$$I_{0wf} = G_0 I_{0f} \text{.....(4)}$$

$$I_{ld} = G_{ld} I_{0f} \text{.....(5)}$$

$$G_1 = G_2$$

As positive sequence impedance is equals to negative sequence impedance

$$K_0 = \frac{Z_{0wn} - Z_{1wn}}{Z_{1wn}} = \frac{Z_{0wf} - Z_{1wf}}{Z_{1wf}} \text{.......(6)}$$

$$G_1 = \frac{Z_{1snf}}{Z_{1swf} + Z_{1snf}} \text{...(7)}$$

$$G_0 = \frac{Z_{0snf}}{Z_{0swf} + Z_{0snf}} \text{...(8)}$$

Where,

G_1 = positive sequence distribution factors.

G_0 = zero sequence distribution factors.

The pre-fault voltage at 'W'

$$V_{afd} = E_{aw} - Z_{1swf} I_{ld} \text{............................(9)}$$

Where V_{afd} is the a-phase voltage at the fault point and I_{ld} is pre-fault current in the line.

Now

$$\frac{V_{as1}}{E_{aw}} = h_1 e^{-j\delta_1}$$

$$I_{ld} = \frac{E_{aw} - V_{as1}}{Z_{1swf} + Z_{1s1f}} = \frac{E_{aw}\left(1 - h_1 e^{-j\delta_1}\right)}{Z_{1swf} + Z_{1s1f}} \quad \text{.................(10)}$$

$$\mathrm{V_{afd}} = \left(3\mathrm{R_f} + \mathrm{Z_\Sigma}\right)\mathrm{I_{0f}}$$

From Eq. (9)

$$E_{aw} - Z_{1swf}\,\frac{E_{aw}\left(1 - h_1 e^{-j\delta_1}\right)}{Z_{1swf} + Z_{1s1f}} = \left(3R_f + Z_\Sigma\right)I_{0f} \quad \text{............(11)}$$

$$E_{aw} = \frac{\left(3R_f + Z_\Sigma\right)I_{0f}\left(Z_{1swf} + Z_{1s1f}\right)}{\left(Z_{1s1f} + Z_{1swf} h_1 e^{-j\delta_1}\right)} \quad \text{.........................(12)}$$

Substituting (12) in (10) we get

$$I_{ld} = G_{ld} I_{0f} \quad \text{..(13)}$$

Where

$$G_{ld} = \frac{\left(3R_f + Z_\Sigma\right)\left(1 - h_1 e^{-j\delta_1}\right)}{\left(Z_{1s1f} + Z_{1swf} h_1 e^{-j\delta_1}\right)} \quad \text{.....................................(14)}$$

Substituting Eq. (2), (3), (4) in (1)

$$Z_{APP} = Z_{1wf} + \frac{3R_f}{G_{ld} + 2G_1 + G_0(1 + K_0)} \quad \text{...........................(15)}$$

$$\Delta Z = \frac{3R_f}{G_{ld} + 2G_1 + G_0(1+K_0)} \text{...(16)}$$

2.3. Apparent impedance calculation for fault after UPFC

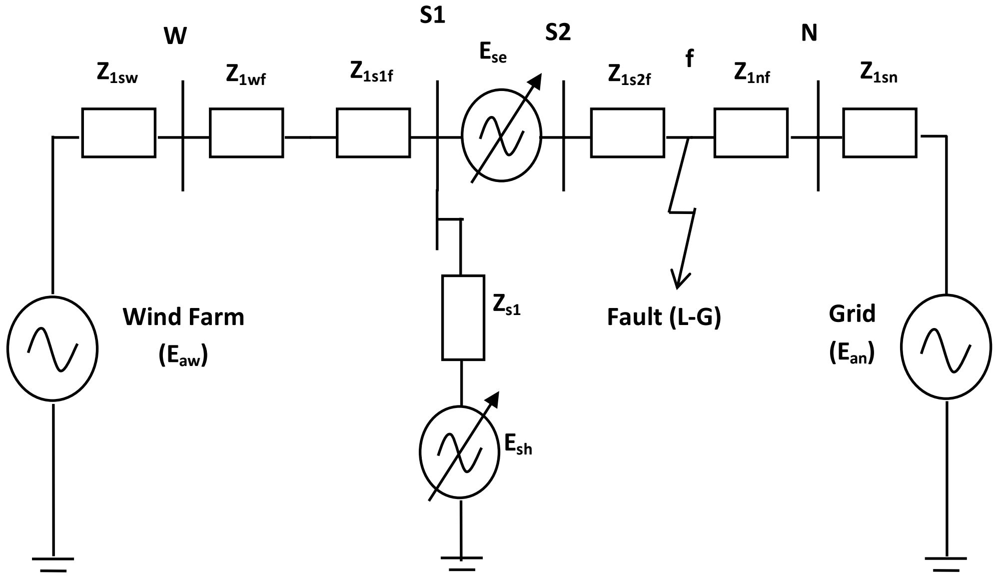

Fig. 2.4. System under study for fault after UPFC

The line diagram of the power system for line-ground fault after UPFC is considered at *f* through a fault resistance R_f shown in Fig. 2.4. The voltage and current information are retrieved at the relaying point at 'W '.

The pre-fault voltage at S_2 is related to voltage at S_1 as follows

$$V_{as2} = \left(1 + re^{j\theta}\right)V_{as1} = \frac{V_{as1}}{C_{s1}} \text{..........(17)}$$

Where

$$C_{s1} = \frac{1}{1 + re^{j\theta}}$$

$$V_{as2} = V_f + \lfloor I_{1wf} Z_{1s1f} + I_{2wf} Z_{2s1f} + I_{0wf} Z_{0s1f} + I_{ld'} Z_{1s1f} \rfloor \text{........}(18)$$

$$V_{aw} = V_{as1} + \lfloor I_{1wf} Z_{1ws1} + I_{2wf} Z_{2ws1} + I_{0mf} Z_{0ws1} + I_{ld} Z_{1ws1} \rfloor \text{..........}(19)$$

But,

$$V_{as1} = C_{s1} V_{as2}$$

Thus,

$$V_{aw} = C_{s1} \left(V_f + \lfloor I_{1wf} Z_{1s1f} + I_{2wf} Z_{2wf} + I_{0wf} Z_{0s1f} + I_{ld'} Z_{1s1f} \rfloor \right) + \lfloor I_{1wf} Z_{1ws1} + I_{2wf} Z_{2ws1} + I_{0wf} Z_{0ws1} + I_{ld} Z_{1ws1} \rfloor \text{..................................}(20)$$

$$Z_{APP} = \frac{V_{aw}}{I_{aw} + K_0 I_{0w}}$$

$$= \frac{C_{s1} \left(V_f + \lfloor I_{1wf} Z_{1s1f} + I_{2wf} Z_{2s1f} + I_{0wf} Z_{0s1f} + I_{ld'} Z_{1s1f} \rfloor \right) + \lfloor I_{1wf} Z_{1ws1} + I_{2wf} Z_{2ws1} + I_{0wf} Z_{0ws1} + I_{ld} Z_{1ws1} \rfloor}{I_{1wf} + I_{2wf} + I_{0wf} + I_{ld} + K_0 I_{0w}}$$

$$= \left(Z_{1ws1} + C_{s1} Z_{1s1f} \right) + \frac{C_0 \lfloor \left(Z_{0ws1} + C_{s1} Z_{0s1f} \right) - \left(Z_{1ws1} + C_{s1} Z_{1s1f} \right) (1 + K_0) \rfloor + C_{s1} \lfloor Z_{1s1f} \left(G_{ldd} - G_{ld} \right) + 3R_f \rfloor}{G_{ld} + 2G_1 + G_0 (1 + K_0)} \text{.....}(21)$$

Now the pre-fault current I_{ld} can be obtained as

$$I_{ld} = \frac{E_{aw} - V_{as1}}{Z_{1sw} + Z_{1ws1}} = \frac{E_{aw} \left(1 - h_1 e^{-j\delta_1} \right)}{Z_{1sws1}} \text{..}(22)$$

$$I_{s1} = \frac{V_{as1} - E_{sh}}{Z_{s1}} = \frac{E_{aw} h_1 e^{-j\delta_1} - E_{sh}}{Z_{s1}} \text{..}(23)$$

$$V_{afd} = V_{as2} - Z_{1s1f} I_{ld'} \text{...}(24)$$

$$\text{or. } \left(3R_f + Z_\Sigma\right) I_{0f} = \frac{V_{as1}}{C_{s1}} - Z_{1s1f}\left(I_{ld} - I_{s1}\right)$$

$$\text{or, } \left(3R_f + Z_\Sigma\right) I_{0f} = \frac{E_{aw} h_1 e^{-j\delta_1}}{C_{s1}} - Z_{1s1f}\left[\frac{E_{aw}\left(1 - h_1 e^{-j\delta_1}\right)}{Z_{1sws1}} - \frac{E_{aw} h_1 e^{-j\delta_1} - E_{sh}}{Z_{s1}}\right]$$

$$\left(3R_f + Z_\Sigma\right) I_{0f} = E_{aw} h_1 e^{-j\delta_1} Z_{1s1f}\left[\frac{1}{C_{s1} Z_{1s1f}} - \frac{1 - h_1 e^{-j\delta_1}}{h_1 e^{-j\delta_1} Z_{1sws1}} + \frac{1}{Z_{s1}} - \frac{1}{Z_{s1} I_{aw} h_1 e^{-j\delta_1}}\right]$$

$$\text{Or, } E_{aw} h_1 e^{-j\delta_1} = V_{as1} = \frac{-\left(3R_f + Z_\Sigma\right) I_{0f}}{Z_{1s1f}\left[-\frac{1}{C_{s1} Z_{1s1f}} + \frac{1 - h_1 e^{-j\delta_1}}{h_1 e^{-j\delta_1} Z_{1sws1}} - \frac{1}{Z_{s1}} + \frac{1}{Z_{s1} I_{aw} h_1 e^{-j\delta_1}}\right]}$$

$$= \frac{-\left(3R_f + Z_\Sigma\right) I_{0f}}{Z_{1s1f}\left[-\frac{1}{C_{s1} Z_{1s1f}} + \frac{1 - h_1 e^{-j\delta_1}}{h_1 e^{-j\delta_1} Z_{1sws1}} - \frac{1}{Z_{s1}} + \frac{1}{Z_{s1} C_{sh}}\right]}$$

$$= G_{vs1} I_{0f} \text{...}(25)$$

Where,

$$G_{vps1} = \frac{-\left(3R_f + Z_\Sigma\right)}{Z_{1s1f}\left[-\frac{1}{C_{s1} Z_{1s1f}} + \frac{1 - h_1 e^{-j\delta_1}}{h_1 e^{-j\delta_1} Z_{1sws1}} - \frac{1}{Z_{s1}} + \frac{1}{Z_{s1} C_{sh}}\right]} \text{.................................}(26)$$

$$V_{as1} = E_{aw} h_1 e^{-j\delta_1} = C_{vs1} I_{0f} \text{...}(27)$$

Or, $$E_{aw} = \frac{G_{vs1} I_{0f}}{h_1 e^{-j\delta_1}}$$

$$I_{ld} = \frac{E_{aw}\left(1 - h_1 e^{-j\delta_1}\right)}{Z_{1sws1}} = \frac{G_{vs1} I_{0f}}{h_1 e^{-j\delta_1}} \frac{\left(1 - h_1 e^{-j\delta_1}\right)}{Z_{1sws1}} \quad \text{......(28)}$$

$$I_{ld} = G_{ld} I_{0f} \quad \text{......(29)}$$

Where,

$$G_{ld} = \frac{G_{vs1}}{h_1 e^{-j\delta_1}} \frac{\left(1 - h_1 e^{-j\delta_1}\right)}{Z_{1sws1}} \quad \text{......(30)}$$

The pre-fault current I'_{ld} at S_2 can be obtained

$$I'_{ld} = \frac{V_{as2} - V_{afd}}{Z_{1s1f}} as(Z_{1s1f} = Z_{1s2f})$$

$$= \frac{\frac{V_{as1}}{C_{s1}} - V_{afd}}{Z_{1s1f}}$$

$$= \frac{\left[\frac{G_{vs1}}{G_{s1}} - \left(3R_f + Z_{\Sigma}\right)\right] I_{0f}}{Z_{1s1f}}$$

$$= G_{ldd} I_{0f} \quad \text{......(31)}$$

Where,

$$G_{ldd} = \frac{\left[\frac{G_{vs1}}{G_{s1}} - \left(3R_f + Z_{\Sigma}\right)\right]}{Z_{1s1f}}$$

Here, I_{ld}, I_{ld}' are the pre-fault current in the line assuming the UPFC is placed between point S_1, S_2 and shunt voltage receiving a current I_{s1}. V_{afd} is the a-phase voltage at the fault point, E_{sh} is the voltage of the shunt source, Z_{s1} its impedance, C_{sh} is the ratio between the a-phase voltage magnitude $|V_{as1}|$ and the magnitude of shunt voltage $|E_{sh}|$. The impedance Z_{1sws1}, Z_{1sns1} is net positive-sequence impedance from 'W' and 'N' sides to point S_1.

2.4 Conclusions

Apparent impedance calculations for transmission line operating with FACTS device like UPFC are presented in this chapter. Further comparing (15) and (16) it can be seen that for the fault resistance R_f =0, the correction factor $\nabla Z = 0$ showing that without the presence of UPFC, the apparent impedance will be actual line positive-sequence impedance from W to F. However, due to the presence of UPFC, even for R_f =0, the apparent impedance has to be corrected by an impedance ∇Z ,which will be influenced by series and shunt converter voltage (magnitude & angle) and impedances. If ∇Z is capacitive, the measured reactance is less than the actual value and If ∇Z is inductive, the measured reactance is higher than the actual. Thus the relay either over-reaches or under-reaches, depending on the value of ∇Z .

Chapter-3

Results and Analysis

3.1Initial conditions for generating tripping boundaries

The trip boundaries are drawn for different operating conditions of the wind farm and UPFC together. Initially, the conditions for voltage and impedances are set as follows to find out the apparent impedance.

$$\frac{V_{as1}}{E_{aw}} = h_1 e^{-j\delta_1} = 0.9565 e^{-j11.225}$$

$$Z_{1sw} = 20e^{j85}$$

$$Z_{0sw} = 1.5 * Z_{1sw}$$

$$Z_{1sn} = 10e^{j85}$$

$$Z_{0sn} = 1.5 * Z_{1sn}$$

$$Z_{1wn} = 36.8e^{j86}$$

$$Z_{0wn} = 111.8e^{j83}$$

$$V_{as2} = (1 + re^{j\theta})V_{as1}$$

$$C_{sh} = V_{as1} / E_{sh}$$

$$Z_{s1} = 0 + j0.1$$

Fig.3.1 shows the trip boundaries for faults before and after UPFC in the line considered including wind farm placed at the incoming end. It is observed that the trip boundaries are at different zone in R-X plot indicating the effect of UPFC on the line. To decide the trip boundaries, different fault resistance and fault location have been considered as shown in the legend of Fig.3.1, Fig.3.2 shows the trip boundaries when only wind farm is present in the transmission line, while the effect of UPFC is removed by putting r=0 and C_{sh}=1 in the UPFC model. Thus, Fig.3.1 shows the trip boundaries contain two closed boundaries in presence of UPFC, one for fault before and another for fault after UPFC. Similarly, when effect of UPFC is removed by setting the parameters accordingly, only one trip boundary is present as shown in Fig.3.2 indicating the presence of wind farm only. Further, the variation in operating parameters in wind farm as well as UPFC and the effects have been considered and the trip boundaries are included in the following sub-sections.

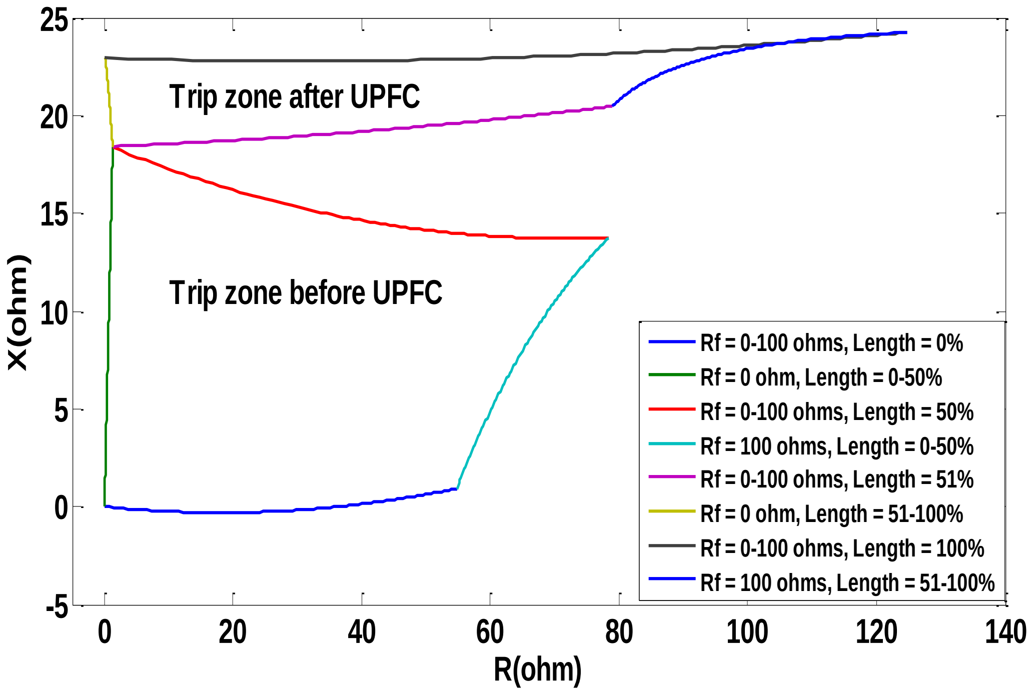

Fig. 3.1 Trip boundaries including both wind farm and UPFC

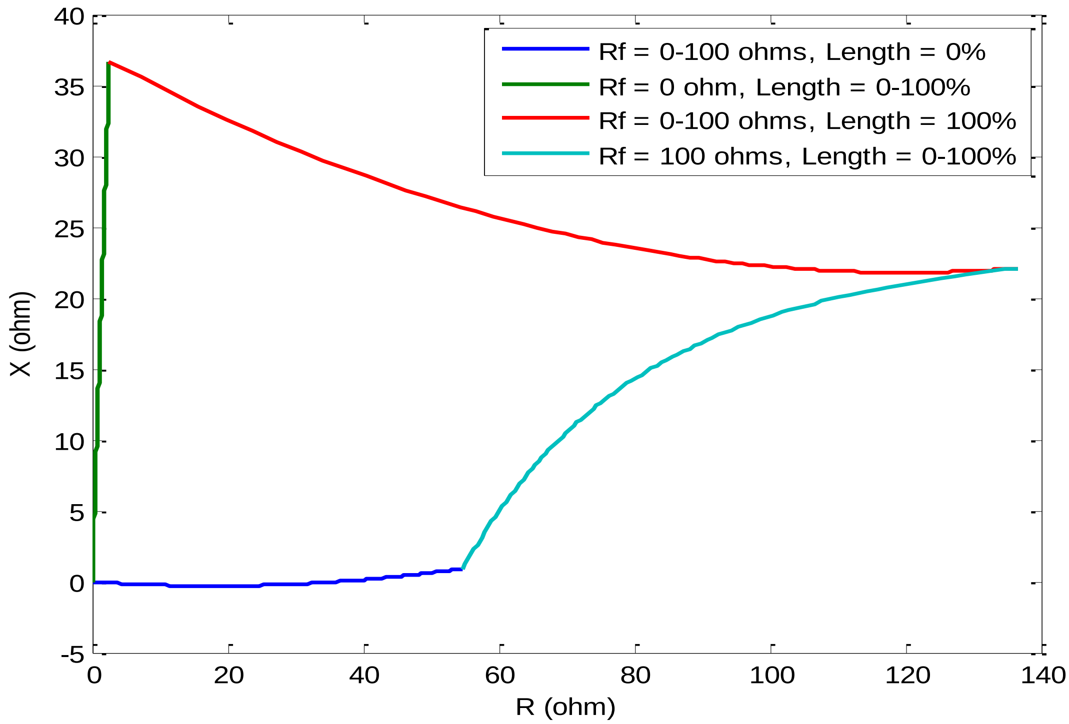

Fig. 3.2 Trip boundaries for wind farm with no-effect of UPFC.

3.2 Variation in wind farm parameters with no-effect of UPFC.

This section deals with the trip boundaries considering the variations in wind farm parameters with no effect of UPFC. Fig. 3.3 shows the adaptive trip boundaries for different loading levels. It is observe that when the value of 'δ' decreases, then the trip boundary is at larger side compared to higher value of 'δ'. In other way, lower 'δ', means lower end generation of wind farm and thus for lower end generation, the trip boundaries must be set at larger value. While considering the effect of varying load level as shown in Fig. 3.4 , it is observed that when the amplitude factor 'h' changes, there is substantial change in the operating trip boundaries of the rely. Thus, the relay trip boundaries are affected by the voltage variation either in grid side.

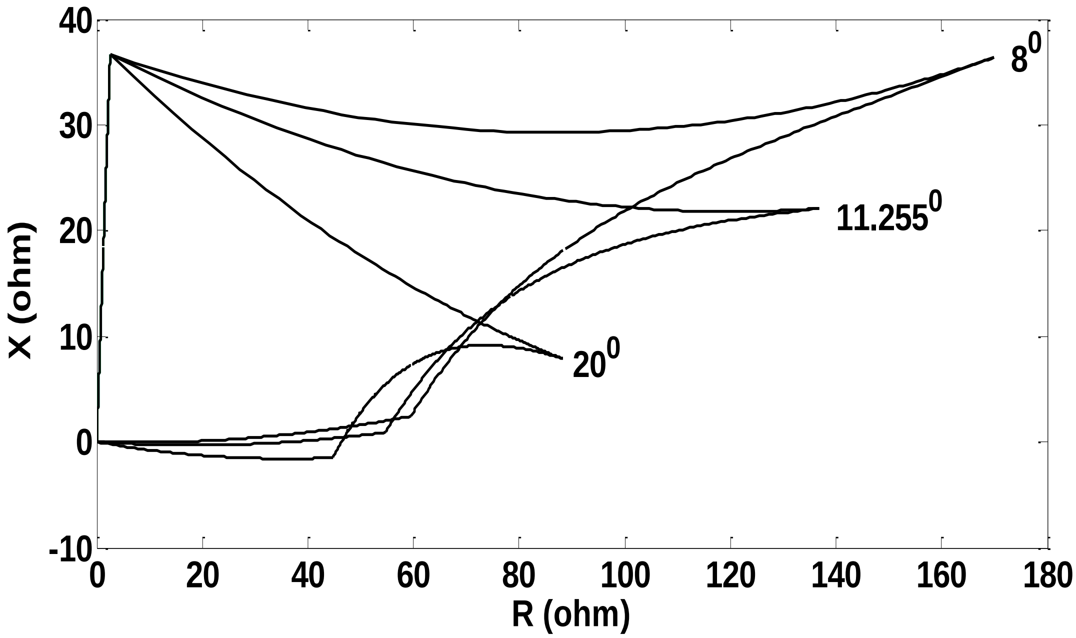

Fig.3.3 Trip boundaries for varying wind farm loading levels $\delta_1 = 20^0$, 11.255^0 and 8^0 with maintained $h_1 = 0.9565$

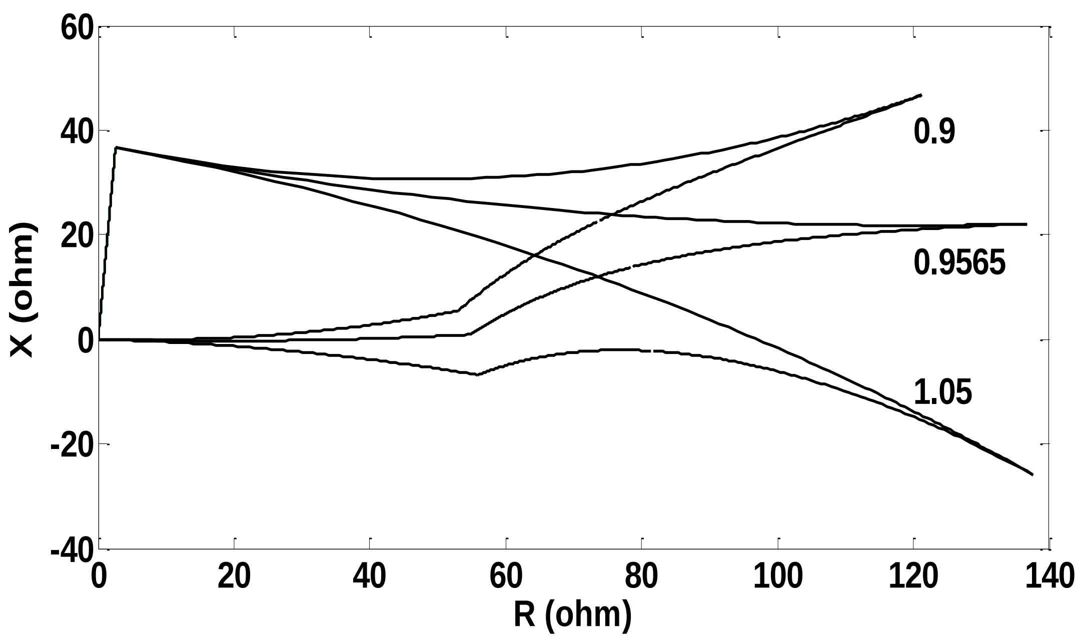

Fig. 3.4 Trip boundaries for varying wind farm voltage levels $h_1 = 1.05$, 0.9565 and 0.9 with maintained $\delta_1 = 11.255$

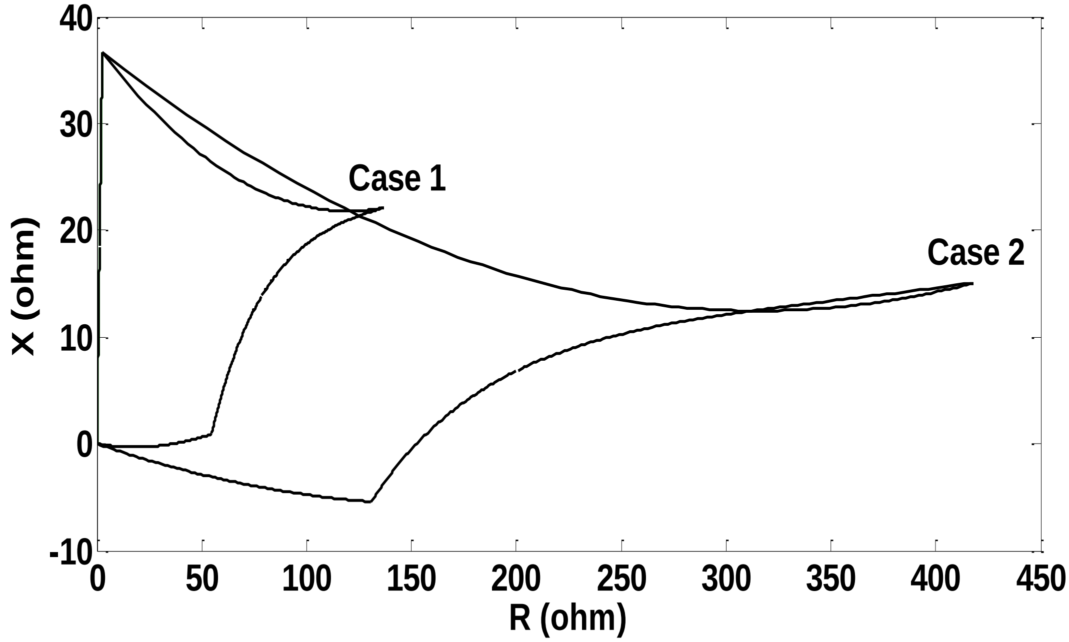

Fig. 3.5. Trip boundaries for varying source impedance of wind farm as depicted in Table-3.1

Table 3.1
Summary of varying source impedance of wind farm

Case	Z_{0sw}	Z_{1sw}	$h_1 e^{-j\delta_1}$
1	$30e^{j85}$	$20e^{j85}$	$0.9565e^{-j11.225}$
2	$180e^{j85}$	$120e^{j85}$	$0.9565e^{-j11.225}$

The effect of source impedance is one of the important considerations as it directly indicates the volume of wind farms connected to the transmission system. Fig. 3.5 shows the variation in trip boundaries when the sequence impedance are increased by 6 times in case-2 compared to case-1

(Table-3.1).This indicated that when the more numbers of wind farms are connected then the relay setting must be at higher side.

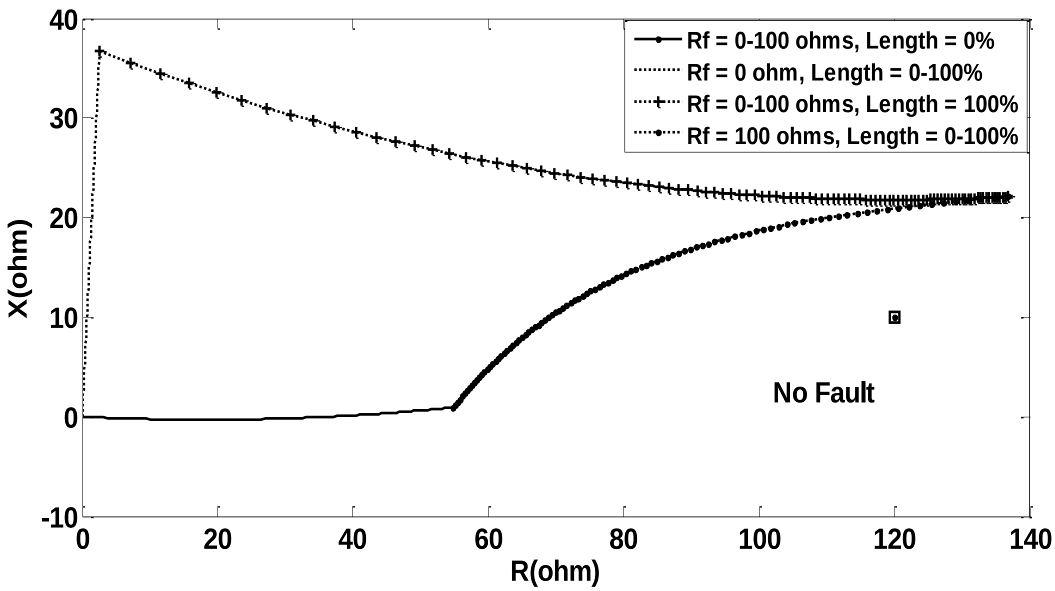

Fig. 3.6 Action of relay during no faults in wind connected transmission line

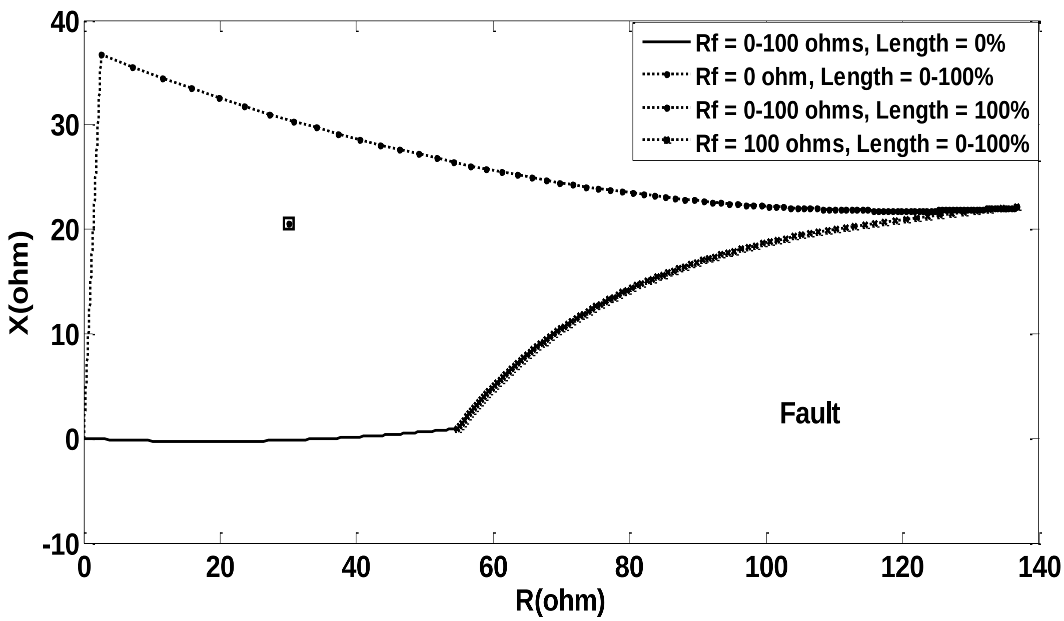

Fig. 3.7 Action of relay during faults in wind connected transmission line

3.3 Variation in UPFC parameters with Wind farm parameters kept unchanged

This sub-section deal with the trip boundaries for variations in UPFC parameters while the parameters of the wind farms are kept unchanged (h=0.9565 and $\delta = 11.225$) Fig. 3.8 shows the trip boundaries for two cases at different location of UPFC keeping the shunt and series parameters constant. It is observed that the relay must be set at higher value for the UPFC placed at relaying point (case-1) compared to the case-2, where the UPFC is placed at middle of the transmission line as shown in Fig. 3.8. Thus, the trip boundaries are significantly affected when the location of UPFC is changed in the transmission line. It can be observed that when the UPFC is placed at middle of the line, there are two trip boundaries required for fault occurring before and after UPFC. However, when UPFC is place at the relaying pint, only one trip boundary is generated as fault always occur after UPFC in the line.

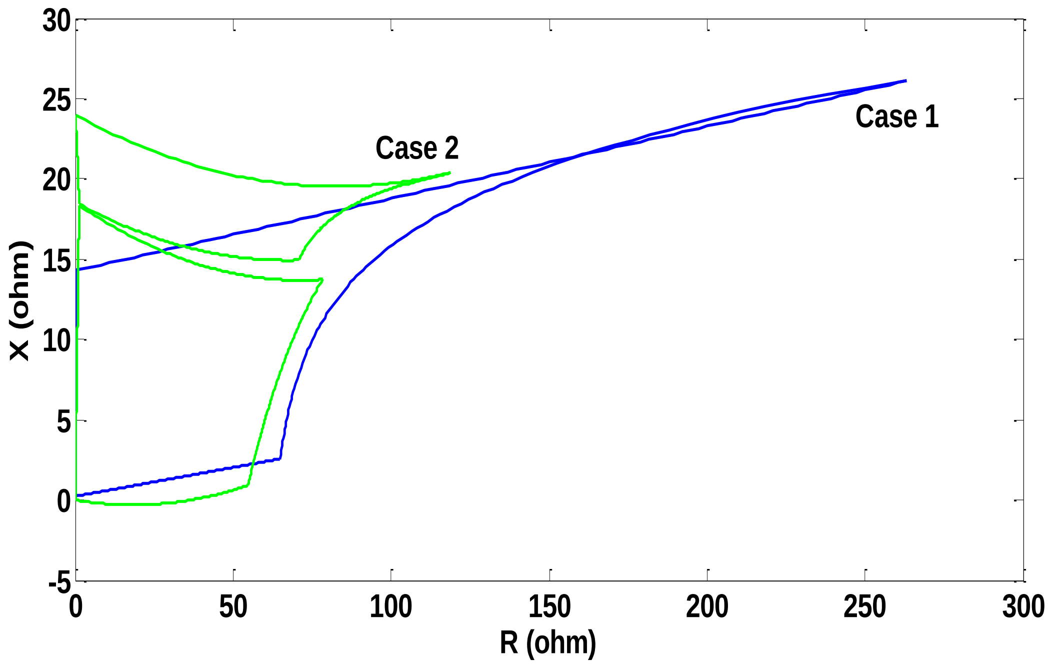

Fig. 3.8. Trip boundaries for varying the position of UPFC as depicted in Table-3.2

The trip boundaries in case of variations in shunt parameters of UPFC keeping series parameters fixed are shown in Fig. 3.9. It is observed that the relay setting is getting affected when the shunt

Parameter is changed. This happens as C_{sh} directly affects the reactance which is reflecting in change in trip boundaries.

Table 3.2

Summary of varying the position of UPFC

Case	**Position of UPFC**	$re^{j\theta}$	C_{sh}
1	At relay point	$0.2e^{j0}$	1.002
2	At middle point	$0.2e^{j0}$	1.002

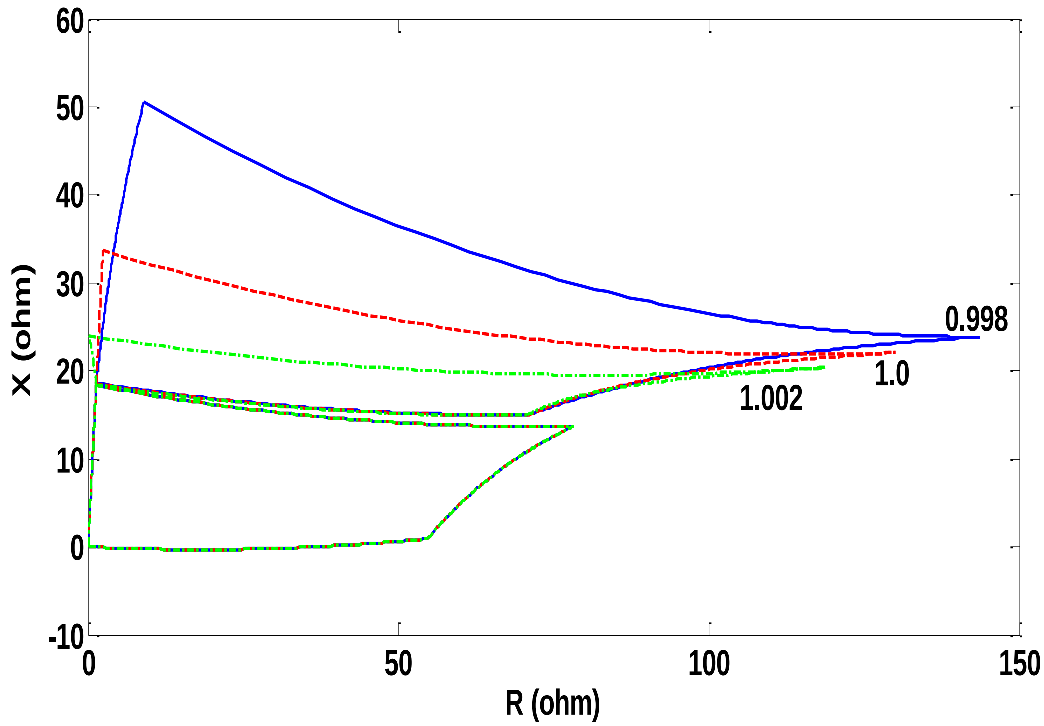

Fig. 3.9 Variation in UPFC shunt part parameter with series parameter constant C_{sh}=0.998, 1.0, 1.002 with UPFC placed at middle of the line

Fig. 3.10 shows the effect of variation in series parameter keeping shunt parameter as fixed, on the trip boundaries. At different values of 'r' and 'θ', the trip boundaries are significantly affected. For Figure 3.9 and 3.10, the trip boundaries for each case contain two tripping boundaries, one for fault before and another for fault after UPFC. The trip boundaries for fault before UPFC are overlapping for all three cases as there is no impact of UPFC for faults before UPFC, while the boundaries are different for faults after UPFC when the UPFC parameters are changed (shunt and series parameter).

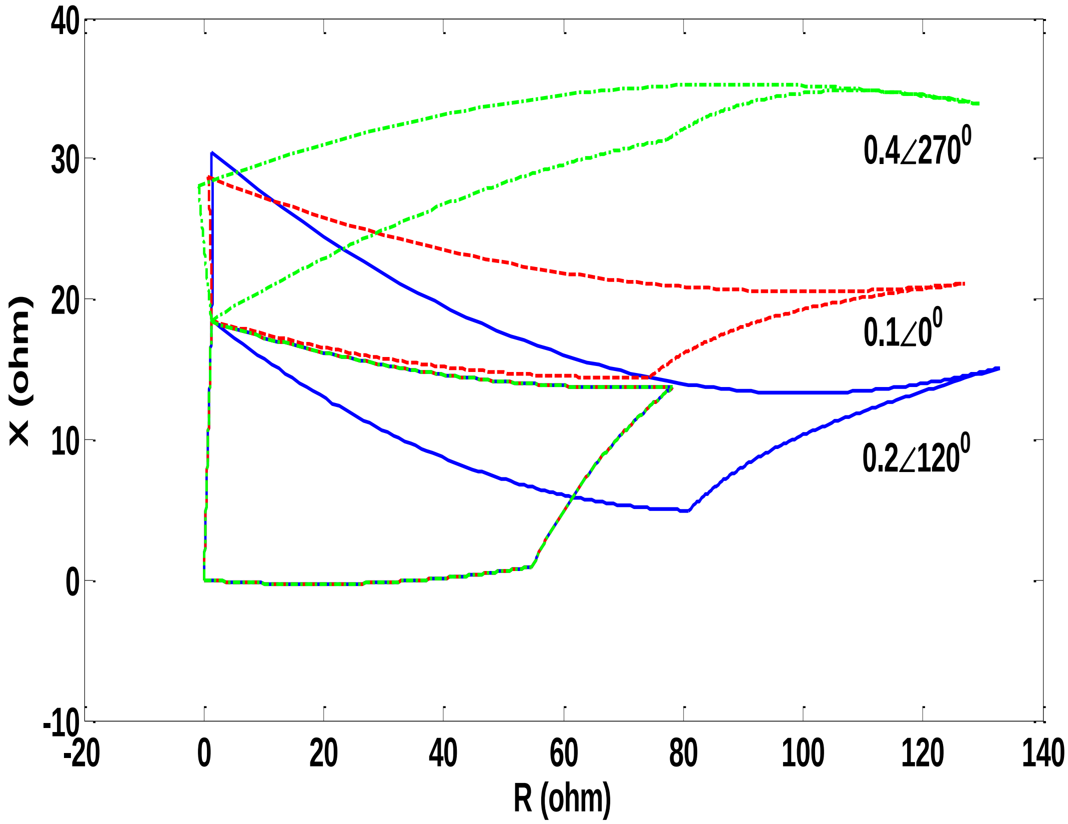

Fig. 3.10 Trip boundaries for variation in UPFC series part parameter with shunt parameter constant $re^{j\theta} = 0.2e^{j120}, 0.1e^{j0} \& 0.4e^{j270}$ **with C_{sh} = 1.001 with UPFC placed at middle of the line.**

3.4 Combined effect of Wind farm and UPFC on trip boundaries

The most important issue is setting the trip boundaries in presence of both wind farm and UPFC. Fig.3.11 shows the adaptive setting of the trip boundaries while varying 'δ' (wind farm parameters) and 'r' (series injected voltage of UPFC). It is observed from the two cases as mentioned in Table-3.3, that the relay requires higher setting in case-1 compared to case-2. Case-1 includes lower 'δ' means lower wing generation and lower 'r' means lower series injected voltage, which needs larger setting of the relay.

The power transfer angle δ_1 will vary according to the power pushed through the network by the wind farm. The UPFC series element will maintain impedance compensation of the transmission line according to the power pushed. Two cases are considered such as reduced generation (δ_1 = 4^0) & accordingly less capacitive series element ($re^{j\theta} = 0.1e^{j120}$) and another with full generation (δ_1 = 25^0) & accordingly more capacitive series element ($re^{j\theta} = 0.4e^{j120}$). In these cases the voltage ratio 'h_1' & shunt element parameter 'C_{sh}' are maintained at 0.98 & 1.001 respectively, as shown in Fig.3.11

Tripping boundaries for variation in 'h_1' (wind parameter) and '$\mathbf{C_{sh}}$'(UPFC shunt parameter) are shown in Fig. 3.12 for case-1 and -2 as mentioned in Table-3.4. The voltage at the coupling point of the wind farm will vary with wind speed, number of units connected at a time, reactive power support, etc. When wind farm voltage E_{aw} will fall, the voltage amplitude ratio h_1 will increase. In this case the shunt element of UPFC should supply reactive power support to increase the voltage by acting as a capacitive element. So for case 1 a higher voltage amplitude ratio (h_1 = 1.1) and capacitive nature of shunt element (C_{sh} = 0.998) is considered. Similarly for Case 2 opposite situation is considered. The power transfer angle δ_1 & series element parameter $re^{j\theta}$ are maintained at 15^0 & $0.1e^{j150}$ respectively. See figure 3.12.

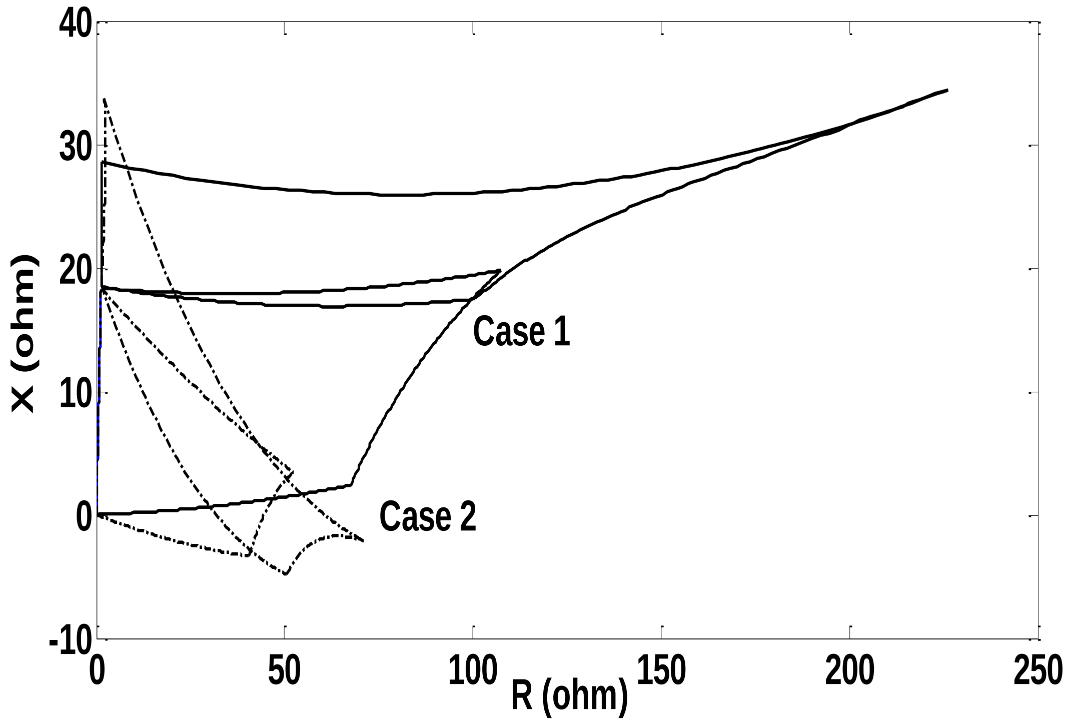

Fig.3.11 Trip boundaries for variations in wind farm loading level and UPFC series element parameter as depicted in Table-3.3 for detailed parameter with UPFC placed at middle of line.

Table 3.3

Summary of varying wind farm loading level and UPFC series element parameter

Case	$h_1e^{-j\delta_1}$	$re^{j\theta}$	C_{sh}
1	$0.985e^{-j4}$	$0.1e^{j120}$	1.001
2	$0.985e^{-j25}$	$0.4e^{j120}$	1.001

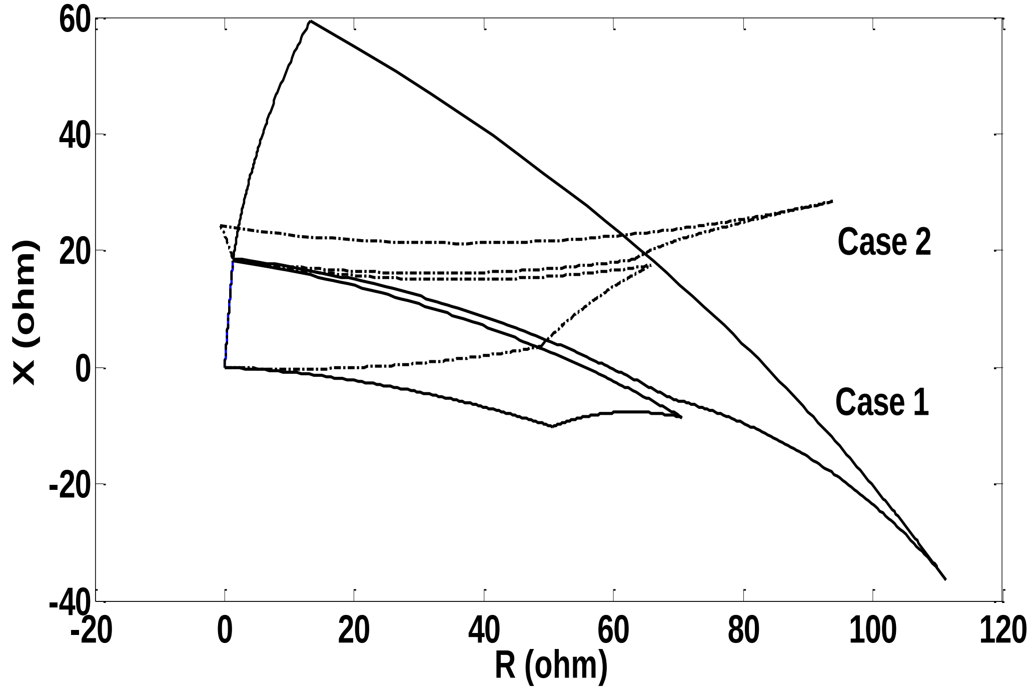

Fig. 3.12. Trip boundaries for variations in wind farm voltage level and UPFC shunt element parameter as depicted in Table-3.4 for detailed parameter with UPFC placed at middle of line.

Table 3.4

Summary of varying wind farm loading level and UPFC shunt element parameter

Case	$h_1 e^{-j\delta_1}$	$re^{j\theta}$	C_{sh}
1	$1.1e^{-j15}$	$0.1e^{j50}$	0.998
2	$0.9e^{-j15}$	$0.1e^{j50}$	1.002

Chapter-4

Discussion and Conclusions

4.1 Discussion

The adaptive setting of the distance relay for transmission lines in presence of UPFC and wind farm is obtained for wide variations in operating parameter of wind farm and UPFC. This includes different cases such as (i) variation in wind parameters while removing the effect of UPFC, (ii) variation in UPFC parameter keeping wind parameters unchanged and (iii) varying parameters of both wind farm and UPFC together. It is observed that the trip boundaries are significantly affected while the wind generations are changed; shunt band series parameters of UPC are changed. Thus the relay setting must be accordingly done to accommodate the adaptive setting of the distance relay. In case of wind farms only one trip boundary is generated while there are two trip boundaries generated for UPFC placed at middle of the transmission line.

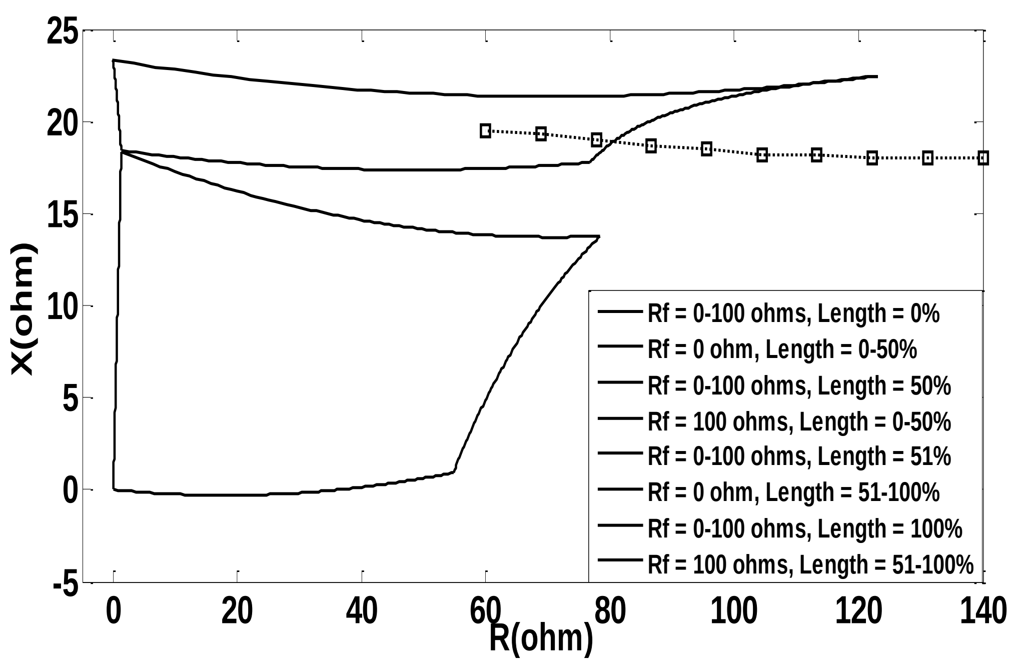

Fig. 4.1. Impedance trajectory for after UPFC. Including R-X trajectory.

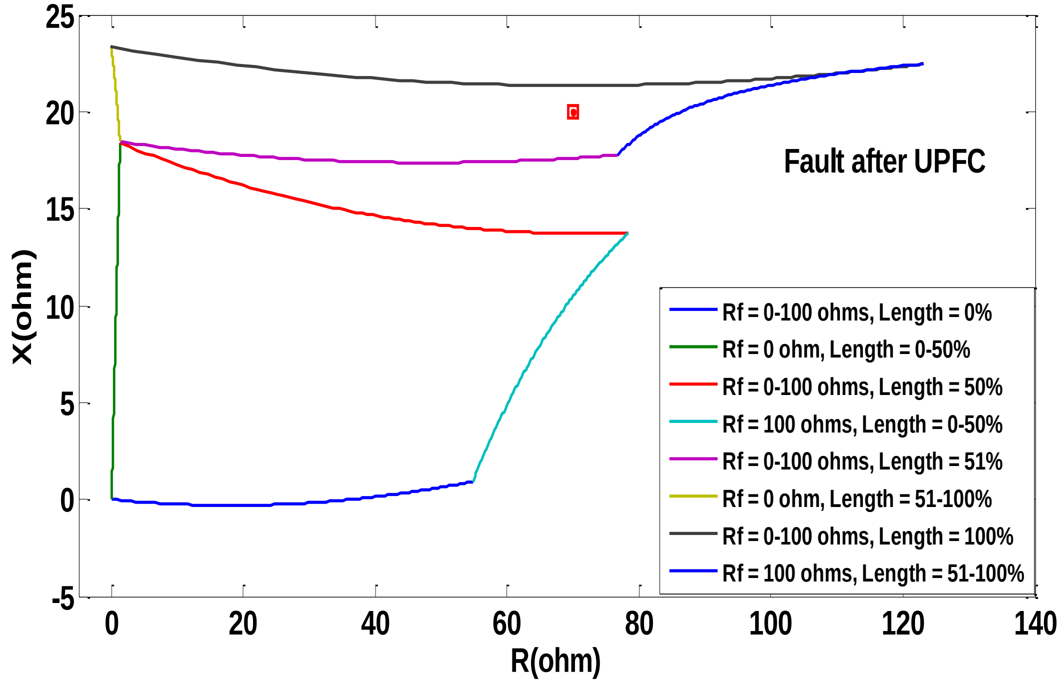

Fig. 4.2. Action of relay during faults after UPFC

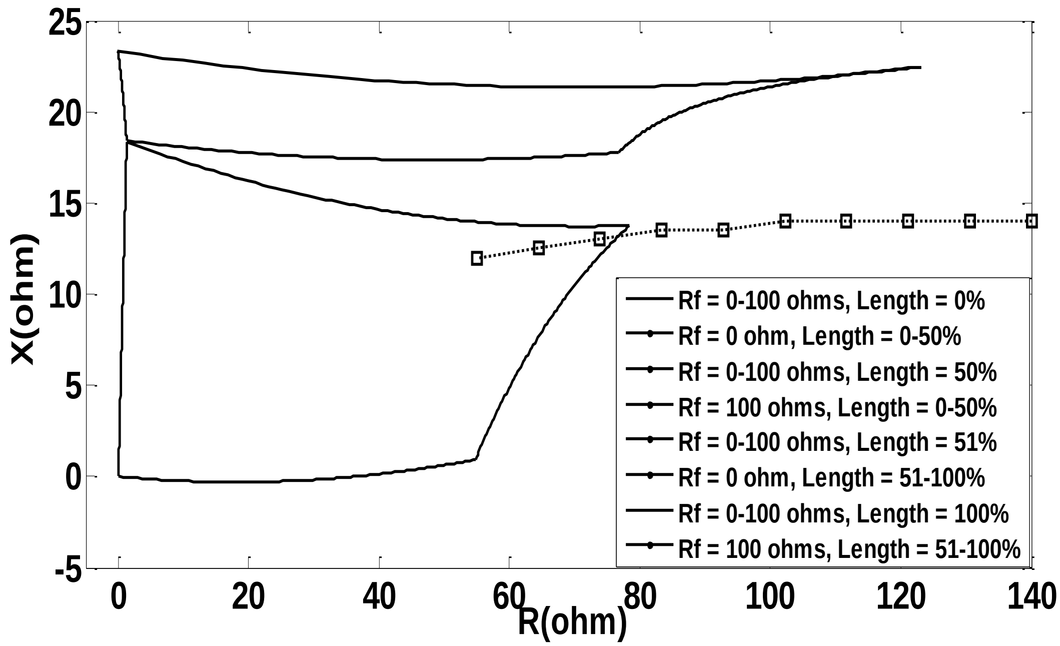

Fig. 4.3. Action of relay during faults before UPFC. Including R-X trajectory.

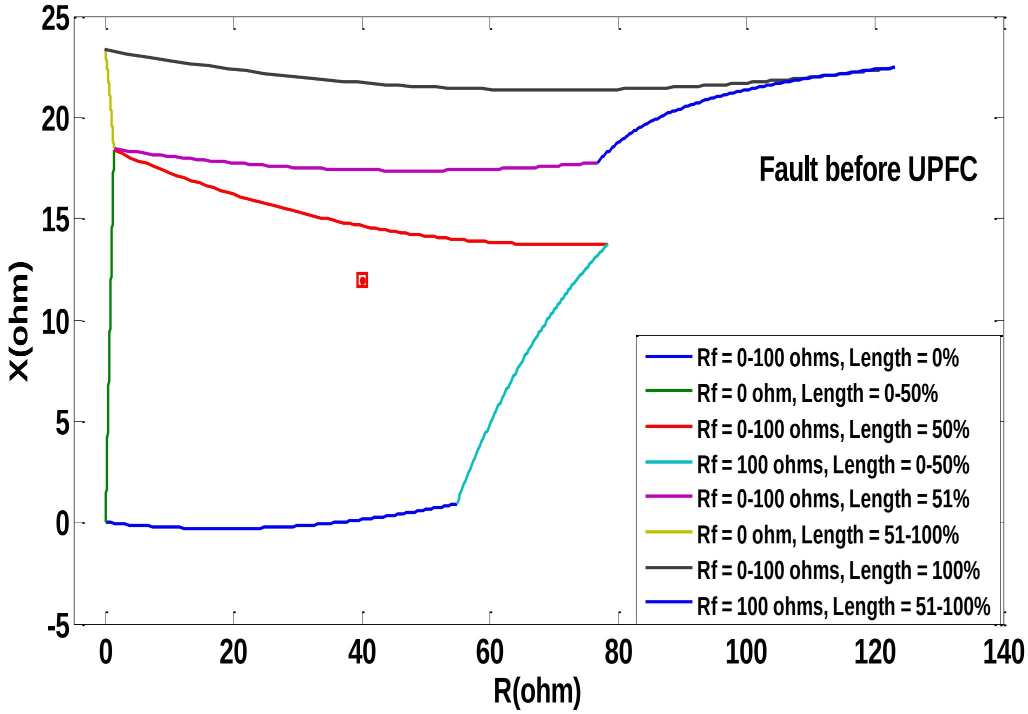

Fig. 4.4. Action of relay during faults before UPFC

The performance of the relay setting and the impedance trajectory for tripping action is tested for faults before and after UPFC as shown in Fig. 4.1 and 4.3. It is observed that the impedance trajectory enters the tripping boundaries for the respective fault situations, for fault before and after UPFC in the line. This shows the effectiveness and reliability of the adaptive setting of the trip boundaries for distance relay setting including both UPFC and wind farms. As the proposed setting uses the relaying end voltage and current information, thus is simple and easier to implement on the DSP/FPGA board for the distance relay module.

4.2 Conclusions

The proposed research focus on generating adaptive relay tripping boundaries for transmission lines including wind farm and UPFC. The difficulties appear as wind speed varies with time, affecting the power and voltage at relying point. Similarly, the function of UPFC in transmission line brings serious problems with respect to relaying as the apparent impedance to fault point gets changed. Thus, the adaptive setting of distance relay in presence of wind farm and UPFC is required to improve the readability of the distance relays. The proposed approach uses local relaying end information for generating the tripping zone and found highly effective considering wide variations in parameters of the wind farm and UPFC.

4.3 Future Scope

The proposed research can be extended for applying the similar techniques to the transmission line having other FACTS devices which are not included in the proposed study. The impact of the FACTS devices such as UPFC on the performance of distance relaying is to be studied. The protection and relay coordination with remote sensing may be considered as a potential area for future study.

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Journals:

1. S.R Samataray, **Rahul Dubey**, B.Chitti Babu, "A Novel Time–Frequency Transform Based Spectral Energy Function for Fault Detection during Power Swing", *International Journal of Electric Power Components and Systems, Taylor & Francis Publishers,* Vol.40, No.08, pp. 881-897, April 2012.

2. **Rahul Dubey**, S.R Samataray, B.Chitti Babu, "Adaptive Distance Relay Setting For Transmission Line Connecting Wind Farm and UPFC", *IEEE Transactions on Power Delivery*-***Revision Under Review*-2012**.

3. **Rahul Dubey**, S.R Samataray, B.Chitti Babu, **"**Wavelet Singular Entropy (WSE) based Out-of-Step protection and Symmetrical Fault Detection during Power Swing", *IET Journal of Generation, Transmission and Distribution- **Under Review 2012.***

International Conferences

1. **Rahul Dubey**, S.R Samataray, B.Chitti Babu, "LLLG Fault Detection in DFIG based WF using WT Based 'E' Function", *International Conference on Advance Energy Research, ICAER-2011, IIT Bombay, 9-11th December, 2011***.**

2. **Rahul Dubey**, S.R Samataray, B.Chitti Babu, "Detection of power quality disturbances in DFIG using wavelet-transform", *International Conference on Power System, IEEE ICPS-2011* **,***IIT Chennai ,22-24th December,2011.*

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6. **Rahul Dubey**, A.K Tripathy, "Fault detection in DFIG wind farm using WSE function", *Students' Conference on Engineering and Systems, IEEE SCES-2012,NIT Allahabad,16-18th March-2012.*