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Adaptive Settings Of Distance Relay For MOV-Protected Series Compensated Line With Distributed Capacitance Considering Wind Power

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ADAPTIVE SETTINGS OF DISTANCE RELAY FOR MOV-PROTECTED SERIES
COMPENSATED LINE WITH DISTRIBUTED CAPACITANCE CONSIDERING
WIND POWER

A Thesis
Presented to
the Graduate School of
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ABSTRACT

Series compensated lines are protected from overvoltage by metal-oxide-varistors (MOVs) connected in parallel with the capacitor bank. The nonlinear characteristics of MOV devices add complexity to fault analysis and distance protection operation. During faults, the impedance of the line is modified by an equivalent impedance of the parallel MOV/capacitor circuit, which affects the distance protection. The intermittent wind generation introduces additional complexity to the system performance and distance protection. Wind variation affects the fault current level and equivalent MOV/capacitor impedance during a fault, and hence the distance relay operation.

This thesis studies the impact of the intermittent wind power generation on the operation of MOV during faults. For the purpose of simulation, an equivalent wind farm model is proposed to generate a wind generation profile using wind farm generation from California independent system operator (ISO) as a guide for wind power variation to perform the study. The IEEE 12-bus test system is modified to include MOV-protected series capacitor and the equivalent wind farm model. The modified test system is simulated in the MATLAB/Simulink environment. The study has been achieved considering three phase and single line to ground (SLG) faults on the series compensated line to show the effect of wind variation on the MOV operation.

This thesis proposes an adaptive setting method for the mho relay distance protection of series compensated line considering effects of wind power variation and MOV operation. The distributed parameters of a transmission line are taken into account to avoid overreaching and underreaching of distance relays.

The study shows that variable wind power affects system power flow and fault current in the compensated line during a fault which affects the operation of MOVs for different fault conditions. The equivalent per-phase impedance of the MOV/capacitor circuit has an effect on the system operation and line protection. Distance protection study is also performed with variable wind power, different line compensation levels, and other system conditions. Results show that variable wind power affects apparent impedance calculation of distance relay through the variable equivalent MOV/capacitor impedance. Underreaching and overreaching issues of the distance relay are discussed. Based on the results, a variable distance relay setting is proposed to mitigate the negative impact. Both fixed and variable distance relay settings are presented and compared to each other. The results demonstrate the ability of the proposed adaptive setting method to resetting the distance relays to adapt to various system conditions, including three wind generation and different compensation levels.

DEDICATION

I would like to dedicate this work to my family and friends who have helped me throughout this journey. Special thanks to my immediate family Viktor, Tatyana, Yelena, Eduard, Igor, Vladislav, Oksana, Nadia, and Tonya Sivov for their unconditional love and support.

ACKNOWLEDGMENTS

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CHAPTER ONE

INTRODUCTION

1.1 Wind Energy

Due to the global energy prices, supply uncertainties, and environmental concerns wind energy is one of the best sources of alternative energy [1]-[2]. Wind energy is the world's fastest growing renewable energy source with the advancement in the related technology. According to Global Wind Energy Outlook 2014, wind power could provide 25-30% of global electricity supply by 2050 [3]. The attractiveness of wind energy include no CO_2 emission, lower dependency on foreign oil and gas, creation of new jobs and numerous other benefits. Utilities give a great consideration to wind power integration [4]-[5]. The penetration of wind energy introduces challenges on the operation and protection of power systems. These challenges must be thoroughly studied and new measures and techniques must be adapted to ensure the reliability of the grid.

1.2 Series Compensation

The series compensation has been used to increase power transfer capability of transmission lines and to improve system stability [6]-[7]. During system faults, high fault currents through the series capacitor cause voltage to rise across the series capacitor bank, which in turn causes overvoltage that may damage the compensation device [8]. Metal-oxide-varistor (MOV) devices, connected in parallel, have been used to protect the series compensation against overvoltage during faults. The MOV-protected series compensation increase complexity of fault analysis and distance protection. Applying the MOV for series compensator protection has been considered in [8]-[16].

1.3 Distance Protection

Protection of transmission lines is vital to the overall system stability of the power system. Distance relays are widely used to protect the transmission line from any type of fault. There are different types of distance relays such as mho, offset mho, reactance, admittance and quadrilateral [17], [18]. A distance relay operates on local voltages and currents present to the relay, and the relay decision is made based on the calculated apparent impedance and the relay settings [18],[19].

The high intermittent wind generation connected to the grid introduce an additional complexity to the fault analysis and distance protection of MOV-protected series compensated lines. The effects of wind power's fluctuation on power system's operation has been considered in [20], and distance protection in [21]-[22].

1.4 Adaptive Settings and Literature Review

Several adaptive distance relaying methods have been proposed in recent publications to correct the relay operation for MOV-protected series compensated lines [13]-[14] and [21]-[24]. With the current adaptive methods not being comprehensive including the effects of wind energy there is still room to develop new adaptive techniques.

In [13] and [14], the method used phasor-measurement units (PMUs) at both ends of the line with a dedicated communication channel to compute the compensation level during a fault and adapt relay setting accordingly. The compensation level was determined by subtracting the measured impedance between PMUs from a known line impedance without series compensation. This method considered both cases with the

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capacitor placed at the end and in the middle of a transmission line. However, for the second case, the method's approach did not address overreaching issues for faults occurring between the relay location and the series capacitor. Also, this method used a medium length transmission line model and neglected the effects of the distributed parameters.

In [23], the Goldsworthy's equivalent impedance model for MOV-protected series capacitor was used. The equivalent MOV/capacitor per phase impedances were used to compute the new sequence impedances of the transmission line impedance matrix. This method ultimately set the trip boundaries of a quadrilateral-type distance relay. The adaptive distance relaying method, however, works only for the case where the series capacitor placed at the line terminal directly following the distance relay. If the capacitor was placed elsewhere in the line, the method would risk significant overreaching/underreaching issues. This method was also developed for a medium length transmission line neglecting the line's distributed parameters.

In [24], the presented method attempted to adapt relay reach setting to three different cases of line percent compensation, 0%, 40%, and 60%. This method made a number of assumptions including the information about the presence or absence of the capacitor and amount of compensation provided to the relay a priori, and neglecting the effects of MOV action on the equivalent MOV/capacitor impedance. Also the method was applied for a series capacitor at a terminal of a medium length transmission line.

In [21]-[22], analysis of the effects of wind power fluctuation on the distance relay was performed for a radial medium length transmission line with lumped

parameters. In [21], the relay considered the impact of wind farm's power fluctuation on distance relay alone without considering line compensation and MOV action. In [22], the relay analysed the impact of simultaneous operation of off-shore wind penetration and flexible AC transmission system (FACTS) devices on distance relay characteristics. The FACTS device was a unified power flow controller (UPFC) device. Therefore, these references [21]-[22] did not consider the simultaneous effects of MOV action with wind farm variation on the distance relay setting.

This thesis considers the distributed parameters of a long transmission line with series compensation that would result in underreach or overreach operation. It also considers the effects of intermittent wind generation on the distance relay setting of compensated line. In summary, this thesis proposes an adaptive setting method for a distance relay of a long transmission compensated line connected to an equivalent wind farm. The proposed algorithm considers distributed line parameters, MOV operation, and wind power variation. The results are presented for a single-line-to-ground bolted fault and mho-type relay is used in this study.

CHAPTER TWO

BACKGROUND

2.1 MOV-Protected Series Capacitor

The MOV scheme consists of a capacitor bank, metal-oxide-varistor bank, a

triggered bypass air gap, a damping reactor, and a bypass switch [8] as shown in Figure

2.1(a). The significant part of the protection system is the MOV device which has

nonlinear voltage-current characteristics as shown in Figure 2.1(b). This figure shows

that for the voltage across the MOV device below the overload voltage (threshold

voltage, or protective voltage, V_{prot}), the MOV acts as an open circuit. For voltages above

the V_{prot}, the MOV acts as a resistor. The higher the overload voltage, the lower is the

MOV resistance. MOV devices have nonlinear characteristic and are used for overvoltage

surge protection. During high transient voltages, the MOV clamps the voltage to a safe

level and dissipates the potentially destructive energy as heat, thus protecting the circuit

elements from overvoltage and preventing system from damage. The MOV consists of

series and parallel arrangement of zinc-oxide disks to achieve the required protective

voltage level and energy requirements. The series capacitor bank on each phase typically

consists of a number of capacitor units connected in a series-parallel arrangement to

make up for the required voltage, current, and MVar rating.

The triggered air gap in the protection scheme is controlled to spark over in an

event when the energy absorbed by MOVs exceeds its nominal power rating. It is

typically used as an intermediate bypass device since it is faster than the bypass circuit

switch but not as instantaneous as the MOV. In the case of prolonged gap conduction

(such as delayed fault clearing), the bypass switch automatically closes to limit the excess

energy for both MOV and the triggered air gap. The damping reactor limits the

magnitude of the capacitor discharge current during the spark over of the triggered gap or

the bypass breaker switching.

(a)   (b)
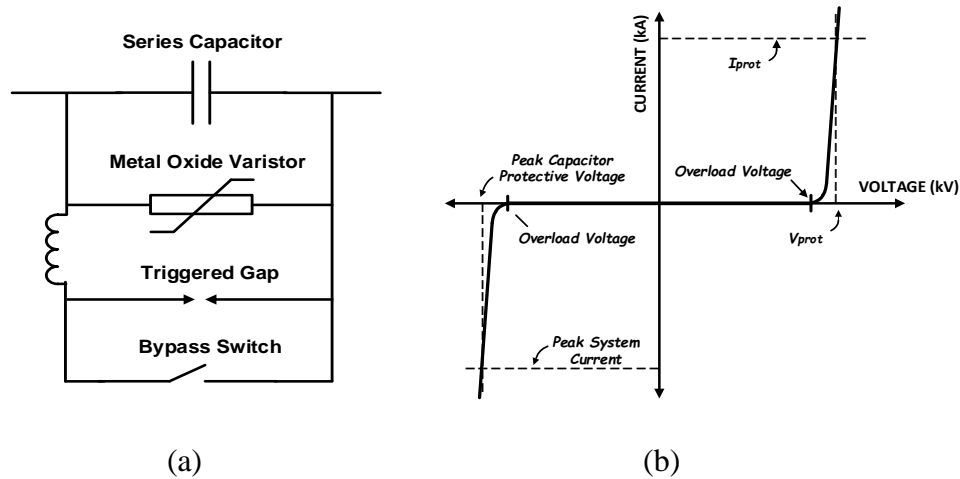
Figure 2.1 MOV [8]: (a) typical overvoltage protection scheme, and (b) V-I
characteristics

During normal system operation, the equivalent impedance of the MOV

connected in parallel with the capacitor is purely capacitive reactance since MOV does

not conduct any current. During faults, the MOV action modifies the per phase line

impedance by partially bypassing the capacitor on the faulted phase. The MOV action

also introduces a resistive component to the line impedance. The parallel MOV/capacitor

connection can be modeled as a series equivalent impedance during the faults [8], as

shown in Figure 2.2.

The Goldsworthy's linearized model in [8] shows an important result that even

though the capacitor is connected in parallel with a highly non-linear device, the resulting

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total current through the combination remains sinusoidal and the MOV/capacitor circuit under fault can be approximated by a reduced single phase circuit of Figure 2. This result is important for determining total line impedance and for distance protection.
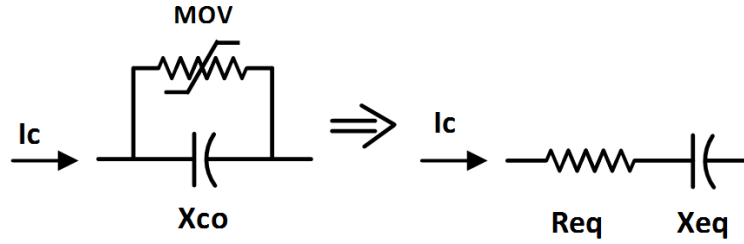
Figure 2.2 Modeling MOV/capacitor as equivalent impedance $Z_{eq} = R_{eq} + X_{eq}$ during system faults [6]

The linearized model was developed by varying the capacitive reactance, capacitor protective voltage level, system voltage, system impedance, MOV v-i characteristics, and other test system's parameters. The computer simulation and field tests involving MOV-protected series capacitors with various system parameters gave many data points for equivalent reactance and resistance values of MOV/capacitor circuit. The R_{eq} and X_{eq} were normalized by the capacitor impedance X_{co}, and the fault current I_{cap} was normalized by the capacitor protective level current I_{prot} as

$$R'_{eq} = R_{eq} / X_{co} \, , \;\; X'_{eq} = X_{eq} / X_{co} \, , \text{ and } I_{pu} = I_{cap} / I_{prot} \, .$$

The generated data points were plotted as in Figure 2.3.
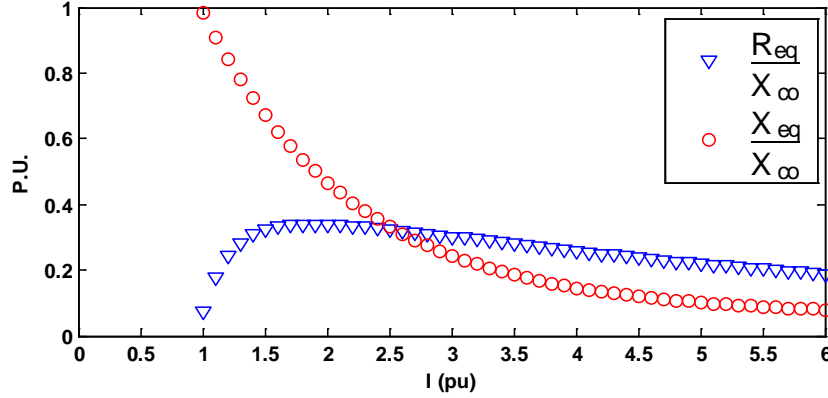
Figure 2.3 Goldsworthy's normalized equivalent MOV/capacitor resistance and reactance vs. normalized fault current levels [6]

The plot brings another important result showing the relationship between the fault current I_{pu} and the equivalent MOV/capacitor impedance. It suggests that for any system and fault current the equivalent impedance can be determined from Goldworthy's relationship Eqs. (2-1) and (2-2) which were obtained via least-squares curve fits as

$$R'_{eq} = X_{co}(0.0745 + 0.49e^{-0.243I_{pu}} - 35e^{-5I_{pu}} - 0.6e^{-1.4I_{pu}}) \text{, and} \qquad (2\text{-}1)$$

$$X'_{eq} = X_{co}(0.101 - 0.005749I_{pu} + 2,088e^{-0.8566I_{pu}}) \text{.} \qquad (2\text{-}2)$$

Note that as the fault current I_{pu} increases the equivalent reactance X_{eq} exponentially approaches zero. The equivalent resistance R_{eq}, on the other hand, increases from zero and then slowly approaches zero as well for increasing I_{pu}.

<u>2.2 Distance Relay Operation</u>

2.2.1   Distance relay zone coordination

A transmission line is normally divided into several protection zones, such as zone 1, zone 2, and zone 3 as shown in Figure 2.4(a). A distance relay (at substation A) is typically set to act as main protection for faults taking place within zone 1, and as backup protection for faults occurring within zones 2 and 3. The reach for zone 1 is defined as 80% of the protected line, based on the impedance of the line (Z_{Line} in ohms). Zone 1 is not set to cover the full 100% of the line to prevent overreaching due to transient voltage or current measurement errors. The reach for zone 2 is typically set to 120% of the protected line. Zone 2 ensures full coverage of the protected line. Finally, the reach for zone 3 is typically set as 100% of the primary line plus 120% of the adjacent line as a backup protection for the entire adjacent line [25].

If a fault occurs within the primary protection zone 1, the distance relay would instantaneously send a trip signal to open the circuit breaker. If a fault occurs within backup zone 2 or 3, the relay tripping signal would be delayed by some predefined number of cycles to give time for other protective system to respond. The relay would send a trip signal if the fault is still present after the delay.

Figure 2.4(b) shows mho type distance relay characteristics where the Z1, Z2, and Z3 are the reach settings for the protection zone 1, zone 2, and zone 3 respectively. In this thesis, only zones 1 and 2 are considered.

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(a)   (b)
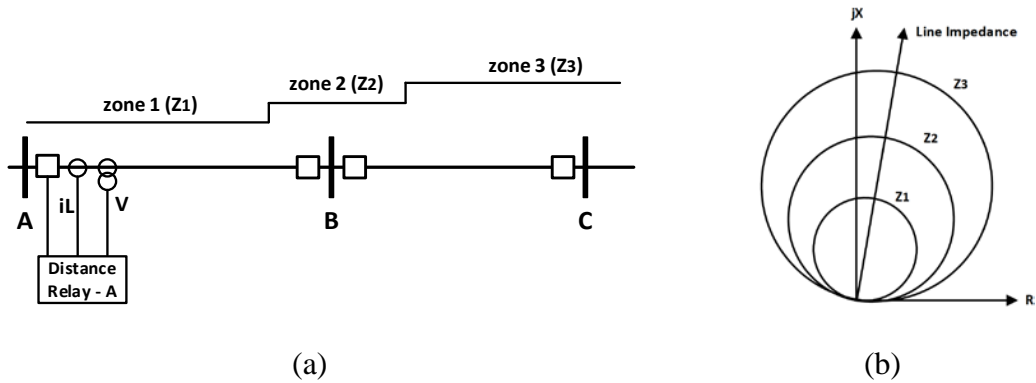
Figure 2.4 Mho distance relay: (a) zones of protection for distance relay-A, and

(b) characteristics with reach setting for the zones

2.2.2   *Distance relay main functions*

The main operation steps of the distance relay include the fault type detection, apparent impedance calculation, and zone protection coordination [26]. The general distance relay operation is summarized in Figure 2.5.

Step 1. Voltage and current signals

The continuous inputs of three phase voltages and currents at relay location are fed into the relay. The signals are passed through a low-pass filter to filter out any harmonics. The magnitudes and phase angles are obtained from Fast Fourier Transform (FFT). Sequence components are obtained using a symmetrical component transformation matrix.

Step 2. Fault detection

The fault detection algorithms, such as the 'Delta' algorithm technique [27], can be used to determine the type of fault from eleven possible fault types to avoid overreaching or underreaching.

Step 3. Apparent impedance calculation

The apparent impedance at the relay location [28], for the given fault type, can be calculated using Table 2.1 for medium length transmission lines. Section 2.3 describes the calculation of apparent impedance for long transmission lines including effects of shunt capacitance.

Step 4. Zone protection coordination

Finally, zones coordination is applied as described in section 2.2.1.

```
                        ┌──────────┐
                        │  Start   │
                        └────┬─────┘
                             ↓
    ┌─────────────────────────────────────────────────────┐
    │  Acquire three phase voltages and currents at relay   │
    │                     location                          │
    └───────────────────────┬───────────────────────────────┘
                             ↓
    ┌─────────────────────────────────────────────────────┐
    │      Lowpass filter and fast fourier transform stage  │
    └───────────────────────┬───────────────────────────────┘
                             ↓
    ┌─────────────────────────────────────────────────────┐
    │                 Fault detection stage                 │
    └───────────────────────┬───────────────────────────────┘
                             ↓
    ┌─────────────────────────────────────────────────────┐
    │             Apparent impedance calculation            │
    └───────────────────────┬───────────────────────────────┘
                             ↓
    ┌─────────────────────────────────────────────────────┐
    │    Trip decision based on zone protection coordination│
    └───────────────────────┬───────────────────────────────┘
                             ↓
                        ┌──────────┐
                        │   End    │
                        └──────────┘
```
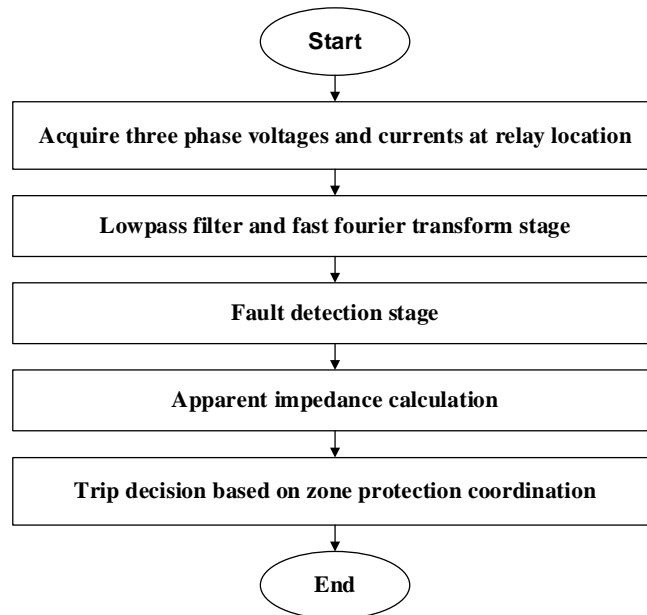
Figure 2.5 Flow chart for general distance relay algorithm

Table 2.1 Apparent impedance calculation for various fault types

Fault Type	Impedance
AG	$V_A / (I_A + 3 k_0 I_0)$
BG	$V_B / (I_B + 3 k_0 I_0)$
CG	$V_C / (I_C + 3 k_0 I_0)$
AB or ABG	$(V_A - V_B) / (I_A - I_B)$
AC or ACG	$(V_A - V_C) / (I_A - I_C)$
BC or BCG	$(V_B - V_C) / (I_B - I_C)$
ABC or ABCG	(V_A / I_A) or (V_B / I_B) or (V_C / I_C)

where:

A, *B*, and *C* indicate faulty phase

G indicate ground fault

V_A, V_B, and V_C, indicate voltage phasors

I_A, I_B, and I_C, indicate current phasors

Z_0 = line zero-sequence impedance

Z_1 = line positive-sequence impedance

k_0 = residual compensation factor, where

$$k_0 = (Z_0 - Z_1)/Z_1$$

$$I_0 = V_{ph}/(Z_0 + 2Z_1)$$

V_{ph} is phase voltage during phase to ground fault.

<u>2.3 Distributed Parameter-Based Distance Relay</u>

2.3.1   Protection Zones Impedance

For long transmission lines (typically longer than 250km), the distributed

parameters have been considered [17], [29] to avoid serious distance relay underreaching

or overreaching. The apparent impedance of relay considering distributed parameters is

given by

$$Z_{app} = z_{c1} * \tanh(\gamma_1 * x) \tag{2-3}$$

where: $z_{c1} = \sqrt{\dfrac{Z_{T1}}{Y_{T1}}}$, $\gamma_1 = \sqrt{Z_{T1} * Y_{T1}}$, $Z_{T1} = R_{T1} + j\omega L_{T1}$, and $Y_{T1} = G_{T1} + j\omega C_{T1}$.

Note that x in equation (2-3) is the distance between the relay and the fault location, R_{T1}

and L_{T1} are distributed resistance and inductance respectively, and G_{T1} and C_{T1} are

distributed conductance and distributed capacitance, respectively. The subscript 1

indicates positive sequence.

Since the relationship of the apparent impedance in (2-3) is consistent with the

fault location x, the expression in (2-4) is used to set protection zones of distance relay by

replacing x with L$_{set}$ as

$$Z_{set} = z_{c1} * \tanh(\gamma_1 * L_{set}) \tag{2-4}$$

for zone 1, L$_{set1}$ = 0.8 × length of the protected line. For zone 2, L$_{set2}$ = 1.2 × length of the

protected line.

2.3.2 Apparent Impedance Trajectory

The case of SLG fault is considered in this thesis. The apparent impedance trajectory is expressed as

$$Z_A = \frac{V_A}{(I_A + k_0 * I_0)} = z_{c1} * \tanh(\gamma_1 * x) \tag{2-5}$$

where k_0 is the zero-sequence current compensation factor expressed as [17],

$$k_0 = \frac{1}{(z_{c1} \sinh(\gamma_1 x))}(z_{c0} \sinh(\gamma_0 x) - z_{c1} \sinh(\gamma_1 x) + Z_0(\cosh(\gamma_0 x) - \cosh(\gamma_1 x))) \tag{2-6}$$

where: $z_{c0} = \sqrt{\dfrac{Z_{T0}}{Y_{T0}}}$, $\gamma_0 = \sqrt{Z_{T0} * Y_{T0}}$, $Z_{T0} = R_{T0} + j\omega L_{T0}$, and $Y_{T0} = G_{T0} + j\omega C_{T0}$.

The zero-sequence impedance of the equivalent system behind the relay is $Z_0 = -V_0/I_0$ [17]. The k_0 factor can be implemented by specifying the fault at x. R_{T0} and L_{T0} are distributed resistance and inductance respectively, G_{T0} and C_{T0} are distributed conductance and distributed capacitance, respectively. The subscript 0 indicates zero sequence. The Simulink block diagram of k_0 calculation is shown in Figure B.4 in Appendix B.

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CHAPTER THREE

TEST SYSTEM MODELING

3.1 Test System Description

The IEEE 12-bus test system is selected to perform the study and is simulated in

MATLAB/Simulink (Mathworks, 2014Ra) and PowerWorld (PowerWorld Simulator

17). PowerWorld Simulator is used here only to verify the power flow results of the

Simulink simulation. Schematic of the system for both software programs are shown in

Figures B.1 through B.6 Appendix B. The original system data is taken from [30] given

in Tables A.1 - A.4 Appendix A. The test system is modified to include MOV-protected

series capacitor on the longest transmission line (600 km, 345 kV) between buses 7 and 8

as shown in Figure 3.1. Also, the synchronous generator at bus 11 (in the original test

system) is replaced by an equivalent wind farm model. The required sequence parameters

of the compensated line are given in Table A.1 in Appendix A.
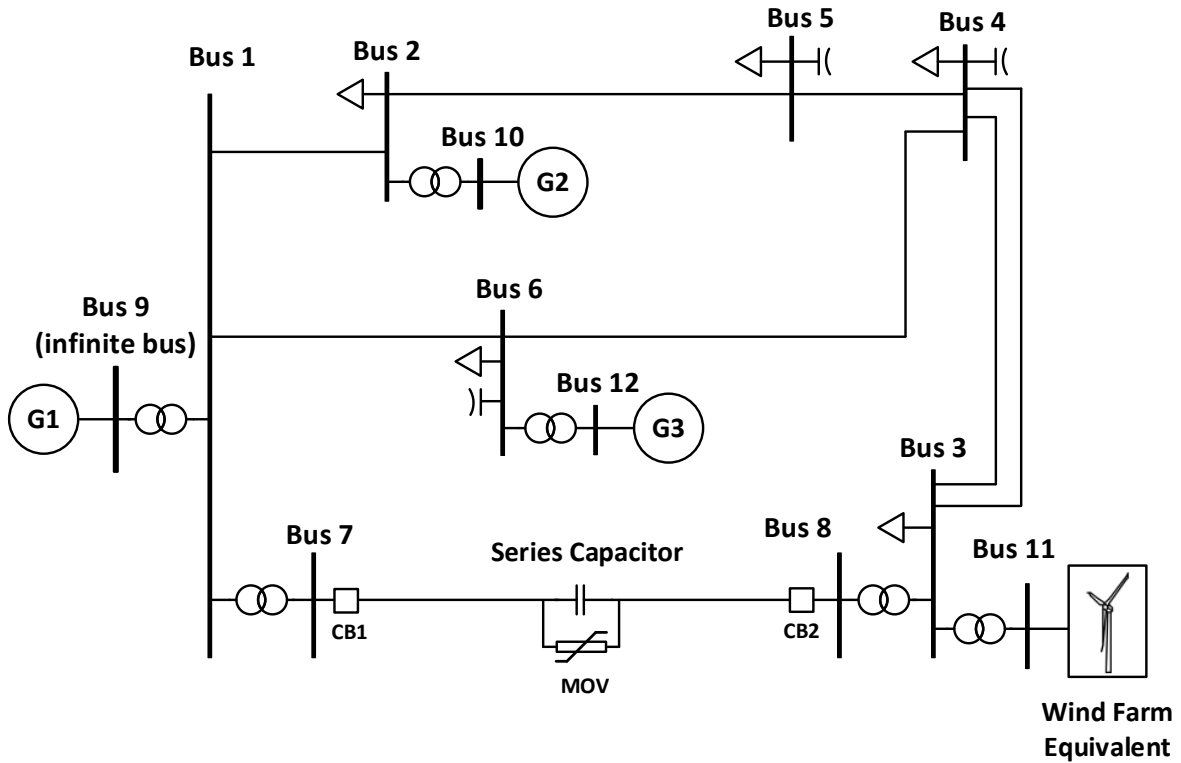
Figure 3.1 The modified IEEE 12-bus test system

3.2 Series Capacitor

Four compensation cases are studied in this thesis (0%, 20%, 40%, and 60%). For the 600 km line with inductive reactance of 226.45 Ω, the 40% compensation, for example, is calculated to be Xc = 90.58 Ω, or equivalently C = 29.3µF of capacitance per phase.

3.3 Distance Relays and Fault Locations

The compensated line is selected to be protected by mho distance relays with relay-A placed at the left terminal of the line and relay-B at the right terminal as shown in Figure 3.2 The SLG fault is tested in the simulation with the fault locations at 0km,

100km, 200km, 300Lkm (left capacitor terminal), 300Rkm (right capacitor terminal), 400km, 500km, and 600km.
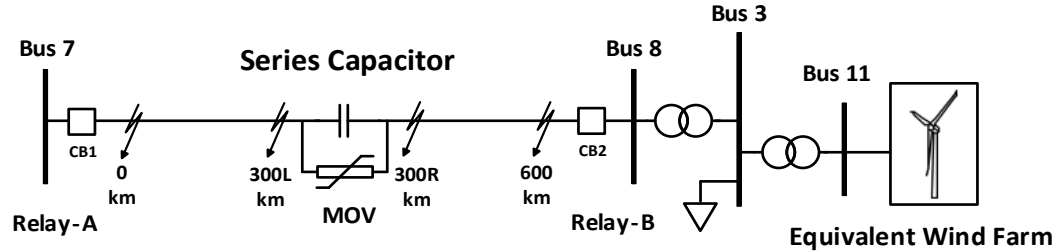
Figure 3.2 Illustration for different fault locations in the compensated line

3.4 MOV Setting

The MOV protective voltage level is commonly designed to be a multiple (typically 2 to 2.5) of the capacitor rated voltage level [8]. The MOV protective voltage level is calculated as [8], [31]

$$V_{prot} = 2\sqrt{2}I_{prot}X_c \tag{3-1}$$

where I_{prot} is the rated capacitor current as seen in Fig 2.1(b). The nominal capacitor current is taken as 760 A rms line current. Thus, the capacitor protective voltage level V_{prot} = 194.7 kV for a 40% compensation. From GE and Eaton datasheets [32], [33], the MOV device which can handle maximum continuous operating voltage (MCOV) of at least 194.7kV, was found to have a nominal discharge current rating of 10 kA per column and a rated discharge energy of 5.6kJ/kV of maximum continuous operating voltage. Taking the MCOV to be 194.7 kV during a fault, a single arrester column is rated to absorb 1.09 MJ of energy. From the simulation, it was found that for a 10 cycle fault duration, the maximum absorbed energy by MOVs on one phase is 12.933 MJ. Based on

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this, at least 12 columns per phase are necessary to withstand worst fault current for a fault duration of 10 cycles without damaging the MOVs. To be safe, fifteen columns were used in this study with a reference current per column set as 10kA, and total per phase MOV energy threshold set as 16.36 MJ. As a result, the trigger gap and bypass switch were not actuated during the simulation studies.

3.5 Equivalent Wind Farm

An equivalent wind farm model is proposed to generate the wind generation profile using the total wind farm generation data from California independent system operator (ISO) [4], [5]. This equivalent wind farm model is connected to bus 11 as shown in Figure 3.1. The base power is considered as 300 MW (average wind power).

The wind profile represents an actual wind farm generation for a windy winter day on Jan 7, 2005. The wind generation data was retrieved from [4] using DigitizeIt and Inkscape software programs as shown in Figure 3.3. This data was then reduced and used in the test system's Simulink model.
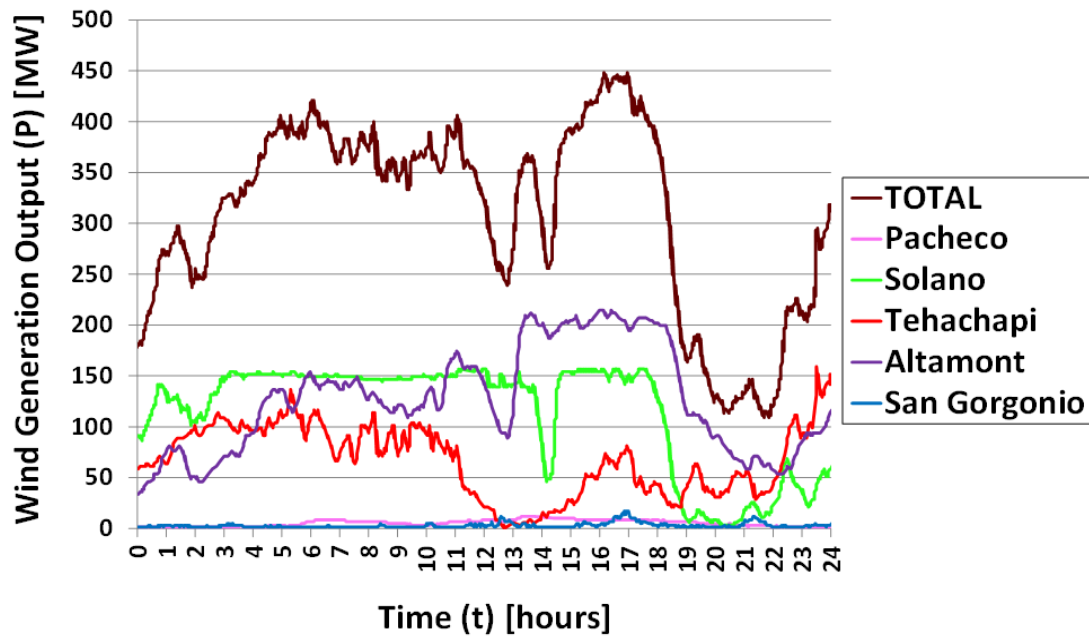
Figure 3.3 California ISO wind farm generation profile, Jan 7, 2005

Due to high wind speeds, a number of wind turbines trip near 12 pm and 2 pm to prevent equipment failure. At around 4 to 5 pm, the wind farms reach a maximum generation level of about 450 MW (peak wind power). Just about 6 pm, an even larger number of wind turbines go offline again due to excessive wind speeds, causing a significant wind generation loss down to about 90 MW (minimum wind power). The effects of this intermittent wind generation on the distance protection of series compensated line is evaluated and is presented in sections 6.3 and 8.1-8.3.

CHAPTER FOUR

OPERATION OF MOV-PROTECTED SERIES CAPACITOR WITH WIND POWER

DURING FAULTS

This chapter presents a study of the effect of wind power variation on the MOV operation with the setting for 40% line compensation level. The wind farm generation data from California ISO for the period of 24 hours is reduced for simulation purposes due to long simulation times as shown in Figure 4.1. The first 10 seconds of the simulation represents the period of fixed power generated at bus 11 with generation of 1.0 pu. The time from 10 sec to 58 seconds in the x-axis represents the wind variation period.
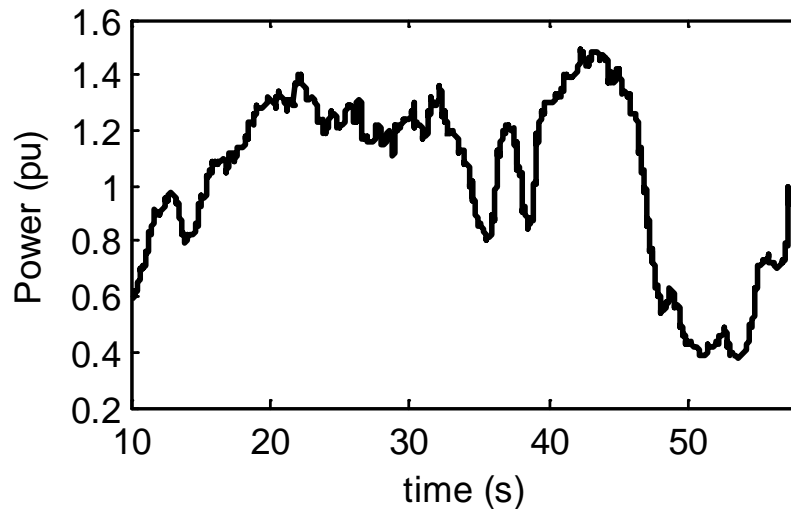
Figure 4.1 Simulated total wind generated power

Three simulation cases are performed. For the first case, three phase and SLG faults are performed near the terminals of the series compensator with 1.0 per unit

constant generated power at bus 11. For the second case, three phase and SLG faults are performed with the total wind power at the peak of wind generation level. For the third case, three phase and SLG faults are performed with the total wind power at the minimum wind farm generation level. As a worst condition, all of the faults have a 10 cycle fault duration in this study.

4.1 With Constant Generated Power at Bus 11

For the first case, the fault occurs at the instant of 5.0 seconds and is cleared at 5.1667 seconds.

For the three phase fault the results show that all MOVs (for each of the three phases) have approximately the same conducting currents and absorbed energy. Figure 4.2 shows the phase "a" MOV voltage, current and energy consumption during the fault. Figure 4.3 shows the V-I characteristics for phase "a". Phases "b" and "c" have similar results as phase "a".

For the SLG fault, the MOV voltage, current and energy consumption for phase "a" are shown in Figure 4.4. The voltages for phases "b" and "c" are shown in Figures 4.5 and 4.6, respectively. Note that only the MOV on phase "a" conducts fault current, while the MOVs on phases "b" and "c" do not conduct fault current. The corresponding V-I characteristic for phase "a" is shown in Fig 4.7. The MOV V-I characteristics and the absorbed energy for phases "b" and "c" are not shown since there are no fault currents observed on these phases and hence no consumed energy by the corresponding MOVs. The maximum and minimum fault currents bypassed by the MOVs along with the absorbed energy during the SLG fault are summarized in Table 4.1.
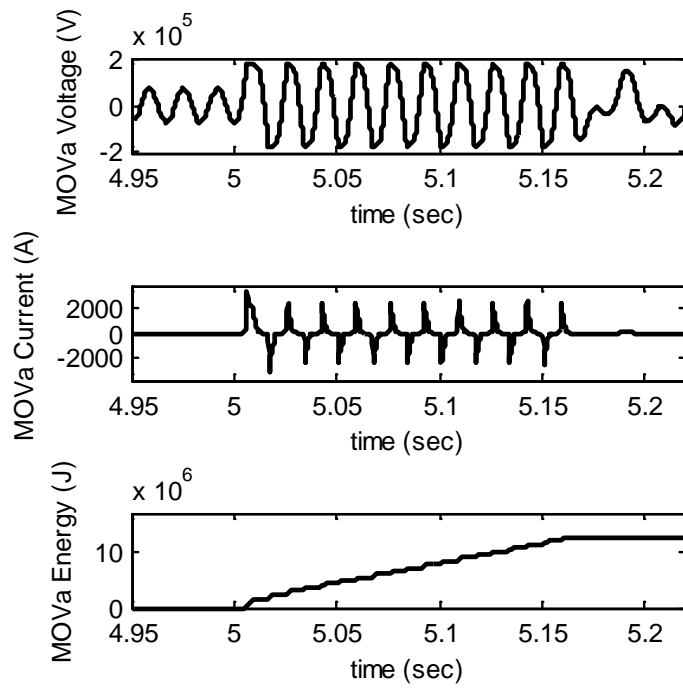
Figure 4.2 MOV characteristics of phase "a" for three phase fault at the terminal of the series capacitor
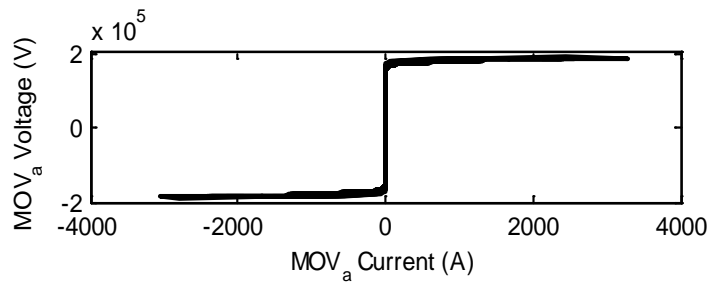
Figure 4.3 MOV V-I characteristics for phases a, b and c, during a three-phase-fault at the terminal of the series capacitor
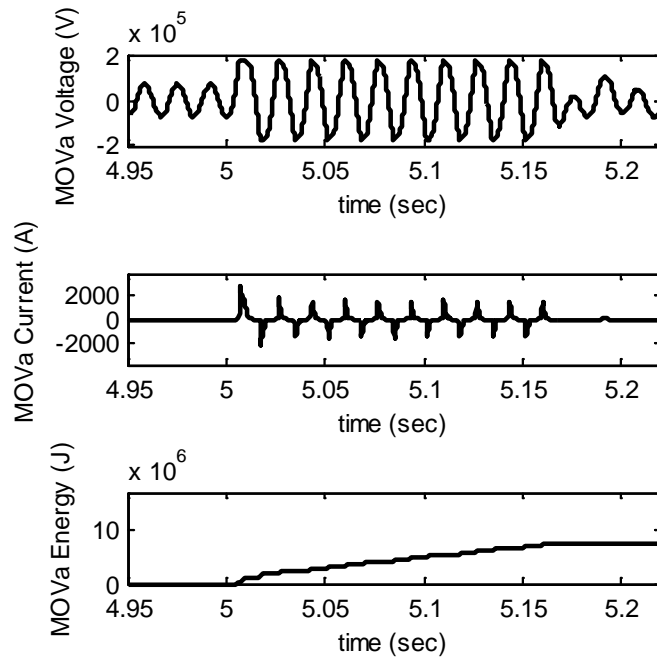
Figure 4.4 Phase a - MOV characteristics with SLG fault at capacitor terminal
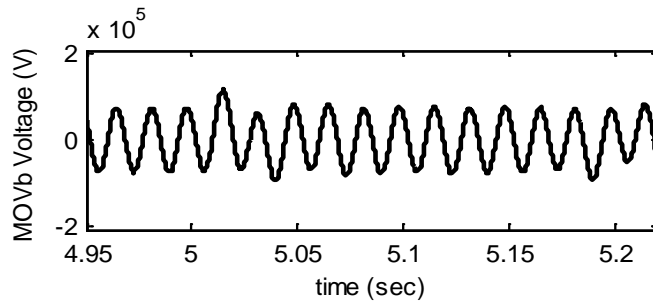
Figure 4.5 Phase b - MOV characteristics with SLG fault at capacitor terminal
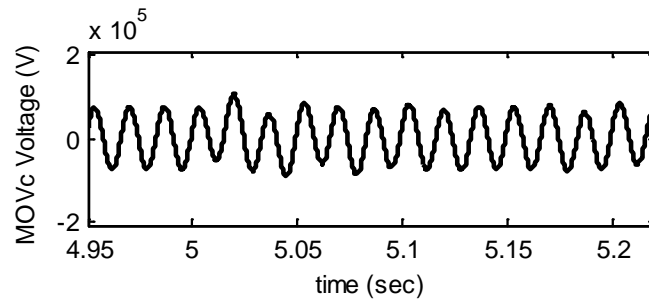
Figure 4.6 Phase c - MOV characteristics with SLG fault at capacitor terminal
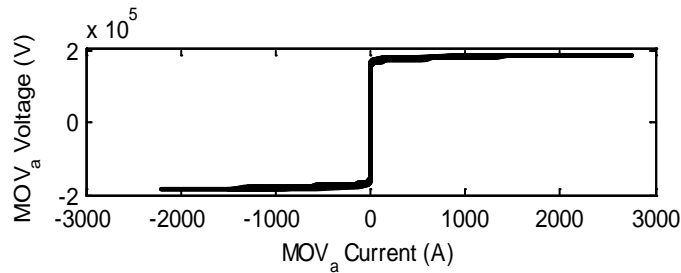
Figure 4.7 MOV V-I characteristics for phases a, b and c, during a SLG fault at the capacitor terminal (constant wind power)

4.2 With Peak Wind Power Level

For the second case, the three phase short circuit results are found to be similar to the previous case but are different in the case of SLG fault. Figure 4.8 shows the wind power profile with a SLG fault occurs at the peak of wind generation. The MOV characteristics for phase "a" are shown in Figures 4.9 and 4.10. The V-I characteristics plots for phases "b" and "c" are not shown because MOVs on these phases do not conduct any fault current. The results for the SLG fault are shown in Table 4.1 which indicates that for SLG fault during peak wind power level, the energy absorbed by the MOV on phase a is smaller than that for the previous case. This can be explained from power flow results. As the wind generation increases at bus 11 due to high wind penetration, the power generation from other generators required to meet the load demand decreases. As a result, the current flowing from the slack generator at bus 9 to the load at bus 8 is smaller than during the first case. Thus, during the 10 cycle fault at the terminals of the compensator, the current passing through the MOV is smaller. The energy absorbed by the MOV is smaller as well. Note that the general behavior of the MOVs are not significantly affected by the intermittency of the wind farm (based on the

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setting in sections 3.2 and 3.4) if the ratings and settings for the MOV-protected

capacitors are designed to be able to handle high fault currents during the maximum

and/or minimum amount of wind penetration.
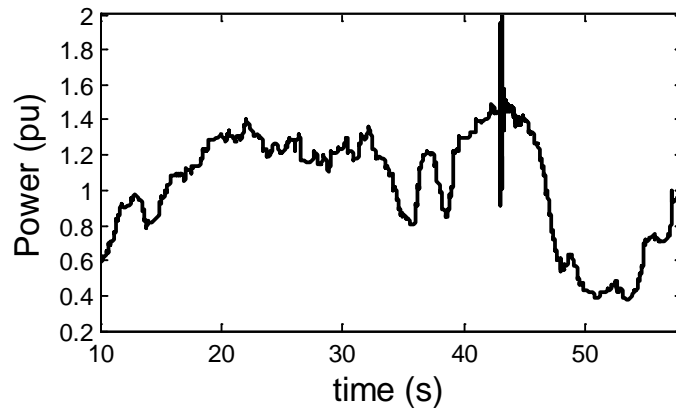
Figure 4.8 Wind farm total generated power with SLG fault at the peak of wind farm
generation level
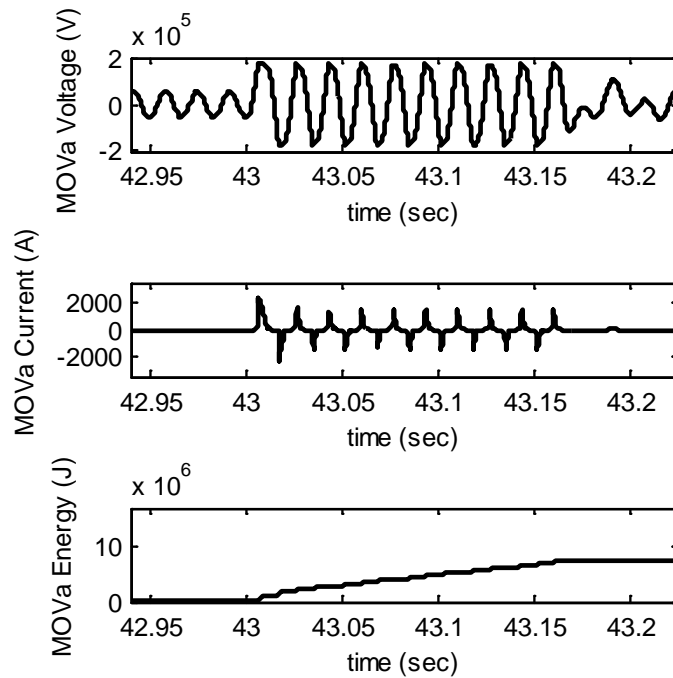
Figure 4.9 Phase a - MOV characteristics with SLG fault at capacitor terminal
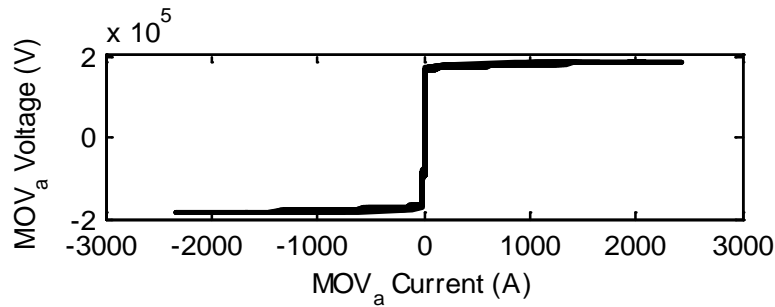
Figure 4.10 MOV V-I characteristics for phase "a" during a SLG fault at the capacitor terminal (peak wind power). Phases "b" and "c" have zero current.

4.3 With Minimum Wind Power Level

For the third case, the three phase fault results are found to be similar to the previous two cases. The wind power profile with SLG fault at the minimum of wind generation level is shown in Figure 4.11. The MOV characteristics for phase "a" are shown in Figures 4.12 and 4.13. The V-I characteristics plots for phases "b" and "c" are not shown because MOVs do not conduct any current. The comparison with the previous two cases is summarized in Table 4.1 which shows that for SLG fault during minimum wind power level, the energy absorbed by MOV on phase "a" is greater compared to the previous two cases. This consequence can also be explained from power flow results. As the wind farm generation reduces due to low wind speed, the other system generators increase the generation to cover the load demands including the load at bus 8. During the low wind power level, the power supplying load demands at bus 8 is coming mainly from the slack generator at bus 9. This power is absorbed by the MOV during the fault near the terminal of the series compensator. From the simulation, the energy absorbed by the MOV during the SLG fault is larger compared to the previous cases as illustrated in

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Table 4.1. Thus, the intermittency of wind penetration levels varies the MOV fault

current and energy absorption, but does not vary the basic operation of the MOV

protection of the series compensator (based on the setting in sections 3.2 and 3.4).
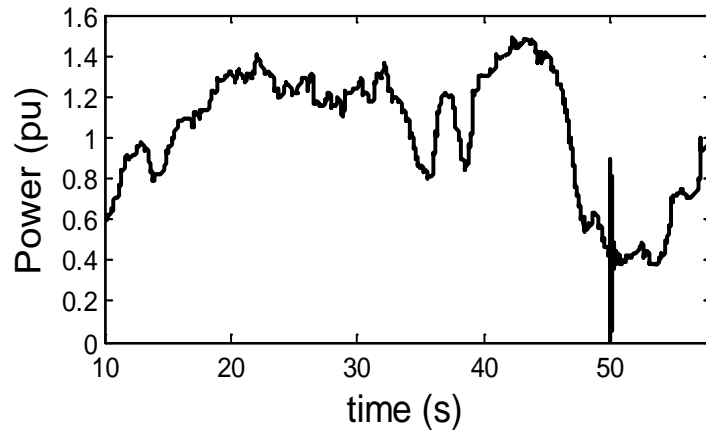
Figure 4.11 Total wind farm power output with SLG fault at the minimum wind farm
generation level

Table 4.1 Unbalanced fault results

Case	MOV of phase	SLG fault at phase a	
		$|I_{rms}|$ (A)	Energy absorbed (MJ)
With wind at peak	a	1442	7.296
	b	0	0
	c	0	0
With average wind	a	2749	7.408
	b	0	0
	c	0	0
With wind at minimum	a	2908	7.747
	b	0	0
	c	0	0
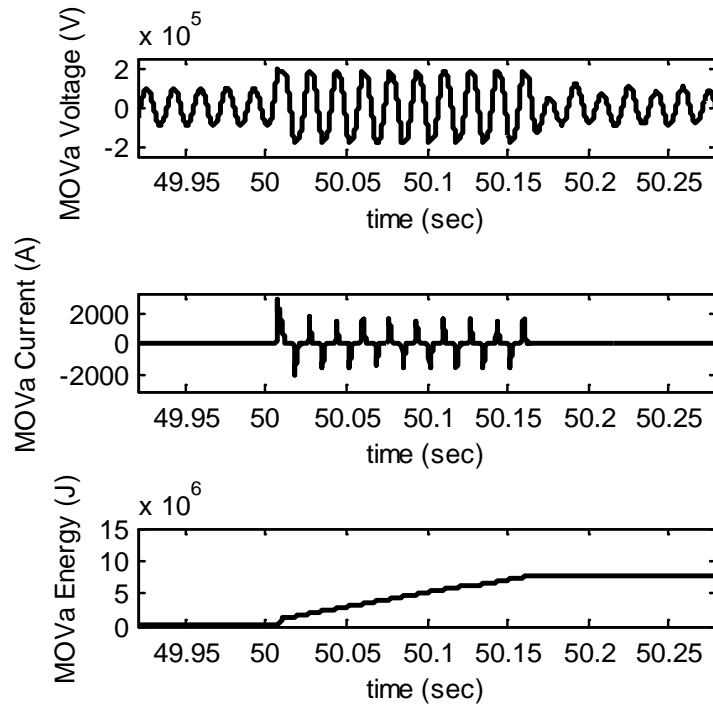
Figure 4.12 Phase a - MOV characteristics with SLG fault at capacitor terminal
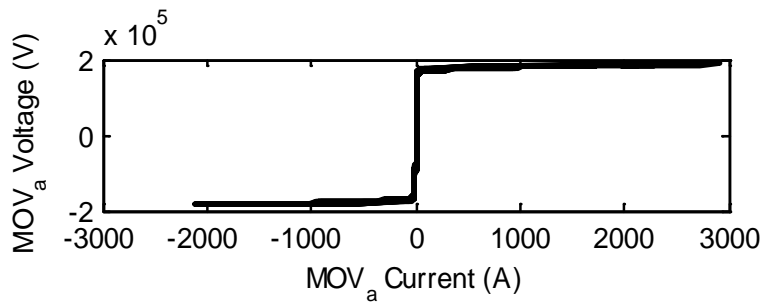
Figure 4.13 MOV V-I characteristics for phase "a" during a SLG fault (minimum wind power). Phases "b" and "c" have zero current.

This chapter analyzed the effect of wind energy variability on the operation of the MOV during faults. The unbalanced fault results showed that the intermittency of wind farm generation affects the current magnitudes and amount of energy absorbed by the MOV during fault conditions. MOV setting and rating analysis must be performed if the

wind farms are to be added to the power system to ensure reliability of MOV protection.

Malfunction operation of MOV due to wind energy variation during the unbalanced fault

may be avoided using coordinated control that can monitor wind power variation and

adjust number of active MOV columns to keep the level of energy consumption

irrespective of the wind energy variation.

CHAPTER FIVE

FIXED SETTING MHO RELAY RESULTS

First, as a base case, the simulation is run for 0% of series compensation and

average wind power. Second, the average wind power condition at different

compensation levels is compared to the 0% compensation base case. Lastly, the three

wind power levels at 60% compensation are presented and compared to the base case.

5.1 Base Case: 0% Compensation with Average Wind Power

The apparent impedance of the base case is shown in Figures 5.5-5.7. From these

figures, it can be observed that the final value of the impedance trajectory falls right on

the line impedance and represents the impedance from the relay to the fault location.

For example, Figure 5.1 shows that at a 0 km fault, relay-A measures apparent

impedance to be 0 Ω. For the same fault location relay-B measures the apparent

impedance to be 40.26+286.26j Ω. Relay B sees a fault at 603 km, which is quite

accurate with a small percent error of 0.5%.

Another example, as seen in Figure 5.7, shows that for a 600km fault, relay-A

measures apparent impedance to be 34.4+289.3j Ω, which is 598km from the relay

location, and relay-B measures 0 Ω, or equivalently 0 km fault. This shows accurate

readings of distance relays A and B with a percent error of 0.33%. A similar analysis can

be done for other fault locations. From the simulation results, it is noticed that 0 km to

400 km faults fall into the primary protection zone 1, whereas 500 km and 600 km faults

fall into the backup protection zone 2. Therefore, the base case verifies that the mho

distance relays accurately measure the apparent impedance and fault location on the

transmission line without series compensation.
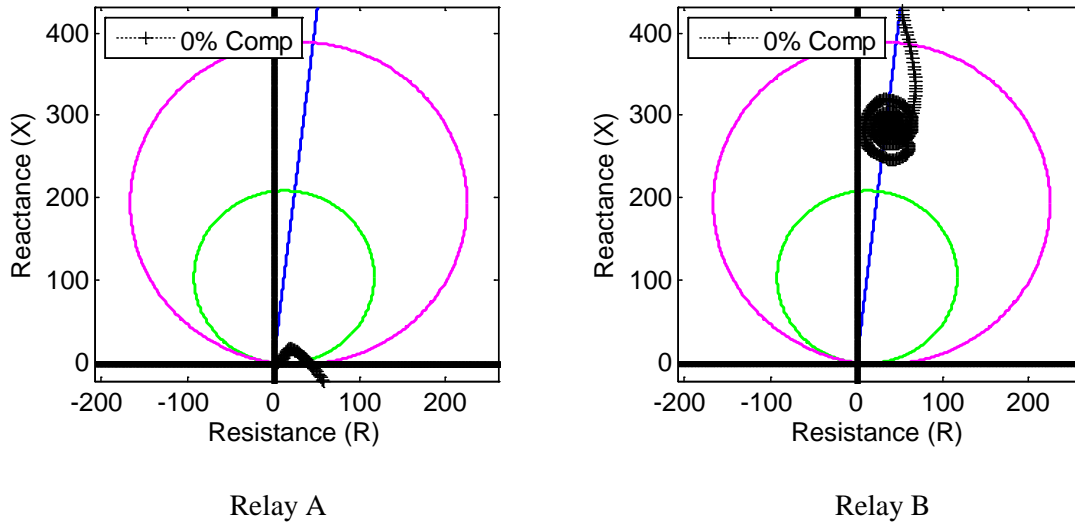
<div align="center">Relay A   Relay B</div>

Figure 5.1 Relays setting (at 0% compensation) and faults trajectory with average wind:

<div align="center">SLG fault at 0 km from bus 7</div>
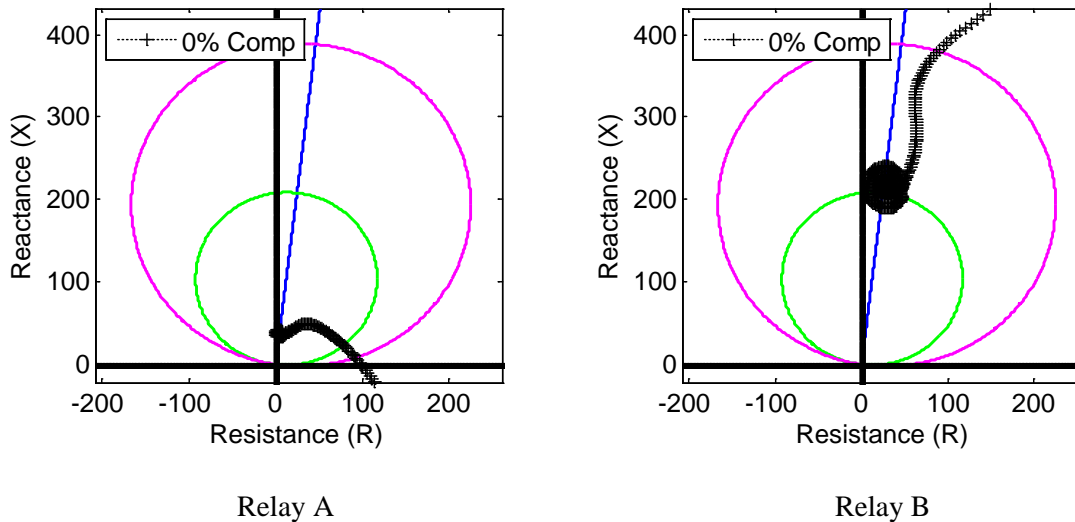
<div align="center">Relay A   Relay B</div>

Figure 5.2 Relays setting (at 0% compensation) and faults trajectory with average wind:

<div align="center">SLG fault at 100 km from bus 7</div>
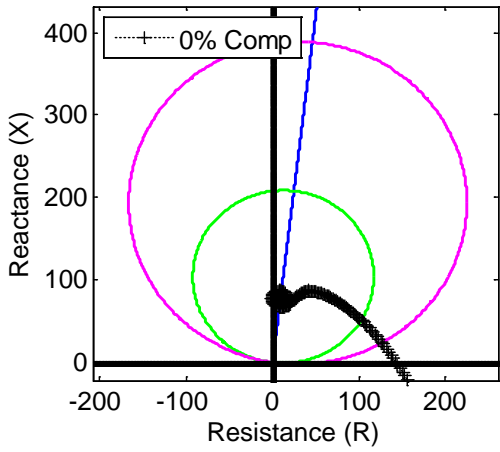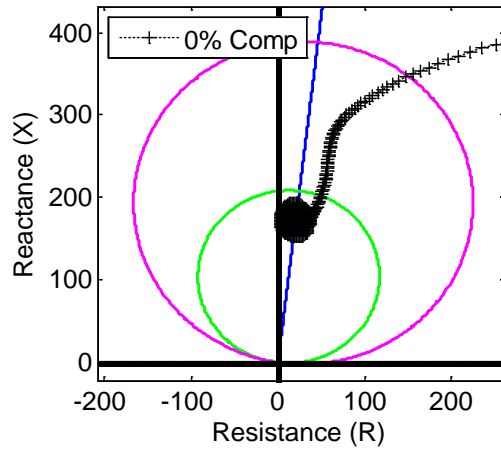
Relay A   Relay B

Figure 5.3 Relays setting (at 0% compensation) and faults trajectory with average wind:

SLG fault at 200 km from bus 7
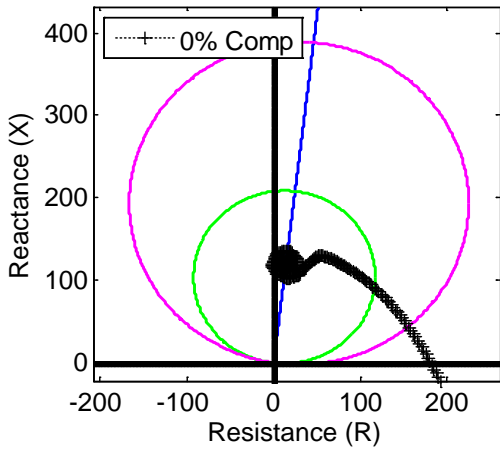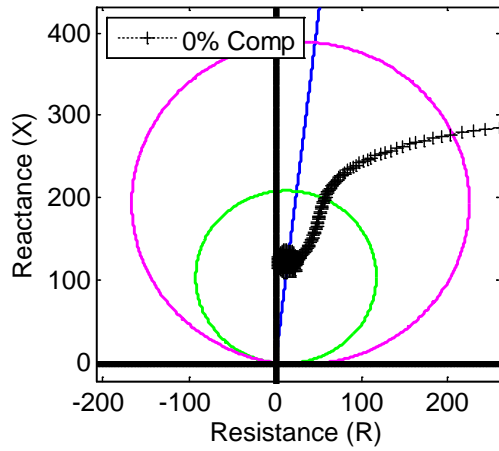
Relay A   Relay B

Figure 5.4 Relays setting (at 0% compensation) and faults trajectory with average wind:

SLG fault at 300 km from bus 7
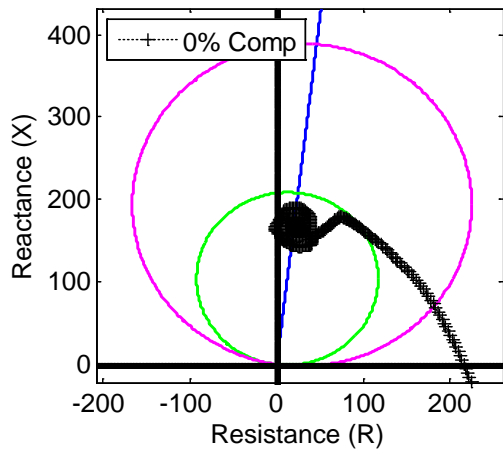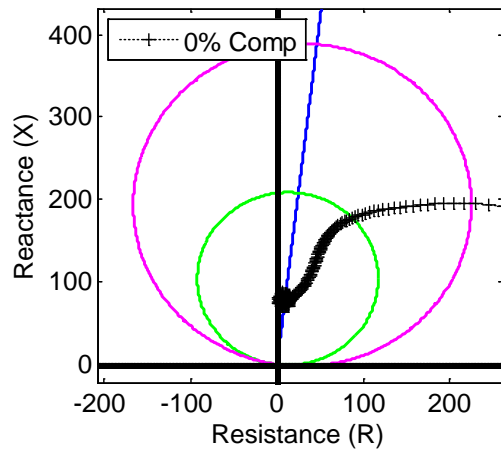
Relay A   Relay B

Figure 5.5 Relays setting (at 0% compensation) and faults trajectory with average wind:

SLG fault at 400 km from bus 7
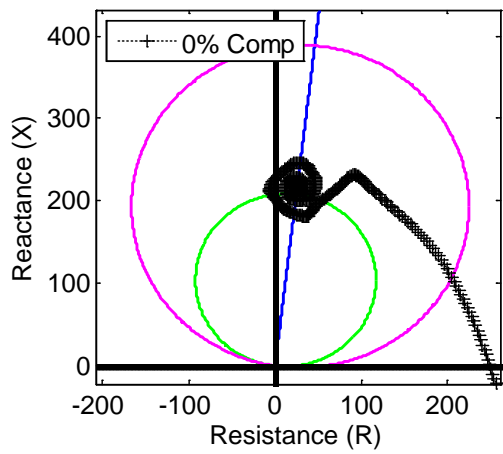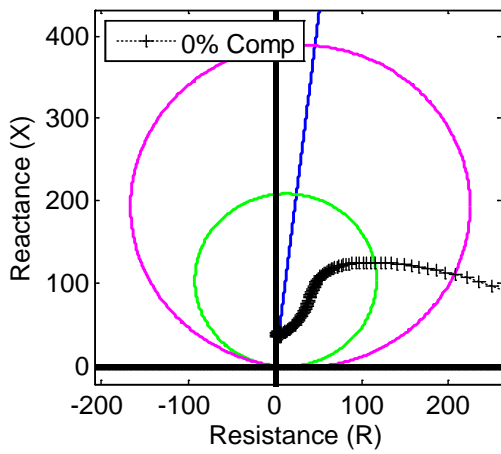
Relay A   Relay B

Figure 5.6 Relays setting (at 0% compensation) and faults trajectory with average wind:

SLG fault at 500 km from bus 7

<div align="center">Relay A   Relay B</div>
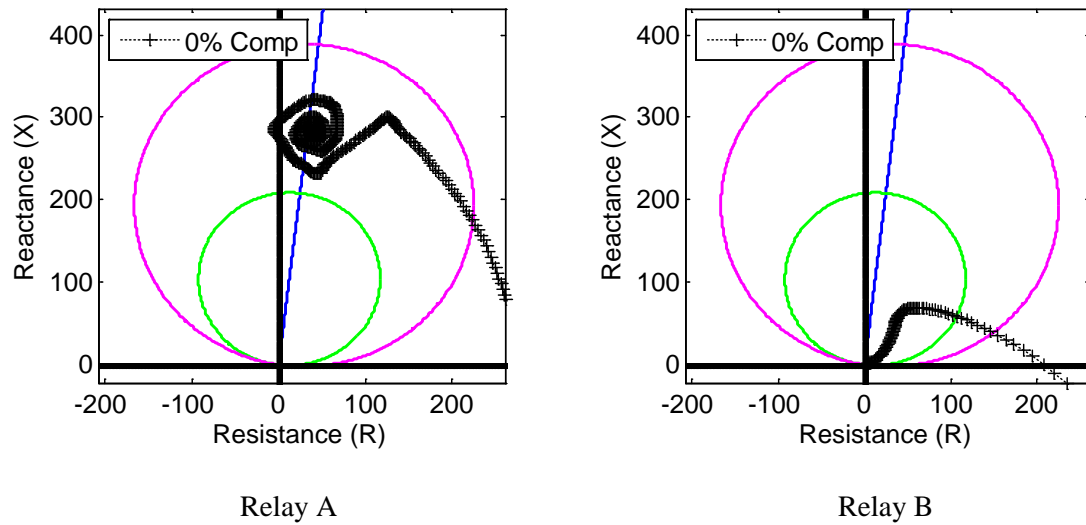
Figure 5.7 Relays setting (at 0% compensation) and faults trajectory with average wind:

SLG fault at 600 km from bus 7

5.2 A Case without Distributed Parameters (0% Compensation and Average Wind)

The apparent impedance for the case where transmission line shunt capacitance is neglected is shown in Figures 5.8-5.11. From these figures, it can be observed that both mho relay reach setting and apparent impedance final values are affected and differ from the base case of section 5.1. The relay reach setting underreaches for faults farther away from the relay location. Figures 5.8 and 5.11 show that the apparent impedances fall outside of relay protection zones 1 and 2, but should really fall inside the backup protection zone. For a 600 km fault in Figure 5.11, for example, relay-A measures apparent impedance to be $53.98+293.57j$ Ω, which is 787 km away from relay location. The distance relay reading shows a percent error of 31%, which definitely cannot be neglected. Figures 5.10 and 5.11 also show that the apparent impedance trajectory of Relay-A shifts from the impedance line for faults farther away from relay. Therefore, the

relay risks to misoperate and affects the reliability of transmission network without considering distributed parameters in the relay setting and apparent impedance calculation.
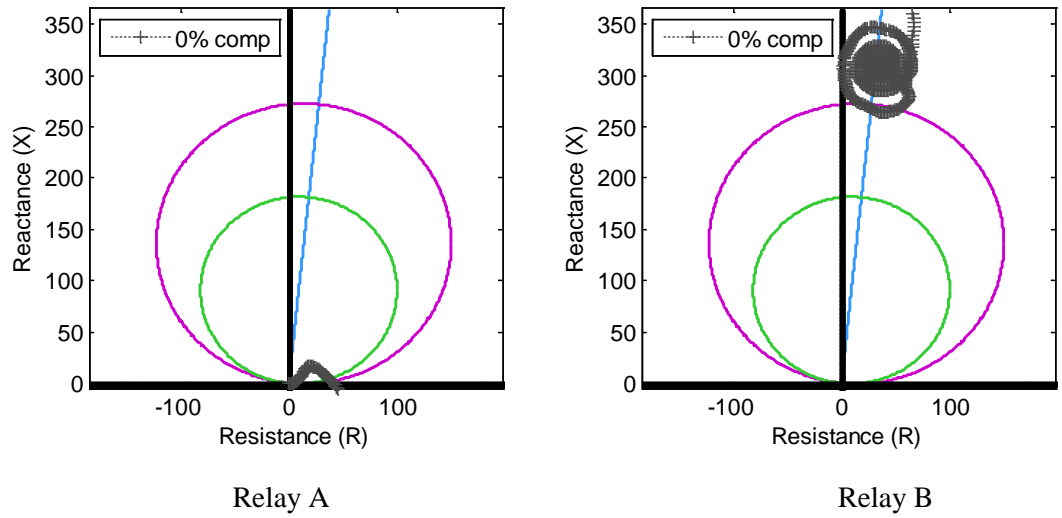
Relay A	Relay B

Figure 5.8 Relays setting without distributed parameters: SLG fault at 0 km from bus 7
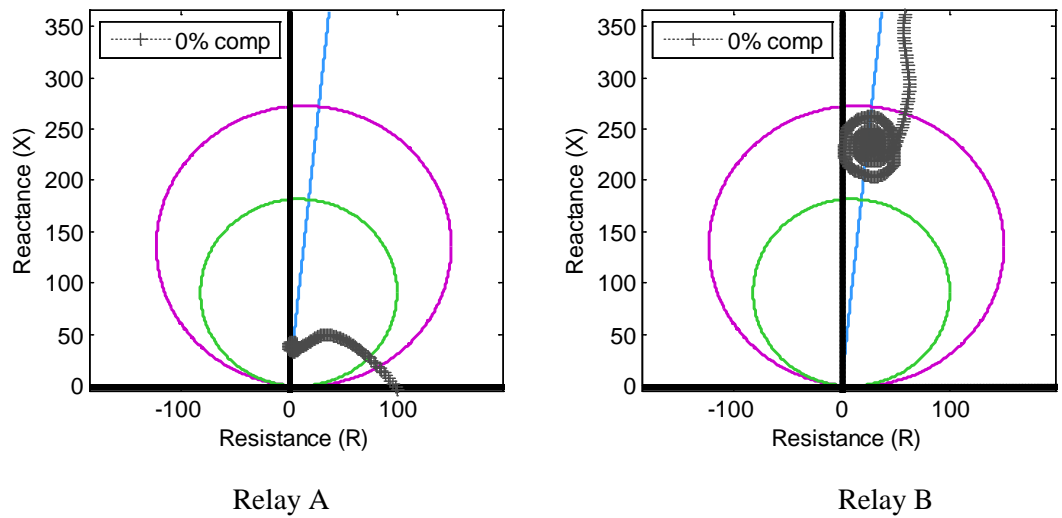
Relay A	Relay B

Figure 5.9 Relays setting without distributed parameters: SLG fault at 100 km from bus 7
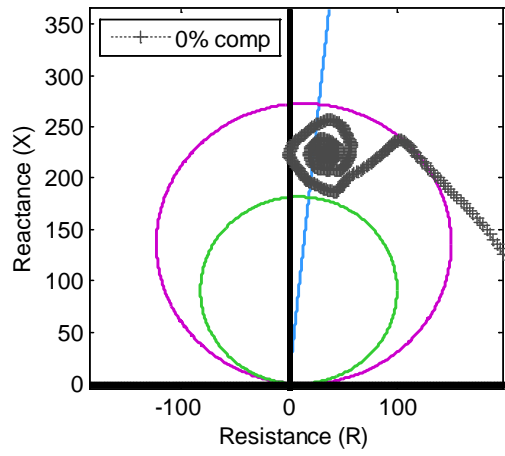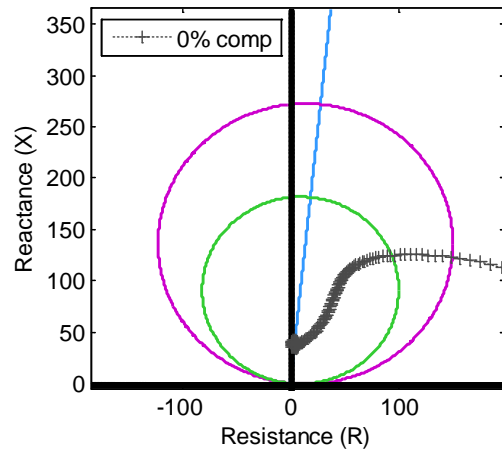
Relay A   Relay B

Figure 5.10 Relays setting without distributed parameters: SLG fault at 500 km from bus 7
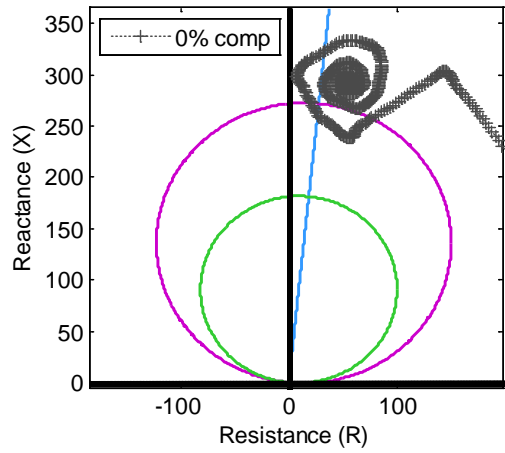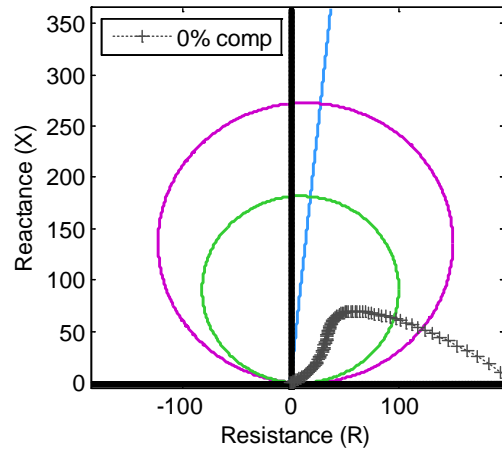
Relay A   Relay B

Figure 5.11 Relays setting without distributed parameters: SLG fault at 600 km from bus 7

5.3 A Case Study of Different Compensation Levels (Considering MOV Action) with Average Wind Power

The apparent impedances for this case are shown in Figures 5.12-5.19, where the purple (star), red (circle), and blue (square) trajectories are the 20%, 40%, and 60% compensation levels, respectively. These figures, shows that different series compensation levels significantly change the apparent impedance seen by the relays A and B. The apparent impedance for the same fault location may fall in a different protection zone as shown by relay B in Figures 5.12, 5.13. The apparent impedance falls into the primary protection zone 1 for a 600km and 500km faults, due to the compensation. An apparent impedance for 600km or 500km fault would normally fall into protection zone 2. The relay reach settings must be able to adapt to changes in line compensation. Without accurate estimation of compensation levels (or equivalent MOV/capacitor impedance), the relays may misoperate and have a great effect on the stability of the entire power system. Compensation levels may change due to partial bypassing of the capacitor as a result of MOV action during faults with intermittent wind generation. For very high fault currents, the MOVs may completely bypass the capacitor bank, reducing the compensation to nearly zero reactive impedance.
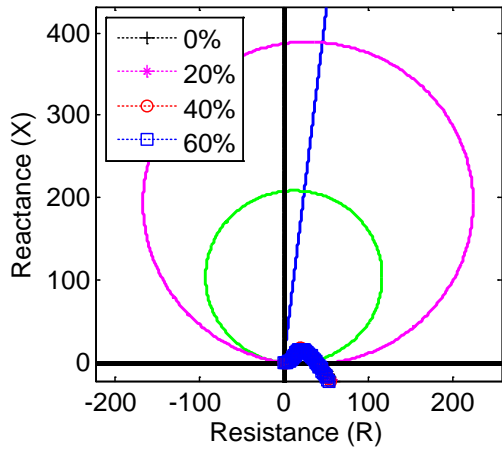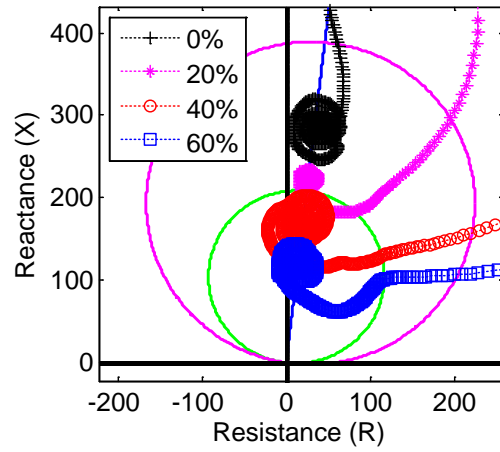
Relay A   Relay B

Figure 5.12 Relays setting (at 0% compensation) and faults trajectories for different

compensations with average wind power: SLG fault at 0 km from bus 7

Relay A   Relay B

Figure 5.13 Relays setting (at 0% compensation) and faults trajectories for different

compensations with average wind power: SLG fault at 100 km from bus 7
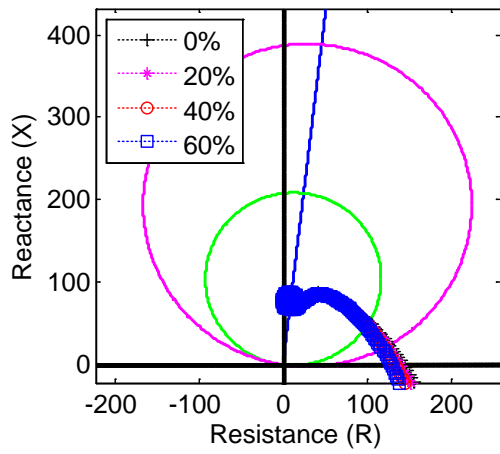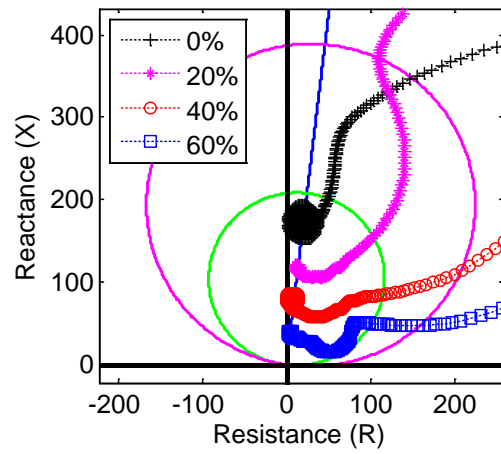
Relay A   Relay B

Figure 5.14 Relays setting (at 0% compensation) and faults trajectories for different
compensations with average wind power: SLG fault at 200 km from bus 7
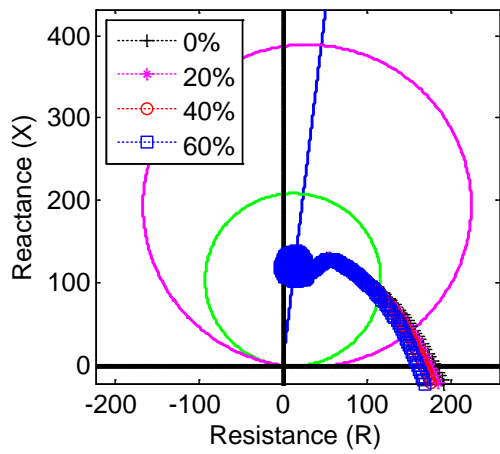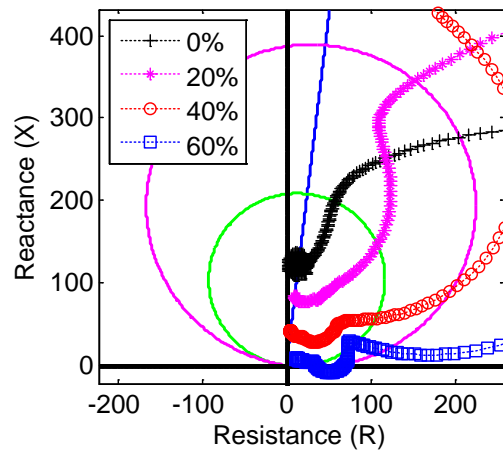
Relay A   Relay B

Figure 5.15 Relays setting (at 0% compensation) and faults trajectories for different
compensations with average wind power: SLG fault at 300 km from bus 7 (LHS of capacitor)
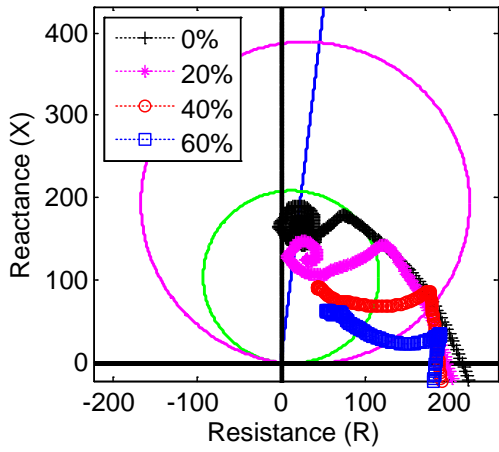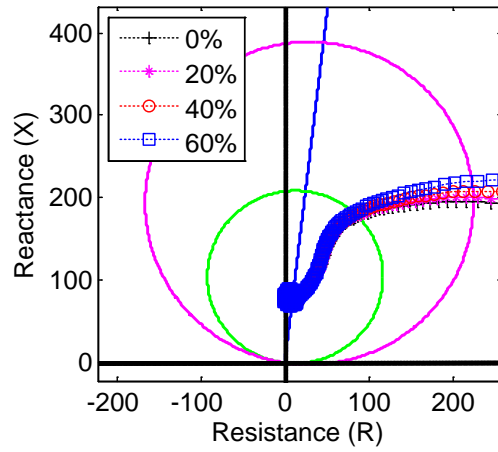
Relay A   Relay B

Figure 5.16 Relays setting (at 0% compensation) and faults trajectories for different
compensations with average wind power: SLG fault at 300 km from bus 7 (RHS of capacitor)
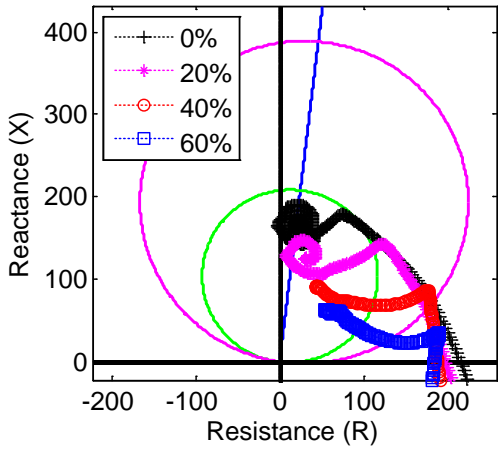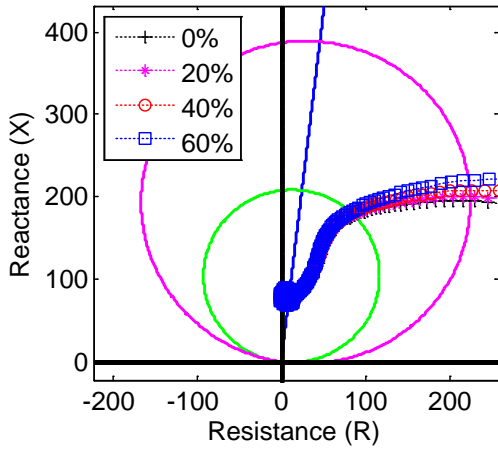
Relay A   Relay B

Figure 5.17 Relays setting (at 0% compensation) and faults trajectories for different
compensations with average wind power: SLG fault at 400 km from bus 7
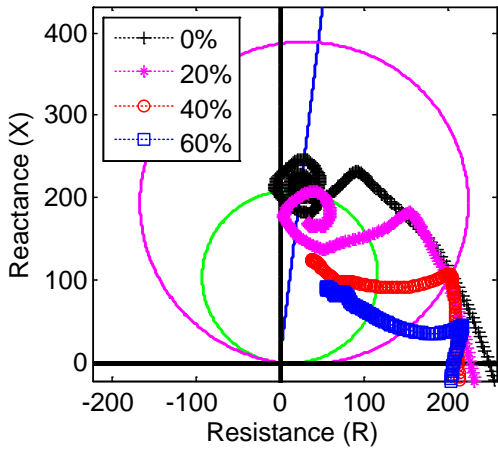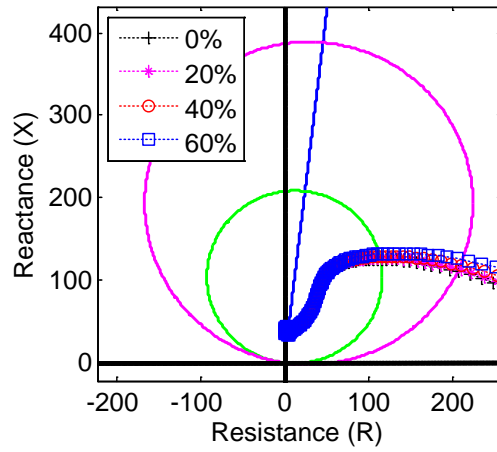
Relay A   Relay B

Figure 5.18 Relays setting (at 0% compensation) and faults trajectories for different

compensations with average wind power: SLG fault at 500 km from bus 7
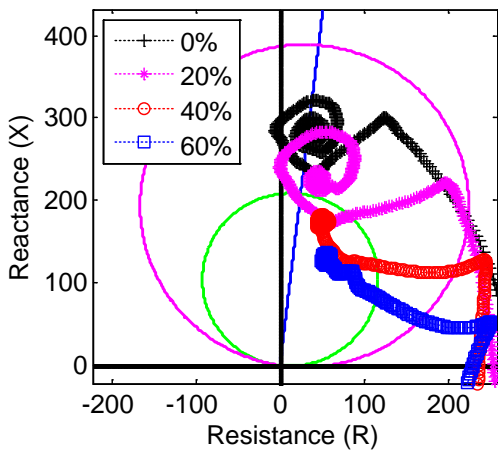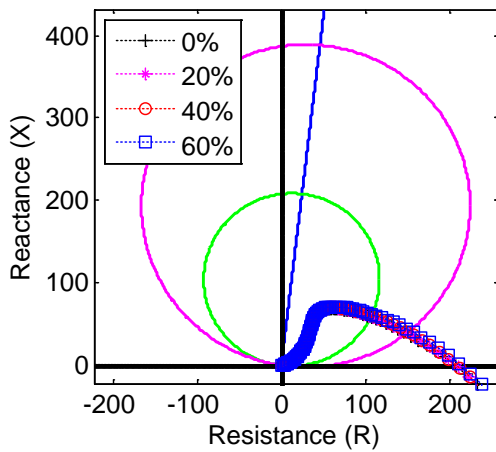
Relay A   Relay B

Figure 5.19 Relays setting (at 0% compensation) and faults trajectories for different

compensations with average wind power: SLG fault at 600 km from bus 7

It can be seen that for faults on the left side of the series capacitor in Figures 5.12-

5.15, the relay-B final values of apparent impedance trajectories fall directly on the

impedance line. For faults on the right side of the series capacitor in Figures 5.16-5.19,

the relay-A final values of apparent impedances are shifted to the right. This is because of

the equivalent impedance of MOV/capacitor, and it can be reasoned by looking at Figure

5.20 and Table 5.1. For faults on the left side of the capacitor, as seen in Figure 5.20(a),

the fault current passing through the MOV/capacitor is only due to the wind farm

generation. For faults on the right side of the capacitor, as seen in Figure 5.20(b), the fault

current passing through the MOV/capacitor is due a large source connected at bus 9. The

strong source on the left side of the capacitor can supply larger fault current than the wind

farm, and has a greater effect on the equivalent impedance of MOV/capacitor parallel

circuit.

(a)

(b)
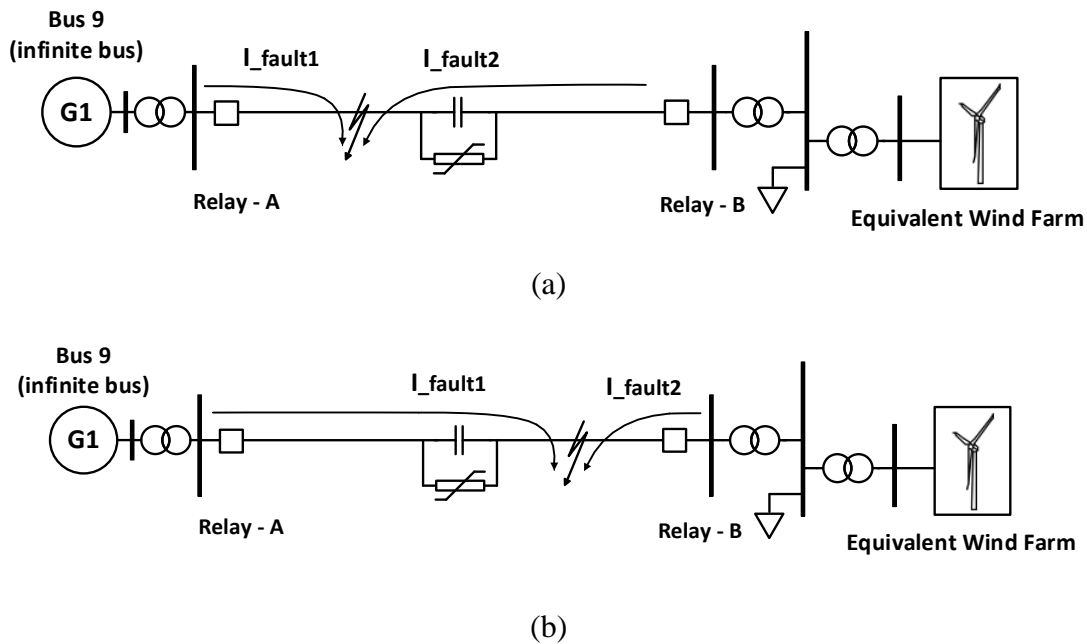
Figure 5.20 Illustration for the fault currents due to SLG fault on: (a) LHS, and (b) RHS

of the series capacitor

The equivalent impedances of MOV/capacitor for different fault locations and compensation levels are summarized in Table 5.1. This table shows that faults from 0km to 300Lkm, the equivalent MOV/Capacitor impedances have small resistive components due to relatively small fault current levels passing through the capacitor bank from the wind farm. For faults from 300Rkm to 600km, the resistive component of equivalent MOV/capacitor impedance is more significant. The values highlighted, in bold, in Table 5.1 identify the equivalent MOV/capacitor impedances with significant resistive components which cause the shift in Figures 5.16-5.19 can be further explained by Figure 5.20. This figure also clarifies the discrepancy between relay-A measurements for 300Rkm to 600km faults and relay-B measurements for 0km to 300Lkm in Figures 5.12-5.19.

Figures 5.21 and 5.22 show an example of the effects of MOV action on the MOV/capacitor equivalent impedance for a 300km fault on the 60% compensated line with the average wind. The MOV partially bypasses the capacitor on phase-A, as seen in Figure 5.21, and modifies phase-A equivalent MOV/capacitor impedance as seen in Figure 5.22. Due to MOV action, the series capacitor impedance on phase-A is modified from -136jΩ (60% compensation) to equivalent MOV/capacitor impedance of 42.4-93.653j Ω. Larger fault current has a greater effect on equivalent impedance. For very high fault current, the compensation is reduced to nearly zero percent which would have a similar effect of apparent impedances (black trajectory) in Figures 5.1-5.7. Without adjusting distance relay settings, overreaching or underreaching may occur and will cause relay to misoperate.

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Table 5.1 Measured equivalent MOV/capacitor impedances during average wind level

Equivalent MOV/Capacitor Impedance (Ω) for a SLGF on phase A				
	0% Compen	20% Compen	40% Compen	60% Compen
0	0.0001	0.876-45.279i	1.906-90.252i	1.09-135.745i
100	0.0001	0.659-45.217i	1.968-91.023i	5.571-134.268i
200	0.0001	0.043-45.278i	1.783-91.13i	7.075-134.817i
300L	0.0001	3.906-44.392i	4.136-90.063i	18.8-128.913i
300R	0.0001	**13.74-32.284i**	**26.582-66.947i**	**42.426-93.653i**
400	0.0001	**10.64-38.431i**	**19.787-78.844i**	**36.208-108.578i**
500	0.0001	**5.761-43.3i**	**8.73-88.204i**	**25.555-123.238i**
600	0.0001	0.18-45.251i	0.027-90.47i	**8.252-134.563i**
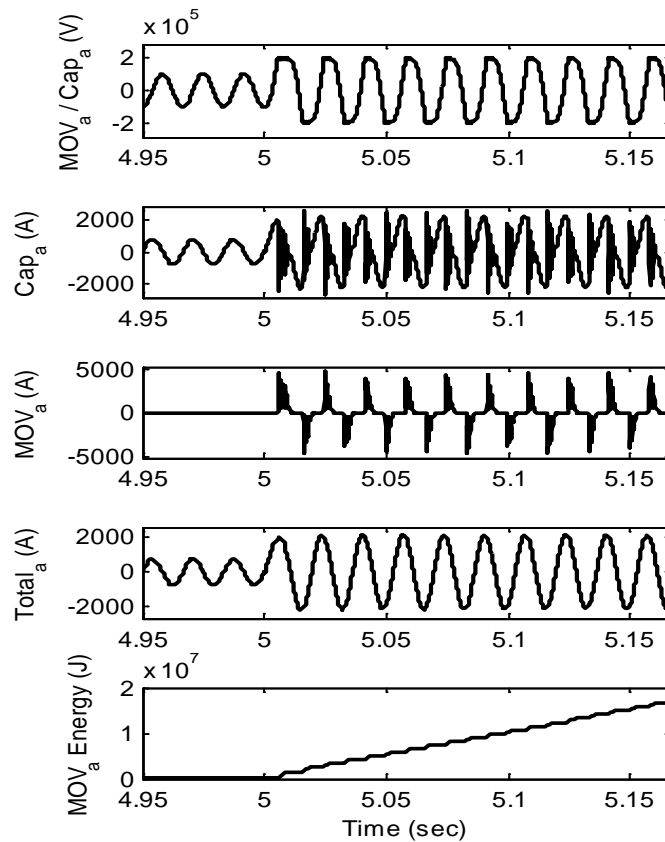
Figure 5.21 Operation of MOV and series capacitor for a 300Rkm fault, with average wind and 60% compensation
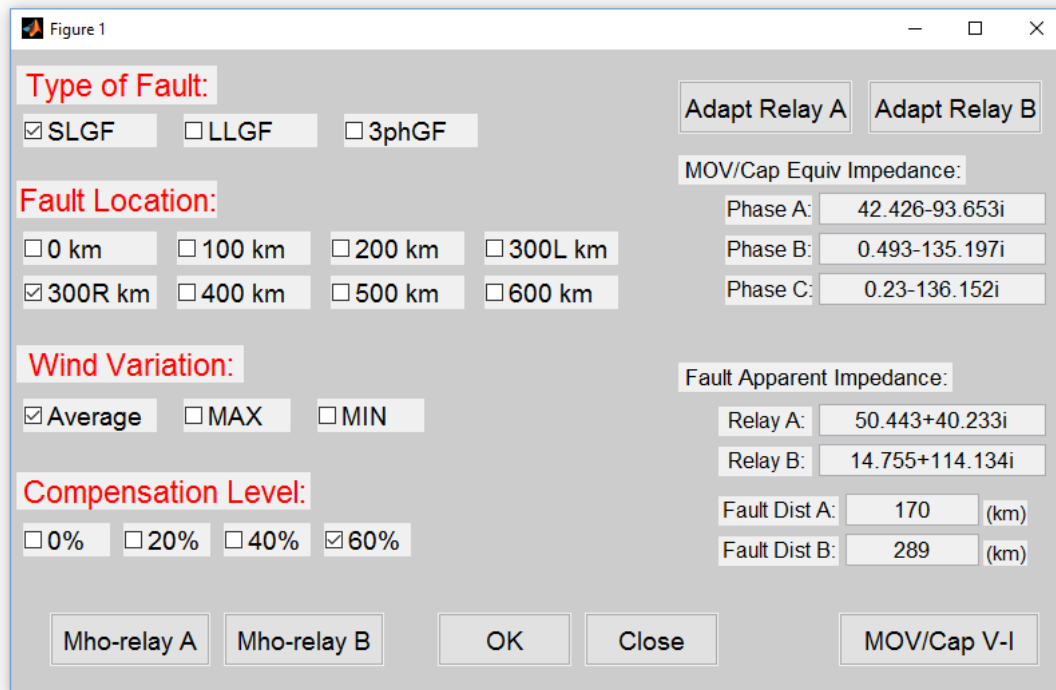
Figure 5.22 Simulink GUI shows unbalanced equivalent MOV/Cap equivalent per phase impedances for a SLGF at 300km from bus 7.

5.4 60% Compensation with Three Wind Power Levels

In this section, the effects of intermittent wind generation on the distance protection of series compensated line are analyzed. The results are shown in Figures 5.23-5.26 for four fault locations on the 60% series compensated line.

For comparison, the black trajectories in Figures 5.23-5.26 represent the apparent impedance measured by relays-A and B for zero compensation as in the base case results. For the case of zero compensation, a wind farm connected at bus 11 has no impact on the distance protection of the line. The black trajectories represent the identically three wind

levels. The trajectories in purple (circle), blue (square), and red (star) denote the apparent impedances for average, maximum, and minimum wind generation levels, respectively.

The variable wind power changes the measured apparent impedance seen by the distance relays. The different generation levels of the wind farm appear to change power flows on the compensated line, which during a fault affect fault current level and MOV/capacitor equivalent impedance. For example, for maximum (or average) wind generation levels, the power flow in the compensated line appears to be at its minimum level as the majority of the large load demand at bus 3 is met by the local wind generation at bus 11. However, for minimum wind generation level, the bulk generation at bus 11 is no longer available. The majority of the power delivered to bus 3 comes from the strong source at bus 9 through the low impedance compensated line. Thus, loss of wind generation results in higher currents through the compensated line which affect equivalent MOV/capacitor impedance during a fault. Therefore, a variation of wind farm generation affects distance protection of the line through the equivalent impedance of the MOV/capacitor. Four examples of the effects of different wind generation level on the apparent impedances of relays A and B are shown in Figures 5.23-5.26.
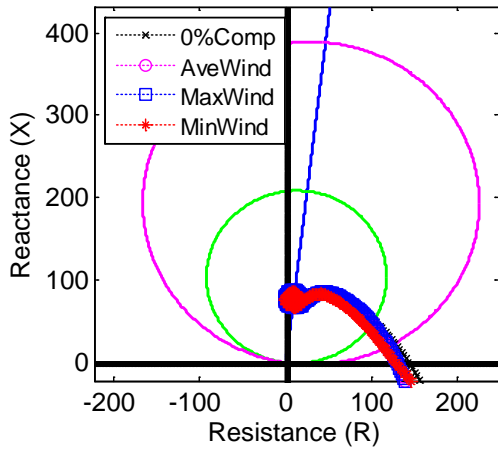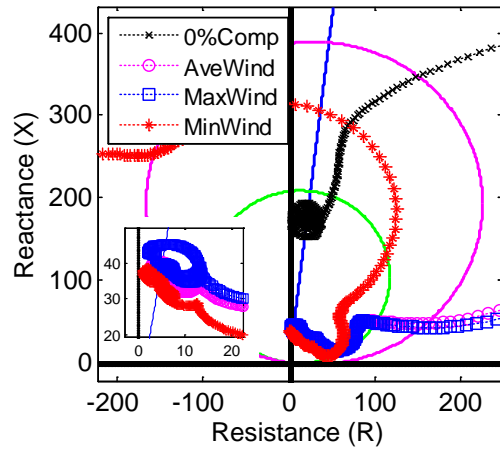
Relay A   Relay B

Figure 5.23 Relays setting (at 0% compensation) and faults trajectories for 60%

compensation with three wind power levels: SLG fault at 200 km from bus 7
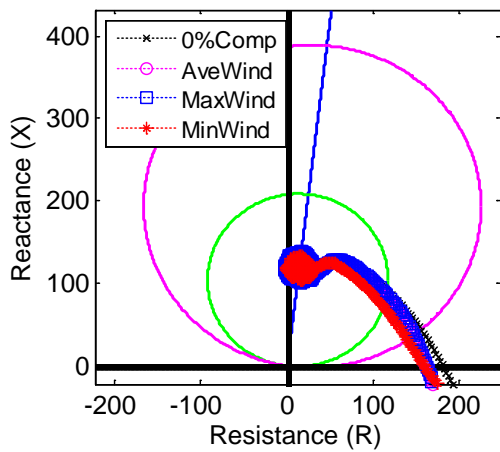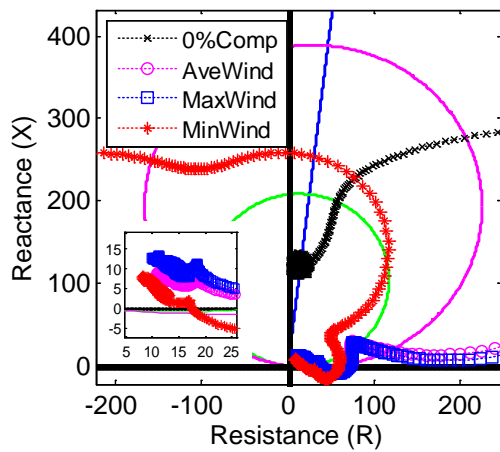
Relay A   Relay B

Figure 5.24 Relays setting (at 0% compensation) and faults trajectories for 60%

compensation with three wind power levels: SLG fault at 300 km from bus 7 (LHS of
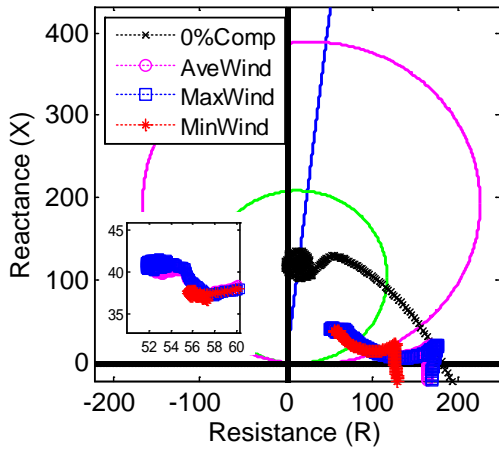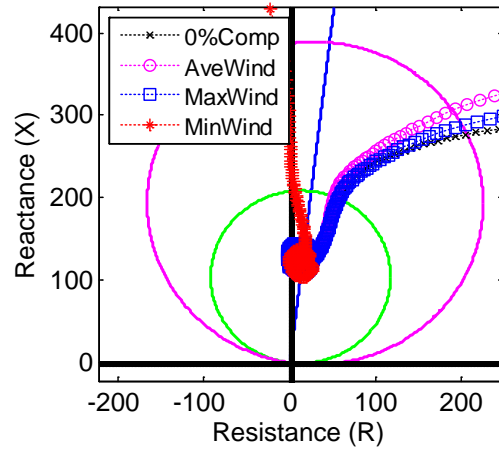
capacitor)

Relay A   Relay B

Figure 5.25 Relays setting (at 0% compensation) and faults trajectories for 60%
compensation with three wind power levels: SLG fault at 300 km from bus 7 (RHS of
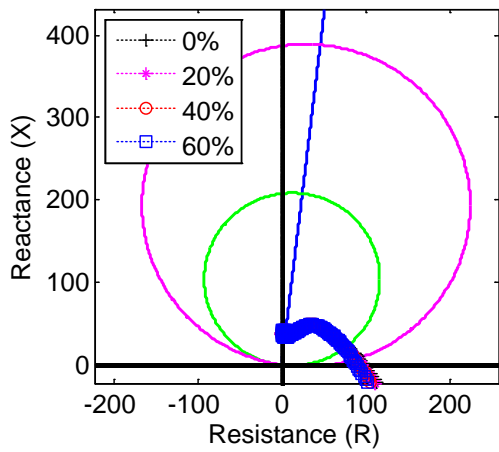capacitor)
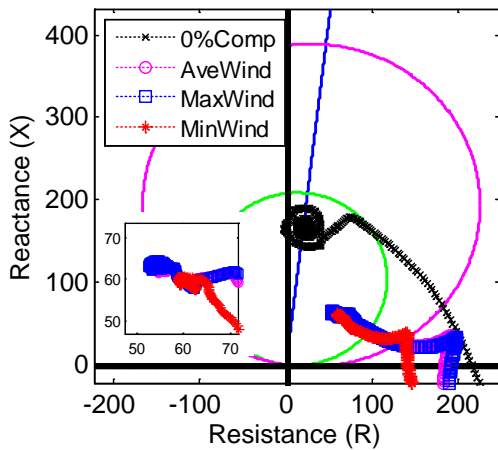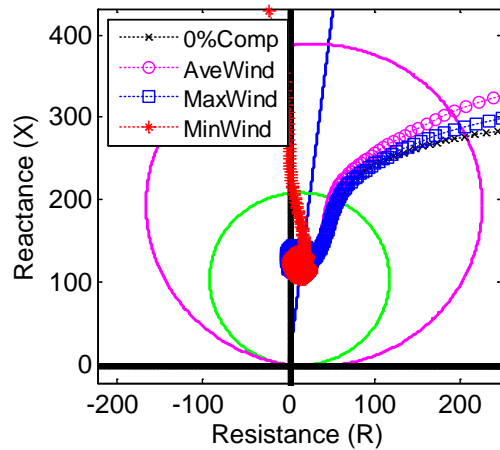
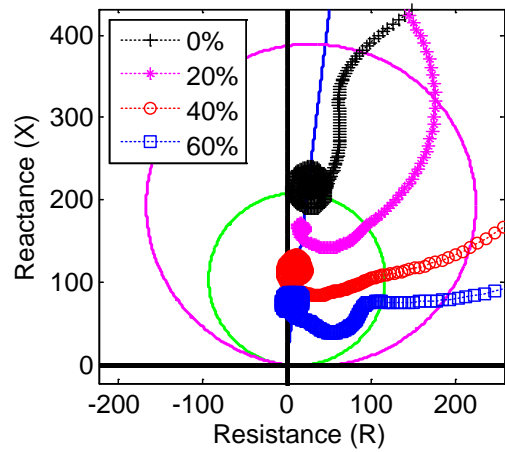Relay A   Relay B

Figure 5.26 Relays setting (at 0% compensation) and faults trajectories for 60%
compensation with three wind power levels: SLG fault at 400 km from bus 7

CHAPTER SIX

PROPOSED ADAPTIVE SETTING

Figures 6.1 and 6.2 show a schematic and a flow chart algorithm for the proposed method, respectively. In Figure 6.1, relays A and B are located at each terminal of the line where local bus voltages and currents are measured and serve as inputs to the relays. Additional current measurement and voltage measurements are required at both terminals of the series capacitor. Also, a dedicated communication channel is required between relay A, series capacitor, and relay B. In addition, PMU measurements can be used to get remote signals.

The flowchart in Figure 6.2 summarizes the proposed algorithm for adaptive setting of distance mho relay with MOV-protected series compensation. The distance relays A and B are initially set for an uncompensated line with zones 1 and 2 reach settings. Voltages and currents are measured at the relay locations A and B. Each measured signal is passed through a low-pass filter and an FFT to obtain magnitude and phase of the signal's fundamental component. The resulting three phase voltages and currents are passed through the relay's fault detection algorithm. The apparent trajectory impedance is calculated as described in section 2.3. From the measured signals at the series capacitor location, the per phase equivalent impedance is calculated for the parallel connection of MOV and capacitor as given in (6-1).

$$Z_{MOV/Cap} = (V_{Left} - V_{Right}) / I_L \qquad\qquad (6\text{-}1)$$

where V_{Left} and V_{Right} are the series capacitor terminal phase voltages, and I_L is the line current at the capacitor location.

The fault location with respect to the capacitor bank can be determined through either directional relay, the direction of active power flow, or other directional discrimination methods. For a fault on the left side of the capacitor bank, the calculated equivalent impedance ZMOV/CAP is seen by relay B to adjust the settings of the relay, but a value of zero is seen by relay A since the impedance between the relay and the fault will include only line impedance with no compensation. Similarly, for a fault on the right side of the capacitor bank the calculated impedance ZMOV/CAP is seen by relay A, but a value of zero is seen by relay B. Once the relay's setting is adjusted the relay makes a decision based on the zone coordination described in sections 2.2 and 2.3.
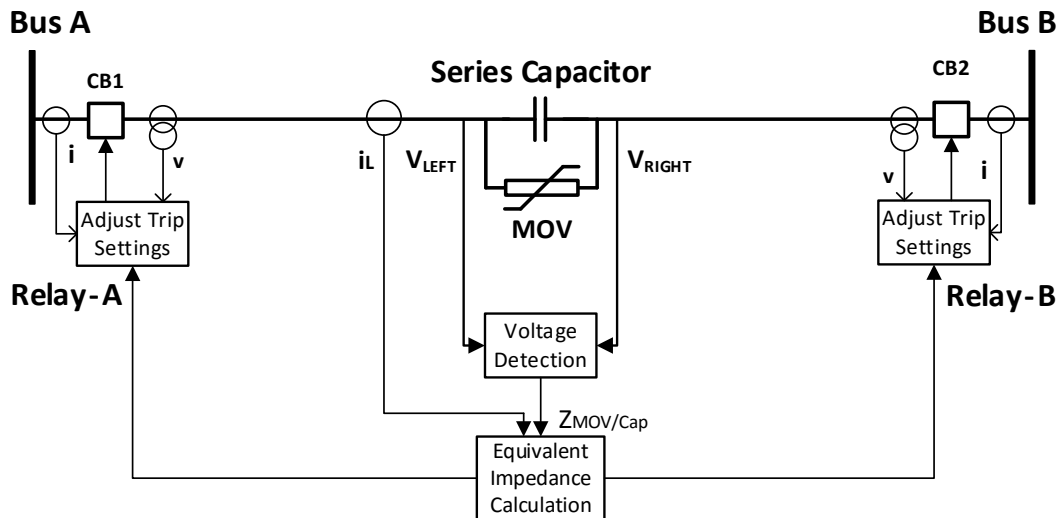
Figure 6.1 Schematic diagram of the proposed adaptive settings of mho relay for series compensated line
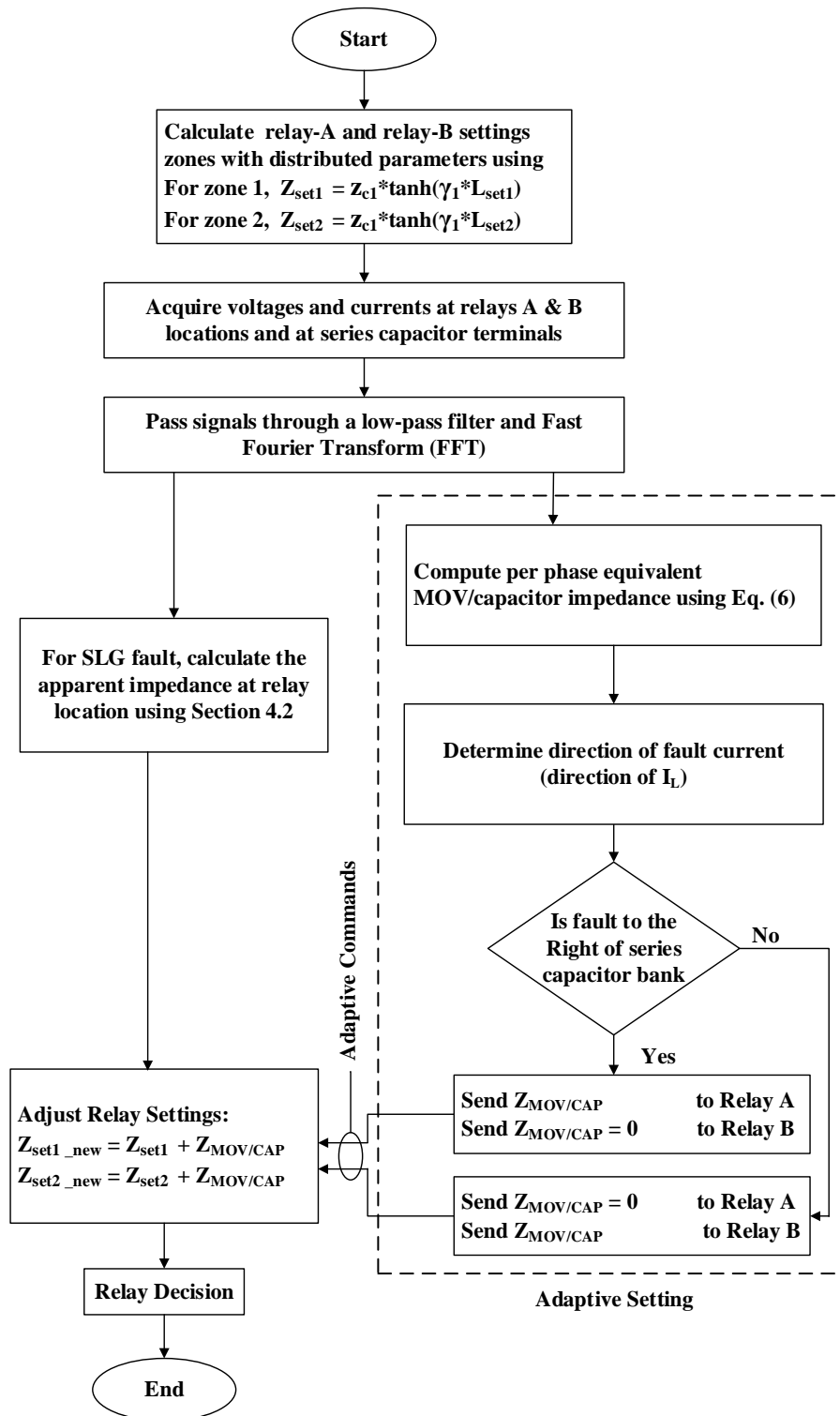
Figure 6.2 Flow chart of the proposed adaptive settings algorithm of mho relay for series compensated line

Tables 7.1-7.3 summarize the end point values of the apparent impedance trajectories for relays A and B corresponding to the three wind levels. The red values in Tables 7.1-7.3 show the variation in apparent impedances due to different MOV/capacitor equivalent impedance values for different compensation cases and wind power levels. The values that are not highlighted in red are the same for all compensation levels due the faults occurring before the series capacitor with MOV protection, which is not seen by the relays.

As shown in Table 7.1-7.3, for the same fault location and compensation level, the apparent impedance values corresponding to the maximum wind level case are sometimes close to the average wind level case, whereas the minimum wind level case values are different. In some cases, such as for faults far away from the series capacitor, all three wind level show similar apparent impedance values. In general, the apparent impedance values are changed due to different fault current levels, which are affected by different wind power levels and percent line compensation through the MOV/capacitor equivalent impedance. In contrast, the relays corresponding to the red values are adaptively reset.

CHAPTER SEVEN

ADAPTIVE SETTING RESULTS

The adaptive setting algorithm in chapter 6 is applied on the modified test system. The relays' settings automatically adapt for different system conditions. The simulation is run for the 60% compensation case at different fault locations and three wind power levels. Figures 7.1-7.18 show the relay setting and fault trajectory for the average, maximum, and minimum wind level cases. In these figures, the relays' settings are changed for different fault locations and wind power levels according to measured MOV/capacitor equivalent impedance during the fault. In Figures 7.1-7.6, for example, it can be seen that the relays zones 1 and 2, and the impedance lines are adaptively set with the change in fault location. For a fault on the LHS of the capacitor Figures 7.1-7.3, the setting of relay A is the same as in chapter 5, whereas that of relay B is changed with respect to the MOV/capacitor equivalent impedance. For the RHS fault cases in Figures 7.4-7.6, the relay A setting is adjusted by the equivalent MOV/capacitor impedance, whereas relay B setting is the same as in chapter 5. From the plots, relay A has different adaptive settings as compared to Relay B, which is due to the reason demonstrated in Figure 5.15. The cases of maximum and minimum wind levels gave similar concept and are shown in Figures 7.7-7.12 and Figures 7.13-7.18 respectively.
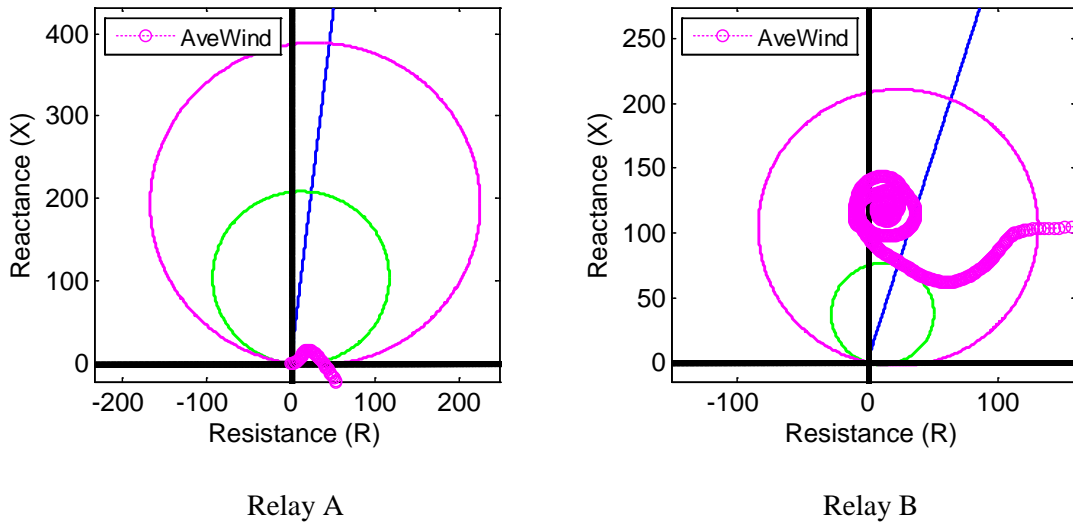
Relay A   Relay B

Figure 7.1 Adapted relay settings for average wind and 60% compensation: SLG fault at

0 km from bus 7
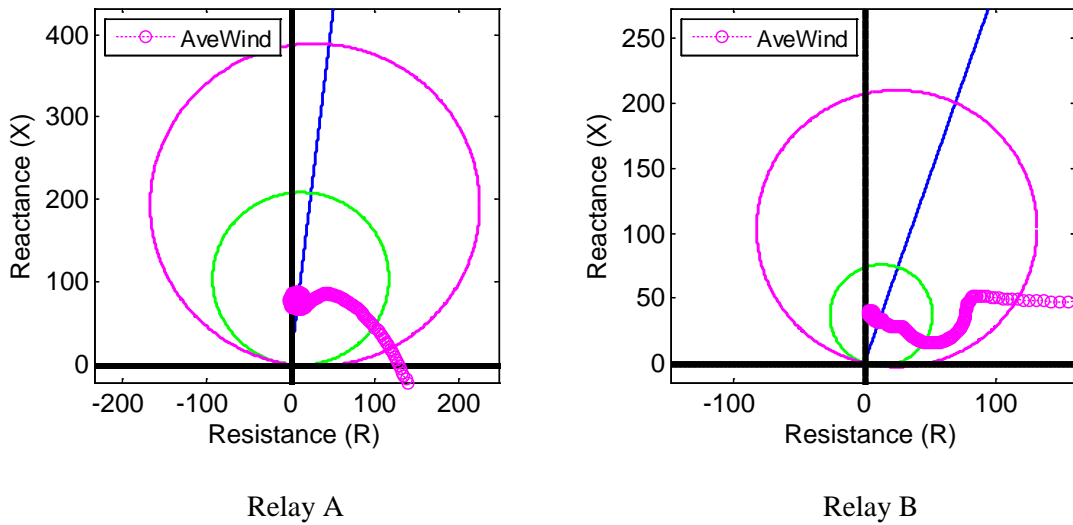
Relay A   Relay B

Figure 7.2 Adapted relay settings for average wind and 60% compensation: SLG fault at
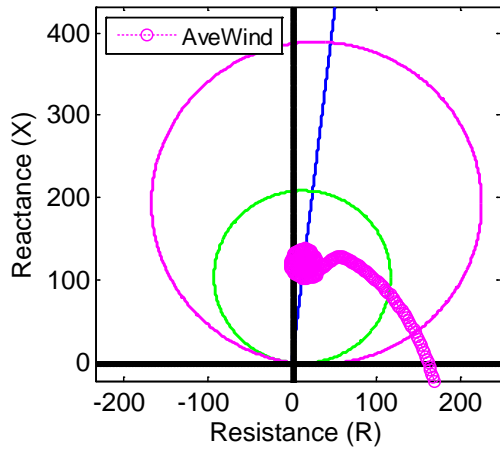
200 km from bus 7
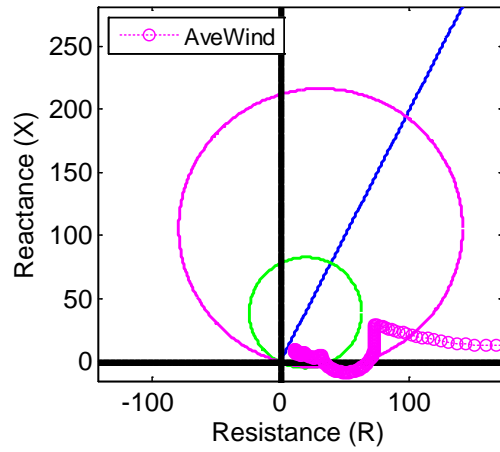
Relay A   Relay B

Figure 7.3 Adapted relay settings for average wind and 60% compensation: SLG fault at

300 km from bus 7 (LHS of capacitor bank)
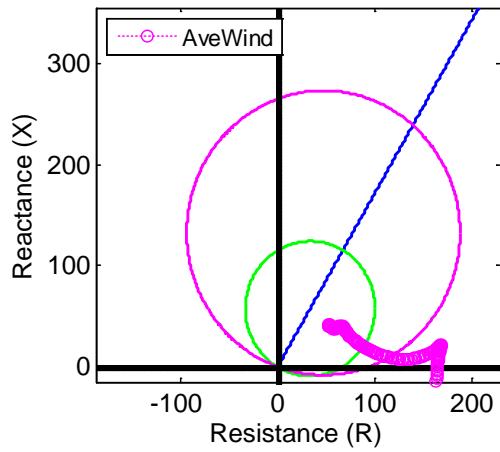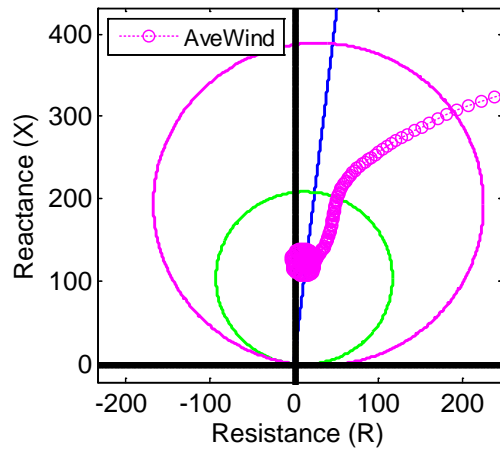
Relay A   Relay B

Figure 7.4 Adapted relay settings for average wind and 60% compensation: SLG fault at

300 km from bus 7 (RHS of capacitor bank)
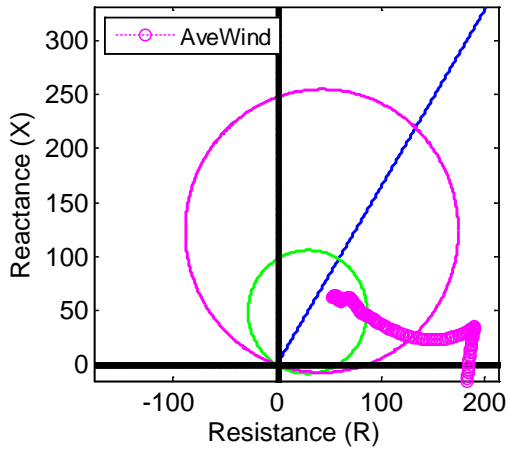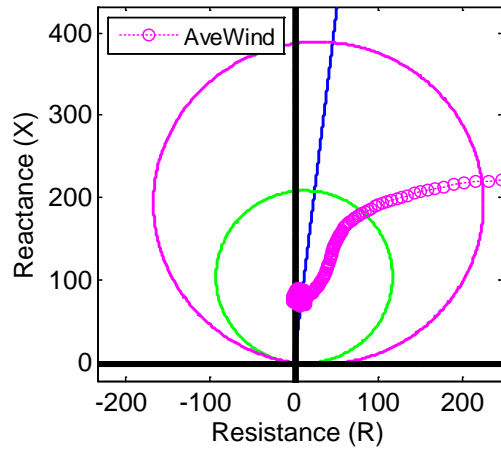
Relay A   Relay B

Figure 7.5 Adapted relay settings for average wind and 60% compensation: SLG fault at
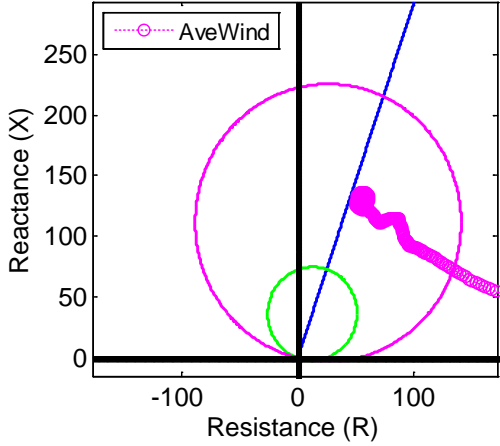
400 km from bus 7
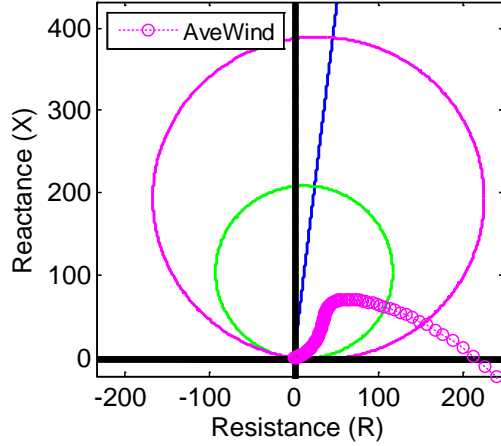
Relay A   Relay B

Figure 7.6 Adapted relay settings for average wind and 60% compensation: SLG fault at

600 km from bus 7
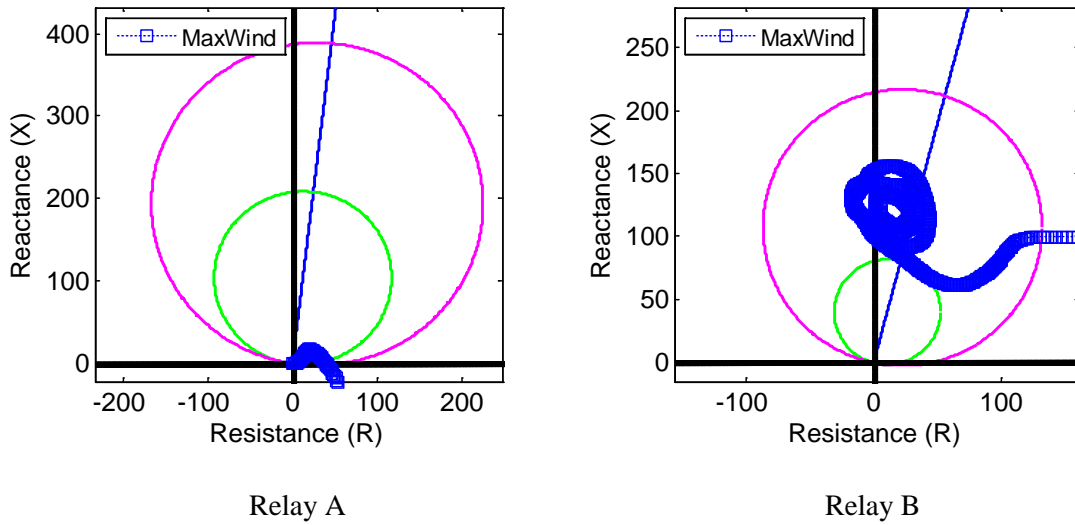
Relay A   Relay B

Figure 7.7 Adapted relay settings for maximum wind and 60% compensation: SLG fault at

0 km from bus 7
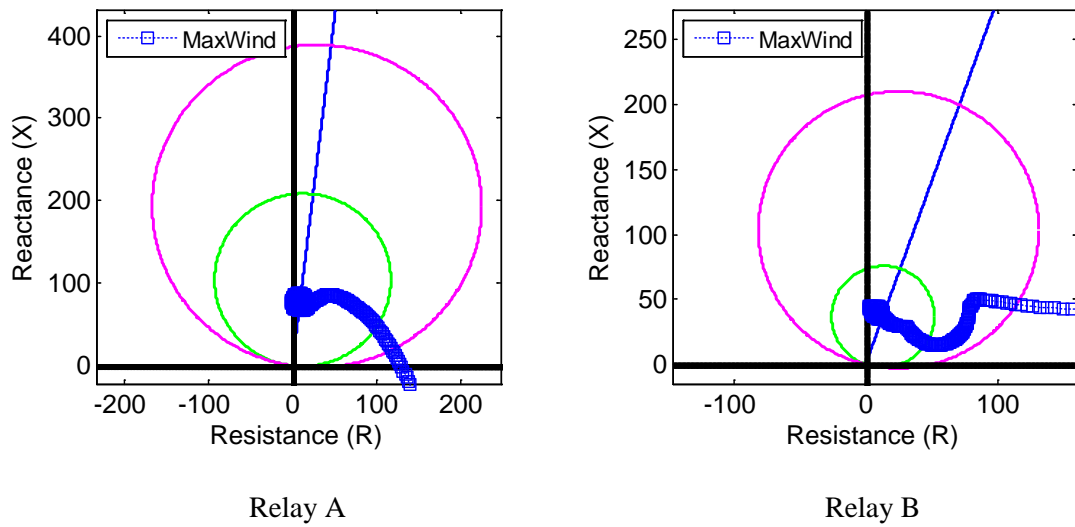
Relay A   Relay B

Figure 7.8 Adapted relay settings for maximum wind and 60% compensation: SLG fault at
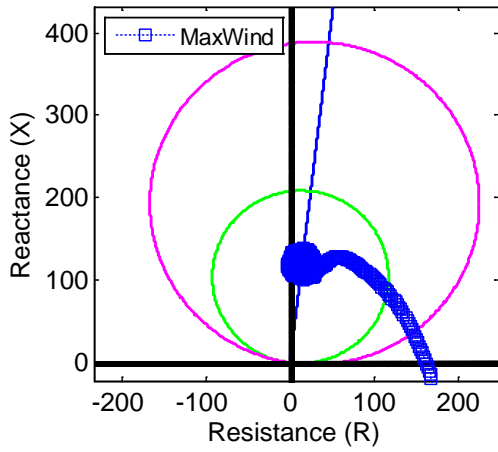
200 km from bus 7
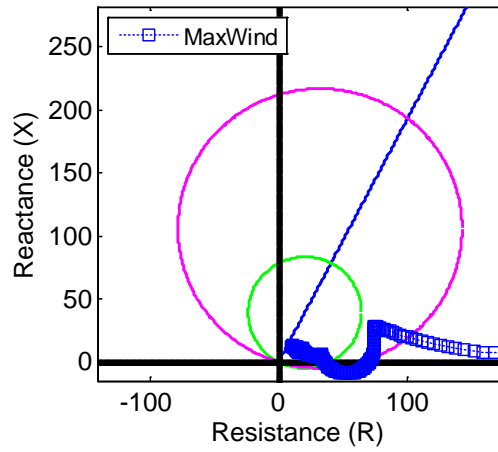
Relay A   Relay B

Figure 7.9 Adapted relay settings for maximum wind and 60% compensation: SLG fault at

300 km from bus 7 (LHS of capacitor bank)
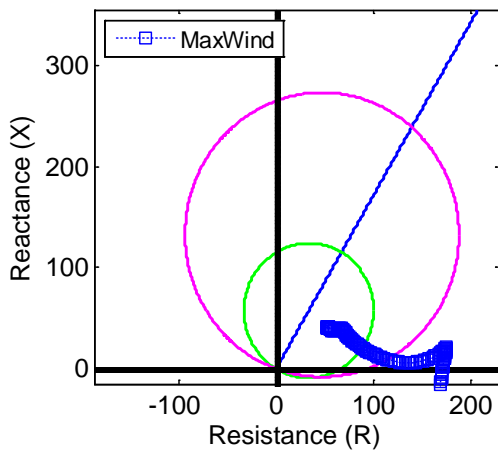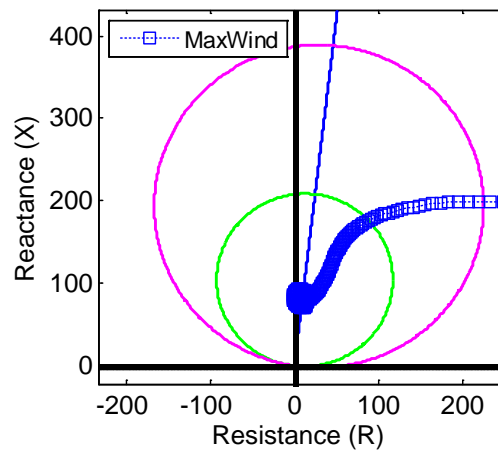
Relay A   Relay B

Figure 7.10 Adapted relay settings for maximum wind and 60% compensation: SLG fault

at 300 km from bus 7 (RHS of capacitor bank)
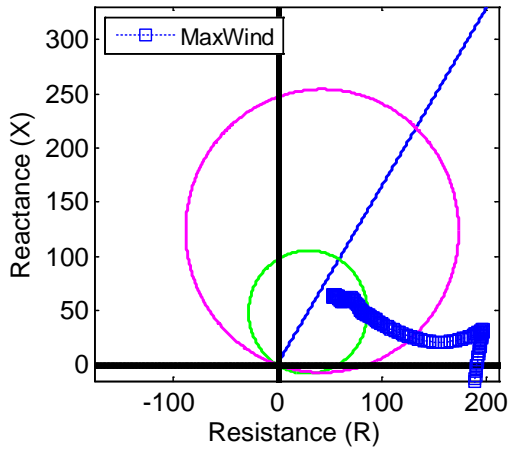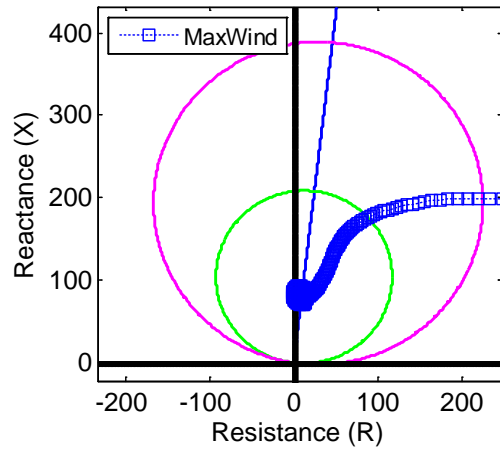
Relay A   Relay B

Figure 7.11 Adapted relay settings for maximum wind and 60% compensation: SLG fault
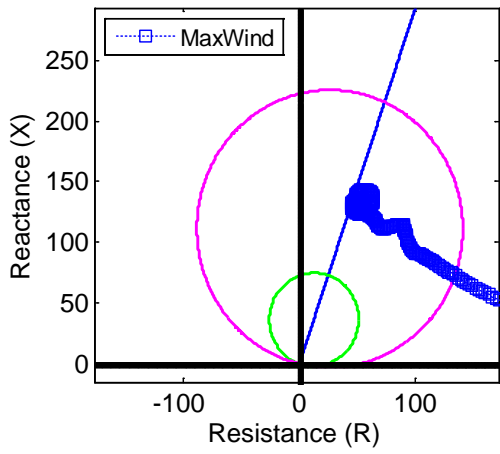
at 400 km from bus 7
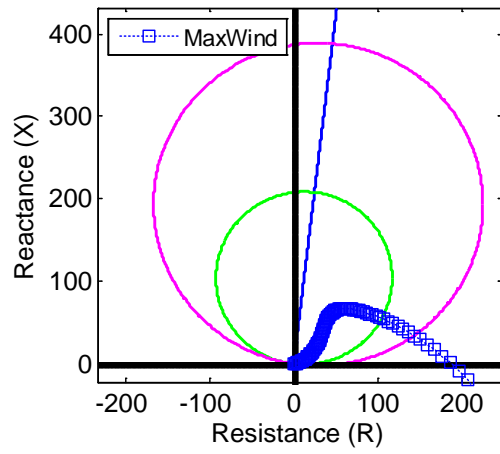
Relay A   Relay B

Figure 7.12 Adapted relay settings for maximum wind and 60% compensation: SLG fault

at 600 km from bus 7
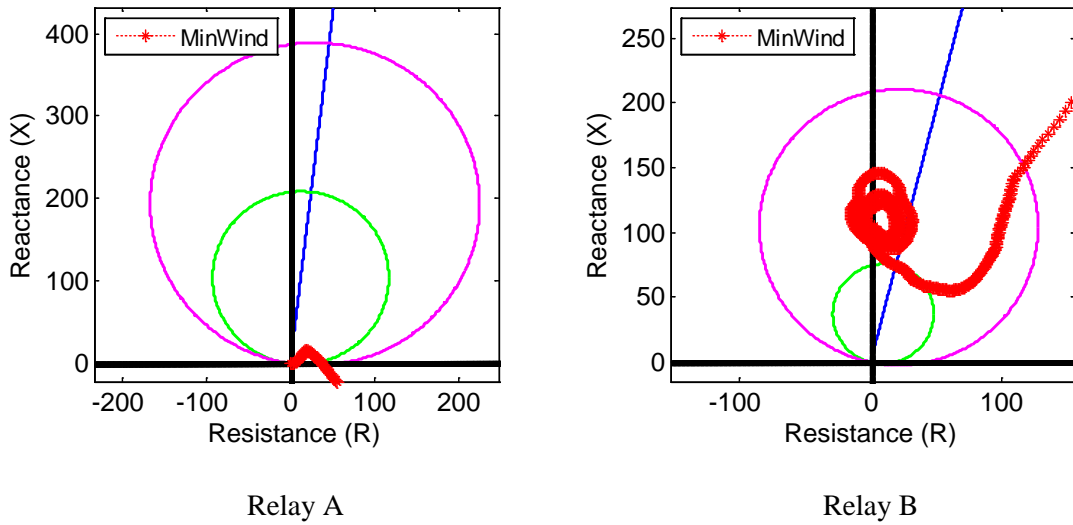
Relay A   Relay B

Figure 7.13 Adapted relay settings for minimum wind and 60% compensation: SLG fault

at 0 km from bus 7
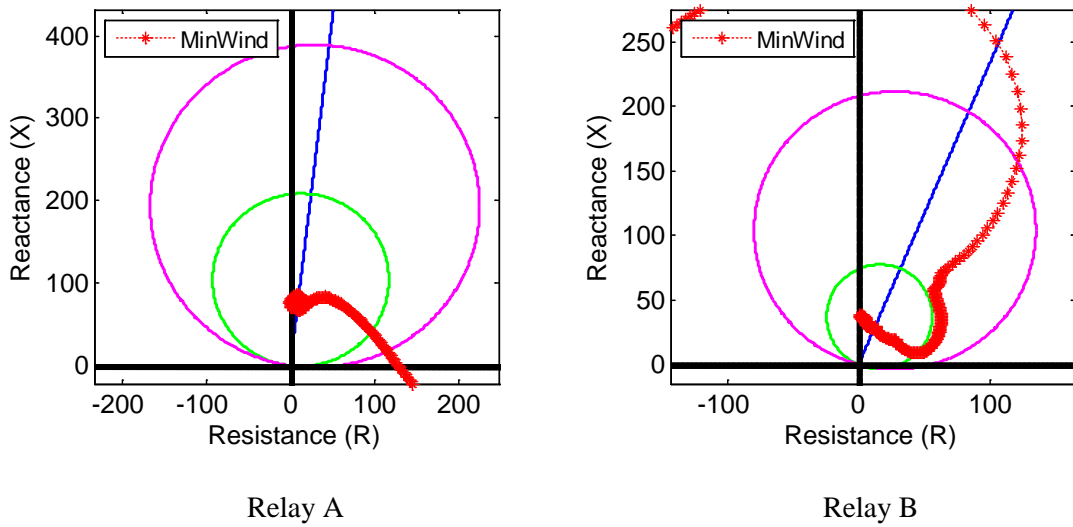
Relay A   Relay B

Figure 7.14 Adapted relay settings for minimum wind and 60% compensation: SLG fault
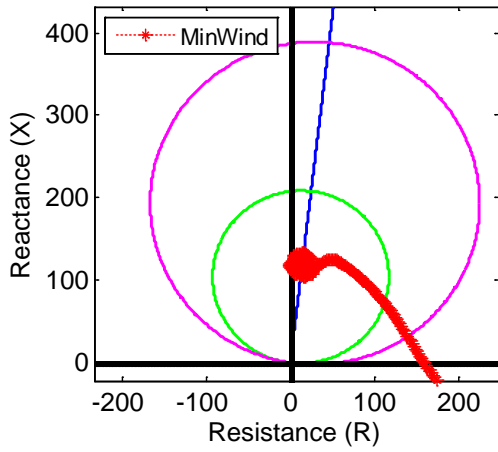
at 200 km from bus 7
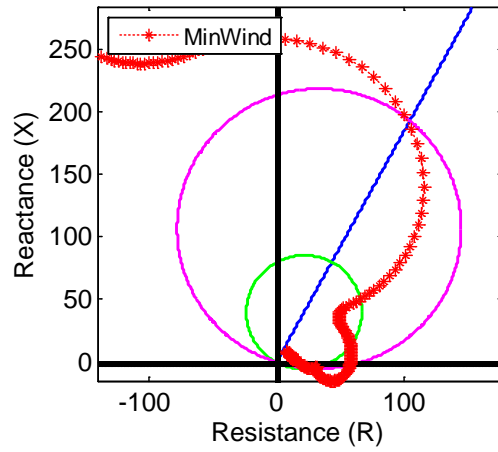
| Relay A | Relay B |

Figure 7.15 Adapted relay settings for minimum wind and 60% compensation: SLG fault

at 300 km from bus 7 (LHS of capacitor bank)
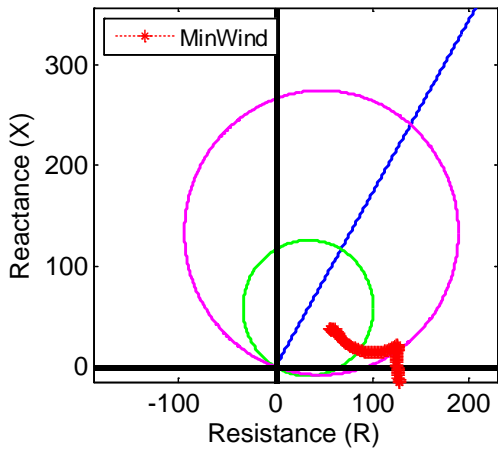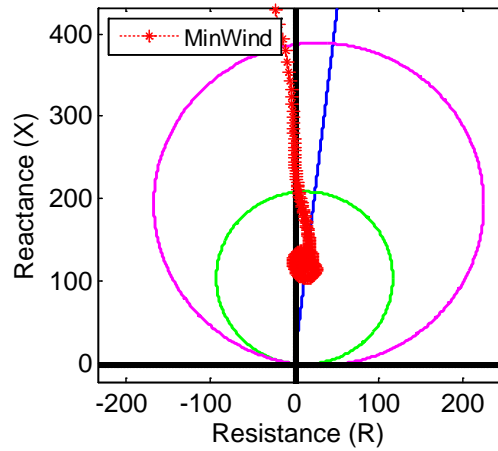
| Relay A | Relay B |

Figure 7.16 Adapted relay settings for minimum wind and 60% compensation: SLG fault

at 300 km from bus 7 (RHS of capacitor bank)
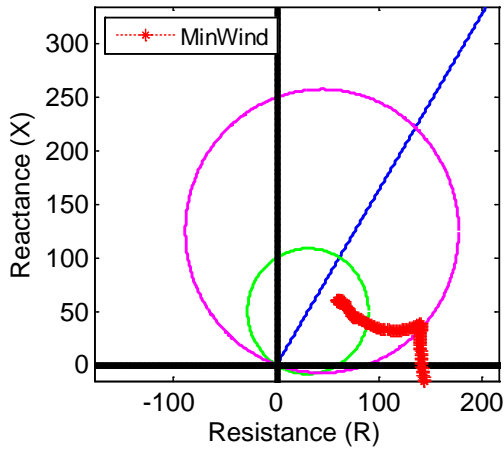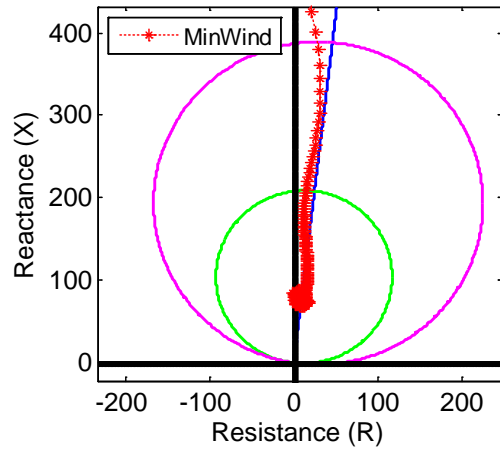
Relay A   Relay B

Figure 7.17 Adapted relay settings for minimum wind and 60% compensation: SLG fault
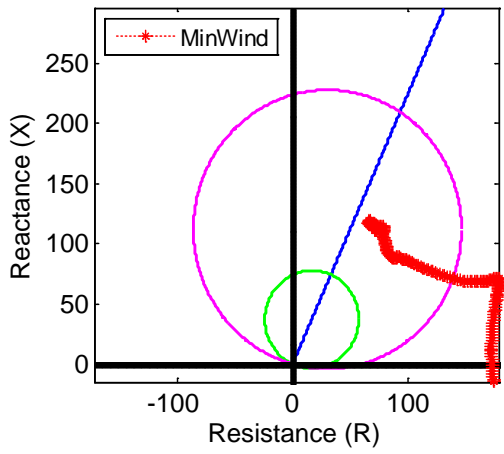
at 400 km from bus 7
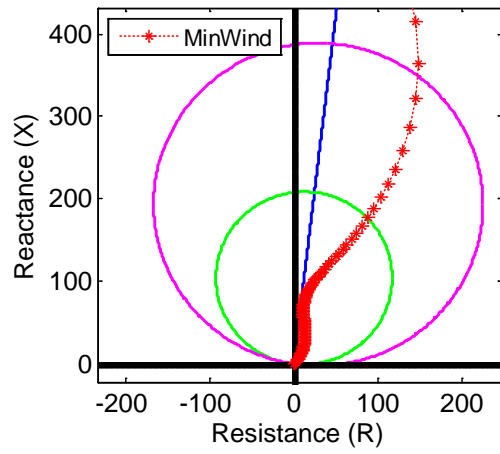
Relay A   Relay B

Figure 7.18 Adapted relay settings for minimum wind and 60% compensation: SLG fault

at 600 km from bus 7

Table 7.1 Apparent trajectory impedance end point for 20% compensation and three wind

power levels

Apparent Impedances for 20% Compensation			
		Relay- A	**Relay-B**
0 km	**Zero Comp**	0	**40.26+286.26i**
	Min Wind	0	**24.04+219.53i**
	Ave Wind	0	**29.46+223.88i**
	Max Wind	0	**30.36+224.34i**
100 km	**Zero Comp**	4.24+37.97i	**29.01+216.72i**
	Min Wind	4.22+37.94i	**16.43+160.23i**
	Ave Wind	4.25+37.97i	**19.33+164.63i**
	Max Wind	4.24+37.98i	**19.57+164.96i**
200 km	**Zero Comp**	8.84+77.49i	**21.81+174.54i**
	Min Wind	8.82+77.33i	**11.68+112.83i**
	Ave Wind	8.85+77.49i	**12.73+115.86i**
	Max Wind	8.84+77.52i	**12.9+116.05i**
300L km	**Zero Comp**	14.62+120.18i	**15.22+123.56i**
	Min Wind	14.7+119.64i	**9.54+77.13i**
	Ave Wind	14.69+120.22i	**11.32+80.17i**
	Max Wind	14.64+120.31i	**12.47+80.32i**
300R km	**Zero Comp**	**14.62+120.18i**	15.22+123.56i
	Min Wind	**30.38+90.08i**	12.52+123.6i
	Ave Wind	**28.64+91.56i**	15.04+123.7i
	Max Wind	**28.28+91.73i**	15.18+123.43i
400 km	**Zero Comp**	**22.5+168.21i**	9.54+78.97i
	Min Wind	**33.36+124.43i**	8.45+79.22i
	Ave Wind	**30.74+125.07i**	9.51+79.03i
	Max Wind	**30.22+125.13i**	9.49+78.87i
500 km	**Zero Comp**	**25.88+215.84i**	4.6+38.4i
	Min Wind	**39.49+166.48i**	4.28+38.59i
	Ave Wind	**34.66+168.45i**	4.61+38.42i
	Max Wind	**33.66+168.82i**	4.56+38.35i
600 km	**Zero Comp**	**39.41+282.3i**	0
	Min Wind	**48.76+219.14i**	0
	Ave Wind	**47.8+226.79i**	0
	Max Wind	**47.05+228.14i**	0

Table 7.2 Apparent trajectory impedance end point for 40% compensation and three wind

power levels

Apparent Impedances for 40% Compensation			
		Relay- A	**Relay-B**
0 km	**Zero Comp**	0	**40.26+286.26i**
	Min Wind	0	**11.83+151.46i**
	Ave Wind	0	**15.2+165.85i**
	Max Wind	0	**12.13+166.95i**
100 km	**Zero Comp**	4.24+37.97i	**29.01+216.72i**
	Min Wind	4.2+37.93i	**9.41+105.82i**
	Ave Wind	4.25+37.97i	**11.56+115.79i**
	Max Wind	4.24+37.98i	**11.19+114.88i**
200 km	**Zero Comp**	8.84+77.49i	**21.81+174.54i**
	Min Wind	8.84+77.32i	**4.86+73.08i**
	Ave Wind	8.88+77.51i	**9+79.98i**
	Max Wind	8.86+77.53i	**10.5+79.55i**
300L km	**Zero Comp**	14.62+120.18i	**15.22+123.56i**
	Min Wind	14.86+119.67i	**4.26+36.3i**
	Ave Wind	14.79+120.29i	**5.28+41.24i**
	Max Wind	14.73+120.39i	**6.87+41.34i**
300R km	**Zero Comp**	**14.62+120.18i**	15.22+123.56i
	Min Wind	**42.6+59.53i**	12.19+123.68i
	Ave Wind	**39.92+61.93i**	14.73+123.87i
	Max Wind	**39.35+62.25i**	14.89+123.61i
400 km	**Zero Comp**	**22.5+168.21i**	9.54+78.97i
	Min Wind	**47.97+87.61i**	8.37+79.3i
	Ave Wind	**43.44+91.21i**	9.43+79.11i
	Max Wind	**42.45+91.74i**	9.41+78.95i
500 km	**Zero Comp**	**25.88+215.84i**	4.6+38.4i
	Min Wind	**46.78+119.57i**	4.28+38.61i
	Ave Wind	**38.16+124.18i**	4.6+38.43i
	Max Wind	**36.4+125.11i**	4.55+38.36i
600 km	**Zero Comp**	**39.41+282.3i**	0
	Min Wind	**54.62+164.96i**	0
	Ave Wind	**51.39+175.56i**	0
	Max Wind	**50.1+177.3i**	0

Table 7.3 Apparent trajectory impedance end point for 60% compensation and three wind

power levels

		Apparent Impedances for 60% Compensation	
		Relay- A	**Relay-B**
0 km	**Zero Comp**	0	**40.26+286.26i**
	Min Wind	0	**2.29+104.41i**
	Ave Wind	0	**10.27+117.23i**
	Max Wind	0	**5.94+123.86i**
100 km	**Zero Comp**	4.24+37.97i	**29.01+216.72i**
	Min Wind	4.25+37.93i	**2.3+64.63i**
	Ave Wind	4.27+37.97i	**7.3+74.16i**
	Max Wind	4.25+37.98i	**5.7+75.46i**
200 km	**Zero Comp**	8.84+77.49i	**21.81+174.54i**
	Min Wind	8.96+77.34i	**5.67+31.91i**
	Ave Wind	8.92+77.53i	**4.81+38.28i**
	Max Wind	8.89+77.56i	**6.4+38.68i**
300L km	**Zero Comp**	14.62+120.18i	**15.22+123.56i**
	Min Wind	15.07+119.74i	**11.67+3.97i**
	Ave Wind	14.86+120.38i	**12.18+8.17i**
	Max Wind	14.76+120.5i	**14.37+8.8i**
300R km	**Zero Comp**	**14.62+120.18i**	15.22+123.56i
	Min Wind	**55.79+37.66i**	11.73+123.43i
	Ave Wind	**52.78+40.69i**	14.3+123.97i
	Max Wind	**52.14+41.1i**	14.56+123.76i
400 km	**Zero Comp**	**22.5+168.21i**	9.54+78.97i
	Min Wind	**59.6+60.14i**	8.18+79.21i
	Ave Wind	**54.47+63.24i**	9.3+79.18i
	Max Wind	**53.46+63.65i**	9.33+79.04i
500 km	**Zero Comp**	**25.88+215.84i**	4.6+38.4i
	Min Wind	**63.98+86.07i**	4.24+38.59i
	Ave Wind	**55.35+90.61i**	4.59+38.45i
	Max Wind	**53.58+91.31i**	4.56+38.39i
600 km	**Zero Comp**	**39.41+282.3i**	0
	Min Wind	**65.75+118.54i**	0
	Ave Wind	**53.47+129.97i**	0
	Max Wind	**52.07+132.08i**	0

CHAPTER EIGHT

CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

Throughout this research, broad areas have been joined together to perform the study. System modeling, wind energy integration, protection systems, fault analysis, nonlinear MOV-protection and other aspects were considered. A transmission system was modeled in MATLAB/Simulink environment and used to analyze effects of inclusion of intermittent wind farm generation on the operation and protection of MOV-protected compensated lines.

In Chapter one, the background of the motivation for the study was presented along with the literature review of the current state of research. It was discussed that the integration of wind energy into the power grid introduces challenges on system operation and protection which must be studied to ensure the reliability of the grid. The operation and protection of MOV-protected series compensated line connected to the intermittent wind farm was brought up. The current state of research for distance protection methods and adaptive settings were discussed in the literature review and an adaptive distance relay algorithm method was proposed.

In Chapter two, the MOV-protected series compensated line was introduced. The Goldsworthy's linear model was discussed which showed that the nonlinear MOV device connected in parallel with the capacitor bank on each phase can be modeled as a reduced single phase equivalent impedance. The distance relay basics for primary and backup protection of transmission lines were given for medium length transmission line. The

distributed parameter-based distance relay for long transmission lines was included as well.

In Chapter three, the development of the modified IEEE 12-bus test system model with MOV-protected series capacitor and a wind farm was given. The MOV-protected series capacitor was connected at the middle of the longest transmission line. The commercially available MOVs were used to determine the MOV's rated discharge energy, maximum continuous operating voltage, and number of columns required for simulation purposes. An equivalent wind energy model using the real-world data was proposed in order to simulate the effects of intermittent wind generation on the system operation and protection.

In Chapter four, a study on effects of wind energy variation on the operation of MOV-protected compensated line was performed. Three wind generation levels were considered: minimum, average, and maximum. It was shown that the intermittency of wind power affects power flow in the compensated line, which in turn affects the fault current level and the equivalent MOV/capacitor impedance. The unbalanced fault results also showed that the intermittency of wind farm generation affects the current magnitudes and amount of energy absorbed by the MOV during fault conditions. The settings and ratings for the MOV and series capacitor may need to be designed for higher ratings with wind farms added to the power system. With increasing the integration of wind power at different locations, setting analysis of MOVs will be needed to guarantee their correct operation.

In Chapter five, four distance protection study cases were performed and analyzed. The first case was used as the base case with mho relay setting and apparent impedance trajectories for zero percent compensation and average wind power level using distributed line parameters. The second case compares the base case to the mho relay setting and apparent impedance trajectories with neglecting the distributed parameters. Significant error in relay setting and apparent impedance calculation were observed and demonstrated the importance of implementing distributed parameter-based distance relay for long transmission lines. The third case compared effects of different compensation levels on the distance protection of series compensated line. It showed the importance of distance relay to determine amount of compensation during the fault for correct relay operation. Finally, case four analyzed the effect of wind power variation on the distance protection for a fixed 60% compensated line.

In Chapter six, an adaptive setting algorithm for distance mho relay was proposed. The proposed algorithm considers the distributed parameters of transmission lines and takes into account the MOV-protected series capacitor operation, wind power variation, and variable compensation levels. The proposed adaptive algorithm monitors voltages and current at the capacitor location and calculates an equivalent MOV/capacitor impedance during a system fault. The impedance value is sent to relay A or B via dedicated communication channel to correct relay setting.

In Chapter seven, adaptive setting results were presented for 60% compensation and different cases of wind power levels. The simulations were also performed for 20% and 40% compensation and are summarized. The adaptive algorithm demonstrated

correct relay A and B operation to different system conditions including different compensation and wind power levels.

In summary, the study showed that the intermittency of wind power affects power flow in the compensated line and the equivalent MOV/capacitor impedance. This equivalent impedance modifies the total line impedance and affects distance protection. The simulation results demonstrated the proposed method's ability to adaptively set relay reach setting for various system conditions, including fluctuation of wind power and different compensation levels.

8.2 Future Work

For multiple MOV protected lines and multiple wind farms, malfunction operation of distance relay due to wind energy variation during the unbalanced fault may be avoided using coordinated adaptive setting that can monitor wind power variation and reset the relays. In this case, PMU measurements are necessary for coordinated adaptive setting.

Study of different types of faults with arc resistance should also be considered. For this purpose another type of relay, such as quadrilateral type, maybe used. Finally, integration of solar and a combination of both solar and wind may also be considered for future studies.

APPENDICES

Appendix A

Test System Data

The following tables were used to build the IEEE 12-bus test system in PowerWorld and

MATLAB/Simulink simulation. The system data was taken from reference [30].

Table A.1. Distributed parameters of the transmission line 7-8

Parameter	Positive (negative) sequence	Zero sequence
R (Ω/km)	0.038806	0.1055
L (mH/km)	1.0011	1.19599
C (µF/km)	0.01159	0.003

Table A.2. Branch Data (System Base: 100MVA)

Line	Voltage (kV)	Length (km)	R (pu)	X (pu)	B (pu)	Rating (MVA)
1-2	230	100	0.01144	0.09111	0.18261	250
1-6	230	300	0.03356	0.26656	0.55477	250
2-5	230	300	0.03356	0.26656	0.55477	250
3-4(1)	230	100	0.01144	0.09111	0.18261	250
3-4(2)	230	100	0.01144	0.09111	0.18261	250
4-5	230	300	0.03356	0.26656	0.55477	250
4-6	230	300	0.03356	0.26656	0.55477	250
7-8	345	600	0.01595	0.17214	3.2853	500

Table A.3. Transformer Data (System Base: 100MVA)

From-To	Voltage (kV)	Leakage reactance (pu)	Rating (MVA)
1-7	230-345	0.0100	1000
1-9	230-22	0.0100	1000
2-10	230-23	0.0100	1000
3-8	230-345	0.0100	1000
3-11	230-25	0.0100	1000
6-12	230-26	0.0200	500

Table A.4. Bus Data (System Base: 100MVA)

Bus	Nominal Voltage (kV)	Specified Voltage (kV)	Load (MVA)	Shunt (MVar)	Generation (MW)
1	230				
2	230		280 + j200		
3	230		320 + j240		
4	230		320 + j240	160	
5	230		100 + j60	80	
6	230		440 + j300	180	
7	345				
8	345				
9	22	1.04			
10	22	1.02			500
11	22	1.01			200
12	22	1.02			300

Appendix B

Simulation Diagrams in PowerWorld and MATLAB/Simulink

This appendix contains test system diagrams in PowerWorld and Simulink including the subsystems for Simulink's block diagrams.
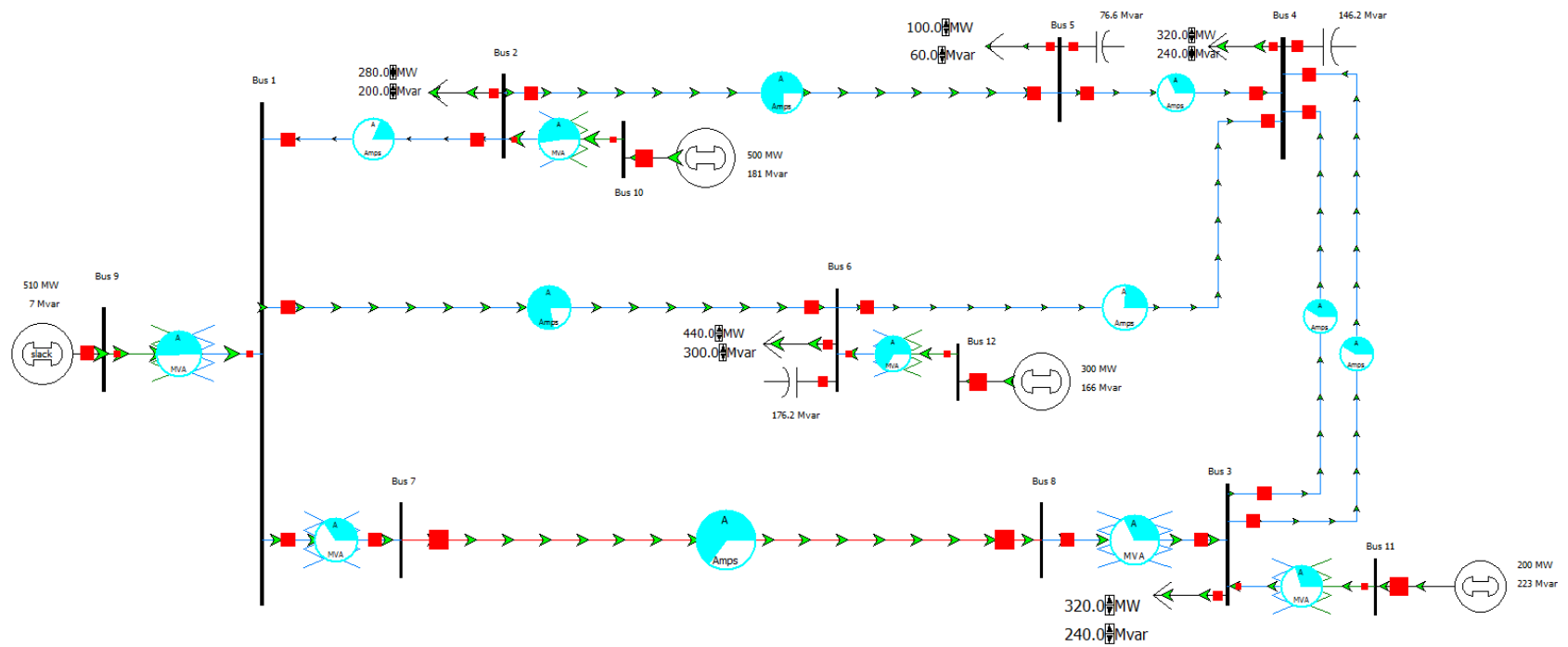
Figure B.1 Test system in PowerWorld
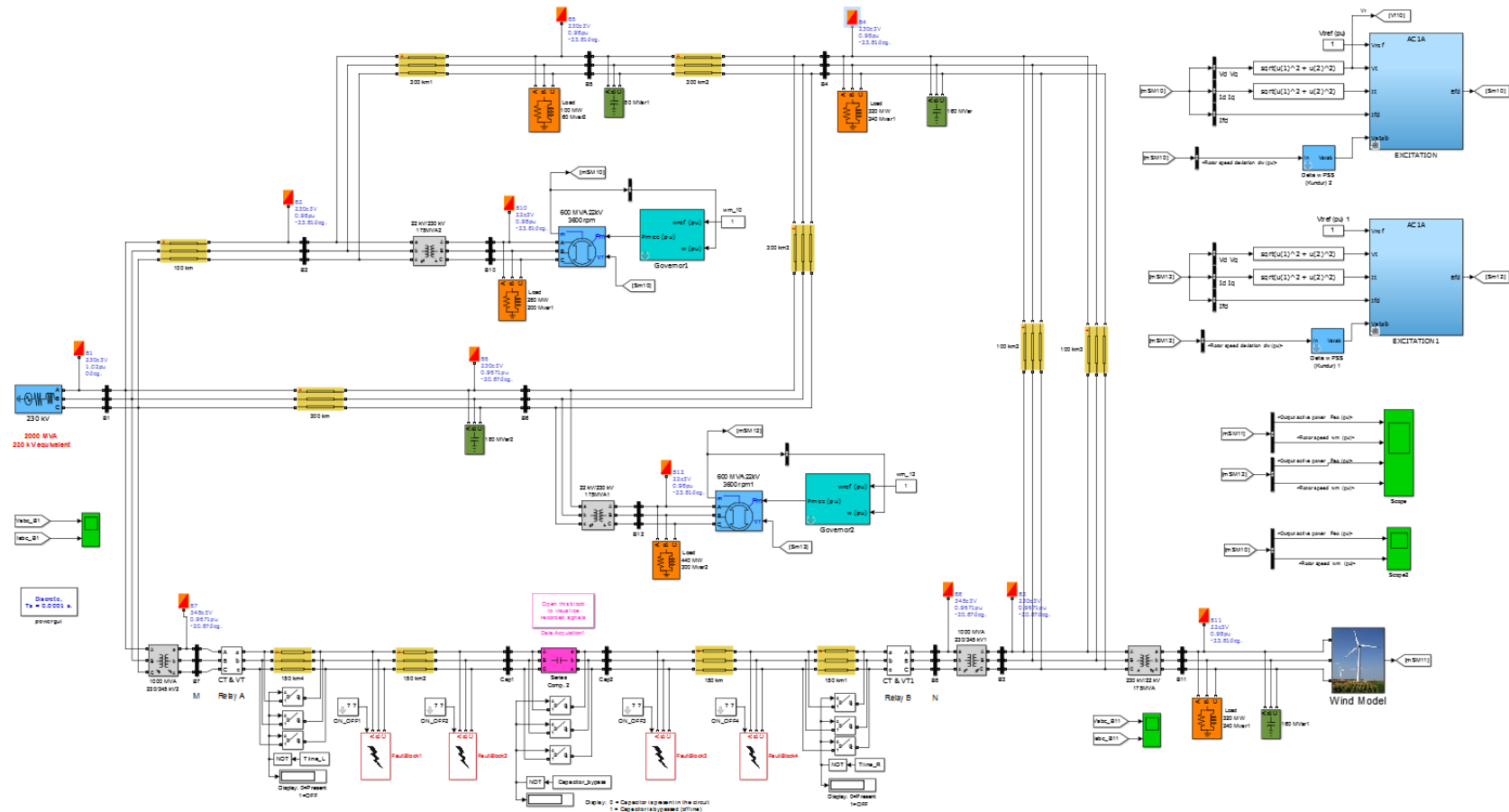
Figure B.2 Test system in MATLAB/SIMULINK
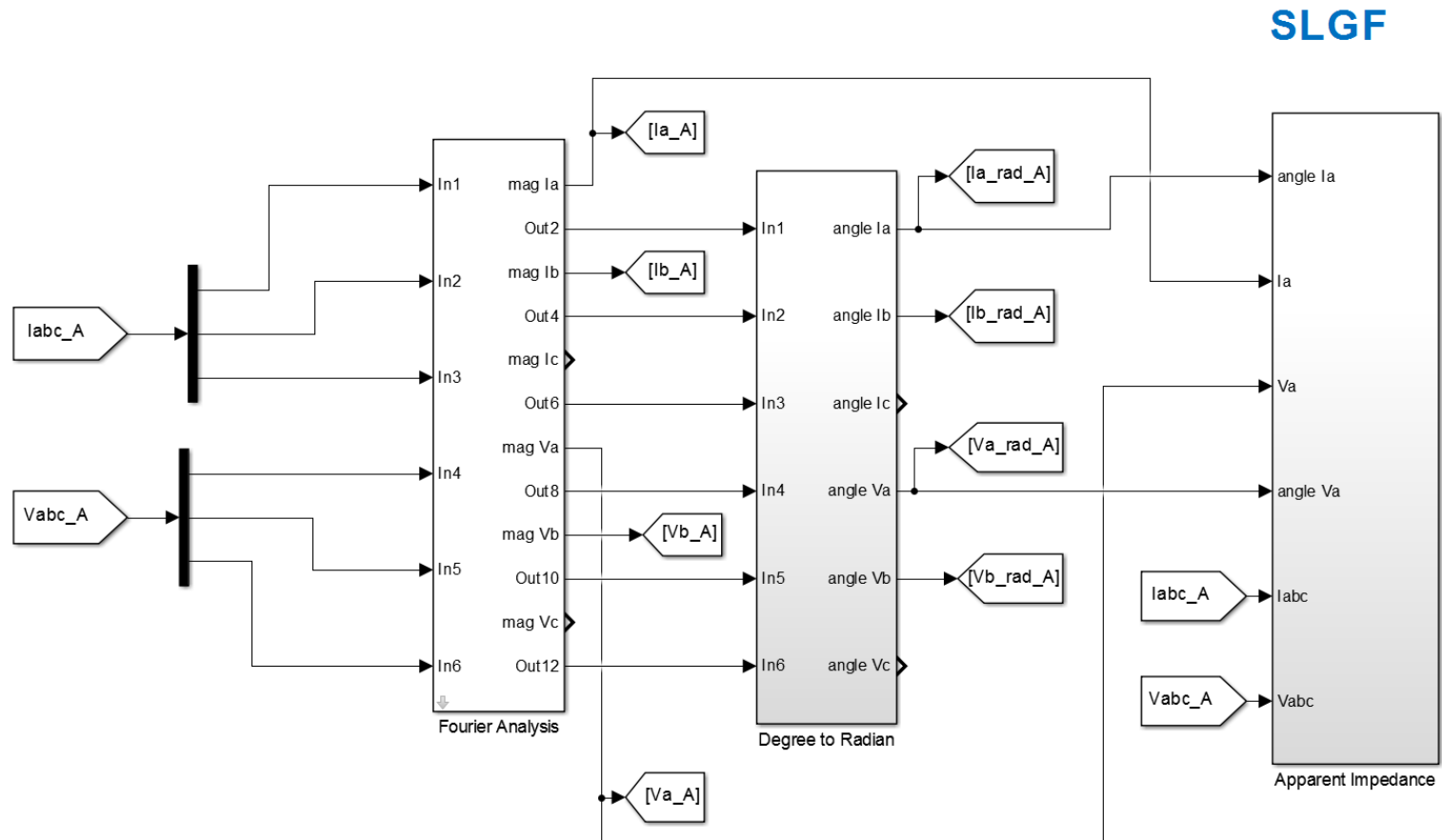
Figure B.3 Apparent Impedance for single-line-to ground fault for relay A. Similar block diagram was used for relay B.

(See Figures B.4 & B5 for Apparent Impedance block)

SLGF
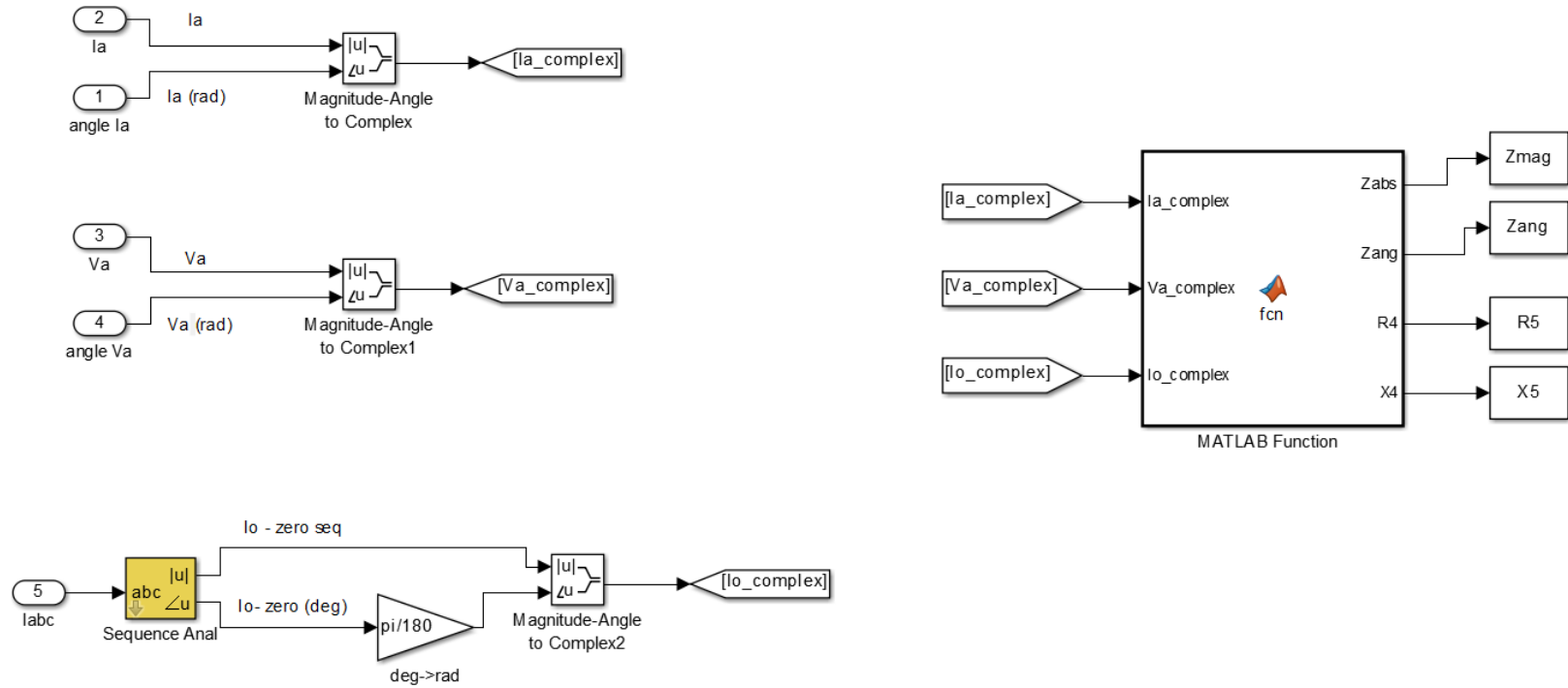
Figure B.4 Apparent Impedance with Fixed Zero Sequence Compensation Factor "m" for phase-A SLGF

(See Appendix D.5 for code of MATLAB Function block)
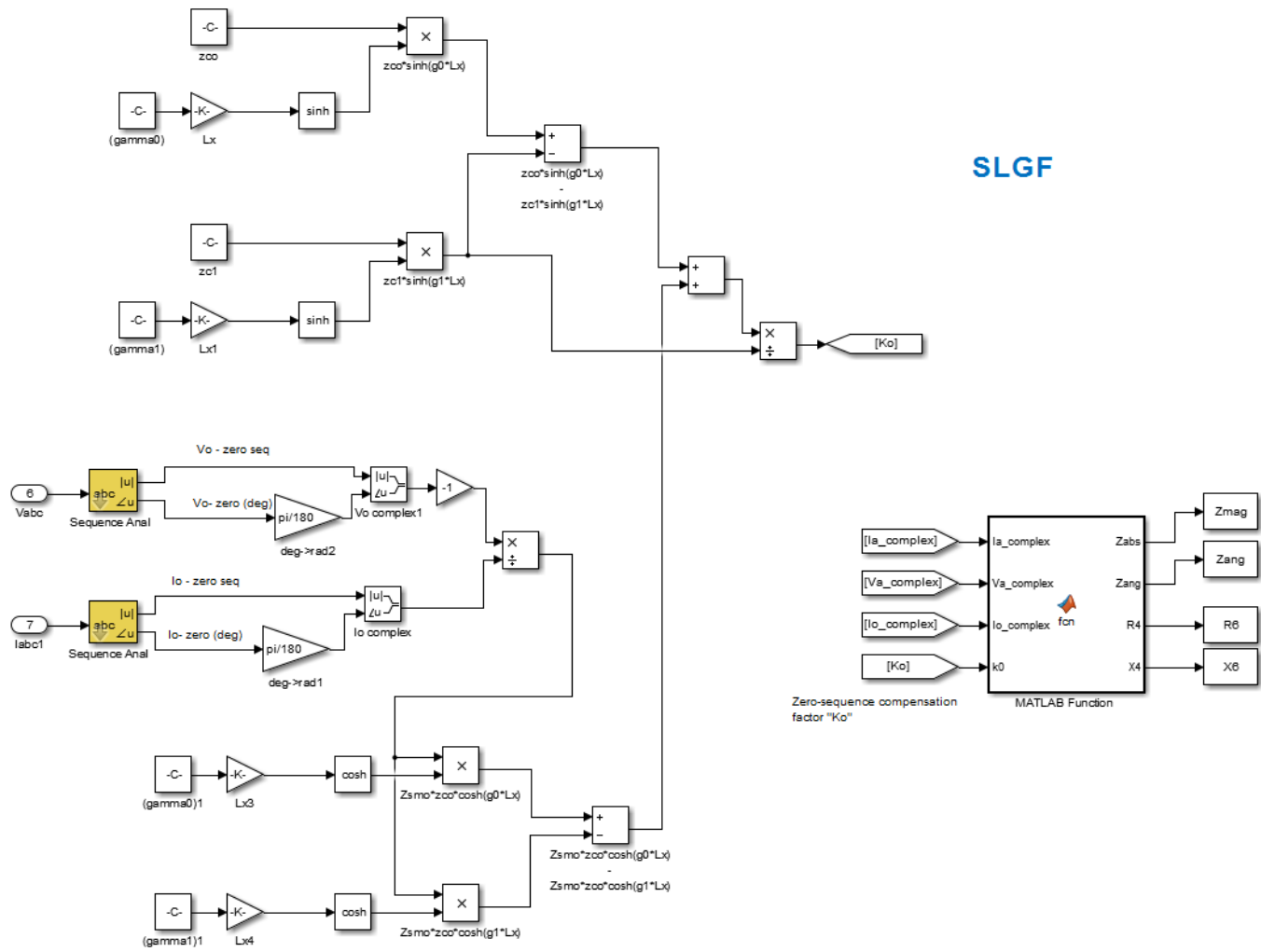
Figure B.5 Apparent Impedance with Variable Zero Sequence Compensation Factor "k0" for phase-A SLGF

(See Appendix D.6 for code of MATLAB Function block)
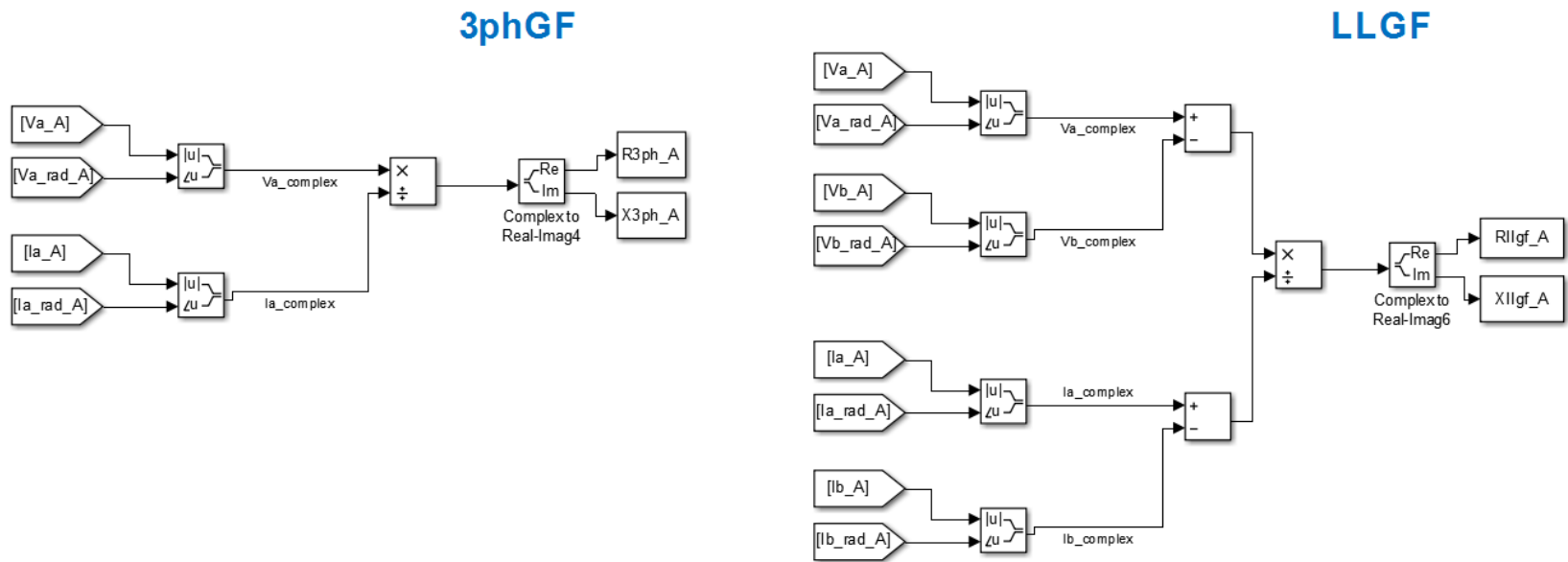
Figure B.6 Apparent Impedance for Three-Phase (A-B-C-G) fault and Line-to-Line-to-Ground (A-B-G) fault for relay A.
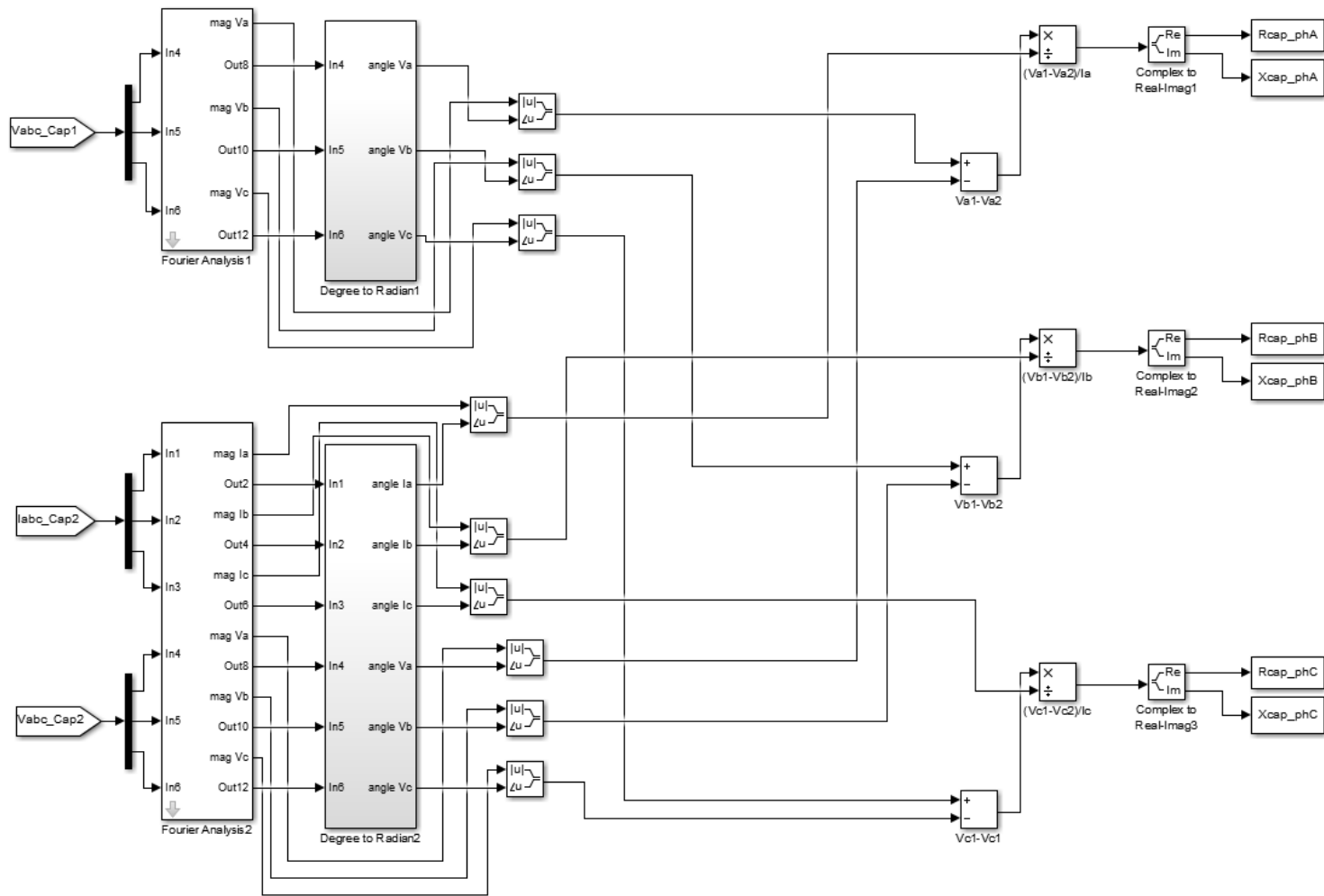
Figure B.7 Equivalent MOV/capacitor impedances for phases A, B, and C.

Appendix C

MATLAB Functions for Figures B.4 and B.5

This appendix presents the MATLAB codes of the functions used in the Simulink simulation in appendix B.

C.1 Function for Fig B.4

```
function [Zabs,Zang,R5,X5] = fcn(Ia_complex,Va_complex,Io_complex)

freq=60;                        %Hz
length=600;                     %km
Roo=0.1055*length;              %zero-sequence resistance
R11=0.038806*length;            %pos-sequence resistance
Loo=(0.7389/377)*length;        %zero-sequence inductance
L11=(0.377416/377)*length;      %pos-sequence inductance

Z00=Roo+1i*2*pi*freq*Loo;       %zero-sequence impedance
Z11=R11+1i*2*pi*freq*L11;       %pos-sequence impedance

m=(Z00-Z11)/Z11;                %fixed zero-sequence comp. factor "m"

%Apparent impedance with fixed zero-sequence compensation factor "m"
Ztotal=(Va_complex)/(Ia_complex+m*Io_complex);
Zabs=abs(Ztotal);
Zang=angle(Ztotal)*180/pi;
R5=real(Ztotal);
X5=imag(Ztotal);
```

C.2 Function for Fig B.5

```
function [Zabs,Zang,R6,X6] = fcn(Ia_complex,Va_complex,Io_complex,k0)

%Apparent Impedance With Variable Zero-Sequence Compensation Factor
"Ko"
Ztotal=(Va_complex)/(Ia_complex+k0*Io_complex);

Zabs=abs(Ztotal);
Zang=angle(Ztotal)*180/pi;
R6=real(Ztotal);
X6=imag(Ztotal);
```

Appendix D

MATLAB Codes (GUI)

This appendix presents the MATLAB codes of the graphical user interphase (GUI) that

enables the user to change between different fault locations, wind power levels, and

percent compensation.

D.1 Creating GUI

```matlab
function myGUI = myGUI(position)
myGUI=[];

%% Create figure
h.f = figure('units','pixels','position',position,...
             'toolbar','none','menu','none');

%% Create checkboxes:
%Fault type
h.ls = uicontrol('style','text','unit','pix','position',[5 440 150
29],...
                 'min',0,'max',2,'fontsize',17,'string',...
                 'Type of Fault:','ForegroundColor','r');

h.c(1) = uicontrol('style','checkbox','units','pixels','position',...
                 [10,408,100,25],'string','SLGF','fontsize',14);
h.c(2) = uicontrol('style','checkbox','units','pixels','position',...
                 [130,408,100,25],'string','LLGF','fontsize',14);
h.c(3) = uicontrol('style','checkbox','units','pixels','position',...
                 [250,408,100,25],'string','3phGF','fontsize',14);


%Fault location
h.ls = uicontrol('style','text','unit','pix','position',...
                 [5 355 150 8],'min',0,'max',2,'fontsize',17,'string',...
                 'Fault Location:','ForegroundColor','r');
h.c(4) = uicontrol('style','checkbox','units','pixels','position',...
                 [10,320,100,25],'string','0 km','fontsize',14);
h.c(5) = uicontrol('style','checkbox','units','pixels','position',...
                 [125,320,100,25],'string','100 km','fontsize',14);
h.c(6) = uicontrol('style','checkbox','units','pixels','position',...
                 [240,320,100,25],'string','200 km','fontsize',14);
h.c(7) = uicontrol('style','checkbox','units','pixels','position',...
                 [355,320,100,25],'string','300L km','fontsize',14);
h.c(8) = uicontrol('style','checkbox','units','pixels','position',...
                 [10,287,100,25],'string','300R km','fontsize',14);
h.c(9) = uicontrol('style','checkbox','units','pixels','position',...
                 [125,287,100,25],'string','400 km','fontsize',14);
```

```matlab
h.c(10) = uicontrol('style','checkbox','units','pixels','position',...
              [240,287,100,25],'string','500 km','fontsize',14);
h.c(11) = uicontrol('style','checkbox','units','pixels','position',...
              [355,287,100,25],'string','600 km','fontsize',14);

%Wind levels
h.ls = uicontrol('style','text','unit','pix','position',...
              [5 232 170 28],'min',0,'max',2,'fontsize',17,...
              'string','Wind Variation:','ForegroundColor','r');

h.c(12) = uicontrol('style','checkbox','units','pixels','position',...
              [10,195,100,25],'string','Average','fontsize',14);
h.c(13) = uicontrol('style','checkbox','units','pixels', 'position',...
              [130,195,80,25],'string','MAX','fontsize',14);
h.c(14) = uicontrol('style','checkbox','units','pixels','position',...
              [230,195,80,25],'string','MIN','fontsize',14);

%Compensation level
h.ls = uicontrol('style','text','unit','pix','position',...
              [5 137 220 28],'min',0,'max',2,'fontsize',17,...
              'string','Compensation Level:','ForegroundColor','r');
h.c(15) = uicontrol('style','checkbox','units','pixels','position',...
              [10,102,65,25],'string','0%','fontsize',14);
h.c(16) = uicontrol('style','checkbox','units','pixels','position',...
              [85,102,65,25],'string','20%','fontsize',14);
h.c(17) = uicontrol('style','checkbox','units','pixels','position',...
              [160,102,65,25],'string','40%','fontsize',14);
h.c(18) = uicontrol('style','checkbox','units','pixels','position',...
              [235,102,65,25],'string','60%','fontsize',14);

%% Create pushbuttons
h.p = uicontrol('style','pushbutton','units','pixels','position',...
              [30,20,120,40],'string','Mho-relay A','callback',...
              @p_call3,'fontsize',14);
h.p = uicontrol('style','pushbutton','units','pixels','position',...
              [160,20,120,40],'string','Mho-relay B','callback',...
              @p_call4,'fontsize',14);
h.p = uicontrol('style','pushbutton','units','pixels','position',...
              [500,418,130,40],'string','Adapt Relay A','callback',...
              @p_call5,'fontsize',14);
h.p = uicontrol('style','pushbutton','units','pixels','position',...
              [642,418,130,40],'string','Adapt Relay B','callback',...
              @p_call7,'fontsize',14);
h.p = uicontrol('style','pushbutton','units','pixels','position',...
              [320,20,100,40],'string','OK','callback',@p_call,...
              'fontsize',14);
h.p = uicontrol('style','pushbutton','units','pixels','position',...
              [430,20,100,40],'string','Close','callback',@p_call2,...
              'fontsize',14);
h.p = uicontrol('style','pushbutton','units','pixels','position',...
              [620,20,150,40],'string','MOV/Cap V-I','callback',...
              @p_call6,'fontsize',14);
```

```matlab
%% Create Labels
h.ls = uicontrol('style','text','unit','pix','position',...
                [500 380 215 22],'min',0,'max',2,'fontsize',13,...
                'string','MOV/Cap Equiv Impedance:',...
                'ForegroundColor','k');
h.ls = uicontrol('style','text','unit','pix','position',...
                [535 350 65 22],'min',0,'max',2,'fontsize',12,...
                'string','Phase A:','ForegroundColor','k');
h.ls = uicontrol('style','text','unit','pix','position',...
                [535 320 65 22],'min',0,'max',2,'fontsize',12,...
                'string','Phase B:','ForegroundColor','k');

h.ls = uicontrol('style','text','unit','pix','position',...
                [535 290 65 22],'min',0,'max',2,'fontsize',12,...
                'string','Phase C:','ForegroundColor','k');

%Read MOV/capacitor equivalent impedance from base workspace
try
    Rcap1=evalin('base','Rcap_phA');              %Phase A
    Vexists=1;
catch
    Vexists=0;
end
if Vexists==1
    %Phase A
    Rcap1=evalin('base','Rcap_phA');
    RcapMOVa=round(Rcap1(end)*1000)/1000;
    Xcap1=evalin('base','Xcap_phA');
    XcapMOVa=round(Xcap1(end)*1000)/1000;
    ZcapMOVa=num2str(RcapMOVa+XcapMOVa*1i);

    %Phase B
    Rcap2=evalin('base','Rcap_phB');
    RcapMOVb=round(Rcap2(end)*1000)/1000;
    Xcap2=evalin('base','Xcap_phB');
    XcapMOVb=round(Xcap2(end)*1000)/1000;
    ZcapMOVb=num2str(RcapMOVb+XcapMOVb*1i);

    %Phase C
    Rcap3=evalin('base','Rcap_phC');
    RcapMOVc=round(Rcap3(end)*1000)/1000;
    Xcap3=evalin('base','Xcap_phC');
    XcapMOVc=round(Xcap3(end)*1000)/1000;
    ZcapMOVc=num2str(RcapMOVc+XcapMOVc*1i);
else
    ZcapMOVa=num2str(0.00+0.00*1i);
    ZcapMOVb=num2str(0.00+0.00*1i);
    ZcapMOVc=num2str(0.00+0.00*1i);
End

%% Create textboxes
h.ed = uicontrol('style','edit','unit','pix','position',...
                [605 350 170 24],'fontsize',13,'string',ZcapMOVa);
h.ed = uicontrol('style','edit','unit','pix','position',...
```

```matlab
                [605 320 170 24],'fontsize',13,'string',ZcapMOVb);
h.ed = uicontrol('style','edit','unit','pix','position',...
                [605 290 170 24],'fontsize',13,'string',ZcapMOVc);

%Line parameters to calculate distance to fault from apparent impedance
line_length = 600;
R1 = 0.038806;
X1 = 0.377416;             %Xl1=2*pi*f*L
Xc = 1.15922e-8*377;       %Xc1=2*pi*f*C

%Distributed Parameters
Zt = R1+1i*X1;             %line impedance
Yt = 1i*Xc;                %admittance
zc = sqrt(Zt/Yt);          %characteristic impedance
gam = sqrt(Zt*Yt);         %propagation constant

try
    R6=evalin('base','R6');
    Zexists=1;
catch
    Zexists=0;
end
try
    Fault_Under300Lkm=evalin('base','Fault_Under300Lkm');
catch
    Fault_Under300Lkm=0;
end

%Calculate distance to fault from Relay A&B
if Zexists==1
            %Relay A
        R6=evalin('base','R6');
        Rapp6=round(R6(end)*1000)/1000;
        X6=evalin('base','X6');
        Xapp6=round(X6(end)*1000)/1000;
        Zapp6=Rapp6+Xapp6*1i;
        Zapp_A=num2str(Zapp6);
        FaultDistA=num2str(round(abs(atanh((Zapp6)/zc)/gam)));
    %Relay B
        R8=evalin('base','R8');
        Rapp8=round(R8(end)*1000)/1000;
        X8=evalin('base','X8');
        Xapp8=round(X8(end)*1000)/1000;
        Zapp8=Rapp8+Xapp8*1i;
        Zapp_B=num2str(Zapp8);
        FaultDistB=num2str(round(abs(atanh((Zapp8)/zc)/gam)));
    else
        Zapp_A=num2str(0+0*1i);
        Zapp_B=num2str(0+0*1i);
        FaultDistA=num2str(0);
        FaultDistB=num2str(0);
    end
end
```

```matlab
%% Create labels and textboxes
h.ls = uicontrol('style','text','unit','pix','position',...
            [500 225 205 22],'min',0,'max',2,'fontsize',13,...
            'string','Fault Apparent Impedance:','ForegroundColor','k');
h.ls = uicontrol('style','text','unit','pix','position',...
            [530 192 70 22],'min',0,'max',2,'fontsize',12,...
            'string','Relay A:','ForegroundColor','k');
h.ls = uicontrol('style','text','unit','pix','position',...
            [530 162 70 22],'min',0,'max',2,'fontsize',12,...
            'string','Relay B:','ForegroundColor','k');
h.ed = uicontrol('style','edit','unit','pix','position',...
            [605 192 170 24],'fontsize',13,'string',Zapp_A);
h.ed = uicontrol('style','edit','unit','pix','position',...
            [605 162 170 24],'fontsize',13,'string',Zapp_B);

h.ls = uicontrol('style','text','unit','pix','position',...
            [530 125 90 22],'min',0,'max',2,'fontsize',12,...
            'string','Fault Dist A:','ForegroundColor','k');
h.ls = uicontrol('style','text','unit','pix','position',...
            [530 95 90 22],'min',0,'max',2,'fontsize',12,...
            'string','Fault Dist B:','ForegroundColor','k');
h.ed = uicontrol('style','edit','unit','pix','position',...
            [625 125 100 24],'fontsize',13,'string',FaultDistA);
h.ed = uicontrol('style','edit','unit','pix','position',...
            [625 95 100 24],'fontsize',13,'string',FaultDistB);
h.ls = uicontrol('style','text','unit','pix','position',...
            [728 125 33 19],'min',0,'max',2,'fontsize',11,...
            'string','(km)','ForegroundColor','k');
h.ls = uicontrol('style','text','unit','pix','position',...
            [728 95 33 19],'min',0,'max',2,'fontsize',11,...
            'string','(km)','ForegroundColor','k');

%% Pushbutton callbacks
%OKAY - pushbutton callback
function m=p_call(varargin)
    vals = get(h.c,'Value');
    checked = find([vals{:}]);

 if isempty(checked)
    checked = 'none';
    fprintf('You did not select the settings for your test. Please use
            checkboxes to select your test and click Okay.');
 end

    [n m]=size(checked);
    if m~=0
        for i=1:1:m
            %Fault type
            if checked(i) == 1
                assignin('base', 'FaultType', 1);
            elseif checked(i)==2
                assignin('base', 'FaultType', 2);
            elseif  checked(i)==3
                assignin('base', 'FaultType', 3);
```

```matlab
            %Fault location
            elseif checked(i)==4
                assignin('base', 'FaultLocation', 4);         %0 km
            elseif checked(i)==5
                assignin('base', 'FaultLocation', 5);         %100 km
            elseif checked(i)==6
                assignin('base', 'FaultLocation', 6);         %200 km
            elseif checked(i)==7
                assignin('base', 'FaultLocation', 7);         %300L km
            elseif checked(i)==8
                assignin('base', 'FaultLocation', 8);         %300R km
            elseif checked(i)==9
                assignin('base', 'FaultLocation', 9);         %400 km
            elseif checked(i)==10
                assignin('base', 'FaultLocation', 10);        %500 km
            elseif checked(i)==11
                assignin('base', 'FaultLocation', 11);        %600 km

            %Wind variation
            elseif checked(i)==12
                assignin('base', 'WindVariation', 12);        %Ave
            elseif checked(i)==13
                assignin('base', 'WindVariation', 13);        %Max
            elseif checked(i)==14
                assignin('base', 'WindVariation', 14);        %Min

            %Percent compensation
            elseif  checked(i)==15
                assignin('base', 'CompensationLevel', 15);     % 0%
            elseif  checked(i)==16
                assignin('base', 'CompensationLevel', 16);     % 20%
            elseif  checked(i)==17
                assignin('base', 'CompensationLevel', 17);     % 40%
            elseif  checked(i)==18
                assignin('base', 'CompensationLevel', 18);     % 60%
            end
        end
    end
    close(h.f);
end

%CANCEL - pushbutton callback
function p_call2(varargin)
    assignin('base', 'Cancelbutton', 1);
    close(h.f);
end

%Plot mho relay A - pushbutton callback
function p_call3(varargin)
    vals = get(h.c,'Value');
    checked = find([vals{:}]);

    [n m]=size(checked);
```

```matlab
    if m~=0
        for i=1:1:m
            %Extra features to change relay setting and re-plot
            if checked(i) == 15
                assignin('base', 'Capacitor_bypass', 0);
            elseif checked(i)>=16 && checked(i)<=18
                assignin('base', 'Capacitor_bypass', 1);
            end
            %Extra features to change relay setting and re-plot
            if checked(i)>=4 && checked(i)<=8
                assignin('base', 'Fault_Under300Lkm', 1);
            elseif checked(i)>=9 && checked(i) <=11
                assignin('base', 'Fault_Under300Lkm', 0);
            end
        end
    end
    R6=evalin('base','R6');
    X6=evalin('base','X6');
    Capacitor_bypass=evalin('base','Capacitor_bypass');
    Fault_Under300Lkm=evalin('base','Fault_Under300Lkm');
    Plot_ApparentImpedance(R6,X6);
end

%Plot mho relay B - pushbutton callback
function p_call4(varargin)
    vals = get(h.c,'Value');
    checked = find([vals{:}]);

    [n m]=size(checked);
    if m~=0
        for i=1:1:m
            %Bypass capacitor in relay setting
            if checked(i) == 15
                assignin('base', 'Capacitor_bypass', 0);
            elseif checked(i)>=16 && checked(i)<=18
                assignin('base', 'Capacitor_bypass', 1);
            end
            if checked(i)>=7 && checked(i)<=11
                assignin('base', 'Fault_Under300Rkm', 1);
            elseif checked(i)>=4 && checked(i) <=6
                assignin('base', 'Fault_Under300Rkm', 0);
            end
        end
    end
    R8=evalin('base','R8');
    X8=evalin('base','X8');
    Capacitor_bypass=evalin('base','Capacitor_bypass');
    Fault_Under300Rkm=evalin('base','Fault_Under300Rkm');
    Plot_ApparentImpedance(R8,X8);
end

%Plot adaptive mho relay A (using equivalent MOV/cap impedance)
function p_call5(varargin)
    vals = get(h.c,'Value');
```

```matlab
        checked = find([vals{:}]);
        [n m]=size(checked);
        if m~=0
           for i=1:1:m
               if checked(i)>=4 && checked(i)<=8
                   assignin('base', 'Fault_Under300Lkm', 1);
               elseif checked(i)>=9 && checked(i) <=11
                   assignin('base', 'Fault_Under300Lkm', 0);
               end
           end
        end
        R6=evalin('base','R6');
        X6=evalin('base','X6');
        Fault_Under300Lkm=evalin('base','Fault_Under300Lkm');
        Plot_AdaptiveImpedance(R6,X6,Rcap1,Xcap1,Fault_Under300Lkm);
    end

    %Plot adaptive mho relay B (using equivalent MOV/cap impedance)
    function p_call7(varargin)
        vals = get(h.c,'Value');
        checked = find([vals{:}]);
        [n m]=size(checked);
        if m~=0
           for i=1:1:m
               if checked(i)>=7 && checked(i) <=11
                   assignin('base', 'Fault_Under300Rkm', 1);
               elseif checked(i)>=4 && checked(i)<=6
                   assignin('base', 'Fault_Under300Rkm', 0);
               end
           end
        end
        R8=evalin('base','R8');
        X8=evalin('base','X8');
        Fault_Under300Rkm=evalin('base','Fault_Under300Rkm');
        Plot_AdaptiveImpedance(R8,X8,Rcap1,Xcap1,Fault_Under300Rkm);
    end

    %Plot MOV/cap voltage, current, absorbed energy, and V-I curves
    function p_call6(varargin)
        try
            F_start=evalin('base','F_start');
            exists=1;
        catch
            exists=0;
        end
        if  exists==1
            Plot_MOVCap_VI_slgf(F_start);
        end
    end

uiwait(h.f);
end
```

D.2 GUI: Simulink Model Initialization

```matlab
filename='TestSystem_ver81';
simfile=strcat(filename,'.slx');
faultblock1=strcat(filename,'/FaultBlock1');
faultblock2=strcat(filename,'/FaultBlock2');
faultblock3=strcat(filename,'/FaultBlock3');
faultblock4=strcat(filename,'/FaultBlock4');
Cancelbutton=0;
Fault_Under300Lkm=0;
Fault_Under300Rkm=0;
Tline_L=1;                       %1=line segment present     0=bypassed
Tline_R=1;                       %1=line segment present     0=bypassed

f=myGUI([50,240,790,480]);       %GUI position = [x, y, width, height]

if Cancelbutton~=1
    %Fault Type
    if FaultType == 1            %SLGF
       set_param(faultblock1, 'FaultA','on', 'FaultB','off',
'FaultC','off','GroundFault','on');
        set_param(faultblock2, 'FaultA','on', 'FaultB','off',
'FaultC','off','GroundFault','on');
        set_param(faultblock3, 'FaultA','on', 'FaultB','off',
'FaultC','off','GroundFault','on');
        set_param(faultblock4, 'FaultA','on', 'FaultB','off',
'FaultC','off','GroundFault','on');
    elseif FaultType==2          %LLGF
        set_param(faultblock1, 'FaultA','on', 'FaultB','on',
'FaultC','off','GroundFault','on');
        set_param(faultblock2, 'FaultA','on', 'FaultB','on',
'FaultC','off','GroundFault','on');
        set_param(faultblock3, 'FaultA','on', 'FaultB','on',
'FaultC','off','GroundFault','on');
        set_param(faultblock4, 'FaultA','on', 'FaultB','on',
'FaultC','off','GroundFault','on');
    elseif FaultType==3          %3phGF
        set_param(faultblock1, 'FaultA','on', 'FaultB','on',
'FaultC','on','GroundFault','on');
        set_param(faultblock2, 'FaultA','on', 'FaultB','on',
'FaultC','on','GroundFault','on');
        set_param(faultblock3, 'FaultA','on', 'FaultB','on',
'FaultC','on','GroundFault','on');
        set_param(faultblock4, 'FaultA','on', 'FaultB','on',
'FaultC','on','GroundFault','on');
    end

    %Fault Location
    if FaultLocation == 4                %Fault at 0 km
        Dist1=0;
        Dist2=300;
        Dist3=150;
        Dist4=150;
```

```matlab
        set_param(faultblock2, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock3, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock4, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        Fault_Under300Lkm=1;
        Fault_Under300Rkm=0;
        Tline_L=0;                      %1=Present  0=bypassed
        Tline_R=1;                      %1=Present  0=bypassed
    elseif FaultLocation==5             %Fault at 100 km
        Dist1=100;
        Dist2=200;
        Dist3=150;
        Dist4=150;
        set_param(faultblock2, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock3, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock4, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        Fault_Under300Lkm=1;
        Fault_Under300Rkm=0;
        Tline_L=1;
        Tline_R=1;
    elseif FaultLocation==6          %Fault at 200 km
        Dist1=200;
        Dist2=100;
        Dist3=150;
        Dist4=150;
        set_param(faultblock2, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock3, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock4, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        Fault_Under300Lkm=1;
        Fault_Under300Rkm=0;
        Tline_L=1;
        Tline_R=1;
    elseif FaultLocation==7           %Fault at 300L km
        Dist1=150;
        Dist2=150;
        Dist3=150;
        Dist4=150;
        set_param(faultblock1, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock3, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock4, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        Fault_Under300Lkm=1;
        Fault_Under300Rkm=0;
        Tline_L=1;
```

```matlab
        Tline_R=1;
    elseif FaultLocation==8          %Fault at 300R km
        Dist1=150;
        Dist2=150;
        Dist3=150;
        Dist4=150;
        set_param(faultblock1, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock2, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock4, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        Fault_Under300Lkm=0;
        Fault_Under300Rkm=1;
        Tline_L=1;
        Tline_R=1;
    elseif FaultLocation==9          %Fault at 400 km
        Dist1=150;
        Dist2=150;
        Dist3=100;
        Dist4=200;
        set_param(faultblock1, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock2, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock3, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        Fault_Under300Lkm=0;
        Fault_Under300Rkm=1;
        Tline_L=1;
        Tline_R=1;
    elseif FaultLocation==10          %Fault at 500 km
        Dist1=150;
        Dist2=150;
        Dist3=200;
        Dist4=100;
        set_param(faultblock1, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock2, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock3, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        Fault_Under300Lkm=0;
        Fault_Under300Rkm=1;
        Tline_L=1;
        Tline_R=1;
    elseif FaultLocation==11          %Fault at 600 km
        Dist1=150;
        Dist2=150;
        Dist3=300;
        Dist4=0;
        set_param(faultblock1, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
```

```matlab
        set_param(faultblock2, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        set_param(faultblock3, 'FaultA','off', 'FaultB','off',
'FaultC','off','GroundFault','off');
        Fault_Under300Lkm=0;
        Fault_Under300Rkm=1;
        Tline_L=1;
        Tline_R=0;
    end

    %WindVariation
    if WindVariation == 12
        SimTime=5.1666;
        F_start=5;
        F_stop=5.16667;
    elseif WindVariation==13
        SimTime=43.1666;
        F_start=43;
        F_stop=43.16667;
    elseif WindVariation==14
        SimTime=50.1666;
        F_start=50;
        F_stop=50.16667;
    end

    %Compensation Level
        NumofCol=20;
        Iref=10e3;
        Vprot=150e3;
    if CompensationLevel==15          % 0%
        Cap_Farads=1;
        Capacitor_bypass=0;
    elseif CompensationLevel==16      % 20%
        Cap_Farads=58.57e-6;
        Capacitor_bypass=1;
        Vprot=62e3;
    elseif CompensationLevel==17      % 40%
        Cap_Farads=29.3e-6;
        Capacitor_bypass=1;
    elseif CompensationLevel==18      % 60%
        Cap_Farads=19.52e-6;
        Capacitor_bypass=1;
        NumofCol=60;
        Iref=500;
        Vprot=222e3;
    end

    RunSimulation=menu('Run Simulation?','Yes','No');
    UIControl_FontSize_bak = get(0, 'DefaultUIControlFontSize');
    set(0, 'DefaultUIControlFontSize', 18);
    UserInput=0;
    while RunSimulation<1
        RunSimulation=menu('Run Simulation?','Yes','No');
    end
```

```matlab
    if RunSimulation == 1
        InputDialogBox('SaveAs Workspace:','SLGF',[200 400 260 100])
    if UserInput ~= 0
        SaveWorkspaceAs=strcat(UserInput,'.mat');
        sim(simfile);
        save(SaveWorkspaceAs);
        Plot_ApparentImpedance(R6,X6);    %Plot mho relay A
        Plot_ApparentImpedance(R8,X8);    %Plot mho relay B
    elseif UserInput == 0
        sim(simfile);
        Plot_ApparentImpedance(R6,X6);    %Plot mho relay A
        Plot_ApparentImpedance(R8,X8);    %Plot mho relay B
    end
    elseif RunSimulation==2
        %exit GUI
    end
end
```

D.3 GUI: SaveAs workspace

```matlab
function InputDialogBox(Title,filename,position)
%Input dialogbox - Save Workspace As
%User may hit return after entering filename.

if nargin<3                        %default values if called without args.
    position = [200 400 260 100];
elseif nargin<2
    filename = 'test1';
elseif nargin<1
    Title = 'Save Workspace:';
end

S.fh = figure('units','pixels','position',position,'menubar','none',...
              'numbertitle','off','name',Title,'resize','off');
S.ed = uicontrol('style','edit','units','pix','position',...
              [10 60 240 30],'string',filename);
S.pb = uicontrol('style','pushbutton','units','pix','position',...
              [30 10 80 35],'string','Ok','callback',{@pb_call});
S.pb = uicontrol('style','pushbutton','units','pix','position',...
              [150 10 80 35],'string','No','callback',{@pb_call2});
set(S.ed,'call',@ed_call)
uicontrol(S.ed)                   %make the edit box active.
uiwait(S.fh)                      %prevent all other processes from
                                  %starting until closed.

 %Okay button
 function [] = pb_call(varargin)
     assignin('base', 'UserInput', get(S.ed,'string'));
     close(S.fh);      %closes GUI, allows the new R to be returned.
 end
```

```matlab
%Cancel button
function [] = pb_call2(varargin)
    assignin('base', 'UserInput', 0);
    close(S.fh);            %closes GUI, allows the new R to be returned.
end

%Save file with default filename if no input
function [] = ed_call(varargin)
    uicontrol(S.pb)
    drawnow
    assignin('base', 'UserInput', get(S.ed,'string'));
    close(gcbf)
end
end
```

D.4 GUI: MOV/Capacitor Voltage, Current, Absorbed Energy, and V-I curves

```matlab
function Plot_MOVCap_VI_slgf(F_start)
back=0.05;
if F_start==5             %Ave Wind
    xmin=5-back;
    xmax=5.16667;
elseif F_start==43        %Max Wind
    xmin=43-back;
    xmax=43.16667;
elseif F_start==50        %Min Wind
    xmin=50-back;
    xmax=50.16667;
end

%Load values from base workspace
MOV_Va=evalin('base','MOV_Va');
MOV_Vb=evalin('base','MOV_Vb');
MOV_Vc=evalin('base','MOV_Vc');
Cap_Ia=evalin('base','Cap_Ia');
Cap_Ib=evalin('base','Cap_Ib');
Cap_Ic=evalin('base','Cap_Ic');
MOV_Ia=evalin('base','MOV_Ia');
MOV_Ib=evalin('base','MOV_Ib');
MOV_Ic=evalin('base','MOV_Ic');
Total_Ia=evalin('base','Total_Ia');
Total_Ib=evalin('base','Total_Ib');
Total_Ic=evalin('base','Total_Ic');
Wa_MOV=evalin('base','Wa_MOV');
Wb_MOV=evalin('base','Wb_MOV');
Wc_MOV=evalin('base','Wc_MOV');


%Adjust plot axes for given fault
MOV_Va_ymax1=1.4*Vmax(1);
MOV_Va_ymin1=-MOV_Va_ymax1;
```

```matlab
MOV_Va_ymax2=1.15*Vmax(1);
MOV_Va_ymin2=-MOV_Va_ymax2;

MOV_Ia_ymax=1.1*Imax(1);
MOV_Ia_ymin=1.1*Imin(1);
Wa_MOV_ymax=1.2*Energy(1);
Wa_MOV_ymin=0;
if Imax(1) > abs(Imin(1))
  MOV_VI_xmax=1.06*Imax(1);
  MOV_VI_xmin=Imin(1)-0.06*Imax(1);
else
  MOV_VI_xmax=Imax(1)-0.1*Imin(1);
  MOV_VI_xmin=1.1*Imin(1);
end

Cap_Ia_ymax=1.1*Icap_max(1);
Cap_Ia_ymin=-1.1*Icap_max(1);
Total_Ia_ymax=1.2*Total_max(1);
Total_Ia_ymin=1.2*Total_min(1);

%% Plots
fsize=9;
figure1 = figure('Color',[1 1 1]);
set(figure1, 'Position', [100 100 350 510])

%MOV/capacitor voltage (phase A)
subplot(5,1,1)
plot(MOV_Va.time,MOV_Va.signals.values,'k','LineWidth',1.5)
axis([xmin xmax MOV_Va_ymin1 MOV_Va_ymax1])
ylabel('MOV_a / Cap_a (V)','FontSize',fsize)
set(gca,'FontSize',fsize)

%Capacitor current (phase A)
subplot(5,1,2)
plot(Cap_Ia.time,Cap_Ia.signals.values,'k','LineWidth',1.5)
axis([xmin xmax Cap_Ia_ymin Cap_Ia_ymax])
ylabel('Cap_a (A)','FontSize',fsize)
set(gca,'FontSize',fsize)

%MOV current (phase A)
subplot(5,1,3)
plot(MOV_Ia.time,MOV_Ia.signals.values,'k','LineWidth',1.5)
axis([xmin xmax MOV_Ia_ymin MOV_Ia_ymax])
ylabel('MOV_a (A)','FontSize',fsize)
set(gca,'FontSize',fsize)

%Total combined current through MOV/capacitor (phase A)
subplot(5,1,4)
plot(Total_Ia.time,Total_Ia.signals.values,'k','LineWidth',1.5)
axis([xmin xmax Total_Ia_ymin Total_Ia_ymax])
ylabel('Total_a (A)','FontSize',fsize)
set(gca,'FontSize',fsize)

%Energy absorbed by MOV (phase A)
```

```matlab
subplot(5,1,5)
plot(Wa_MOV.time,Wa_MOV.signals.values,'k','LineWidth',1.5)
axis([xmin xmax 0 Wa_MOV_ymax])
xlabel('Time (sec)','FontSize',fsize)
ylabel('MOV_a Energy (J)','FontSize',fsize)
set(gca,'FontSize',fsize)

%% MOV/capacitor V-I plots:
figure2 = figure('Color',[1 1 1]);
set(figure2, 'Position', [460 300 350 170])

%V-I curve for MOV/cap (phase A)
subplot(3,1,1)
plot(MOV_Ia.signals.values,MOV_Va.signals.values,'k','LineWidth',1.5)
axis([MOV_VI_xmin MOV_VI_xmax MOV_Va_ymin2 MOV_Va_ymax2])
ylabel('MOV_a Voltage (V)','FontSize',fsize)
xlabel('MOV_a Current (A)','FontSize',fsize)
set(gca,'FontSize',fsize)

%V-I curve for MOV/cap (phase B)
subplot(3,1,2)
plot(ans.MOV_Ib.signals.values,ans.MOV_Vb.signals.values,'k','LineWidth',1.5)
ylabel('MOV_b Voltage (V)','FontSize',fsize)
xlabel('MOV_b Current (A)','FontSize',fsize)
set(gca,'FontSize',fsize)

%V-I curve for MOV/cap (phase C)
subplot(3,1,3)
plot(ans.MOV_Ic.signals.values,ans.MOV_Vc.signals.values,'k','LineWidth',1.5)
ylabel('MOV_c Voltage (V)','FontSize',fsize)
xlabel('MOV_c Current (A)','FontSize',fsize)
set(gca,'FontSize',fsize)
end
```

D.5 GUI: Mho Relay A&B Apparent Impedance Plots

```matlab
function Plot_ApparentImpedance(R6,X6)
theta = 0:.01:(2*pi);
p=0;
q=-100:0.6:550;
r=-300:0.3:300;
s=0;
%------------------- Transmission Line Impedance ---------------
line_length = 600;
R1 = 0.038806;
X1 = 0.377416;                    %Xl1=2*pi*f*L
Xc = 1.15922e-8*377;              %Xc1=2*pi*f*C
%----------Distributed Parameters Compensation-----------------
Zt = R1+1i*X1;                    %line impedance
```

```matlab
Yt = 1i*Xc;                             %admittance
zc = sqrt(Zt/Yt);                       %characteristic impedance
gam = sqrt(Zt*Yt);                      %propagation constant
Lset = 600;                             %relay reach
%-------------------------------------------------------------------
Zset1 = zc*tanh(gam*Lset*0.8);          %protection zone 1 80% reach
Zset2 = zc*tanh(gam*Lset*1.2);          %protection zone 2 120% reach
%-------------------------------------------------------------------

%Zone 1
Req1=real(Zset1);
Xeq1=imag(Zset1);
Zangle1=atan(Xeq1/Req1);
%Zone 2
Req2=real(Zset2);
Xeq2=imag(Zset2);
Zangle2=atan(Xeq2/Req2);

% radius of zone 1 circle
R_zone1 = sqrt((Req1)^2+(Xeq1)^2)/2;
%center of zone 1 circle (a,b)
a=R_zone1*(cos(Zangle1));
b=R_zone1*(sin(Zangle1));
%circle of radius Zone 1 centred at (a,b)
c = R_zone1*cos(theta)+a;
d = R_zone1*sin(theta)+b;
% radius of Zone 2 circle
R_zone2 = sqrt((Req2)^2+(Xeq2)^2)/2;
%center of zone 2 circle (f,e)
f=R_zone2*(cos(Zangle2));
e=R_zone2*(sin(Zangle2));
%circle of radius zone 2 centred at (f,e)
g = R_zone2*cos(theta)+f;
h = R_zone2*sin(theta)+e;
%impedance line
t=0:0.1:250;
u=t*(b/a);

plot1 = figure('position',[455 200 350 300]);
set(gca,'fontsize',13)
plot2=plot(t,u,'b',c,d,'g',g,h,'m','LineWidth',2);
hold on
plot3=plot(p,q,'k--',r,s,'k--','LineWidth',0.4);
plot4=plot(R6,X6,'r+');
ymax=1.11*max(h);
ymin=-22;
xmax=1.15*max(g);
xmin=1.34*min(g);
axis([xmin xmax ymin ymax]);
xlabel('Resistance (R)');
ylabel('Reactance (X)');
hold off
grid off
end
```

D.6 GUI: Adaptive Mho Relay A & B Plots with Equivalent MOV/Capacitor Impedance

```matlab
function
Plot_AdaptiveImpedance_RelayAB(R6,X6,Rcap1,Xcap1,Fault_Under300km)
theta = 0:.01:(2*pi);
p=0;
q=-100:0.6:550;
r=-300:0.3:300;
s=0;
%Transmission Line Impedance
line_length = 600;
R1 = 0.038806;
X1 = 0.377416;                  %Xl1=2*pi*f*L
Xc = 1.15922e-8*377;            %Xc1=2*pi*f*C
%Distributed Parameters
Zt = R1+1i*X1;                  %line impedance
Yt = 1i*Xc;                     %admittance
zc = sqrt(Zt/Yt);              %characteristic impedance
gam = sqrt(Zt*Yt);             %propagation constant
Lset = 600;                     %relay reach
Zset1 = zc*tanh(gam*Lset*0.8);  %zone 1 80% reach
Zset2 = zc*tanh(gam*Lset*1.2);  %zone 2 120% reach
%Zone 1
Req1=real(Zset1);
Xeq1=imag(Zset1);
Zangle1=atan(Xeq1/Req1);
%Zone 2
Req2=real(Zset2);
Xeq2=imag(Zset2);
Zangle2=atan(Xeq2/Req2);

%---1. Equivalent MOV/capacitor impedance Dynamics ---
% radius of zone 1 circle
R_zone1 = sqrt((Req1)^2+(Xeq1)^2)/2;    %radius zone 1 80% reach
%center of zone 1 circle (a,b)
a=R_zone1*(cos(Zangle1));
b=R_zone1*(sin(Zangle1));
%circle of radius Zone 1 centred at (a,b)
c = R_zone1*cos(theta)+a;
d = R_zone1*sin(theta)+b;
% radius of Zone 2 circle
R_zone2 = sqrt((Req2)^2+(Xeq2)^2)/2;    %radius zone 1 80% reach
%center of zone 2 circle (f,e)
f=R_zone2*(cos(Zangle2));
e=R_zone2*(sin(Zangle2));
%circle of radius zone 2 centred at (f,e)
g = R_zone2*cos(theta)+f;
h = R_zone2*sin(theta)+e;
%impedance line
t=0:0.1:250;
u=t*(b/a);
```

```matlab
plot4 = figure('position',[100 200 350 300]);      %[x,y,width,height]
plot4=plot(p,q,'k--',r,s,'k--',t,u,'r',c,d,'g',g,h,'m',Rcap,Xcap,'b+');
%axis([-175 225 -2 375]);
xlabel('Resistance (R)');
ylabel('Reactance (X)');
grid off

%--- 2. Relay A&B - Adaptive Setting ---
Rcap=Rcap1(end);
Xcap=Xcap1(end);
if Fault_Under300km==1
    Zcap=0;                                %*** Fault on LHS of
capacitor
    Zset1 = zc*tanh(gam*Lset*0.8)+Zcap;    %zone 1 80% reach
    Zset2 = zc*tanh(gam*Lset*1.2)+Zcap;    %zone 2 120% reach
else
    Zcap=Rcap+1i*Xcap+1i;                  %*** Fault on RHS of
capacitor
    Zset1 = zc*tanh(gam*Lset*0.8)+Zcap;    %zone 1 80% reach
    Zset2 = zc*tanh(gam*Lset*1.2)+Zcap;    %zone 2 120% reach
End

%Zone 1
Req1=real(Zset1);
Xeq1=imag(Zset1);
Zangle1=atan(Xeq1/Req1);
%Zone 2
Req2=real(Zset2);
Xeq2=imag(Zset2);
Zangle2=atan(Xeq2/Req2);
%radius of zone 1 circle
R_zone1 = sqrt((Req1)^2+(Xeq1)^2)/2;
%center of Zone 1 circle (a,b)
a=R_zone1*(cos(Zangle1));
b=R_zone1*(sin(Zangle1));
%circle of radius Zone 1 centred at (a,b)
c = R_zone1*cos(theta)+a;
d = R_zone1*sin(theta)+b;
%radius of zone 2 circle
R_zone2 = sqrt((Req2)^2+(Xeq2)^2)/2;
%center of Zone 2 circle (f,e)
f=R_zone2*(cos(Zangle2));
e=R_zone2*(sin(Zangle2));
%circle of radius Zone 2 centred at (f,e)
g = R_zone2*cos(theta)+f;
h = R_zone2*sin(theta)+e;
%impedance line
t=0:0.1:250;
u=t*(b/a);

p1 = figure('position',[455 200 350 300]);
set(gca,'fontsize',13)
p2=plot(t,u,'b',c,d,'g',g,h,'m','LineWidth',2);
hold on
```

```matlab
p3=plot(p,q,'k--',r,s,'k--','LineWidth',0.4);
p4=plot(R6,X6,'b+');
hold off
legend([p4],{'SLGF'},'Location','northwest','FontSize',10);

if Fault_Under300km==1    %*** Fault on LHS of capacitor
    ymax=1.11*max(h);
    ymin=-22;
    xmax=1.15*max(g);
    xmin=1.34*min(g);
else
    ymax=1.3*max(h);          %*** Fault on RHS of capacitor
    ymin=-15;
    xmax=1.22*max(g);
    xmin=1.8*min(g);
end
axis([xmin xmax ymin ymax]);
xlabel('Resistance (R)');
ylabel('Reactance (X)');
grid off
end
```

Appendix E

Additional MATLAB Codes

This appendix presents extra MATLAB codes that compares different study cases

presented throughout the thesis.

E.1 Base Case 1 - Apparent Impedance Trajectories

```matlab
%Apparent Impedance Trajectories for 0% compensation and Average Wind
%Level

theta = 0:.01:(2*pi);
p=0;
q=-100:0.6:450;
r=-250:0.3:350;
s=0;
%Transmission Line Impedance
line_length = 600;
R1 = 0.038806;
X1 = 0.377416;                  %Xl1=2*pi*f*L
Xc = 1.15922e-8*377;            %Xc1=2*pi*f*C
%Distributed Parameters
Zt = R1+1i*X1;                  %line impedance
```

```matlab
Yt = 1i*Xc;                         %admittance
zc = sqrt(Zt/Yt);                   %characteristic impedance
gam = sqrt(Zt*Yt);                  %propagation constant
Lset = 600;                         %relay reach
Zset1 = zc*tanh(gam*Lset*0.8);    %zone 1 80% reach
Zset2 = zc*tanh(gam*Lset*1.2);    %zone 2 120% reach
%Zone 1
Req1=real(Zset1);
Xeq1=imag(Zset1);
Zangle1=atan(Xeq1/Req1);
%Zone 2
Req2=real(Zset2);
Xeq2=imag(Zset2);
Zangle2=atan(Xeq2/Req2);

filename=['C:\matlab_dot_mat_files\00_SLGF_000km_NoCapac_AveWind.mat';
 'C:\matlab_dot_mat_files\00_SLGF_100km_NoCapac_AveWind.mat';
 'C:\matlab_dot_mat_files\00_SLGF_200km_NoCapac_AveWind.mat';
 'C:\matlab_dot_mat_files\00_SLGF_300km_NoCapac_AveWind.mat';
 'C:\matlab_dot_mat_files\00_SLGF_400km_NoCapac_AveWind.mat';
 'C:\matlab_dot_mat_files\00_SLGF_500km_NoCapac_AveWind.mat';
 'C:\matlab_dot_mat_files\00_SLGF_600km_NoCapac_AveWind.mat'];
[n,m]=size(filename);

for i=1:1:n
C = strsplit(filename(i,:),'\');
fileName=char(C(3))

S=load(filename(i,:))
    Rave00_l=S.R6;                  %apparent impedance seen by relay A
    Xave00_l=S.X6;
    Rave00_r=S.R8;                  %apparent impedance seen by relay B
    Xave00_r=S.X8;

%---Mho relay zone 1 and 2 setting (0% compensation)---
%radius of zone 1 circle
R_zone1 = sqrt((Req1)^2+(Xeq1)^2)/2;     %circle radius zone 1
%center of zone 1 circle (a,b)
a=R_zone1*(cos(Zangle1));
b=R_zone1*(sin(Zangle1));
%circle of radius Zone 1 centred at (a,b)
c = R_zone1*cos(theta)+a;
d = R_zone1*sin(theta)+b;

%radius of zone 2 circle
R_zone2 = sqrt((Req2)^2+(Xeq2)^2)/2;     %circle radius zone 2
%center of zone 2 circle (f,e)
f=R_zone2*(cos(Zangle2));
e=R_zone2*(sin(Zangle2));
%circle of radius Zone 2 centred at (f,e)
g = R_zone2*cos(theta)+f;
h = R_zone2*sin(theta)+e;

%impedance line
```

```matlab
t=0:0.1:150;
u=t*(b/a);

%%Plots:
%Mho relay A
ha(1) = figure('position',[100 200 380 330]);
p1=plot(t,u,'b',c,d,'g',g,h,'m','LineWidth',2);
hold on
p3=plot(p,q,'k--',r,s,'k--','LineWidth',1);
p2=plot(Rave00_l,Xave00_l,':k+');
hold off
legend([p2],{'0% Comp'},'Location','northwest','FontSize',13);
set(gca,'fontsize',13)
ymax=1.11*max(h);
ymin=-22;
xmax=1.16*max(g);
xmin=1.25*min(g);
%axis([-190 240 -10 400]);
axis([xmin xmax ymin ymax]);
xlabel('Resistance (R)');
ylabel('Reactance (X)');

%Mho relay B
ha(2) = figure('position',[550 200 380 330]);
p1=plot(t,u,'b',c,d,'g',g,h,'m','LineWidth',2);
hold on
p3=plot(p,q,'k--',r,s,'k--','LineWidth',1);
p2=plot(Rave00_r,Xave00_r,':k+');
hold off
legend([p2],{'0% Comp'},'Location','northwest','FontSize',13);
set(gca,'fontsize',13)
ymax=1.11*max(h);
ymin=-22;
xmax=1.16*max(g);
xmin=1.25*min(g);
axis([xmin xmax ymin ymax]);
xlabel('Resistance (R)');
ylabel('Reactance (X)');

%Save figures
FigName=strcat(fileName(1,9:29),'_BaseCase.fig');
%0km_NoCapac_AveWind_BaseCase.fig

savefig(ha, FigName);
%close(ha);
end
```

```matlab
%Effects of Compensation Levels on Apparent Impedances of Relays A&B
theta = 0:.01:(2*pi);
p=0;
q=-100:0.6:450;
r=-250:0.3:350;
s=0;
%Transmission Line Impedance
line_length = 600;
R1 = 0.038806;
X1 = 0.377416;
Xc = 1.15922e-8*377;
%Distributed Parameters Compensation
Zt = R1+1i*X1;
Yt = 1i*Xc;
zc = sqrt(Zt/Yt);
gam = sqrt(Zt*Yt);
Lset = 600;
Zset1 = zc*tanh(gam*Lset*0.8);
Zset2 = zc*tanh(gam*Lset*1.2);

filename=['SLGF_000km_WithCap_AveWind.mat';
'SLGF_100km_WithCap_AveWind.mat';
'SLGF_200km_WithCap_AveWind.mat';
'SLGF_300LkmWithCap_AveWind.mat';
'SLGF_300RkmWithCap_AveWind.mat';
'SLGF_400km_WithCap_AveWind.mat';
'SLGF_500km_WithCap_AveWind.mat';
'SLGF_600km_WithCap_AveWind.mat'];
[n,m]=size(filename);

for i=1:1:n

if i==4 || i==5

C00=strcat('C:\matlab_dot_mat_files\00_SLGF_300km_NoCapac_AveWind.mat')
;
else

C00=strcat('C:\matlab_dot_mat_files\00_',filename(i,1:10),'_NoCapac_Ave
Wind.mat');
end
C20=strcat('C:\matlab_dot_mat_files\20_',filename(i,1:m));
C40=strcat('C:\matlab_dot_mat_files\40_',filename(i,1:m));
C60=strcat('C:\matlab_dot_mat_files\60_',filename(i,1:m));
C = strsplit(C60,'\');

WindType=filename(i,20:26)
if strcmp(WindType,'AveWind')
    WindType = 'Average Wind';
```

```matlab
elseif strcmp(WindType,'MaxWind')
    WindType = 'Maximum Wind';
elseif strcmp(WindType,'MinWind')
    WindType = 'Minimum Wind';
end

S=load(C00)              % 0% compensation
    Rave00_l=S.R6;       %apparent impedance seen by relay A
    Xave00_l=S.X6;
    Rave00_r=S.R8;       %apparent impedance seen by relay A
    Xave00_r=S.X8;

S=load(C20)              % 20% compensation
    Rave20_l=S.R6;       %apparent impedance seen by relay A
    Xave20_l=S.X6;
    Rave20_r=S.R8;       %apparent impedance seen by relay A
    Xave20_r=S.X8;

S=load(C40)              % 40% compensation
    Rave40_l=S.R6;       %apparent impedance seen by relay A
    Xave40_l=S.X6;
    Rave40_r=S.R8;       %apparent impedance seen by relay A
    Xave40_r=S.X8;

S=load(C60)              % 60% compensation
    Rave60_l=S.R6;       %apparent impedance seen by relay A
    Xave60_l=S.X6;
    Rave60_r=S.R8;       %apparent impedance seen by relay A
    Xave60_r=S.X8;

fileName=char(C(6));
Zcap=0;
Req1=real(Zset1);
Xeq1=imag(Zset1);
Zangle1=atan(Xeq1/Req1);
Req2=real(Zset2);
Xeq2=imag(Zset2);
Zangle2=atan(Xeq2/Req2);
% radius of Zone 1 circle
R_zone1 = sqrt((Req1)^2+(Xeq1)^2)/2;
%center of Zone 1 circle (a,b)
a=R_zone1*(cos(Zangle1));
b=R_zone1*(sin(Zangle1));
%circle of radius Zone 1 centred at (a,b)
c = R_zone1*cos(theta)+a;
d = R_zone1*sin(theta)+b;
% radius of Zone 2 circle
R_zone2 = sqrt((Req2)^2+(Xeq2)^2)/2;
%center of Zone 2 circle (f,e)
f=R_zone2*(cos(Zangle2));
e=R_zone2*(sin(Zangle2));
%circle of radius Zone 2 centred at (f,e)
g = R_zone2*cos(theta)+f;
h = R_zone2*sin(theta)+e;
```

```matlab
%impedance line
t=0:0.1:150;
u=t*(b/a);

%% Plots:
%Mho relay A
ha(1) = figure('position',[100 200 380 330]);
p1=plot(t,u,'b',c,d,'g',g,h,'m','LineWidth',2);
hold on
p6=plot(p,q,'k--',r,s,'k--','LineWidth',0.4);
p2=plot(Rave00_l,Xave00_l,':k+');
p3=plot(Rave20_l,Xave20_l,':m*');
p4=plot(Rave40_l,Xave40_l,':ro');
p5=plot(Rave60_l,Xave60_l,':bs');
hold off
legend([p2,p3,p4,p5],{'0%','20%','40%','60%'},'Location','northwest','F
ontSize',13);
set(gca,'fontsize',13)
ymax=1.11*max(h);
ymin=-22;
xmax=1.15*max(g);
xmin=1.34*min(g);
axis([xmin xmax ymin ymax]);
xlabel('Resistance (R)');
ylabel('Reactance (X)');

%Mho relay B
ha(2) = figure('position',[550 200 380 330]);
p1b=plot(t,u,'b',c,d,'g',g,h,'m','LineWidth',2);
hold on;
p6b=plot(p,q,'k--',r,s,'k--','LineWidth',0.4);
p2b=plot(Rave00_r,Xave00_r,':k+');
p3b=plot(Rave20_r,Xave20_r,':m*');
p4b=plot(Rave40_r,Xave40_r,':ro');
p5b=plot(Rave60_r,Xave60_r,':bs');
hold off
legend([p2b,p3b,p4b,p5b],{'0%','20%','40%','60%'},'Location','northwest
','FontSize',13);
set(gca,'fontsize',13)
ymax=1.11*max(h);
ymin=-22;
xmax=1.15*max(g);
xmin=1.34*min(g);
axis([xmin xmax ymin ymax]);
xlabel('Resistance (R)');
ylabel('Reactance (X)');

%Save figures
D = strsplit(filename(i,1:m),'.');
FigName=strcat(D(1),'_0_20_40_60.fig');

savefig(ha, FigName{1});
end
```

E.3 Case 3 - Relays A&B's Apparent Impedance Plots for Average, Maximum, and Minimum Wind Levels with the Base Case Plots

```
%Case 2: Comparing Ave, Max, & Min Wind Levels with Base Case
theta = 0:.01:(2*pi);
p=0;
q=-100:0.6:450;
r=-250:0.3:350;
s=0;
%Transmission Line Impedance
line_length = 600;
R1 = 0.038806;
X1 = 0.377416;
Xc = 1.15922e-8*377;
%Distributed Parameters Compensation
Zt = R1+1i*X1;
Yt = 1i*Xc;
zc = sqrt(Zt/Yt);
gam = sqrt(Zt*Yt);
Lset = 600;
Zset1 = zc*tanh(gam*Lset*0.8);
Zset2 = zc*tanh(gam*Lset*1.2);

%Zone 1
Req1=real(Zset1);
Xeq1=imag(Zset1);
Zangle1=atan(Xeq1/Req1);
%Zone 2
Req2=real(Zset2);
Xeq2=imag(Zset2);
Zangle2=atan(Xeq2/Req2);

% radius of Zone 1 circle
R_zone1 = sqrt((Req1)^2+(Xeq1)^2)/2;
%center of Zone 1 circle (a,b)
a=R_zone1*(cos(Zangle1));
b=R_zone1*(sin(Zangle1));
%circle of radius Zone 1 centred at (a,b)
c = R_zone1*cos(theta)+a;
d = R_zone1*sin(theta)+b;
% radius of Zone 2 circle
R_zone2 = sqrt((Req2)^2+(Xeq2)^2)/2;
%center of Zone 2 circle (f,e)
f=R_zone2*(cos(Zangle2));
e=R_zone2*(sin(Zangle2));
%circle of radius Zone 2 centred at (f,e)
g = R_zone2*cos(theta)+f;
h = R_zone2*sin(theta)+e;
%impedance line
t=0:0.1:150;
u=t*(b/a);
```

```matlab
filename=[
'C:\matlab_dot_mat_files\60_SLGF_000km_WithCap';
'C:\matlab_dot_mat_files\60_SLGF_100km_WithCap';
'C:\matlab_dot_mat_files\60_SLGF_200km_WithCap';
'C:\matlab_dot_mat_files\60_SLGF_300LkmWithCap';
'C:\matlab_dot_mat_files\60_SLGF_300RkmWithCap';
'C:\matlab_dot_mat_files\60_SLGF_400km_WithCap';
'C:\matlab_dot_mat_files\60_SLGF_500km_WithCap';
'C:\matlab_dot_mat_files\60_SLGF_600km_WithCap'];
 [n,m]=size(filename);

for i=1:1:n
Ave=strcat(filename(i,1:m),'_AveWind.mat');
Max=strcat(filename(i,1:m),'_MaxWind.mat');
Min=strcat(filename(i,1:m),'_MinWind.mat');
C = strsplit(filename(i,1:m),'\');      %ex: 60_SLGF_100km_WithCap
A=C{3};
if A(9:11)=='000'
 NoCap='C:\matlab_dot_mat_files\00_SLGF_000km_NoCapac_AveWind.mat';
elseif A(9:11)=='100'
 NoCap='C:\matlab_dot_mat_files\00_SLGF_100km_NoCapac_AveWind.mat';
elseif A(9:11)=='200'
 NoCap='C:\matlab_dot_mat_files\00_SLGF_200km_NoCapac_AveWind.mat';
elseif A(9:11)=='300'
 NoCap='C:\matlab_dot_mat_files\00_SLGF_300km_NoCapac_AveWind.mat';
elseif A(9:11)=='400'
 NoCap='C:\matlab_dot_mat_files\00_SLGF_400km_NoCapac_AveWind.mat';
elseif A(9:11)=='500'
 NoCap='C:\matlab_dot_mat_files\00_SLGF_500km_NoCapac_AveWind.mat';
elseif A(9:11)=='600'
 NoCap='C:\matlab_dot_mat_files\00_SLGF_600km_NoCapac_AveWind.mat';
end

S=load(NoCap)
    Rzero_l=S.R6;        %apparent impedance seen by relay A
    Xzero_l=S.X6;
    Rzero_r=S.R8;        %apparent impedance seen by relay A
    Xzero_r=S.X8;

S=load(Ave)
    Rave_l=S.R6;         %apparent impedance seen by relay A
    Xave_l=S.X6;
    Rave_r=S.R8;         %apparent impedance seen by relay A
    Xave_r=S.X8;

S=load(Max)
    Rmax_l=S.R6;         %apparent impedance seen by relay A
    Xmax_l=S.X6;
    Rmax_r=S.R8;         %apparent impedance seen by relay A
    Xmax_r=S.X8;
S=load(Min)
    Rmin_l=S.R6;         %apparent impedance seen by relay A
    Xmin_l=S.X6;
    Rmin_r=S.R8;         %apparent impedance seen by relay A
```

```matlab
    Xmin_r=S.X8;

fileName=char(C(3));

%%Plots:
ha(1) = figure('position',[100 200 380 330]);
p1=plot(t,u,'b',c,d,'g',g,h,'m','LineWidth',2);
hold on
p6=plot(p,q,'k--',r,s,'k--','LineWidth',1);
p2=plot(Rzero_l,Xzero_l,':kx');
p3=plot(Rave_l,Xave_l,':mo');
p4=plot(Rmax_l,Xmax_l,':bs');
p5=plot(Rmin_l,Xmin_l,':r*');
hold off
set(gca,'fontsize',13)
legend([p2,p3,p4,p5],{'0%Comp','AveWind','MaxWind','MinWind'},'Location
','northwest','FontSize',12);
ymax=1.11*max(h);
ymin=-22;
xmax=1.1*max(g);
xmin=1.34*min(g);
axis([xmin xmax ymin ymax]);
xlabel('Resistance (R)');
ylabel('Reactance (X)');

ha(2) = figure('position',[550 200 380 330]);
p1b=plot(t,u,'b',c,d,'g',g,h,'m','LineWidth',2);
hold on
p6b=plot(p,q,'k--',r,s,'k--','LineWidth',1);
p2b=plot(Rzero_r,Xzero_r,':kx');
p3b=plot(Rave_r,Xave_r,':mo');
p4b=plot(Rmax_r,Xmax_r,':bs');
p5b=plot(Rmin_r,Xmin_r,':r*');
hold off
set(gca,'fontsize',13)
legend([p2b,p3b,p4b,p5b],{'0%Comp','AveWind','MaxWind','MinWind'},'Loca
tion','northwest','FontSize',12);
ymax=1.11*max(h);
ymin=-22;
xmax=1.1*max(g);
xmin=1.34*min(g);
axis([xmin xmax ymin ymax]);
xlabel('Resistance (R)');
ylabel('Reactance (X)');

%Save figures
C = strsplit(filename(i,1:m),'\');              %ex:
60_SLGF_200km_WithCap
FigName=strcat(C(3),'_ave_max_min_wind.fig');

savefig(ha, FigName{1});
%close(ha);
end
```

E.4 Case 4 - Adaptive Mho Relay Setting Plots for Average Wind with Equivalent MOV/Capacitor impedance Plots

```matlab
%-- Case 4: Adaptive Mho Relay Setting for Average Wind --
theta = 0:.01:(2*pi);
p=0;
q=-100:0.6:550;
r=-300:0.3:300;
s=0;
%Transmission Line Impedance
line_length = 600;
R1 = 0.038806;
X1 = 0.377416;
Xc = 1.15922e-8*377;
%Distributed Parameters Compensation
Zt = R1+1i*X1;
Yt = 1i*Xc;
zc = sqrt(Zt/Yt);
gam = sqrt(Zt*Yt);
Lset = 600;
Zset1 = zc*tanh(gam*Lset*0.8);
Zset2 = zc*tanh(gam*Lset*1.2);

%Different Wind Levels can be changed (Ave, Max, or Min)
filename=[
'SLGF_000km_WithCap_AveWind.mat';
'SLGF_100km_WithCap_AveWind.mat';
'SLGF_200km_WithCap_AveWind.mat';
'SLGF_300LkmWithCap_AveWind.mat';
'SLGF_300RkmWithCap_AveWind.mat';
'SLGF_400km_WithCap_AveWind.mat';
'SLGF_500km_WithCap_AveWind.mat';
'SLGF_600km_WithCap_AveWind.mat'];
[n,m]=size(filename);

for i=1:1:n
fileName_=filename(i,1:end);
C60=strcat('C:\matlab_dot_mat_files\60_',filename(i,1:m));
C = strsplit(C60,'\');

WindType=filename(i,20:26)
if strcmp(WindType,'AveWind')
    WindType = 'Average Wind';
elseif strcmp(WindType,'MaxWind')
    WindType = 'Maximum Wind';
elseif strcmp(WindType,'MinWind')
    WindType = 'Minimum Wind';
end

S=load(C60)
    Rave60_l=S.R6;        %apparent impedance seen by relay A
    Xave60_l=S.X6;
```

```matlab
    Rave60_r=S.R8;          %apparent impedance seen by relay A
    Xave60_r=S.X8;

Rcap=S.Rcap_phA(end);
fprintf('\nRcap=%d\n',Rcap)
Xcap=S.Xcap_phA(end);
fprintf('\nXcap=%d\n',Xcap)

%Adaptive Mho Relay A Setting with Equivalent MOV/capacitor impedance
fileName=char(C(3));
if strcmp(fileName(9),'0') || strcmp(fileName(9),'1') ||
strcmp(fileName(9),'2') || strcmp(fileName(9:12),'300L')
    Zcap=0;                          %Fault on LHS of capacitor bank
    Zset1 = zc*tanh(gam*Lset*0.8)+Zcap;     %zone 1 80% reach
    Zset2 = zc*tanh(gam*Lset*1.2)+Zcap;     %zone 2 120% reach
else
    Zcap=Rcap+1i*Xcap+1i;            %Fault on RHS of capacitor bank
    Zset1 = zc*tanh(gam*Lset*0.8)+Zcap;     % zone 1 80% reach
    Zset2 = zc*tanh(gam*Lset*1.15)+Zcap;    %zone 2 120% reach
end
%Zone 1
Req1=real(Zset1);
Xeq1=imag(Zset1);
Zangle1=atan(Xeq1/Req1);
%Zone 2
Req2=real(Zset2);
Xeq2=imag(Zset2);
Zangle2=atan(Xeq2/Req2);

% radius of Zone 1 circle
R_zone1 = sqrt((Req1)^2+(Xeq1)^2)/2;
%center of Zone 1 circle (a,b)
a=R_zone1*(cos(Zangle1));
b=R_zone1*(sin(Zangle1));
%circle of radius Zone 1 centred at (a,b)
c = R_zone1*cos(theta)+a;
d = R_zone1*sin(theta)+b;
% radius of Zone 2 circle
R_zone2 = sqrt((Req2)^2+(Xeq2)^2)/2;
%center of Zone 2 circle (f,e)
f=R_zone2*(cos(Zangle2));
e=R_zone2*(sin(Zangle2));
%circle of radius Zone 2 centred at (f,e)
g = R_zone2*cos(theta)+f;
h = R_zone2*sin(theta)+e;
%impedance line
t=0:0.1:250;
u=t*(b/a);

%% Plots:
%Mho relay A
ha(1) = figure('position',[100 300 380 330]);
set(gca,'fontsize',13)
p1a=plot(t,u,'b',c,d,'g',g,h,'m','LineWidth',2);
```

```matlab
hold on
p2a=plot(p,q,'k--',r,s,'k--','LineWidth',0.4);
p3a=plot(Rave60_l,Xave60_l,':mo');
hold off
legend([p3a],{'0%','20%','40%','60%'},'Location','northwest','FontSize'
,12.5);
if strcmp(fileName(9),'0') || strcmp(fileName(9),'1') ||
strcmp(fileName(9),'2') || strcmp(fileName(9:12),'300L')
    ymax=1.11*max(h);
    ymin=-22;
    xmax=1.15*max(g);
    xmin=1.34*min(g);
else
    ymax=1.3*max(h);
    ymin=-15;
    xmax=1.22*max(g);
    xmin=1.8*min(g);
end

axis([xmin xmax ymin ymax]);
xlabel('Resistance (R)');
ylabel('Reactance (X)');

%Adaptive Mho Relay B Setting with Equivalent MOV/capacitor impedance
if strcmp(fileName(9:12),'300R') || strcmp(fileName(9),'4') ||
strcmp(fileName(9),'5') || strcmp(fileName(9),'6')
    Zcap=0;                                 %Fault on RHS of capacitor
    Zset1 = zc*tanh(gam*Lset*0.8)+Zcap;     %zone 1 80% reach
    Zset2 = zc*tanh(gam*Lset*1.2)+Zcap;     %zone 2 120% reach
else
    Zcap=Rcap+1i*Xcap+1i;                   %Fault on LHS of capacitor
    Zset1 = zc*tanh(gam*Lset*0.8)+Zcap;     %zone 1 80% reach
    Zset2 = zc*tanh(gam*Lset*1.12)+Zcap;    %zone 2 120% reach
end
%zone 1
Req1=real(Zset1);
Xeq1=imag(Zset1);
Zangle1=atan(Xeq1/Req1);
%zone 2
Req2=real(Zset2);
Xeq2=imag(Zset2);
Zangle2=atan(Xeq2/Req2);

% radius of Zone 1 circle
R_zone1 = sqrt((Req1)^2+(Xeq1)^2)/2;
%center of Zone 1 circle (a,b)
a=R_zone1*(cos(Zangle1));
b=R_zone1*(sin(Zangle1));
%circle of radius Zone 1 centred at (a,b)
c = R_zone1*cos(theta)+a;
d = R_zone1*sin(theta)+b;
% radius of Zone 2 circle
R_zone2 = sqrt((Req2)^2+(Xeq2)^2)/2;
%center of Zone 2 circle (f,e)
```

```matlab
f=R_zone2*(cos(Zangle2));
e=R_zone2*(sin(Zangle2));
%circle of radius Zone 2 centred at (f,e)
g = R_zone2*cos(theta)+f;
h = R_zone2*sin(theta)+e;
%impedance line
t=0:0.1:250;
u=t*(b/a);

%Mho relay B
ha(2) = figure('position',[550 300 380 330]);
set(gca,'fontsize',13)
p1b=plot(t,u,'b',c,d,'g',g,h,'m','LineWidth',2);
hold on;
p2b=plot(p,q,'k--',r,s,'k--','LineWidth',0.4);
p3b=plot(Rave60_r,Xave60_r,':mo');
hold off
legend([p3b],{'0%','20%','40%','60%'},'Location','northwest','FontSize'
,12.5);
if strcmp(fileName(9:12),'300R') || strcmp(fileName(9),'4') ||
strcmp(fileName(9),'5') || strcmp(fileName(9),'6')
    ymax=1.11*max(h);
    ymin=-22;
    xmax=1.15*max(g);
    xmin=1.34*min(g);
else
    ymax=1.3*max(h);
    ymin=-15;
    xmax=1.22*max(g);
    xmin=1.5*min(g);
end
axis([xmin xmax ymin ymax]);
xlabel('Resistance (R)');
ylabel('Reactance (X)');

%Save figures
D = strsplit(filename(i,1:m),'.');
FigName=strcat(D(1),'_AdaptSetting.fig');

savefig(ha, FigName{1});
%close(ha);
end
```

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