PERFORMANCE COMPARISON BETWEEN DUAL-BLINDER AND A PHASOR-BASED OUT OF STEP DETECTION FUNCTIONS USING HARDWARE IN THE LOOP TEST

By

Mustafa Amir Saad

Approved:

Ahmed Eltom
Professor of Electrical Engineering
(Thesis Supervisor)

Gary Kobet
Adjunct Professor of Electrical Engineering
(Committee Member)

Nurhidajat Sisworahardjo
Assistant Professor of Electrical Engineering
(Committee Member)

PERFORMANCE COMPARISON BETWEEN DUAL-BLINDER AND A PHASOR-BASED OUT OF STEP DETECTION FUNCTIONS USING HARDWARE IN THE LOOP TEST

By

Mustafa Amir Saad

A Thesis Submitted to the Faculty of the University of
Tennessee at Chattanooga in Partial Fulfillment
of the Requirements of the Degree of
Master of Science

The University of Tennessee at Chattanooga
Chattanooga, Tennessee

May 2014

ABSTRACT

When an Out of Step (OOS) event occurs between two connected areas in the power system, the two areas should be separated before the OOS results in generation loss, equipment damage, and eventually a total black-out. This separation is achieved via the OOS function that implemented at specific transmission lines. One of the commonly used methods to achieve the OOS tripping functionality is the Dual-Blinder Scheme, which compare the locally measured impedance to a set value.

In this research, a Phasor-Based OOS tripping function, based on the derivatives of the voltage phase angle difference between the two areas, is evaluated against the Dual-Blinder method using a real-time digital simulator, a protective relay, and a Synchrophasor Vector Processor (SVP).

The evaluation shows that the Phasor-Based function predicted the OOS before the Dual-Blinder OOS function when the power system was having damping problems. In other cases, the Dual-Blinder OOS function tripped faster in most of the considered cases. Finally, this research suggests some improvements for implementing the Phasor-Based OOS function in the future.

TABLE OF CONTENTS

ABSTRACT iii

LIST OF TABLES vi

LIST OF FIGURES vii

LIST OF ABBREVIATIONS x

CHAPTER

1. INTRODUCTION 1
   1.1 Power Swing and Out of Step Phenomenon 1
   1.2 Thesis Objective 3

2. LITERATURE REVIEW 5
   2.1 Distance Relays Behavior during Power Swings 5
   2.2 The Dual Blinder OOS and the Swing Center Voltage PSB functions 7
      2.2.1 Dual-Blinder Scheme 8
      2.2.2 Swing Center Voltage and its Rate of Change 8
   2.3 Phasor-Based OOS function 11

3. METHODOLOGY 15
   3.1 Hardware in the Loop Test, an Overview 15
   3.2 Test System Description 17
      3.2.1 The Power System Model 17
      3.2.2 The Amplifier 26
      3.2.3 The 411L relays 28
      3.2.4 The SVP 29
         3.2.4.1 SVP Overview 29
         3.2.4.2 Phasor-Based OOS Program Blocks Description 30
         3.2.4.3 Parameters Selection for the SVP OOS-Algorithm 37
   3.3 Testing procedure 41
      3.3.1 Disturbance Scenarios 41
         3.3.1.1 Cases Description 41
      3.3.2 The Stability Study 43
      3.3.3 The Final Test 43

4. RESULTS AND DISCUSSIONS 44

4.1 Results 45
4.1.1 Case-1 45
4.1.2 Case-2 46
4.1.3 Case-3 46
4.1.4 Case-4 49
4.1.5 Case-5 52
4.1.6 Case-6 55
4.1.7 Case-7 58
4.1.8 Case-8 58
4.1.9 Case-9 61
4.1.10 Case-10 64
4.1.11 Case-11 67
4.1.12 Case-12 67
4.1.13 Case-13 68
4.2 Results Discussion 71

5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK 77
5.1 Conclusions 77
5.2 Recommendations for Future Work 78

REFERENCES 80

APPENDICES

A. SYSTEM DATA 81

B. SVP OOS PROGRAM (V3_OOS_PMU) CODE 85

C. STATION_A'S RELAY EVENT FILES 97

D. AREAS' PHASE DIFFERENCE DURING DISTURBANCES 109

VITA 117

LIST OF TABLES

4.1 Tripping time of each function during simulated disturbances……………………………71

LIST OF FIGURES

2.1 Two Machine System 5

2.2 Impedance trajectories measured at the relay during power swings [1]. 6

2.3 Dual-Blinder Scheme [5] 7

2.4 Voltage phasor diagram of a Two Machine System [7] 9

2.5 SCV logic implemented in the 411L relay [7] 10

2.6 Different power swings plotted on (δ, t) plane. 12

2.7 The top power swing in Figure 2.8 plotted on (S, A) plane......................................13

2.8 The middle power swing in Figure 2.8 plotted on (S, A) plane.................................13

2.9 The bottom power swing in Figure 2.8 plotted on (S, A) plane 14

3.1 Conceptual blocks of the hardware in the loop test system 16

3.2 Hardware connections between the relays, the amplifier and the simulator...............17

3.3 One line diagram of the Two Area System..18

3.4 CAPE model of the Two Area System 19

3.5 Subsystems of the model 20

3.6 Console subsystem...21

3.7 Area-1 subsystem blocks 23

3.8 Area-2 subsystem blocks. 24

3.9 Part of the Controls subsystem blocks 25

3.10 Doble F6350 configuration software 26

3.11 Overall logical and electrical V-I signals conditioning and amplification 27

3.12 Project (V3_PMU_OOS) POUs 30

3.13 OOS_prog (PRG) blocks 32

3.14 Spontaneous spikes during fault inception, clearing and reclosing. 35

3.15 Blocks of algorithm FBs. 36

3.16 Algorithm setting parameters..37

3.17 SVP data and algorithm logic in Excel 39

3.18 Fault locations on the test system 41

4.1 The impedance trajectory during Case-1 45

4.2 The impedance trajectory during Case-2 46

4.3 The 411L and the SVP trip signals (top, middle) in Case-3 47

4.4 The impedance trajectory when the 411L tripped in Case-3. 48

4.5 The impedance trajectory when the SVP tripped in Case-3. 48

4.6 The 411L and the SVP trip signals (top, middle) in Case-4 50

4.7 The impedance trajectory when the SVP tripped in Case-4 51

4.8 The impedance trajectory when the 411L tripped in Case-4 51

4.9 The 411L and the SVP trip signals (top, middle) in Case-5. 53

4.10 The impedance trajectory when the SVP tripped in Case-5. 54

4.11 The impedance trajectory when the 411L tripped in Case-5 54

4.12 The 411L and the SVP trip signals (top, middle) in Case-6. 56

4.13 The impedance trajectory when the 411L tripped in Case-6. 57

4.14 The impedance trajectory when the SVP tripped in Case-6. 57

4.15 The impedance trajectory after GN1 outage (Case-7). 58

4.16 The 411L and the SVP trip signals (top, middle) in Case-8 59

4.17 The impedance trajectory when the 411L tripped in Case-8. 60

4.18 The impedance trajectory when the SVP tripped in Case-8. 60

4.19 The 411L and the SVP trip signals (top, middle) in Case-9. 62

4.20 The impedance trajectory when the 411L tripped in Case-9 63

4.21 The impedance trajectory when the SVP tripped in Case-9 63

4.22 The 411L and the SVP trip signals (top, middle) in Case-10. 65

4.23 The impedance trajectory when the 411L tripped (Case-10)....................................66

4.24 The impedance trajectory when the SVP tripped (Case-10).) 66

4.25 The impedance trajectory during Case-11 67

4.26 The impedance trajectory during Case-12. 68

4.27 The OOS trip signals: 411L (top), SVP (middle) and Z1P trip in Case-13...............69

4.28 The impedance trajectory when the SVP tripped in Case-13 70

4.29 The impedance trajectory when the 411L tripped in Case-13 70

4.30 Slip versus acceleration for Case-4. 72

4.31 Slip versus acceleration for Case-13...72

4.32 Slip versus acceleration for Case-6...74

4.33 Slip versus acceleration for Case-9...74

4.34 SVP variables in Case-6...75

4.35 SVP variables in Case-9...76

LIST OF ABBREVIATIONS

AVR, Automatic Voltage Regulator

CAPE, Computer Aided Protection Engineering

CT, Current Transformer

CTR, Current Transformer Ratio

EHV, Extra High Voltage

FB, Functional Block.

FUN, Function.

I/O, Input/output

IED, Intelligent Electronic Device

LL, Line to Line

LN, Line to Neutral

OFGS, Over Frequency Generation Shedding

OOS, Out of Step

OSBD, Out of Step Blocking Delay

OSTC, Out of Step Tripping On The Way out with Count

OOSD, Out of Step Tripping Delay

OSTI, Out of Step Tripping On The Way IN

OSTO, Out of Step Tripping On The Way OUT

PDC, Phasor Data Concentrator

PLC, Programmable Logic Controller

PMU, Phasor Measurement Unit

PMCU, Phasor Measurement and Control Unit

POU, Program Organization Unit

PRG, Program

PSB, Power Swing Blocking

PSS, Power System Stabilizer

SCADA, Supervisory Control And Data Acquisition

SCV, Swing Center Voltage

SEL, Schweitzer Electrical Laboratories

SVP, Synchrophasor Vector Processor

TPH, Three Phase

UFLS Under Frequency Load Shedding

VT, Voltage Transformer

VTR, Voltage Transformer Ratio

CHAPTER 1

INTRODUCTION

1.1 Power Swing and Out of Step Phenomenon

While the power system is operating in the steady state, the generator mechanical input power is equal to the electrical output power. This balance results in an almost constant generator load angle (δ_g). When a disturbance occurs (fault, switching, or outage) the electrical power output suddenly changes. The balance between the generator input and output powers no longer exists after the disturbance. The rotor experiences accelerations and decelerations, and the generator load angle δ_g varies. The generator active power output will vary based on the oscillation of δ_g. Depending on specific parameters (e.g. generator inertia, the response of the protection and excitation systems and the fault type/location), the generator may reach a new steady state point, and the power swing in this case is a stable one, or go into instability, and the power swing in this case is an unstable [1].

Power swings affect the transmission lines relays, and when a power swing occurs, it is always accompanied with voltage sags and current fluctuations, Voltage sags may trigger the under-voltage functions in the line relays, and current fluctuations may pick up the line relays overcurrent functions. The change in the voltages and the currents is also measured as impedance variation on the R-X plane. Impedance (distance) relays may pick up and trip if the impedance locus resulting from the power swing (stable or unstable) passes into one of the relay zones. If the power swing is stable and such a trip occurs, it may worsen the power system situation and may lead to widespread instability. Tripping of distance relays for stable power swings is undesirable. A Power Swing Blocking (PSB) function may be implemented in the distance relays that might be affected by power swings [1].

Tielines between different areas are one of the critical components of the power system. They facilitate power transfer between utilities and geographic areas and maintain the continuity of the service during planned or sudden outages. If an unstable power swing occurs, the tieline relays should be able to detect it, then the two areas that are about to lose synchronism should be separated. The detection and the separation are achieved through the Out of Step (OOS) function. After the separation, the two areas have to be stabilized, normally through Under Frequency Load Shedding (UFLS) or Over Frequency Generation Shedding (OFGS), both areas can be resynchronized by closing the tieline to achieve the same or a nearby pre-disturbance steady state operating point. In distance relays the OOS function has to be set along with the PSB function, otherwise the relay will trip for every swing that its impedance locus moves into one of the relay zones, and no practical usage will be achieved by implementing OOS function [2].

Many methods to block tripping for stable power swings and to trip only for unstable power swings have been implemented and new algorithms are currently being proposed and evaluated. Recent advancement in synchronized phasor measurements has extended the usage of the phasor measurements from model validation, post event analysis, and other off-line studies into the real-time applications of the phasor measurements. Phasor measurements come from dedicated Phasor Measurement Units (PMUs) or from protective relays that have PMU functionality. These measurements are then aligned and saved by so called Phasor Data Concentrators (PDCs) and become available for Supervisory Control and Data Acquisition (SCADA), state estimators, or any other application. PDCs do not process the data or run algorithms, but the Synchrophasor Vector Processors (SVPs) do. The SVP is a user programmable real-time processor that can use the phasor measurements as an input for the protection and control algorithms running inside. Finally the SVP issues the appropriate control decision [3].

1.2 Thesis Objective

The objective of the thesis is to compare the performance of Dual-Blinder, which detects the OOS by comparing the measured impedance at the relay location with a blinder setting on the R-X plant, and a Phasor-Based OOS function, which uses the phasor measurements from the two ends of the protected line to calculate the phase angle difference and its first two derivatives (the Slip-S and the Acceleration-A), and constructs a trajectory on S-A plane. The OOS is determined based on two parallel blinders that are set after performing a stability study. Very little is known about the performance of the Phasor-Based OOS function, and the comparison of the performance of these two OOS function will help improving the Phasor-Based OOS function in the future.

There are different approaches to utilize the phasor measurements in developing OOS functions [1], [4]. Some of the developed functions utilize the angle difference only, and other designs use the phase angle and the first derivative (the Slip-S). The function evaluated in this research uses the first and the second derivatives and it will be referred to in the rest of this research as the Phasor-Based OOS function.

The methodology implemented in this research is the hardware in the loop test. The real-time digital simulator (OP5600 HILbox) and the Intelligent Electronic Devices (IEDs) that exist in the power system industry, 411L relays and SEL-3378 SVP, are used in this research. The

IEDs are connected to the real-time digital simulator output ports. Thus, the 411L relays are receiving the real-time measurements of the voltages and the currents through the simulator analog output cards. The 411L relays work also as PMUs, and they send the voltage phasor measurements to the SVP. IEDs' outputs are wired back to the real-time digital simulator. The compared functions run inside the 411L and the SVP, and the tripping of each method is evaluated and compared in every simulated disturbance.

This thesis is divided into five chapters: Introduction, Literature review, Methodology, Results and Discussion, and Finally the Conclusion and Recommendations for the Future Work.

Current chapter –Chapter One- provides a general background about the power swing problem in the transmission lines with more emphasis on the tielines between two areas. The chapter also presents the objective of this thesis.

Chapter Two is a theoretical background about the Out of Step detecting and tripping methods that are used in this research, and how each method detects the Out of Step (OOS) situation. The chapter describes Phasor-Based OOS algorithm, and it goes through the previous work that has been done in this area..

Chapter Three describes the methodology used and various hardware and software components of the hardware in the loop test. The chapter provides a description of the power system modeled inside the real-time digital simulator. Also, Chapter Three explains the studies done to come up with the parameters settings of each function.

Chapter Four is the results, discussion, and evaluation of each method.

Chapter Five is the research conclusion and the suggested future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Distance Relays Behavior during Power Swings

During power swing situations, distance relays may detect the power swing as a fault if the impedance measured by the relay enters the relay characteristics. Figure 2.1 shows a Two Machine System used to illustrate how the distance relays measure the impedance during power swings.

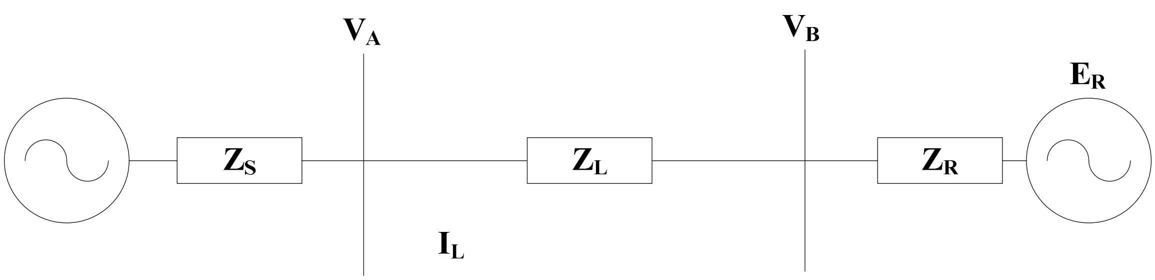


Figure 2.1 Two Machine System.

Current I_L is calculated by:

$$\frac{E_S - E_R}{Z_s + Z_L + Z_R} \qquad (2.1)$$

Also

$$V_A = E_S - I_L * Z_s \qquad (2.2)$$

The impedance measured by the relay will be [1] :

$$Z = \frac{V_A}{I_L} = \frac{E_S - I_L * Z_s}{I_L} = \frac{E_S}{I_L} - Z_s = \frac{E_S * (Z_s + Z_L + Z_R)}{E_S - E_R} - Z_s \quad \text{...(2.3)}$$

Assuming the phase angle difference between E_S and E_R is δ_{diff} and the ratio of the two source voltage magnitudes is $K = \left[\frac{|E_S|}{|E_R|}\right]$, the term $\frac{E_S}{E_S - E_R}$ could be written as

$$\frac{E_S}{E_S - E_R} = \frac{k(\cos\delta_{diff} + j\sin\delta_{diff})}{k(\cos\delta_{diff} + j\sin\delta_{diff}) - 1} = \frac{k[(k - \cos\delta_{diff}) - j\sin\delta_{diff}]}{(k - \cos\delta_{diff})^2 + \sin^2\delta_{diff}} \quad \text{...............................(2.4)}$$

When k = 1, equation (2.4) becomes

$$\frac{E_S}{E_S - E_R} = \frac{1}{2}(1 - j\cot\frac{\delta_{diff}}{2}) \quad \text{...(2.5)}$$

Finally, the impedance measured by the relay at Bus-A is

$$Z = \frac{V_A}{I_L} = \frac{(Z_s + Z_L + Z_R)}{2}(1 - j\cot\frac{\delta_{diff}}{2}) - Z_s \quad \text{.......(2.6)}$$

During power swing events, δ_{diff} varies, and the impedance changes, as illustrated in Figure (2.2)

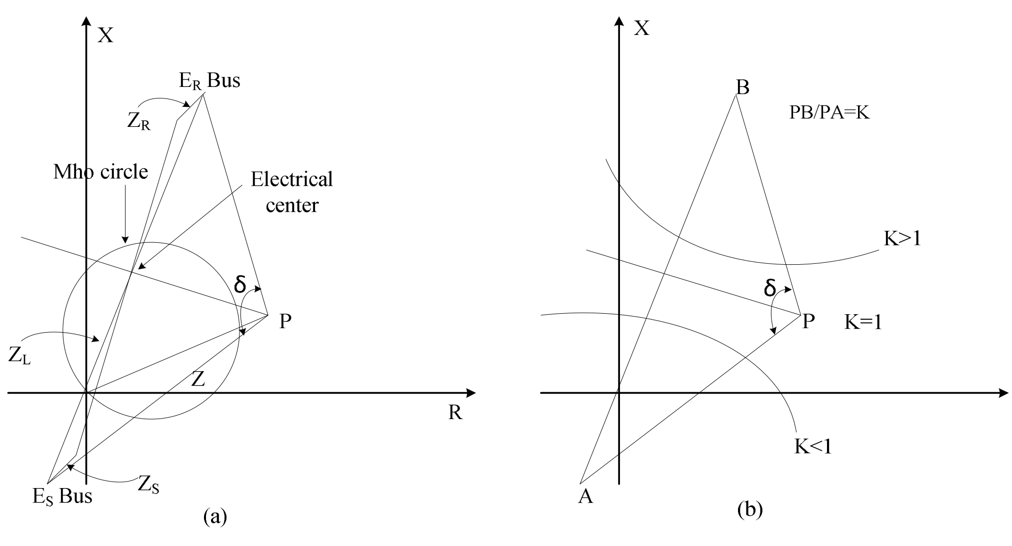


Figure 2.2 Impedance trajectories measured at the relay during power swings [1].

2.2 The Dual-Blinder OOS and the Swing Center Voltage PSB functions

As it has been discussed in section 2.1, both the stable and the unstable power swings impact the impedance measured at the relay. If this impedance falls in one of the relay zones, that will result in a relay misoperation. In general, relay tripping shouldn't be allowed during power swings, and this disallowance is achieved through the PSB function. If the swing becomes unstable, separation, achieved through the OOS function, should be made at specific locations (e.g. tielines between areas) in the grid to avoid total blackout.

In this study the OOS in the relay is implemented using Dual-Blinder while PSB is achieved by Swing Center Voltage method which uses the swing center voltage to detect power swings and block the distance element.

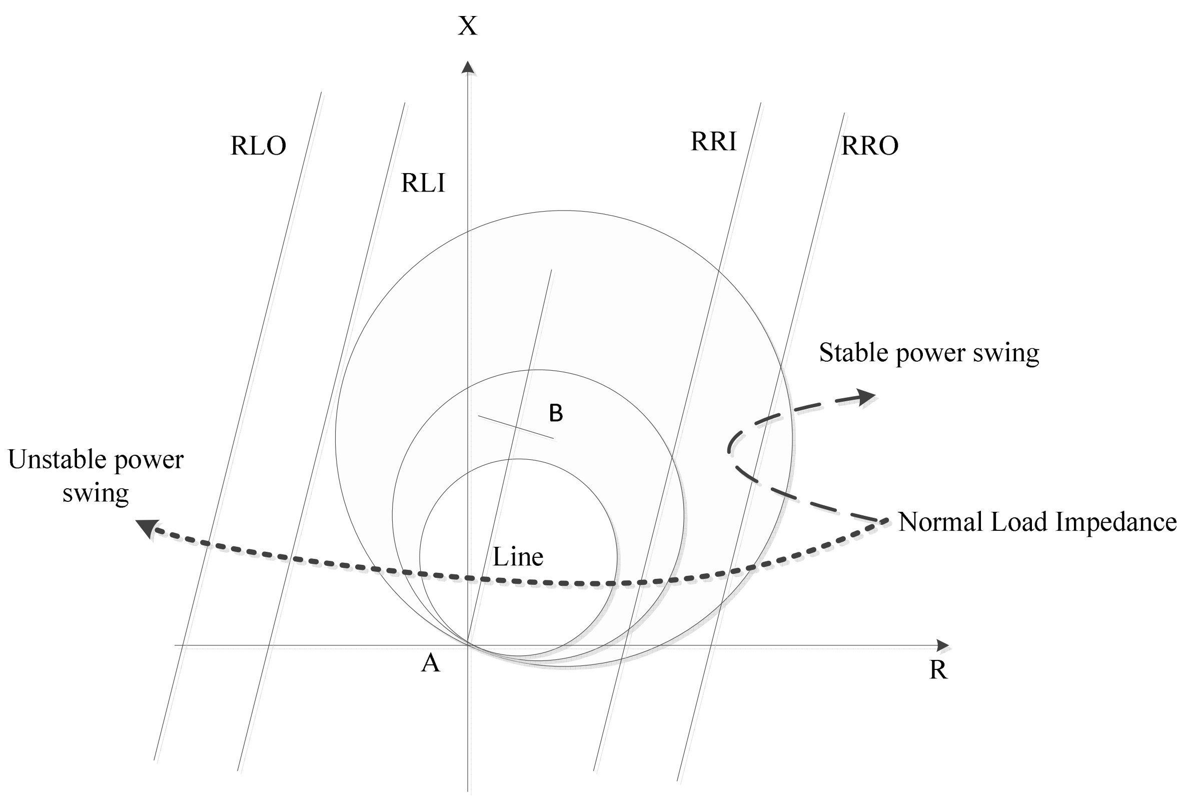


Figure 2.3 Dual-Blinder Scheme [5].

2.2.1 Dual-Blinder Scheme

This method uses two blinders on each side of the relay zones. The scheme also has two timers: Out of Step Blocking Delay (OSBD) and Out of Step Tripping Delay (OOSD). The OOSD timer must be set shorter than the OSBD timer [5].

These blinders along with the timers can detect and discriminate between stable swings, faults, and unstable swings. When the impedance crosses the Resistive Right Outer blinder (RRO) in Figure 2.3, the two timers start counting down. Stable swing is declared if the timer OSBD expires before the impedance locus crosses Resistive Right Inner blinder (RRI). Unstable swing is detected if the timer OOSD expires and the impedance locus cross RRI; this case is called Out of Step In the way to the zone (OSTI). If the OOSD timer expires and the impedance locus crosses Resistive Left Inner blinder (RLI), this case is called Out of Step the way Out of the zone (OSTO). If both timers are still counting down while the impedance crosses RRO-RRI, then this case is a fault [5].

Single Blinders Scheme with one blinder on each side is not able to block distance elements during power swings. It is used to disable reclosing after the relay tripped for an Out of Step condition and not for a fault [1].

Dual-Blinder Scheme is widely used in the protective relays to implement PSB and OOS functions. Extensive stability studies are required to set the blinders and the timers properly.

2.2.2 Swing Center Voltage and its Rate of Change

Swing Center Voltage (SCV) is the voltage at the electrical center. The electrical center between two systems is the location where the voltage is zero when the voltage phase angle difference δ_{diff} between two systems is 180º. In Figure 2.2 the electrical center lies in the intersection of the transmission line and the impedance locus. The electrical center is a measure of impact of the Out of Step condition on the generators. The impact of the Out of Step on the generators will be less harmful with the electrical center away from the generators [1] [6] [7].

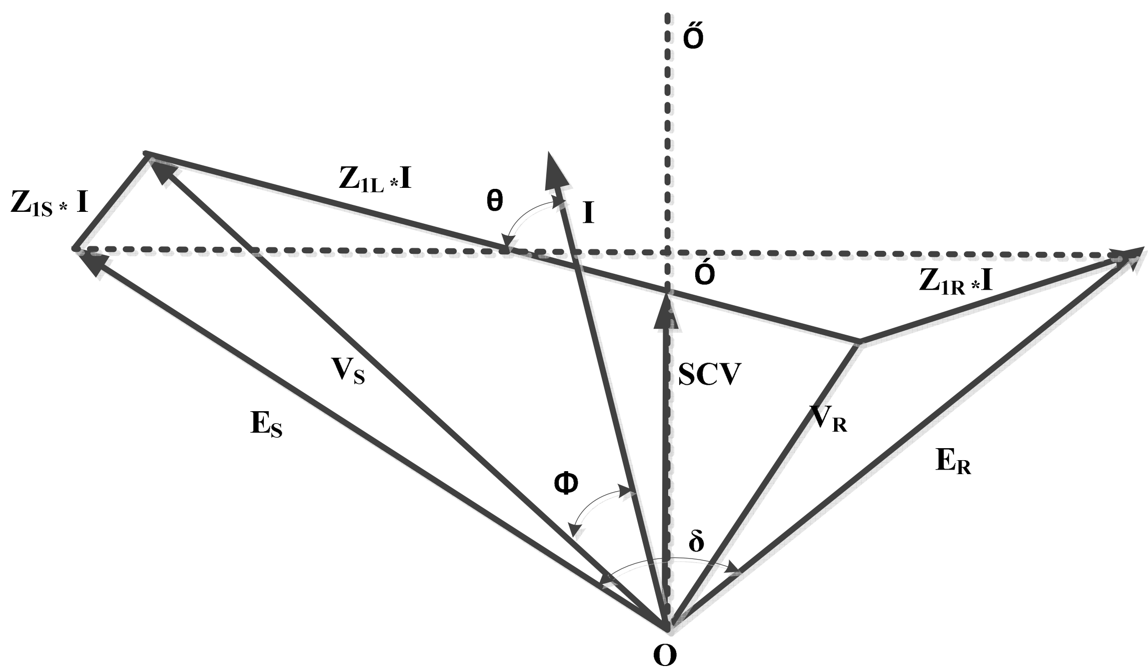


Figure 2.4 Voltage phasor diagram of a Two Machine System [7].

The SCV could be approximated at the relay location with the equation (2.7) below:

$SCV \approx |V_s|.cos\varphi$ ....(2.7)

Where

V_S is the voltage measured at the relay location.

Φ is the angle between V_S and local current as shown in Figure 2.4.

Provided that the local SCV is estimated using | V_S|, the relationship between SCV and phase angle difference δcan be written as:

$$SCV1 = E_1.cos(\frac{\delta}{2}) \quad (2.8)$$

The time derivative of the equation (2.8) becomes the following:

$$\frac{dSCV1}{dt} = -\frac{1}{2}.E_1.sin(\frac{\delta}{2}) \quad (2.9)$$

Power swing blocking is achieved using the SCV1 and its rate of change with a specific logic to detect power swings. No settings are needed by the relay engineer for this function, because of that the method is known also as “Zero setting PSB method”. Figure 2.7 shows the overall logic of this function [7].

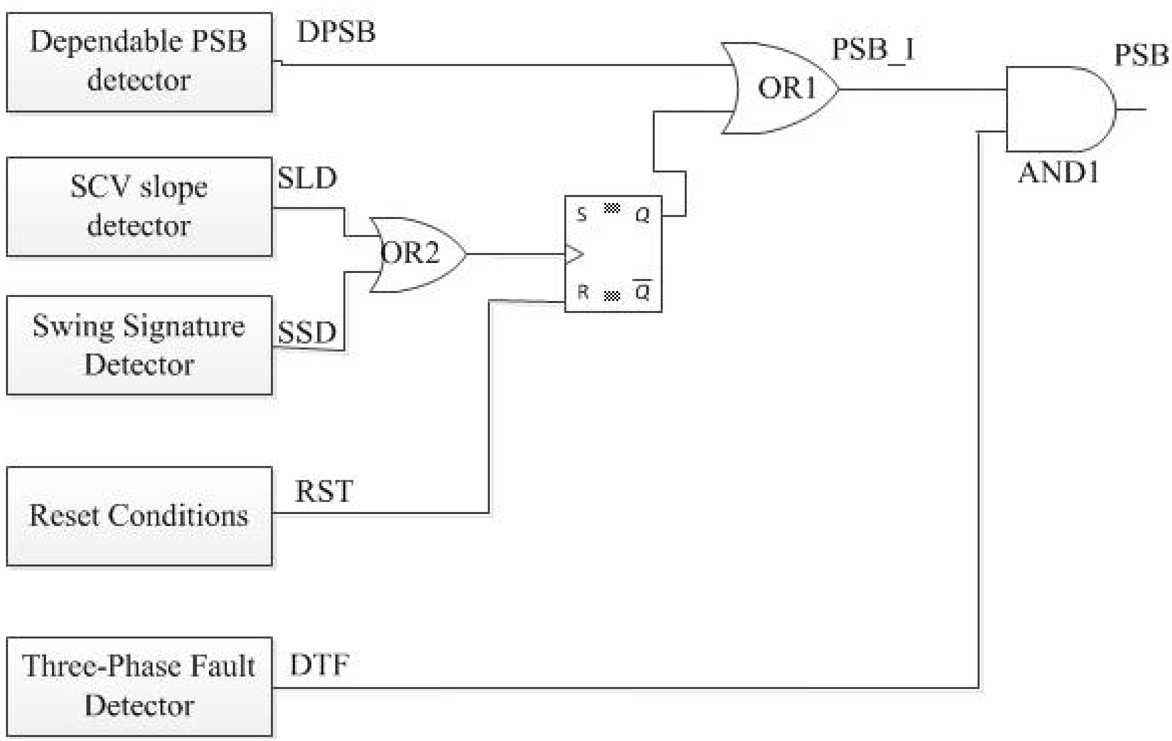


Figure 2.5 SCV logic implemented in the 411L relay [7].

In 411L, the relays used in this research, the SCV or the Zero Setting method provides only the PSB functionality and the Dual-Blinders scheme is used to provide the OOS functionality. Stability studies are still required if OSTI option (described in section 2.2.2) is selected. The stability studies are needed to determine the minimum value of the impedance (Z) measured by the relay during the all possible stable swings and set the blinder RRI (Figure 2.4) to be to the left of that value. When the impedance locus crosses RRI, the OSTI relay word-bit is asserted, and the trip is issued. No stability study is required when the chosen tripping option is OSTO or OSTC. When the PSB is implemented via the Zero Settings method, the timers OSBD and OOSD are not used or being set [6], [7].

2.3 Phasor-Based OOS function

This algorithm described in [3], [4] and [8] receives two voltage phase angles in the format of the C37.188-2005 protocol and calculates the difference between them and the first two derivatives of the difference. The first derivative of the phase angle difference (the Slip-S) is calculated with the equation 2.10

$$\dot{\delta}_i = \frac{1}{360}\frac{\delta_i - \delta_{i-1}}{t_i - t_{i-1}}[Hz] \qquad (2.10)$$

The second derivative of the phase angle difference is obtained (the Acceleration-A) using the equation 2.11

$$\ddot{\delta}_i = \frac{1}{360}\frac{\dot{\delta}_i - \dot{\delta}_{i-1}}{t_i - t_{i-1}}[\frac{Hz}{s}] \qquad (2.11)$$

The voltages used in this algorithm are the voltages at the tieline terminals provided that the electrical center is in the selected tieline.

When a disturbance occurs (e.g. fault, switching, or outage) it creates a power swing and the voltage phase angle difference δ_{diff} between the two areas varies. Both the slip (first derivative of δ_{diff}) and the acceleration (second derivatives of δ_{diff}) will have values other than their nearly zero initial values.

The algorithm monitors the values of (S, A) and depending on its setting it decides if the swing is a stable and no action is required, or an unstable and it sends trip signals to the relays. Figures 2.7, 2.8 and 2.9 provide a graphical representation of how the power swings shown in Figure 2.6are reflected in (S, A) plane.

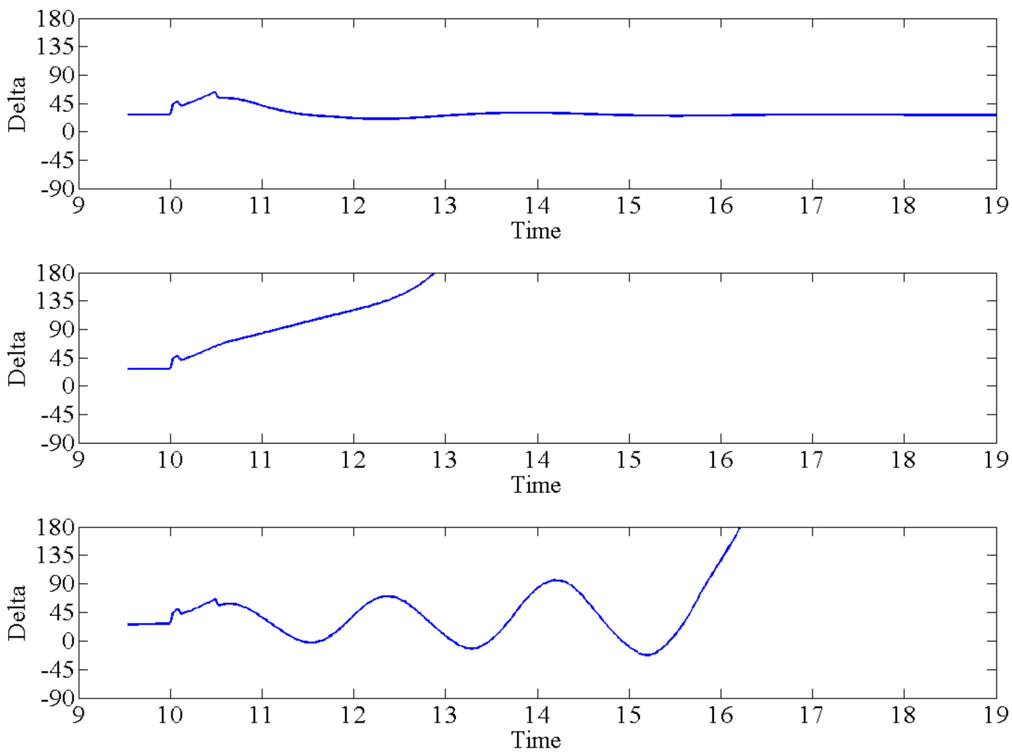


Figure 2.6 Different power swings plotted on (δ, t) plane.

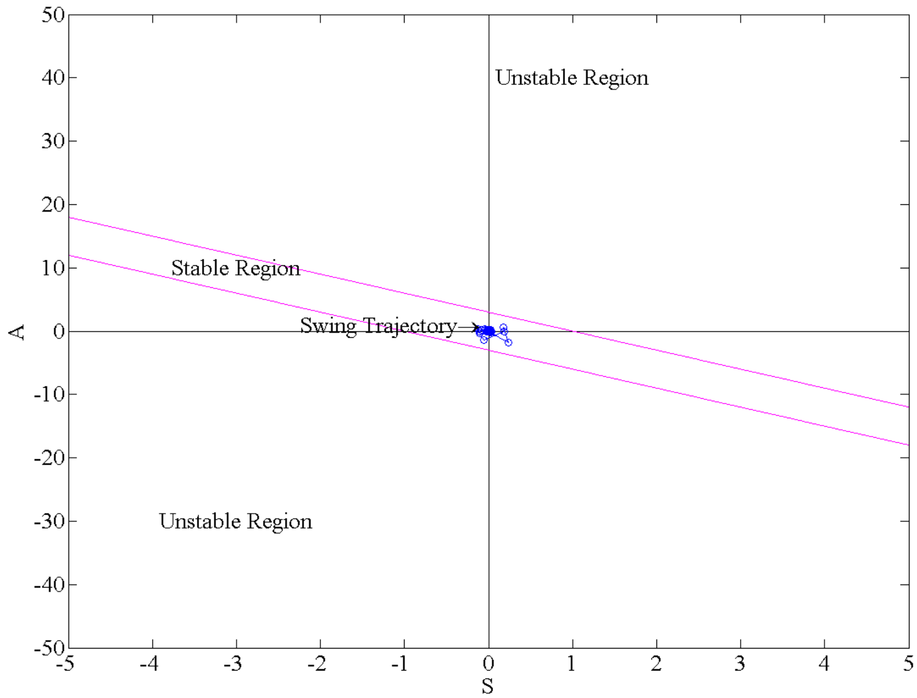


Figure 2.7 The top power swing in Figure 2.8 plotted on (S, A) plane.

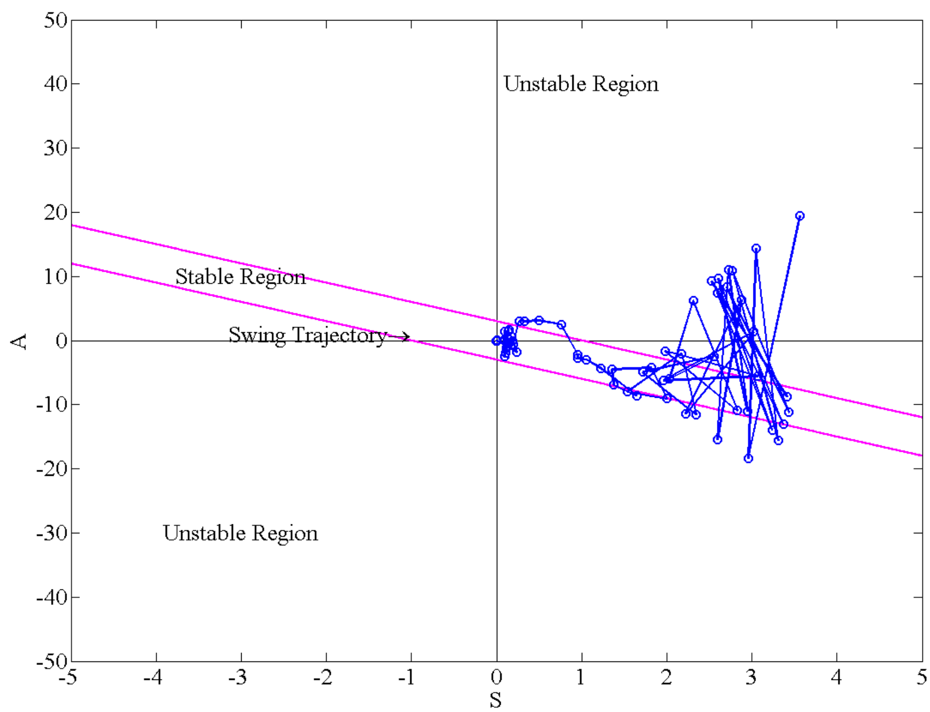


Figure 2.8 The middle power swing in Figure 2.8 plotted on (S, A) plane.

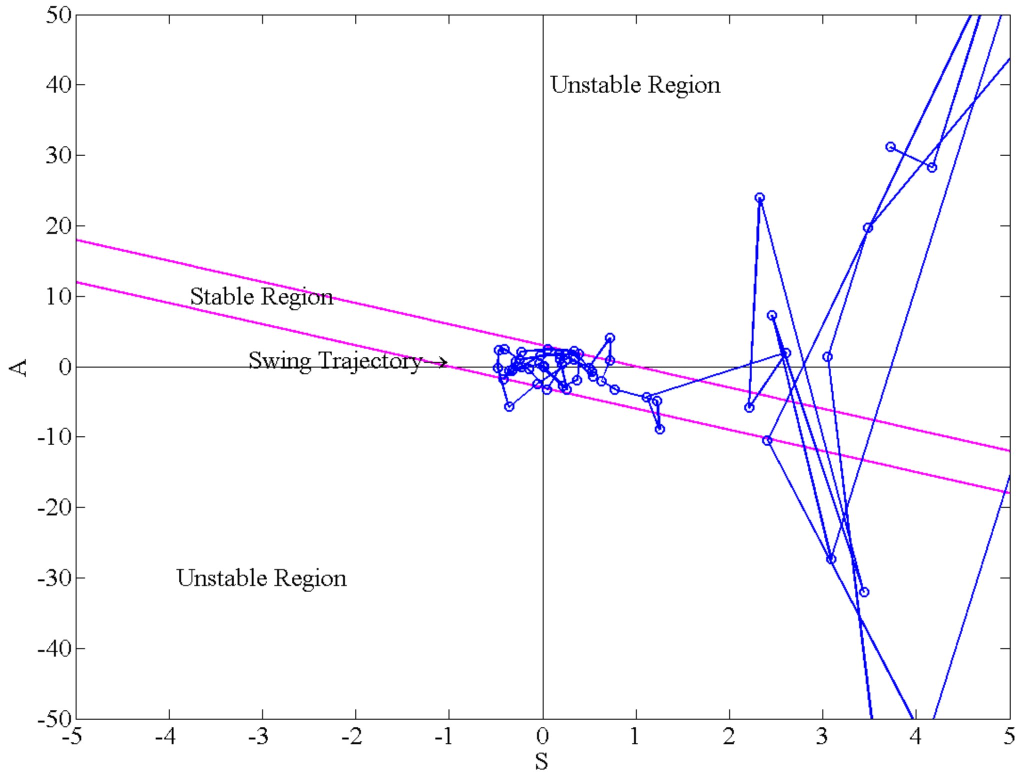


Figure 2.9 The bottom power swing in Figure 2.8 plotted on (S, A) plane.

.

In figures 2.7, 2.8 and 2.9, the algorithm determines whether the swing is a stable or not based on the parallel blinders settings. Stable swings will have slip and acceleration values within these two blinders, unstable power swings will go out of the blinders, sometimes the unstable trajectory will move out of the blinders before the Out of Step condition happens. In such cases, the algorithm takes the advantage of using the first and the second order of the angle difference to predict the OOS condition [8].

Hardware Implementation of this algorithm has been performed using SEL-3378 SVP [3], [4]. Also Matlab simulation has been performed where both the algorithm and the power system were modeled and run in the Matlab environment [8].

CHAPTER 3

METHODOLOGY

3.1 Hardware in the Loop Test, an Overview

Hardware in the loop is a real-time simulation that is performed when it is hard or not feasible to test the controller's behavior in the actual plant/process. Instead the process is modeled and executed inside the real-time digital simulator, which is connected through Input / Output (I/O) cards to the controller/s. In this study the process (a power system) has been modeled and run in the real-time digital simulator (OP5600 HILbox). The controllers used in this research are the Intelligent Electronic Devices (IEDs):

1- Two SEL-411L protection and automation control microprocessor relays (it will be refered to in the rest of this study as 411L).

2- SEL-3378 Synchrophasor Vector Processor (SVP).

During the real-time simulation, the control commands received from the IEDs affect the running power system model in real-time (e.g. if one relay issues a trip signal the controlled breaker in the model will opens immediately). Figure 3.1 shows the conceptual blocks of the study system.

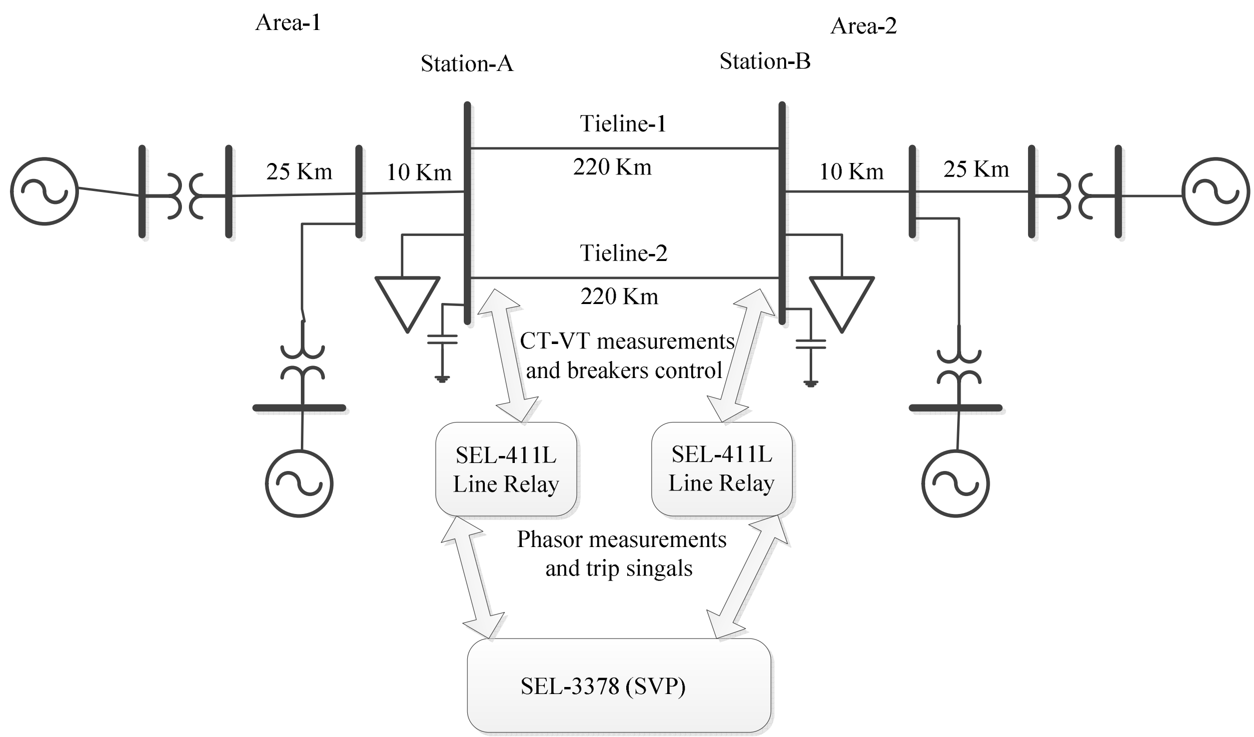


Figure 3.1 Conceptual blocks of the hardware in the loop test system.

The two OOS functions, which are implemented in both of the SVP and Station-A's 411L relay, are tested with different real scenarios. Voltages and currents at the simulator output card are amplified using Doble F6350 amplifier. The amplifier outputs are connected to the relays Current Transformers (CTs) and Voltage Transformers (VTs). Relays outputs (trip, close, etc.) are wired back to the simulator through the simulator input card. The two 411L send phasor measurements to the SVP. Station-A's 411L receives the SVP-OOS trip signal and maps it to one of its output contacts, which is connected to the real-time digital simulator's input card. Figure 3.2 shows the hardware connections between the relays, the amplifier, and the simulator.

This chapter goes through the test system modeling and the settings of each one of the used devices: the amplifier, 411L relays at Tieline-2 terminals and the SVP.

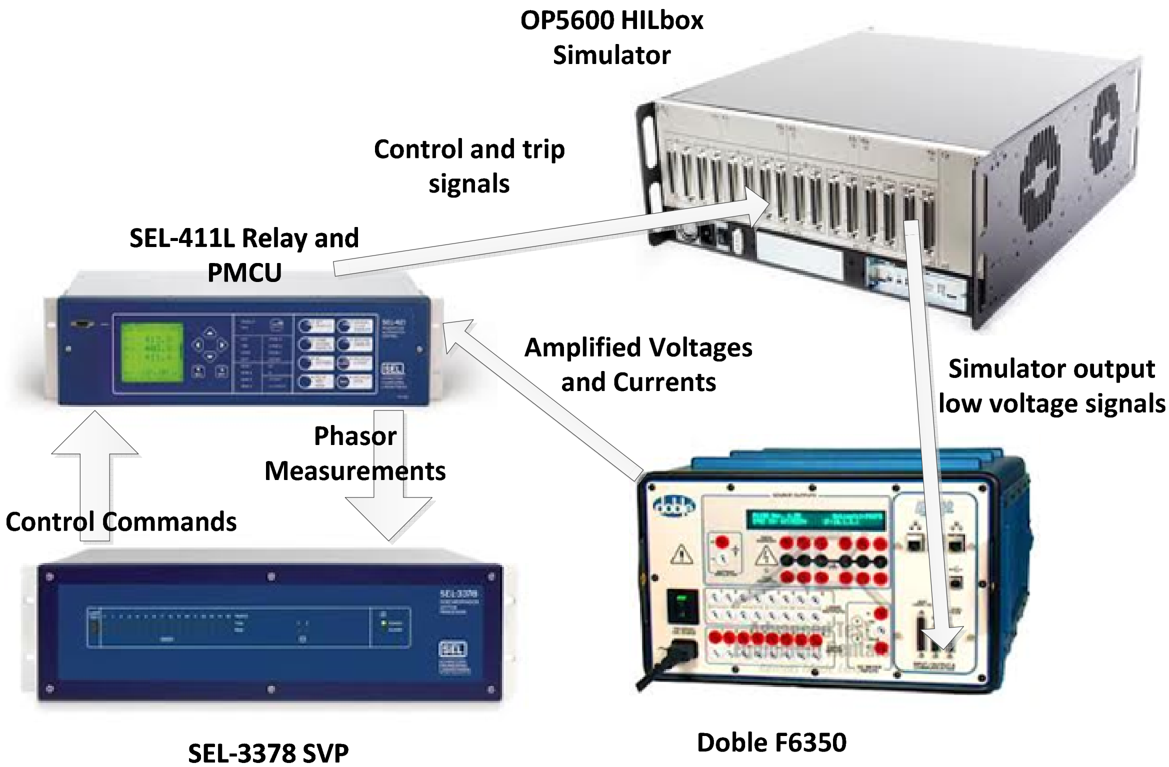


Figure 3.2 Hardware connections between the relays, the amplifier and the simulator.

3.2 Test System Description

3.2.1 The Power System Model

The power system model used in this study is Kundur Two Area System [9]. The system consists of two symmetrical areas with two generators in each area. The four generators of the system have the same capacity of 900MVA. The other parameters of the generators are the same except for the inertia and the active power set-point. Area-1 generators have an inertia constant of 6.5 MJ/MVA while Area-2 generators have an inertia constant of 6.175 MJ/MVA. The active power set point is identical for generator-1 and generator-3 and slightly different for generator-2and generator-4. Figure 3.3 is the one line diagram of the modeled system.

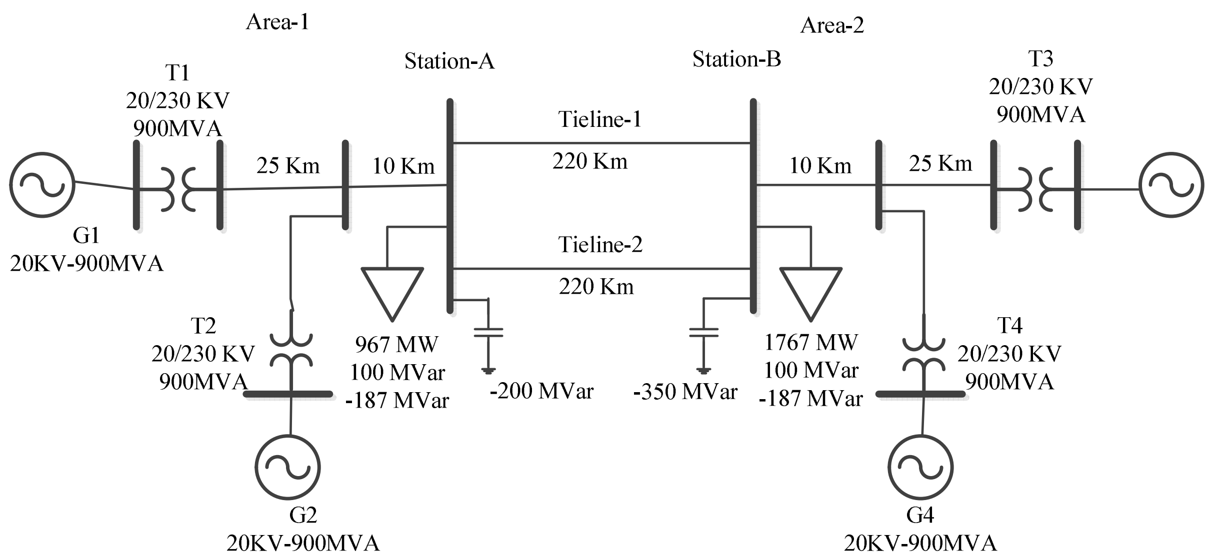


Figure 3.3 One line diagram of the Two Area System.

Area-2 is importing 413MW of power from Area-1 via the two 230KV, 220Km tielines. Under normal conditions the voltage phase angle difference (δ_{diff}) between the two areas measured at the tielines terminals is 26º. Matlab power flow results have been verified by modeling the same system in CAPE (Figure 3.4), and similar results were found.

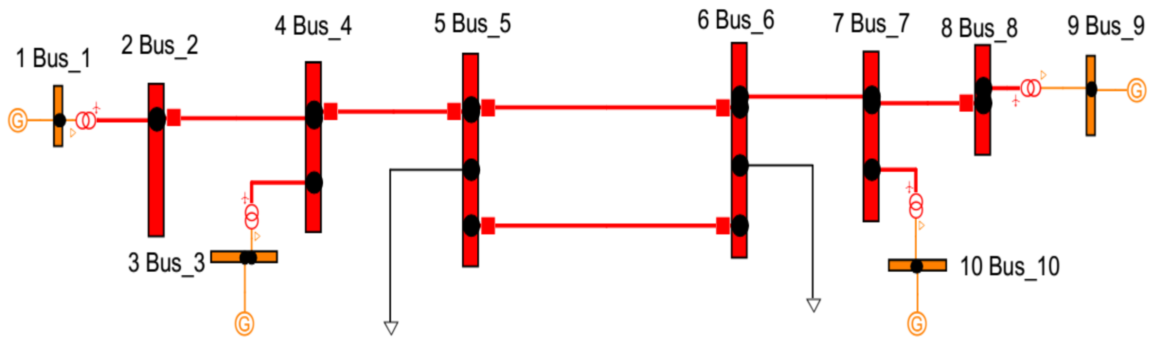


Fig 3.4 CAPE model of the Two Area System.

Matlab model is divided into four subsystems (Figure 3.5). The size of each subsystem is determined by the real-time execution cycle and the number of the blocks in the subsystem.

Each subsystem is assigned to one core of the simulator cores during execution. The simulator used in this study has twelve cores; so it is able to run a system that consists of twelve subsystems. If one subsystem has an execution time longer than the real-time execution step, overrun will be reported, and the simulation is no longer in real-time, that may lead to a loss of data and an improper response from the connected controllers. When an overrun occurs, the subsystem has to be divided into two different subsystems and assigned to two separate cores. The first subsystem of the study model is the console which runs in the computer that connected via Ethernet connection to the target (the target is the twelve cores real-time digital simulator).

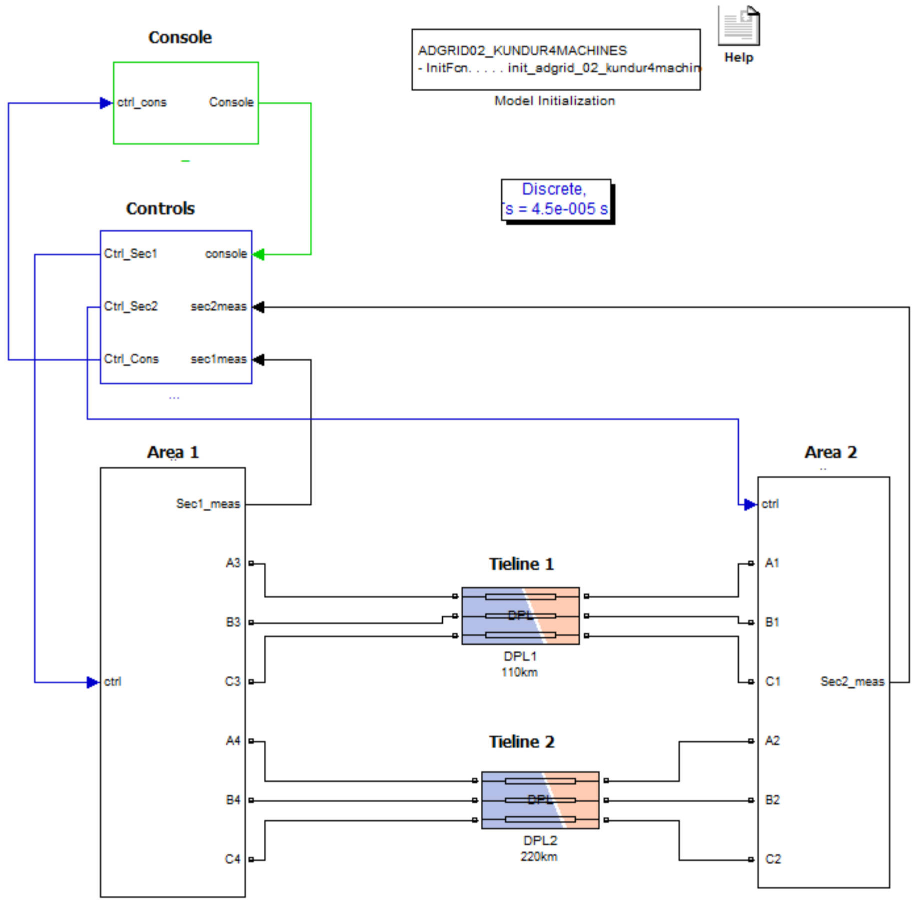


Fig 3.5 Subsystems of the model.

The console subsystem provides the interaction between the user and the running model. The user has no access - during the simulation- to the running subsystems on the target. The user can only send commands and monitor the signals available in the console subsystem. The console subsystem developed in this study is shown in Figure 3.6.

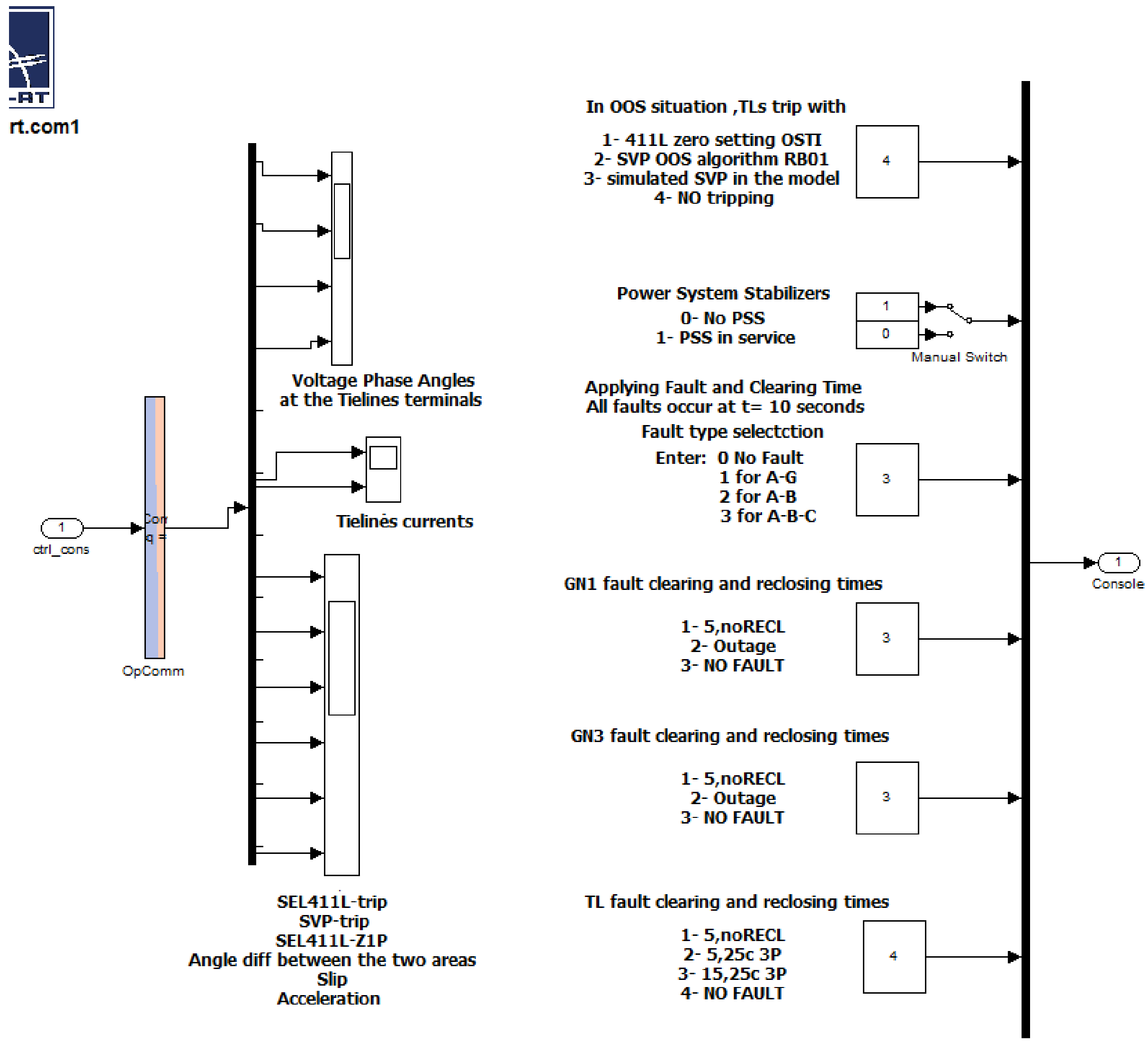


Fig 3.6 Console subsystem.

The three other subsystems are:

1- Area-1 subsystem (Fig 3.7) which consists of: generator-1, generator-2 and two short 230KV transmission lines (10 and 25Km) and Area-1 load and fault blocks, data acquisition and I/O's blocks (Fig 3.9).

2- Area-2 subsystem (Fig 3.8) which consists: generator-3, generator-4 and two short 230KV transmission lines (10 and 25Km) and Area-2 load and fault blocks, data acquisition and I/O's.

3- Controls subsystem which contains the machine controls (exciters and speed governor) and the tielines breakers control. Also the controls subsystem contains the data recording blocks where some selected signals are recorded during the simulation and saved in a Matlab matrix file. The data recording feature allows plotting the results and optimizing the settings of the SVP and the 411L relay used in this study (Figure 3.9). Beside that the controls subsystem manages the disturbance scenarios. The user selects a specific disturbance scenario from the console menus, and the command is received in the controls subsystem and then interpreted into the appropriate breakers and fault blocks actions, finally the breakers control signals are sent to the area where the disturbance is happening. The controls subsystem contains the Matlab implementation of the Phasor-Based OOS function which is used to optimize the settings of the actual program that runs in the SVP.

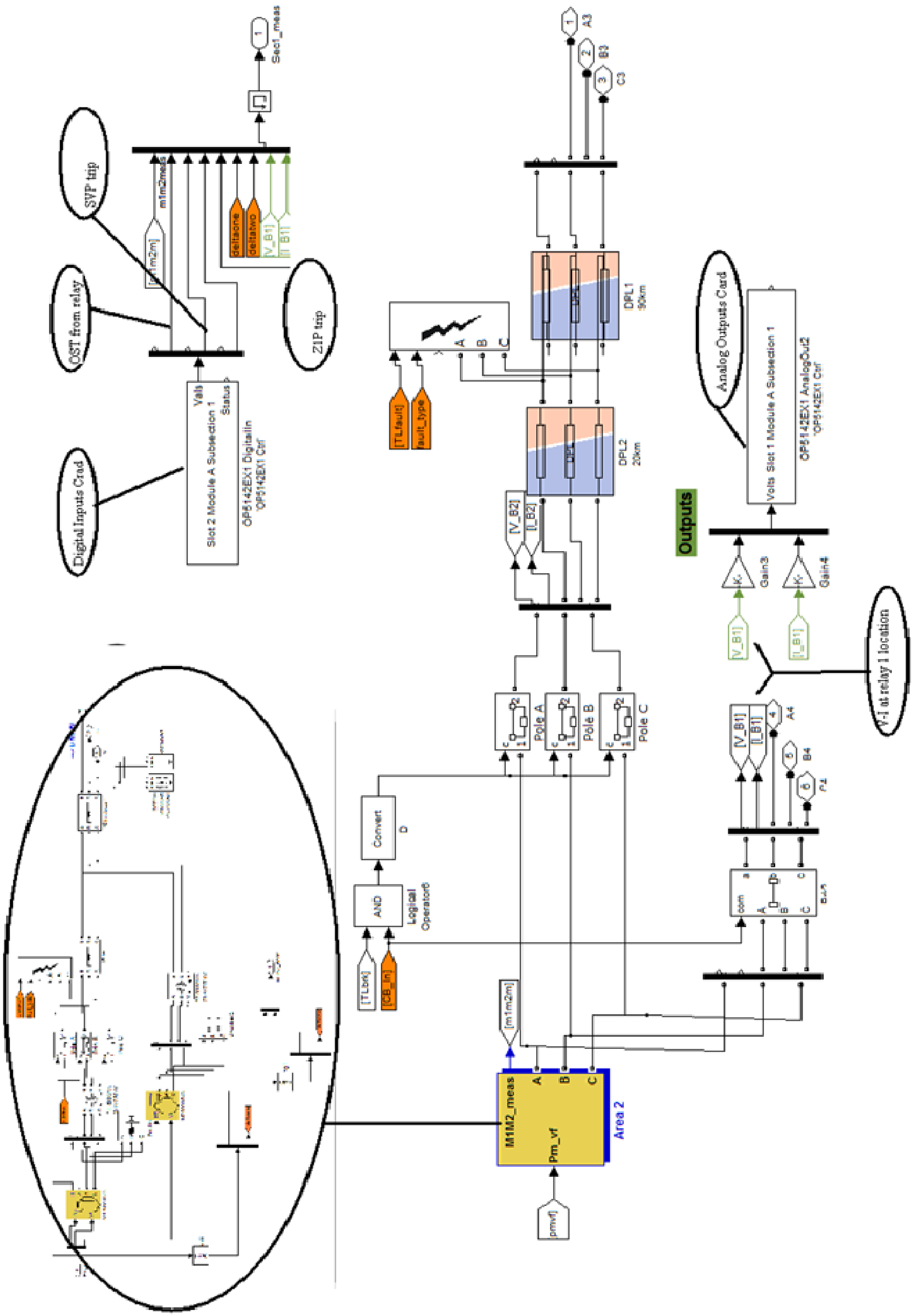


Figure 3.7 Area-1 subsystem blocks.

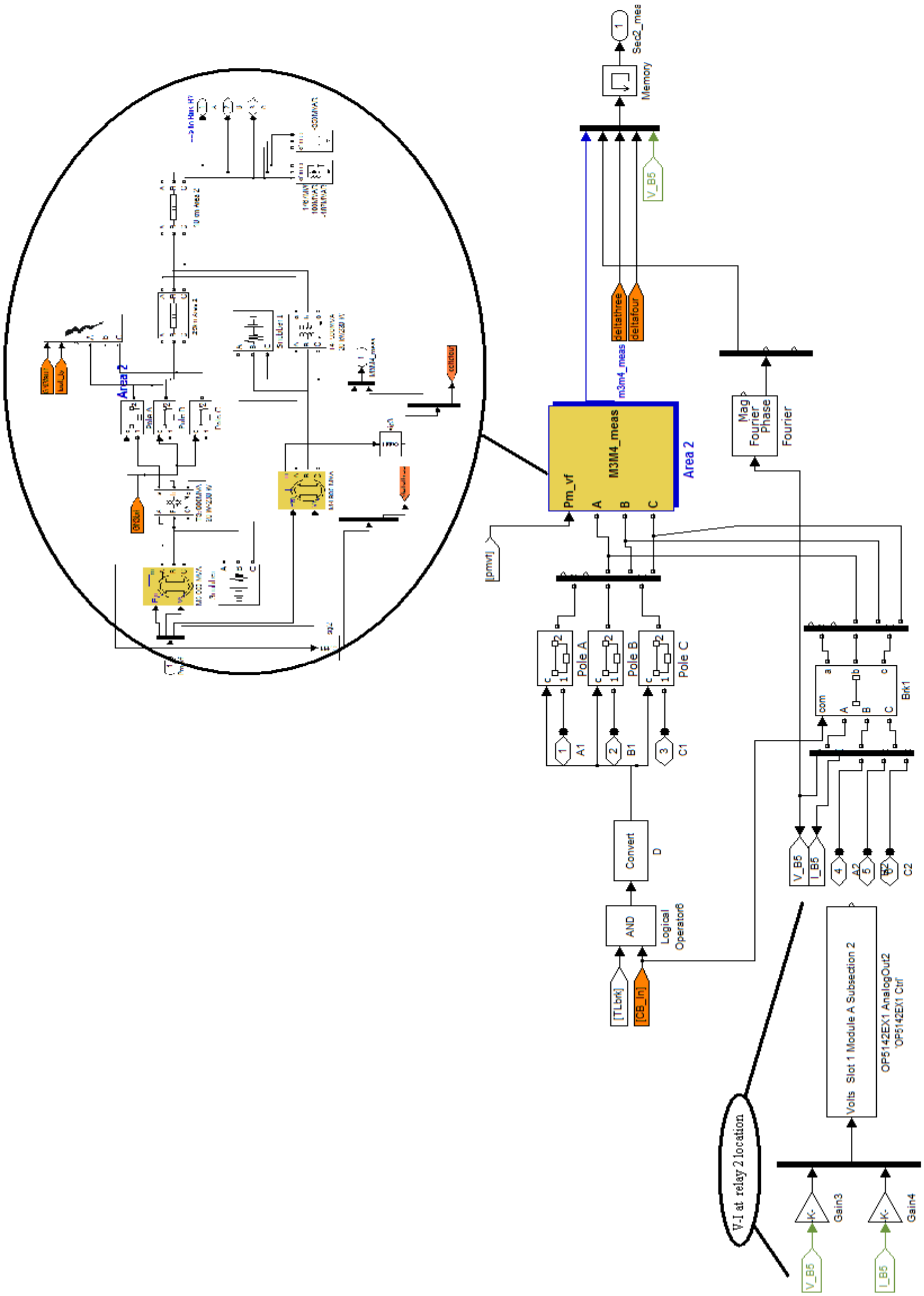


Figure 3.8 Area-2 subsystem blocks.

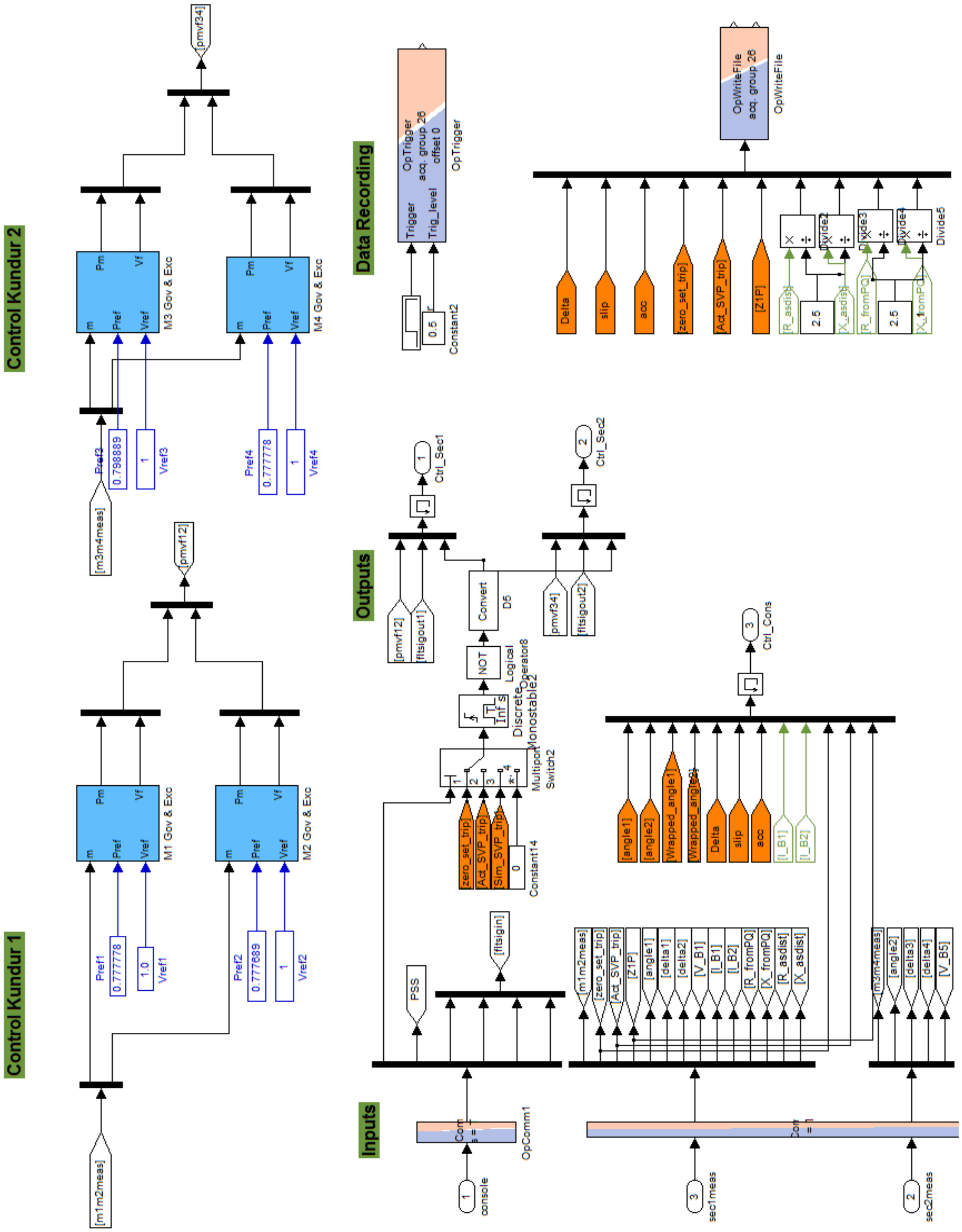


Fig 3.9 Part of the Controls subsystem blocks.

3.2.2 TheAmplifier

The amplifier (Doble F6350) is used in this study as seen in Figure 3.10to amplify the voltage signals that are coming out of the simulator analog output ports to the level of the secondary voltage of the 411L relays. This amplification is needed as the maximum output voltage from the simulator is only 16V while the rated secondary voltage of the relays is 66.39V Line to Neutral (LN).

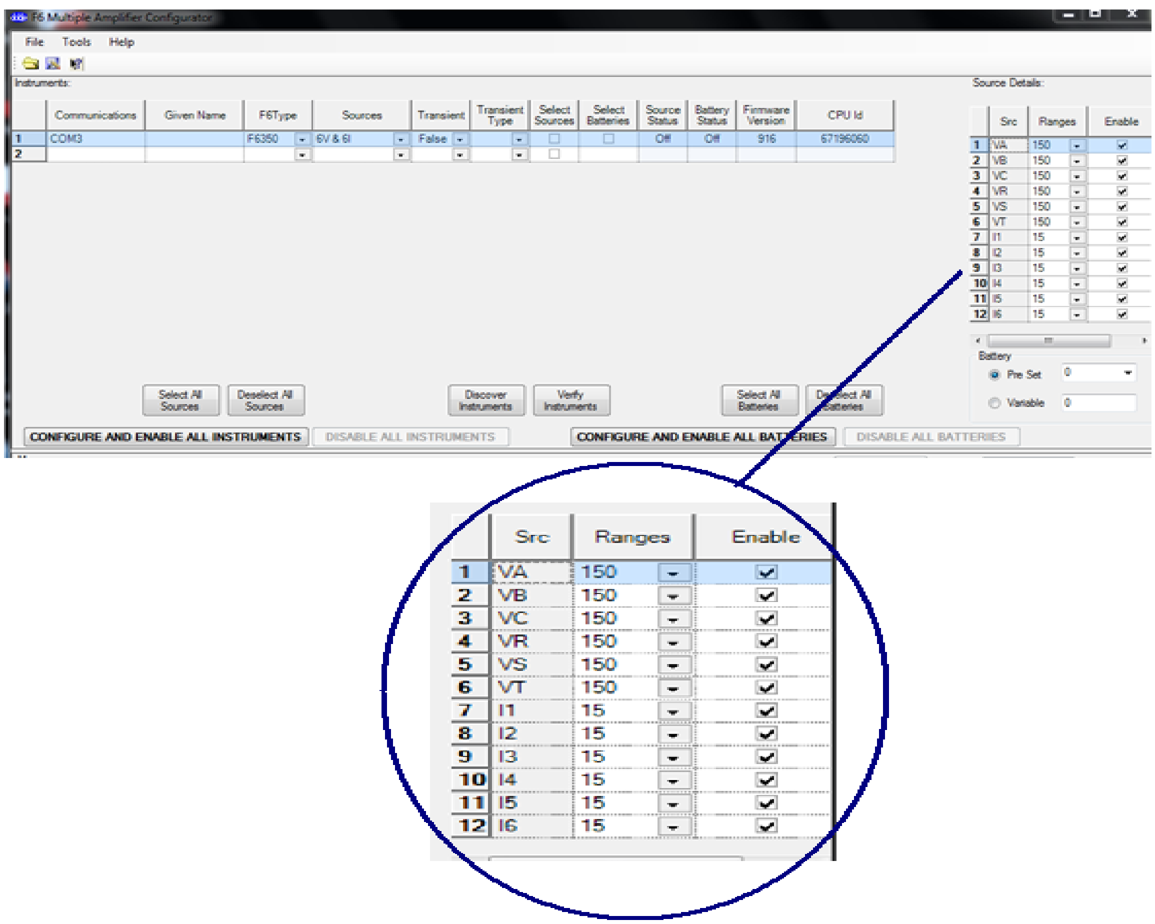


Figure 3.10 Doble F6350 configuration software.

Figure 3.11 provides a block diagram of the amplification process. DobleF6350 offers three voltage amplification gains: 75/6.7V, 150/6.7V and 300/6.7V. The selection of a specific gain is determined by the amplifier input voltage which comes from the simulator output port and also by the required voltage at the relay VT terminals. The voltage level of the line terminals in the Matlab model is 132.8KV for phase voltage. The relay secondary rated voltage of the VT terminals is 66.39. With amplifier gain of 150V/6.7V, the output required is 66.39V and the input required is 2.96V. 2.96V is the value that the simulator should generate in its output port. The conditioning is made by dividing, using a gain block, the phase voltage of 132.8KV by 44785.83 to result in 2.96V at the output port.

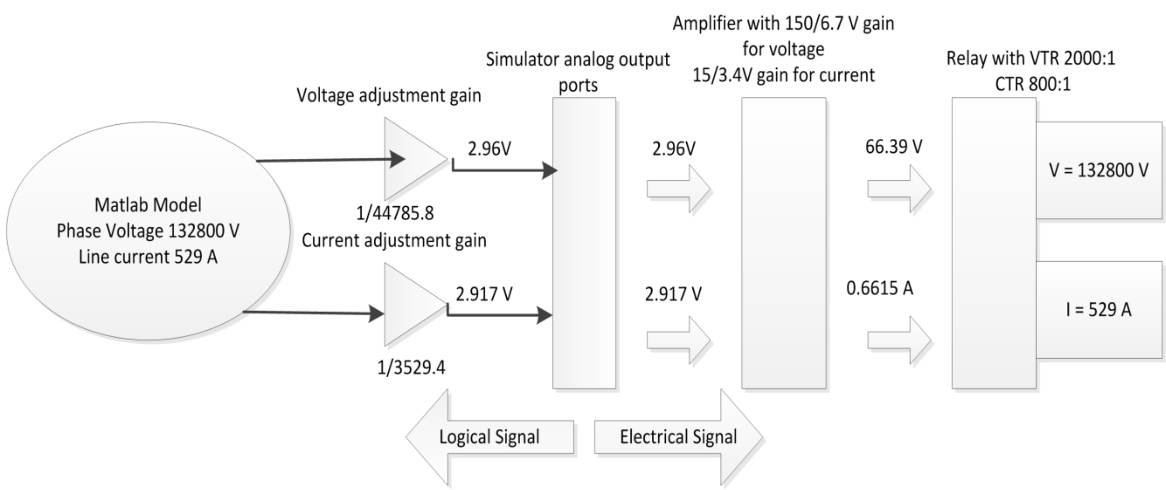


Figure 3.11 Overall logical and electrical V-I signals conditioning and amplification.

The current amplification process starts by selecting a CT Ratio (CTR) in the relays, since the load current is 529A; the selection of 800:1 CTR is a reasonable one and it brings the secondary current at the relay CT terminals to 0.66125A. The amplifier provides two options for current amplification: 3.4/7.5V and 3.4/15V, in this study 3.4/15V is selected, and the amplifier should receive an input of 0.66125*15/3.4 = 2.917V. Finally the value of the gain inside the Matlab model is calculated by dividing the load current by the desired amplifier input (which is the simulator output) 529/ 2.917 = 3529.4.

3.2.3 The 411L relays

411L is a high speed transmission line differential, distance and overcurrent relay. Two 411L relays are used to protect Tieline-2 terminals (at stations A and B) in Figure 3.2. The CTR selected is 800:1 and the VTR is 2000:1. The 411L at Station-B is only used as a PMU. Below is a description of the settings of the 411L at the Station-A.

Two Mho phase distance zones Z1 and Z2are set at 80% and 120% of the line impedance with zero and fifteen cycles tripping delay respectively. Permissive Overreach Transfer Trip (POTT) scheme is assumed. Out of step element EOOS is set to Y1 which enables the (PSB) using The Zero Setting method discussed in section (2.2.6).OOS right side blinders: RR6, RR7 are set to 10 and 32Ω secondary respectively , and the left side blinders: RL6, RL7 are set to -10,-32Ω secondary respectively.

The blinder settings are based on the minimum impedance value during stable swings found among the thirteen cases that have been simulated. 411L OOS function offers three tripping options:

1. Out of Step Tripping on the way INTO the way (OSTI),
2. Out of Step Tripping on the way OUT the way (OSTO).
3. Out of Step Tripping on the way out with Count (OSTC).

Since the objective of the study is to compare the 411L-OOS function with the Phasor-Based OOS one, the tripping option should be chosen so that the 411LL trips right after the OOS situation is detected. Thus the OSTI option is selected since the other tripping options trip after the OOS has already occurred. It is assumed here that the tielines breakers are sized to trip during large angular separation between the areas. The relay is set to trip for Z1P, Z2PT and OSTI, and also for RB01 which is the remote bit that receives the SVP-OOS algorithm trip signal.

Beside their protection functionalities, the 411L relays send phasor measurements to the SVP via Ethernet network. Phasor data are in the format of C37.118-2005 protocol.

3.2.4 The SVP

3.2.4.1 SVP Overview

The SVP (SEL-3378) is a user programmable controller that receives and aligns phasor measurements in the format ofC37.118-2005 protocol. The SVP is capable to receive phasor data from up to twenty PMUs and sends the timely aligned phasor data to up to six external C37.118 clients. SVP has also a real-time processing engine that can be programmed to use phasor time correlated data for protection, control and monitoring purposes.

In this study SVP is programmed to receive/correlate phasor data via Ethernet cables from the two 411L relays in Station-A in Area-1 and Station-B in Area-2 .The SVP runs an OOS algorithm to detect OOS conditions. When the SVP detects an OOS condition, it sends trip signals to the tieline relays to separate the two areas. However for simplicity in this research, the SVP sends the trip signal to only one of the two 411L relays (the one at Station-A). The 411L at station-A receives the trip signal at RB01 and it asserts OUTPUT-102 contact which is wired to the simulator digital input port, and the trip signal then controls the breakers on both terminals of the tieline.

3.2.4.2 Phasor-Based OOS Program Blocks Description

The SVP user programs are built with IEC-61311-3 programming language. This language has been developed as a unified platform for the Programmable Logic Controllers (PLCs), which allows integration between multiple vendors in one project and makes the programming of the PLCs more standardized. The code that is downloaded in the PLC is called (Project). The project components are called Program Organization Units (POUs), and a POU could be a program (PRG), a function (FUN) or a function block (FB).

The developed project to implement the OOS function is named (V3_PMU_OOS). All FBs in this project are user defined. As shown in Figure 3.12, there are three POUs of the type PRG. The highlighted one is the main program (OOS_prog), the other two PRGs are the built-in services:

1- Time alignment client server (TCS) which aligns the phasor measurements.

2- WATCHDOG which is monitors the program execution.

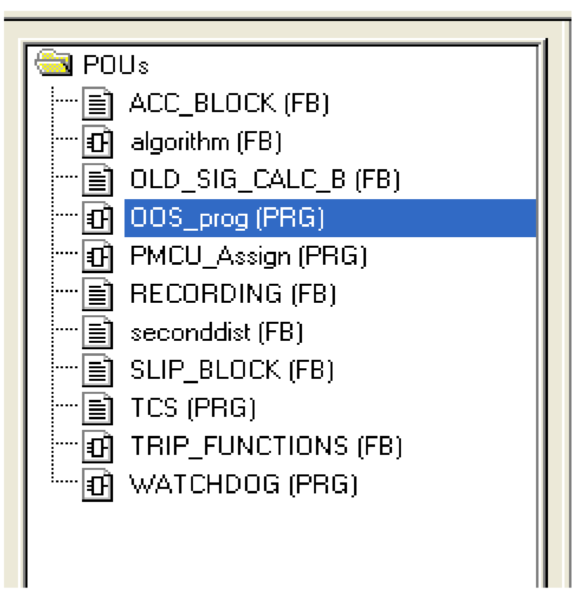


Figure 3.12 Project (V3_PMU_OOS) POUs

The OOS algorithm that uses phasor data has been described in the research papers [3], and [8]. However, some modifications have been added in this study to the basic algorithm. The functional blocks that have been programmed in the SVP for this study are shown in Figure 3.13, and the functional blocks of the program are described in more details in the next paragraphs.

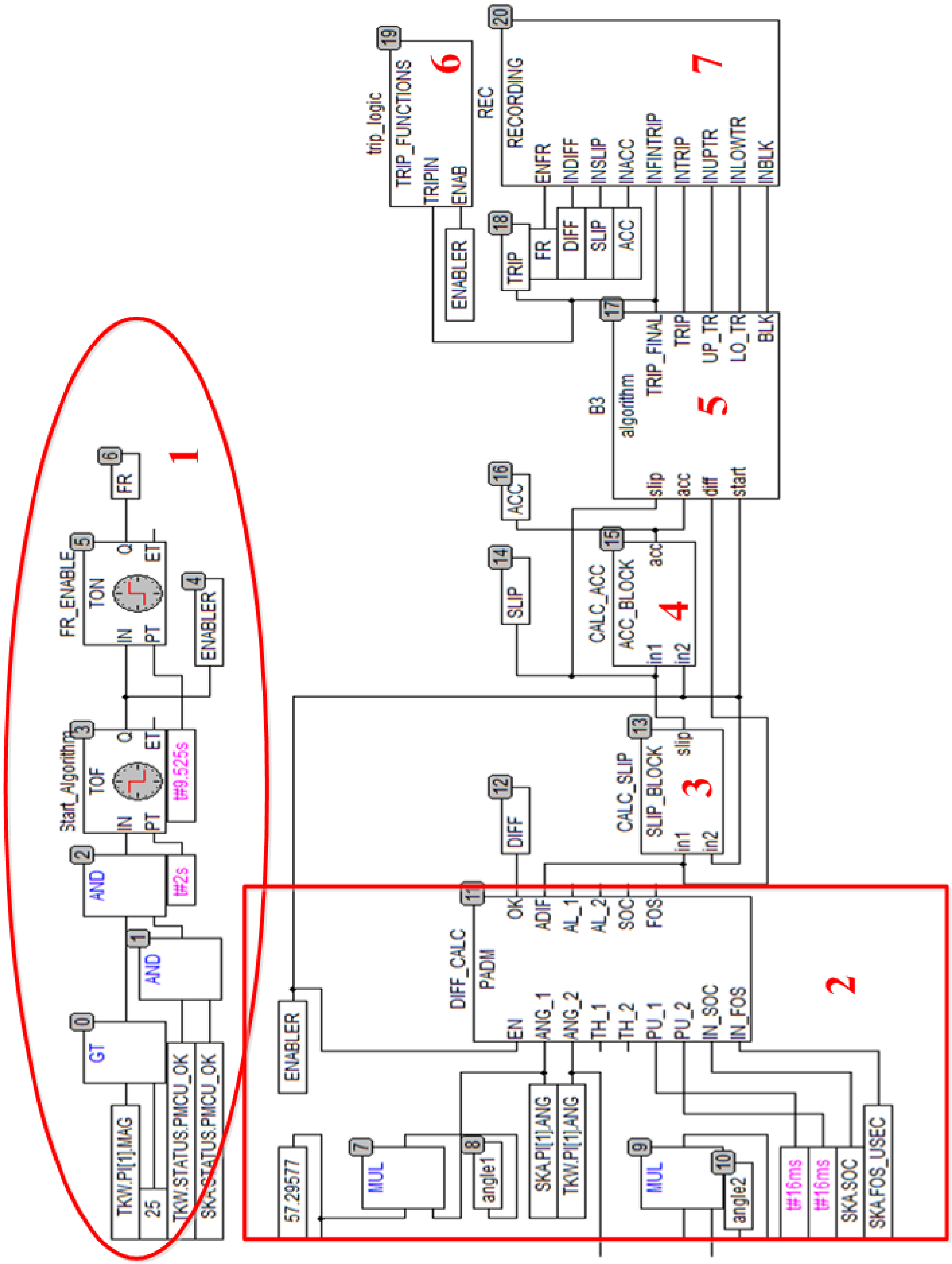


Figure 3.13 OOS_prog (PRG) blocks.

Below is the description of each part of the program as they are numbered in Figure 3.13:

1. This is the starting blocks of the program. In order to enable the other program blocks, the phasor measurements should be received and correlated properly. Also the voltage at the relays should be higher than 25KV, which means that the simulator is running the model and the amplifier is working properly to provide 132.8KV (primary) at the relay VT terminals.
2. These blocks convert the received phasor data from radians to degrees and also calculate the voltage phase angle difference (δ_{diff}) between the two phasors.
3. SLIP_BLOCK calculates the slip from δ_{diff} and the previous value of δ_{diff}.
4. ACC_BLOCK calculates the acceleration from the slip and the old slip values.
5. Algorithm is the FB where the program decides whether the swing is a stable one or not. The decision is based on the selection of the parallel blinders which define the stable/unstable regions. The parameters required to set the parallel blinders (K, A_offset_1 and A_offset_2) are marked in Figure 3.16. The block also accounts for the spontaneous spikes in the first and second derivatives during switching and fault situations (Figure3.14) by blocking the algorithm for a specific time delay selected based on the maximum clearing time used the power system model and also the dead time for reclosing, without this blocking signal the algorithm would trip for any spontaneous spikes that results from a disturbance (misoperation).The algorithm also has a tripping threshold, unless δ_{diff}> 40º or δ_{diff}< -40º the algorithm won't send a trip signal even when the trajectory locus moves to the unstable region in (S, A) plane. This adds more security during the normal load conditions. Figure 3.15 shows the building blocks of the Algorithm FB.

6. TRIP_FUNCTIONS is the FB that sends the trip signal to the relays and reset the remote bit after a specific delay; it also blocks the tripping during the first 250milliseconds of the program execution due to the initial derivatives spikes.
7. RECORDING is the FB that records the variable values while the program is running, this function is used mainly to optimize and monitor the program behavior.

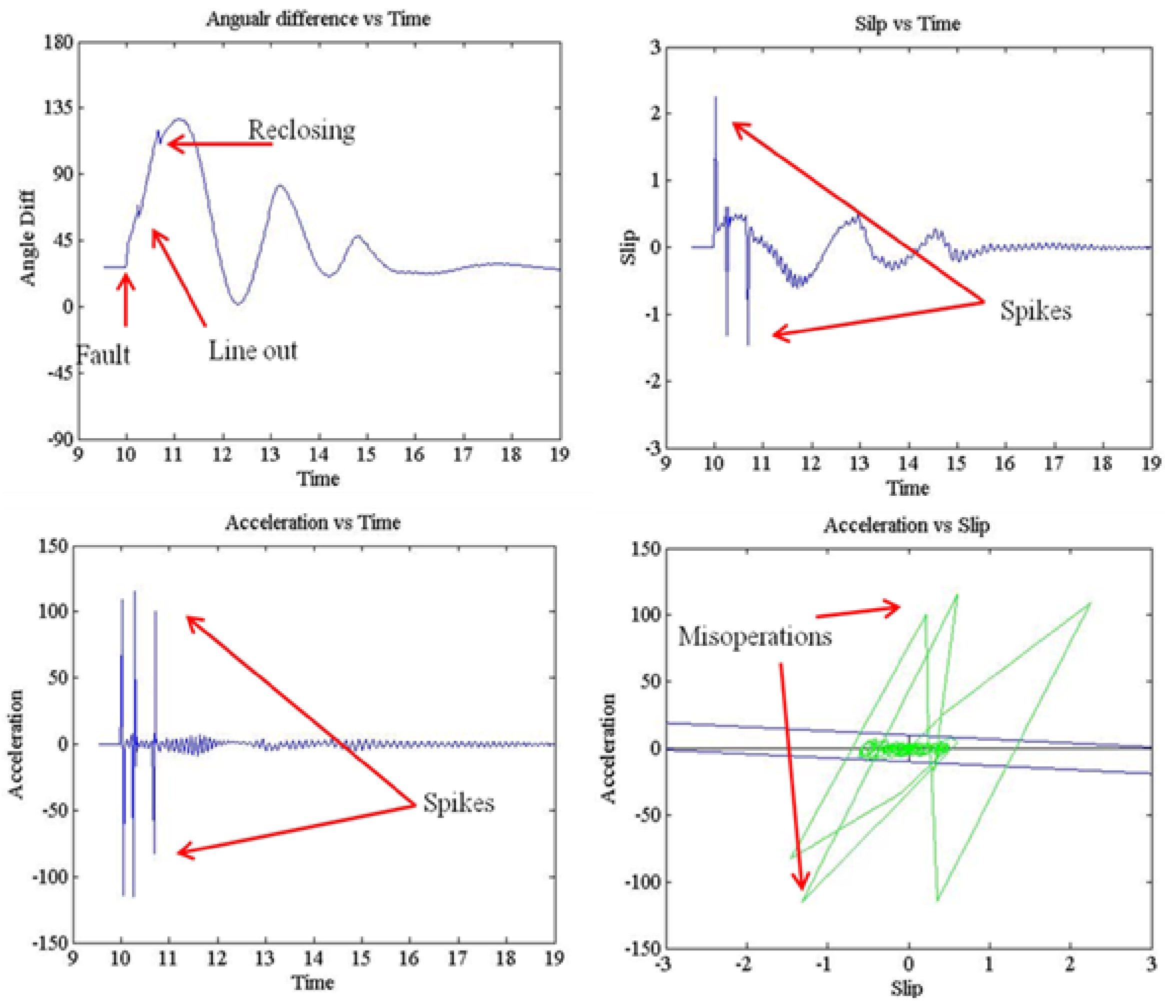


Figure 3.14 Spontaneous spikes during fault inception, clearing and reclosing.

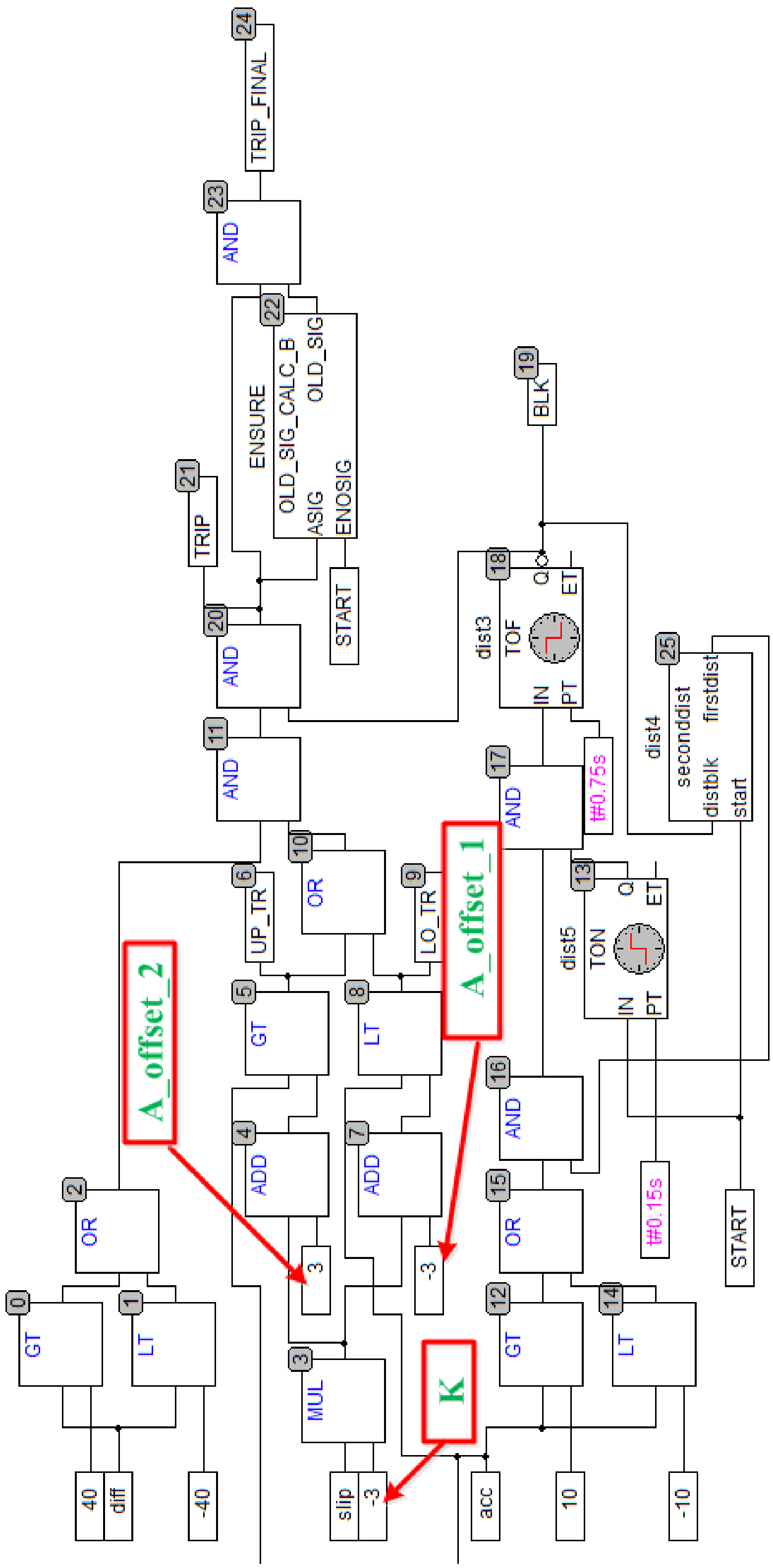


Figure 3.15 Blocks of algorithm FBs.

3.2.4.3 Parameters Selection for the SVP OOS-Algorithm

The algorithm detects the OOS condition based on the parallel blinders on the (S, A) plane as discussed in section (2.2.6). The parallel blinder setting parameters are three parameters (K, A_offset-1 and A_offset-2) as shown in Figure 3.16 below.

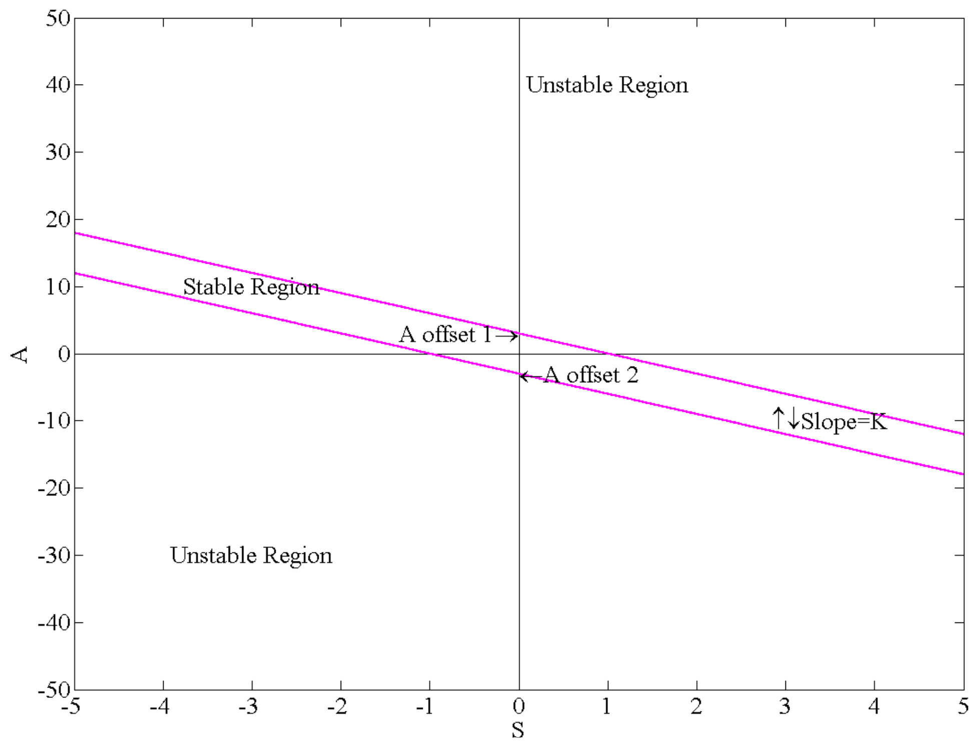


Figure 3.16 Algorithm setting parameters.

In order to obtain the most fitting settings, thirteen disturbance scenarios have been run on the simulator. The δ_{diff}, slip and acceleration have been recorded using the RECORDING function block (discussed in 3.2.4.2). At first, the data were pulled from the SVP as screenshots via MS-OneNote, and then they were converted to txt format and imported to an Excel file.

Excel data were imported to Matlab and the trajectory on the (S, A) plane was plotted for every case. The blinders were set abruptly at the beginning and plotted in the same graphs. The graphical representation was useful in the preliminary stage to narrow down the parameters selection options.

Microsoft Excel was used to check the algorithm output and refine the settings. The generalized blinders logic used in the algorithm could be written as follows:

Region= IF (A> S*K+ A_offset-1) is TRUE THEN the Region is (UNSTABLE) ELSE, IF (A<S*K-A_offset-2) is TRUE THEN the Region is (UNSTABLE) ELSE the region is (STABLE).

Where

A is the acceleration.

S is the slip.

K is the slop of the parallel lines.

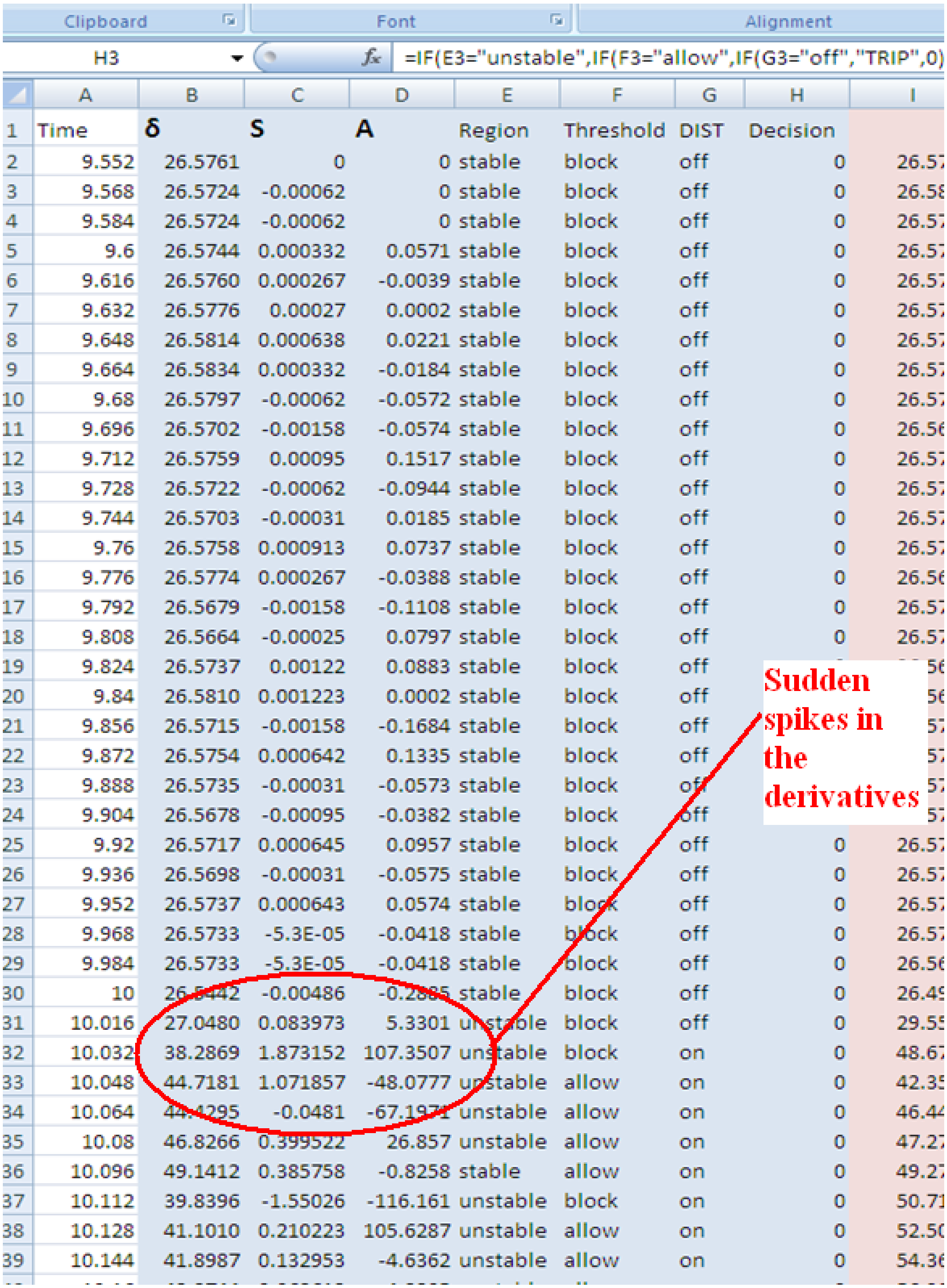
A_offset-1 is the offset for the upper line.

A_offset-2 is the offset for the lower line.

The generalized logical statement discussed previously has been implemented in the excel sheet as the following:

Region =IF (D2> (C2*K) +A_offset-1,"unstable", IF (D2< (C2*K)- A_offset-2,"unstable","stable")).

Where Column (D) contains the acceleration data and Column (C) contains the slip data. Figure 3.17 shows the SVP data and the logic implemented in Excel.



	A	B	C	D	E	F	G	H	I
1	Time	δ	S	A	Region	Threshold	DIST	Decision	
2	9.552	26.5761	0	0	stable	block	off	0	26.57
3	9.568	26.5724	-0.00062	0	stable	block	off	0	26.58
4	9.584	26.5724	-0.00062	0	stable	block	off	0	26.57
5	9.6	26.5744	0.000332	0.0571	stable	block	off	0	26.57
6	9.616	26.5760	0.000267	-0.0039	stable	block	off	0	26.57
7	9.632	26.5776	0.00027	0.0002	stable	block	off	0	26.57
8	9.648	26.5814	0.000638	0.0221	stable	block	off	0	26.57
9	9.664	26.5834	0.000332	-0.0184	stable	block	off	0	26.57
10	9.68	26.5797	-0.00062	-0.0572	stable	block	off	0	26.57
11	9.696	26.5702	-0.00158	-0.0574	stable	block	off	0	26.56
12	9.712	26.5759	0.00095	0.1517	stable	block	off	0	26.57
13	9.728	26.5722	-0.00062	-0.0944	stable	block	off	0	26.57
14	9.744	26.5703	-0.00031	0.0185	stable	block	off	0	26.57
15	9.76	26.5758	0.000913	0.0737	stable	block	off	0	26.57
16	9.776	26.5774	0.000267	-0.0388	stable	block	off	0	26.56
17	9.792	26.5679	-0.00158	-0.1108	stable	block	off	0	26.57
18	9.808	26.5664	-0.00025	0.0797	stable	block	off	0	26.57
19	9.824	26.5737	0.00122	0.0883	stable	block	off		56
20	9.84	26.5810	0.001223	0.0002	stable	block	off		56
21	9.856	26.5715	-0.00158	-0.1684	stable	block	off		57
22	9.872	26.5754	0.000642	0.1335	stable	block	off		57
23	9.888	26.5735	-0.00031	-0.0573	stable	block	off		57
24	9.904	26.5678	-0.00095	-0.0382	stable	block	off		57
25	9.92	26.5717	0.000645	0.0957	stable	block	off	0	26.57
26	9.936	26.5698	-0.00031	-0.0575	stable	block	off	0	26.57
27	9.952	26.5737	0.000643	0.0574	stable	block	off	0	26.57
28	9.968	26.5733	-5.3E-05	-0.0418	stable	block	off	0	26.57
29	9.984	26.5733	-5.3E-05	-0.0418	stable	block	off	0	26.56
30	10	26.5442	-0.00486	-0.2885	stable	block	off	0	26.49
31	10.016	27.0480	0.083973	5.3301	unstable	block	off	0	29.55
32	10.032	38.2869	1.873152	107.3507	unstable	block	on	0	48.67
33	10.048	44.7181	1.071857	-48.0777	unstable	allow	on	0	42.35
34	10.064	44.4295	-0.0481	-67.1971	unstable	allow	on	0	46.44
35	10.08	46.8266	0.399522	26.857	unstable	allow	on	0	47.27
36	10.096	49.1412	0.385758	-0.8258	stable	allow	on	0	49.27
37	10.112	39.8396	-1.55026	-116.161	unstable	block	on	0	50.71
38	10.128	41.1010	0.210223	105.6287	unstable	allow	on	0	52.50
39	10.144	41.8987	0.132953	-4.6362	unstable	allow	on	0	54.36

Figure 3.17 SVP data and algorithm logic in Excel.

Two additional IF-statements were implemented; the first one checks the δ_{diff} threshold (Column B in Figure 3.18) with the syntax:

Threshold= IF (B2>40,"allow", IF (B2< -40,"allow","block").

The other IF-statement accounts for disturbances in the system. DIST variable –in Column G— represents the trip blocking signal during system disturbances. Disturbances always create sudden shifts in δ_{diff} that result in spontaneous spikes in the derivatives. The spikes in the derivatives may lead to wrong trip decisions and this why the blocking is introduced for a specific time delay. The IF-statement that is developed to achieve this task is a lengthy one because it checks the value of the acceleration and the also previous values of the DIST in order to implement the time delay. The statement comes in the syntax:

DIST=IF(D30>10,"on",IF (G29="on","on",IF (G28="on","on",IF (G27="on","on",IF (G26="on","on"))))).

The above statement continues checking the value of the DIST column up to the previous 44 rows. With an execution cycle of seventeen milliseconds, the resulted tripping delay is in 765(17*45) milliseconds. Finally the trip decision is taken by the following statement: IF (E2="unstable", IF (F2="allow", IF (G2="off', "TRIP", 0), 0), 0).

At the end of this stage, the parameters (-3,-3, 3) were selected so that the SVP doesn't trip for any stable power swing (security) and trips only for the unstable power swings (dependability).

3.3 Testing procedure

3.3.1 Disturbance Scenarios

In order to evaluate the performance of the Phasor-Based and the Dual-Blinder OOS functions during power swings, thirteen different scenarios have been simulated with the real-time simulator. During each simulation the two 411L relays were receiving the voltage and current measurements in real-time (section 3.2.2) and processing their embedded programs and settings and responding accordingly. Figure 3.18 below shows the locations where the faults were applied to the power system model. The disturbances are applied after ten seconds of the simulation starting. The reclosing dead-time assumed in these scenarios is twenty five cycles.

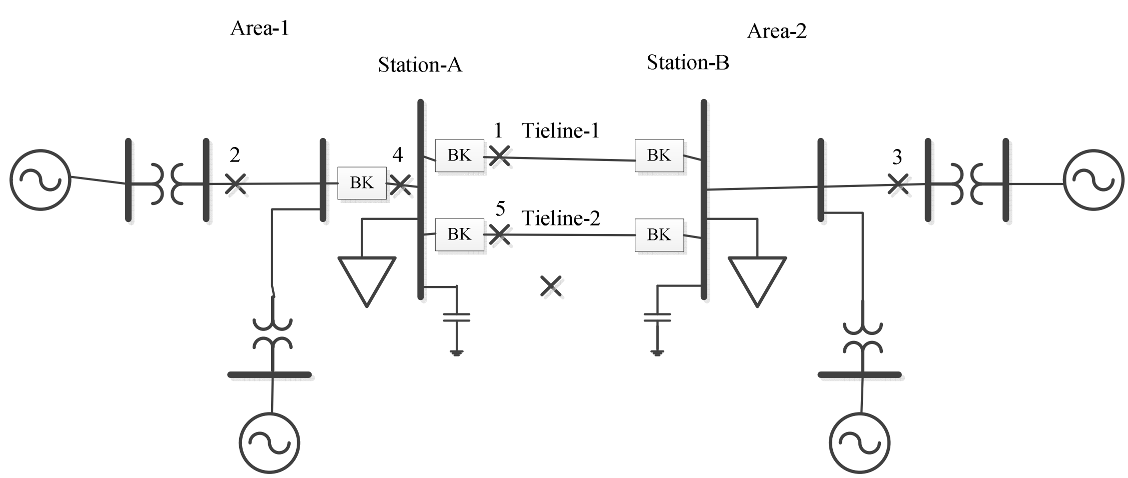


Figure 3.18 Fault locations on the test system.

3.3.1.1 Cases Description

Case-1 is a stable power swing created by applying a TPH fault on Tieline-1 at the location no-1 (20 Km from Station-A). The fault is cleared after five cycles, and the line breakers reclose successfully.

Case-2 is a stable power swing created by applying a TPH fault on Tieline-1 at the location no-1. The fault is cleared after fifteen cycles, and the line breakers reclose successfully.

Case-3 is an unstable power swing created by applying a TPH fault on Tieline-1 at the locationno-1. The fault is cleared after five cycles, and no reclosing is made.

Case-4is an unstable power swing created by applying a TPH fault on the Tieline-1 at the locationno-1. The fault is cleared after five cycles, and the breakers reclose, but Power System Stabilizers (PSSs) are off.

Case-5 is an unstable power swing created by applying a TPH fault at thelocationno-2 (the GSU HV-terminals). The fault is cleared after five cycles, and no reclosing is made.

Case-6 is an unstable power swing created by applying a TPH fault at thelocationno-3 (the GSU HV-terminals). The fault is cleared after five cycles, and no reclosing is made.

Case-7 is a stable power swing created by an unplanned outage of GN1.

Case-8 is an unstable power swing created by an unplanned outage ofGN3.

Case-9 is an unstable power swing created by applying a TPH fault on Area-1's 10 Km line at the location no-4. The fault is cleared after five cycles, and the line breakers reclose successfully.

Case-10 is an unstable power swing created by applying a TPH fault on Area-1's 10 Km line at the location no-4. The fault is cleared after 1five cycles, and the line breakers reclose successfully.

Case-11is a stable power swing created by applying a TPH fault on Tieline-2 at the location no-5 (20 Km from Station-A). The fault is cleared after five cycles, and line the breakers reclose successfully.

Case-12 is a stable power swing created by applying a TPH fault on Tieline-2 at the location no-5. The fault is cleared after fifteen cycles, and the line breakers reclose successfully.

Case-13is an unstable power swing created by applying a TPH fault on the Tieline-2 at the location no-5. The fault is cleared after five cycles, and the line breakers reclose successfully with all the PSS are off.

3.3.2 The Stability Study

The thirteen cases had been run at first as a stability study in order to set the dual blinders (RR6-RR7) in the 411L of Tieline-2 at Station-A. The setting of these parameters requires running a stability study to find out the minimum impedance value that measured during the studied stable power swings. The parameter RR6 is set to be less than this value. When the relay word-bit RR6 becomes true that means the impedance value measured at the relay is less than the minimum impedance found in the studies cases and the OOS function issues an OOS signal.

During the simulations the SVP received the phasor measurements from the two relays at the Tieline-2terminals. The OOS program calculated δ_{diff}, slip and acceleration. At this stage no trip decision was issued during. The algorithm block wasn't added to the OOS program yet. The setting steps of the SVP OOS program have been explained in section (3.2.4.3).

3.3.3 The Final Test

After performing the stability study and the setting of both 411L L and SVP OOS functions, the disturbance scenarios were run again to evaluate the response of the two functions. The trip signals from the two functions, OSTI and RB01, which are assigned to Station-A relay's outputs: OUTPUT-101 and OUTPUT-102, are connected to the simulator and recorded in the recording matrix discussed in section (3.2.1). The response of the two functions is also depicted in the relay event files (Appendix C). In the next chapter the results of each case are shown.

CHAPTER 4

RESULTS AND DISCUSSION

The thirteen disturbance scenarios discussed in the previous chapter were run on the real-time digital simulator after the SVP and the 411L have been set to perform the OOS functionality. The trip signals from each device were recorded on a time graph according to the time they were received in the digital simulator's input card. The 411L location is at Station-A and it is protecting Tieline-2. The disturbances occurred ten seconds after the simulations started.

The impedance plane R-X is used to depict the value of the impedance at the tripping time of each device. In these results, the origin of the R-X plane is the relay location (electrically). The impedance measured by the relay has been recalculated with Matlab using two different formulas: $Z = \frac{Va - Vb}{I a - Ib}$ and also by $R = \frac{V2 * P}{P2 + Q2}$, $X = \frac{V2 * Q}{P2 + Q2}$. The impedance value when the OOS occurs is of concern since it reflects the angle difference between the two systems at the tripping time; the stress is higher on the breaker as the angle difference is approaching to 180°.

The relay event file was retrieved from the relay after each disturbance and was used to confirm the simulator recorded results. The relay event files provide additional data such as the SCV and PSB and other relay word bits. The relay event files are provided in Appendix C.

4.1 Results

4.1.1 Case-1

Case-1 was a TPH close-in fault on the Tieline-1, 20 Km from Station-A. The fault was cleared after five cycles, and the Tieline-1 was reclosed after twenty five cycles. The disturbance created a stable swing and no trip signal was issued. Figure 4.1 below illustrates the impedance trajectory during this disturbance.

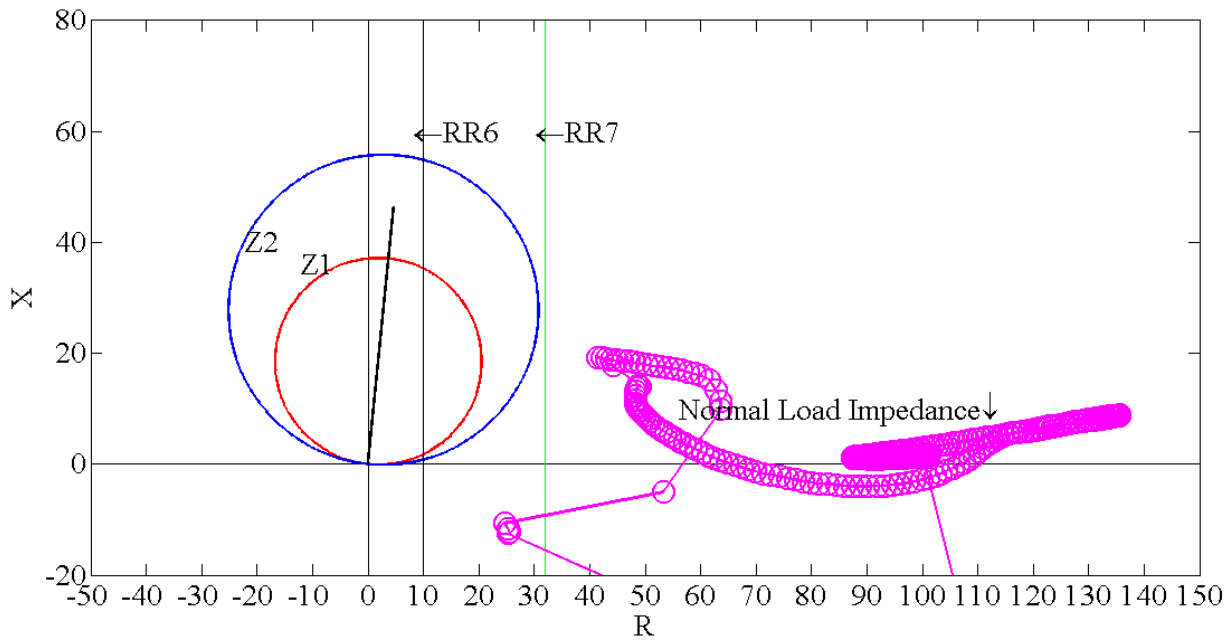


Figure 4.1 The impedance trajectory during Case-1.

4.1.2 Case-2

Case-2 was a TPH close-in fault on the Tieline-1, 20 Km from Station-A. The fault was cleared after fifteen cycles, and the Tieline-1 was reclosed after twenty five cycles. The disturbance created a stable swing and no trip signal was issued. Figure 4.2 below illustrates the impedance trajectory during this disturbance.

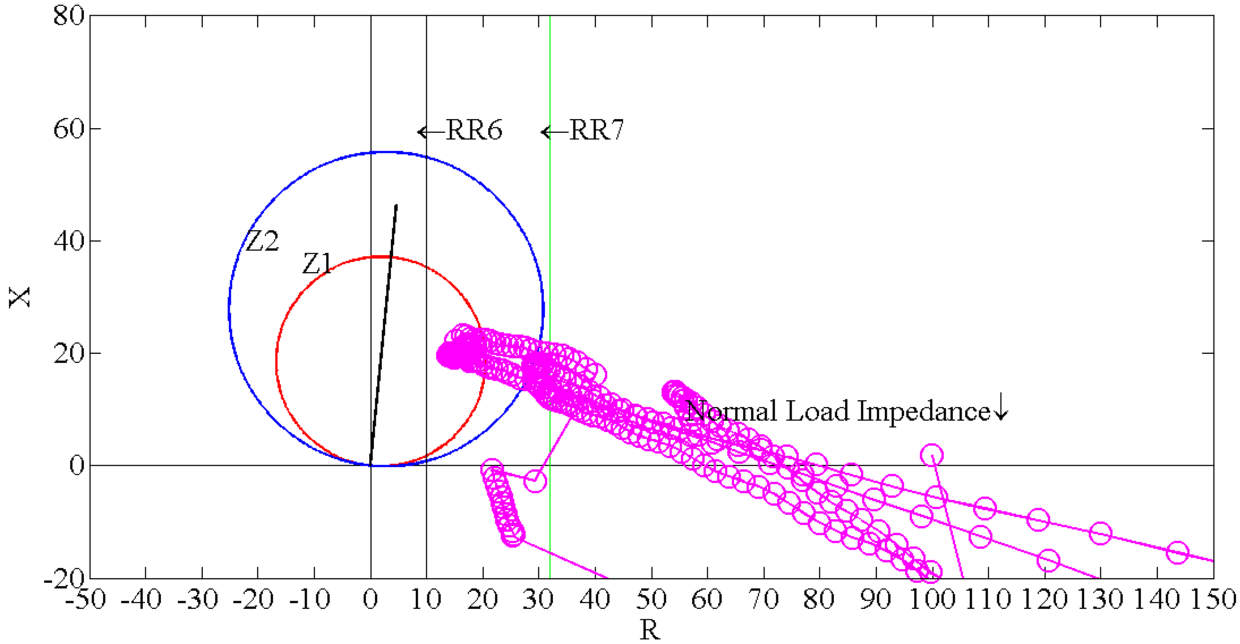


Figure 4.2 The impedance trajectory during Case-2.

4.1.3 Case-3

Case-3 was a TPH fault on Tieline-1, 20 Km from Station-A. The fault was cleared after five cycles, and no reclosing was performed. This disturbance created an unstable swing. Figure 4.3 shows the trip signals. The 411L relay tripped before the SVP, also the Impedance trajectory at each tripping moment is shown in Figure 4.4 and Figure 4.5.

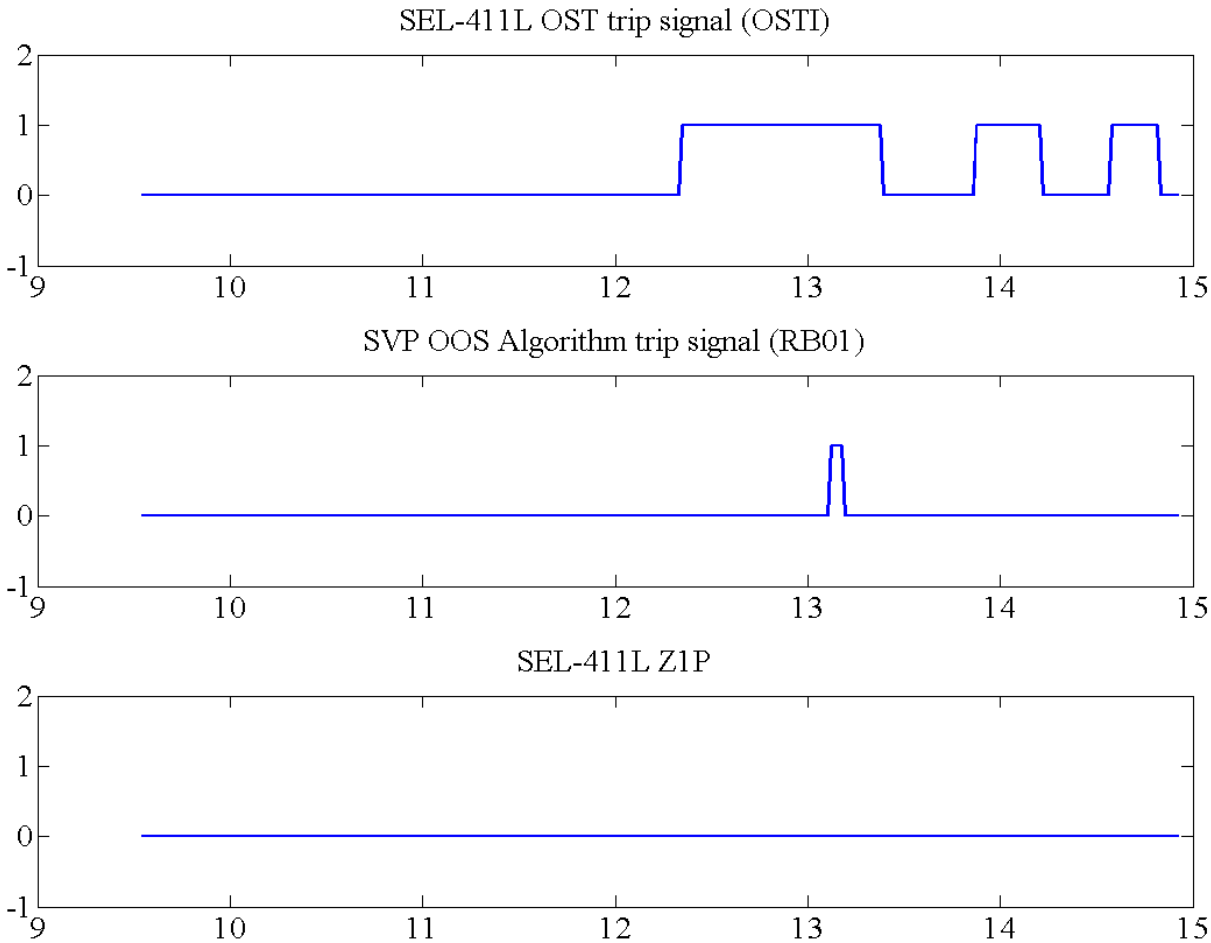


Figure 4.3 The 411L and the SVP trip signals (top, middle) in Case-3.

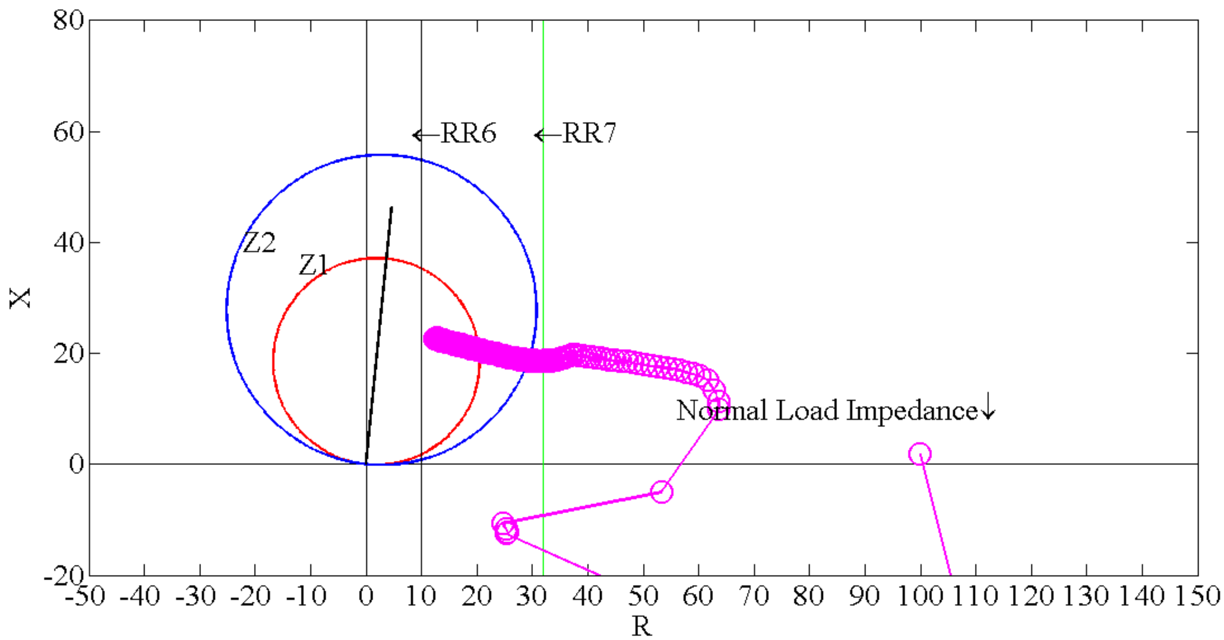


Figure 4.4 The impedance trajectory when the 411L tripped in Case-3.

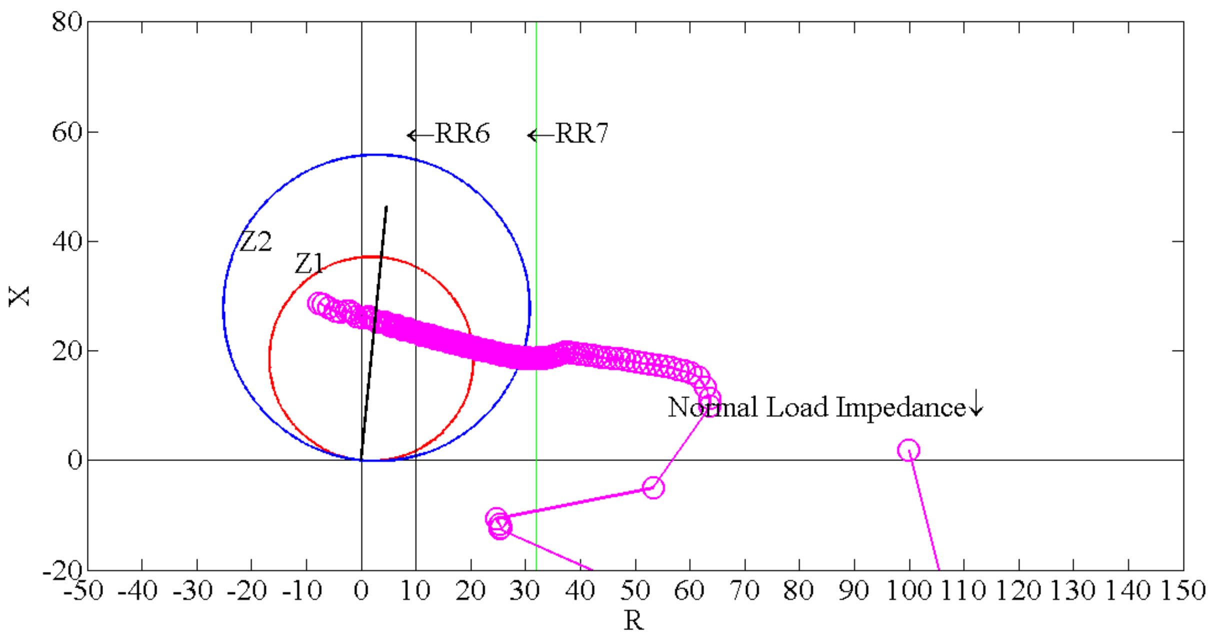


Figure 4.5 The impedance trajectory when the SVP tripped in Case-3.

4.1.4 Case-4

Case-4 was a TPH fault on Tieline-1, 20 Km from Station-A. The fault was cleared after five cycles, Tieline-1 was reclosed after twenty five cycles, the Power System Stabilizers (PSSs) were off. This disturbance created an unstable swing. The SVP tripped before the 411L relay as shown in Figures 4.6, also the Impedance trajectory at each tripping moment is shown in Figure 4.7 and Figure 4.8.

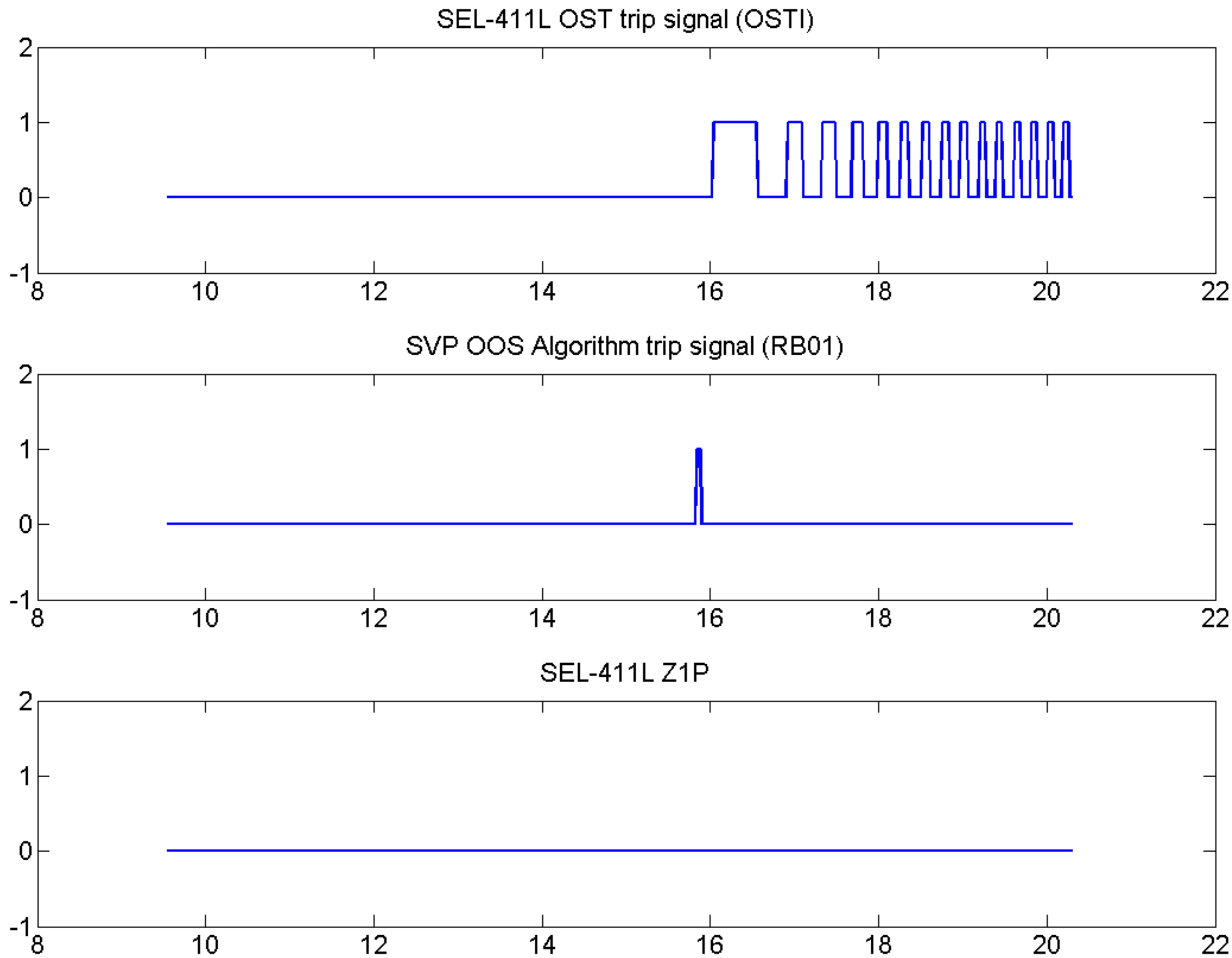


Figure 4.6 The 411L and the SVP trip signals (top, middle) in Case-4.

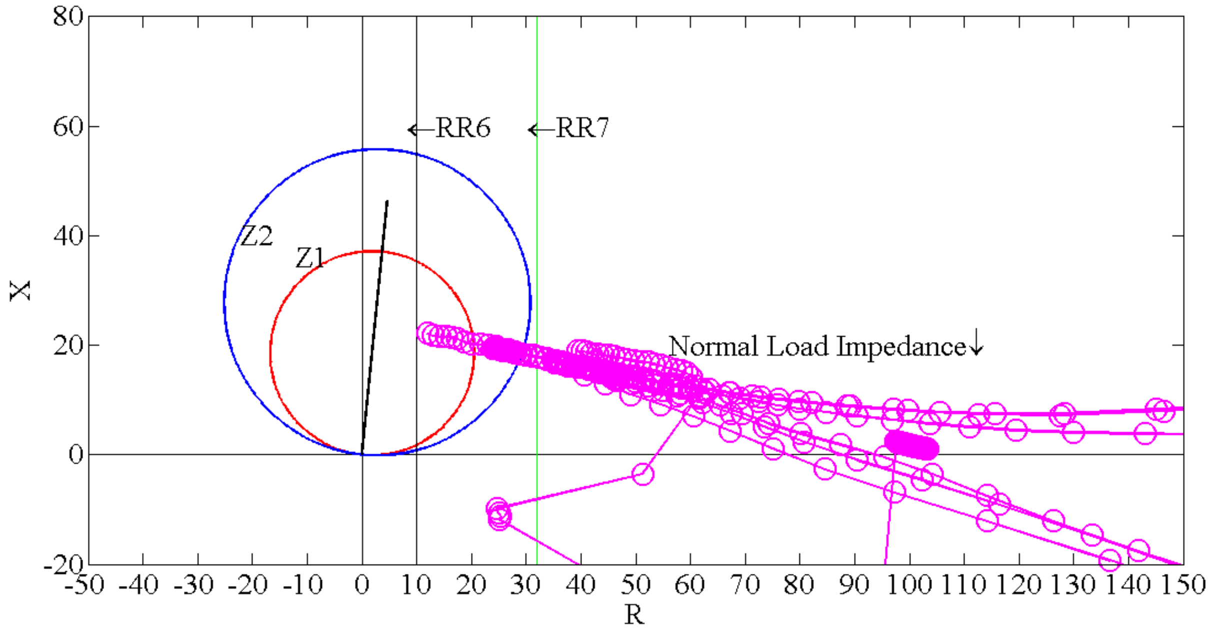


Figure 4.7 The impedance trajectory when the SVP tripped in Case-4.

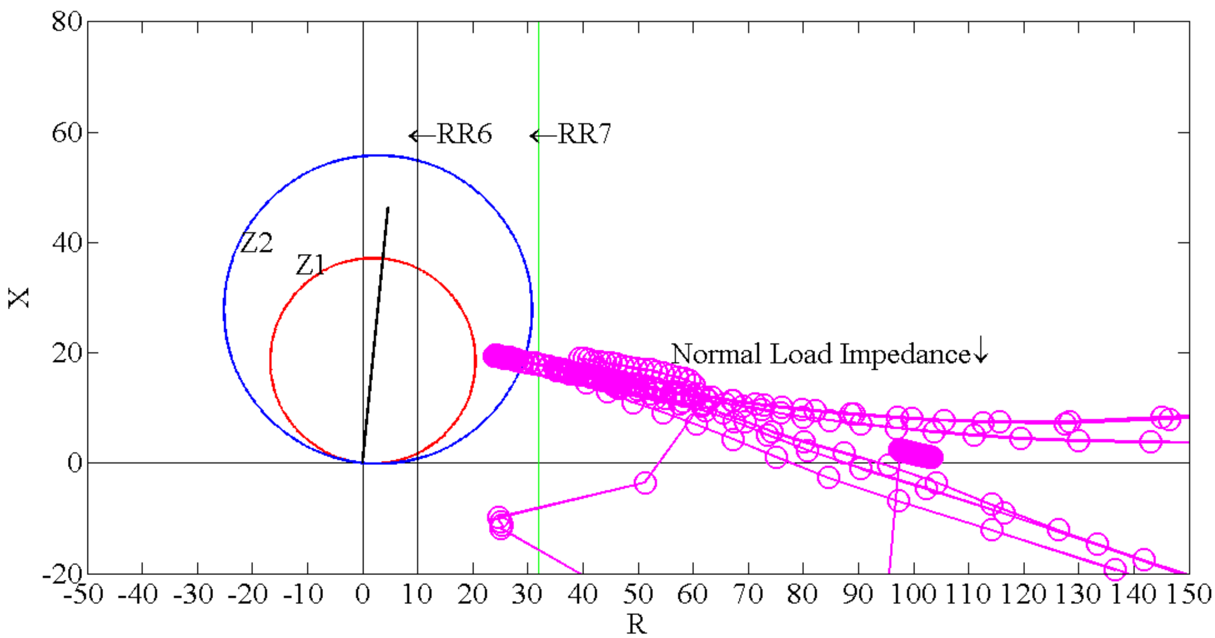


Figure 4.8 The impedance trajectory when the 411L tripped in Case-4.

4.1.5 Case-5

Case-5 was a TPH close-in fault near GN1, the fault was cleared after five cycles, and no reclosing was performed. This disturbance created an unstable swing. The SVP tripped before the 411L relay as shown in Figures 4.9; also the Impedance trajectory at each tripping moment is shown in Figure 4.10 and Figure 4.11.

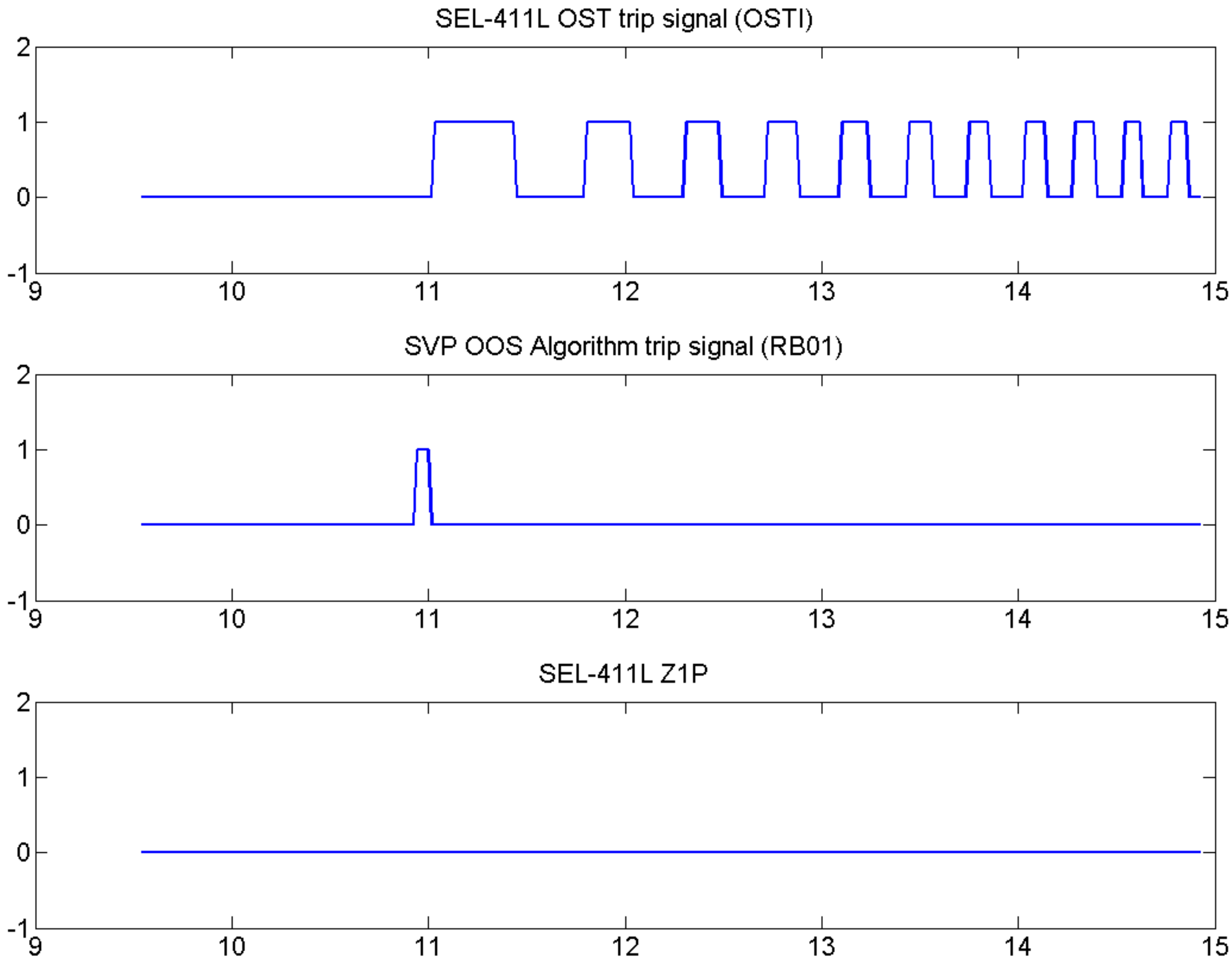


Figure 4.9 The 411L and the SVP trip signals (top, middle) in Case-5.

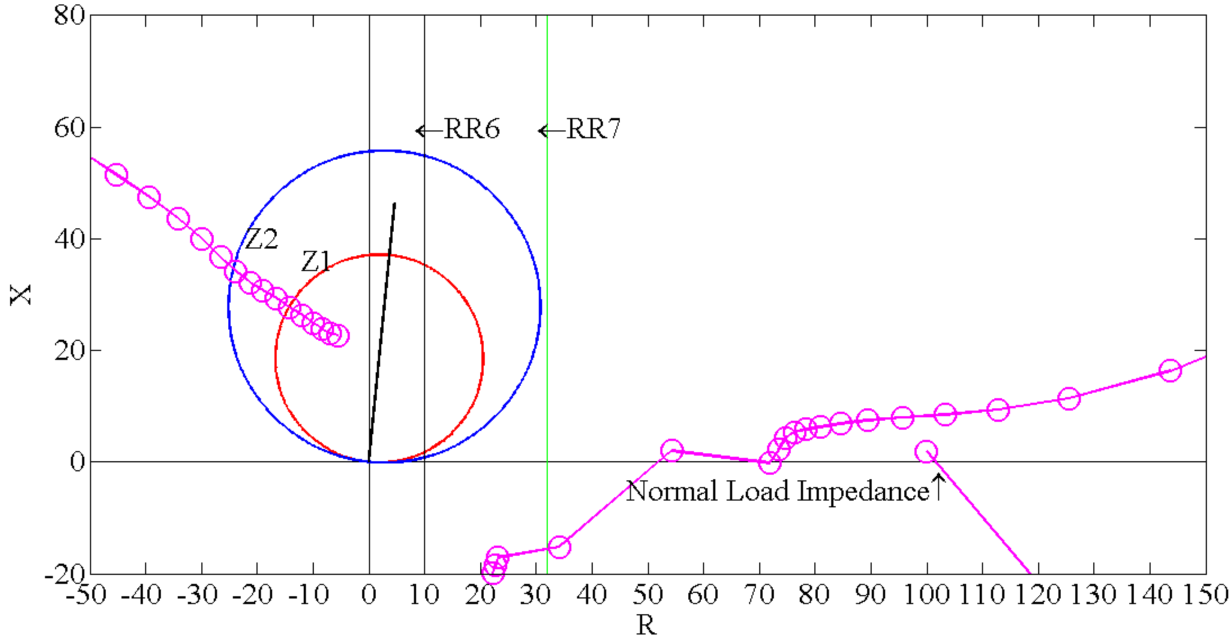


Figure 4.10 The impedance trajectory when the SVP tripped in Case-5.

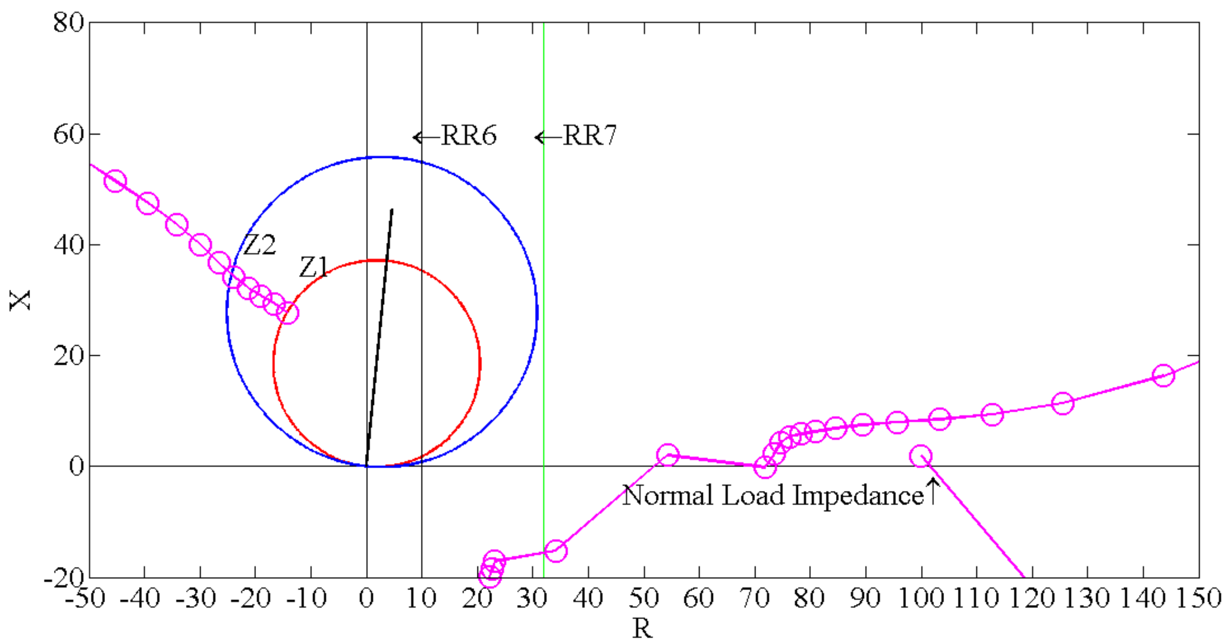


Figure 4.11 The impedance trajectory when the 411L tripped in Case-5.

4.1.6 Case-6

Case-6 was a TPH close-in fault near GN3, the fault was cleared after five cycles, and no reclosing was performed. This disturbance created an unstable swing. The 411L relay tripped before the SVP as shown in Figures 4.12, also the Impedance trajectory at each tripping moment is shown in Figure 4.13 and Figure 4.14.

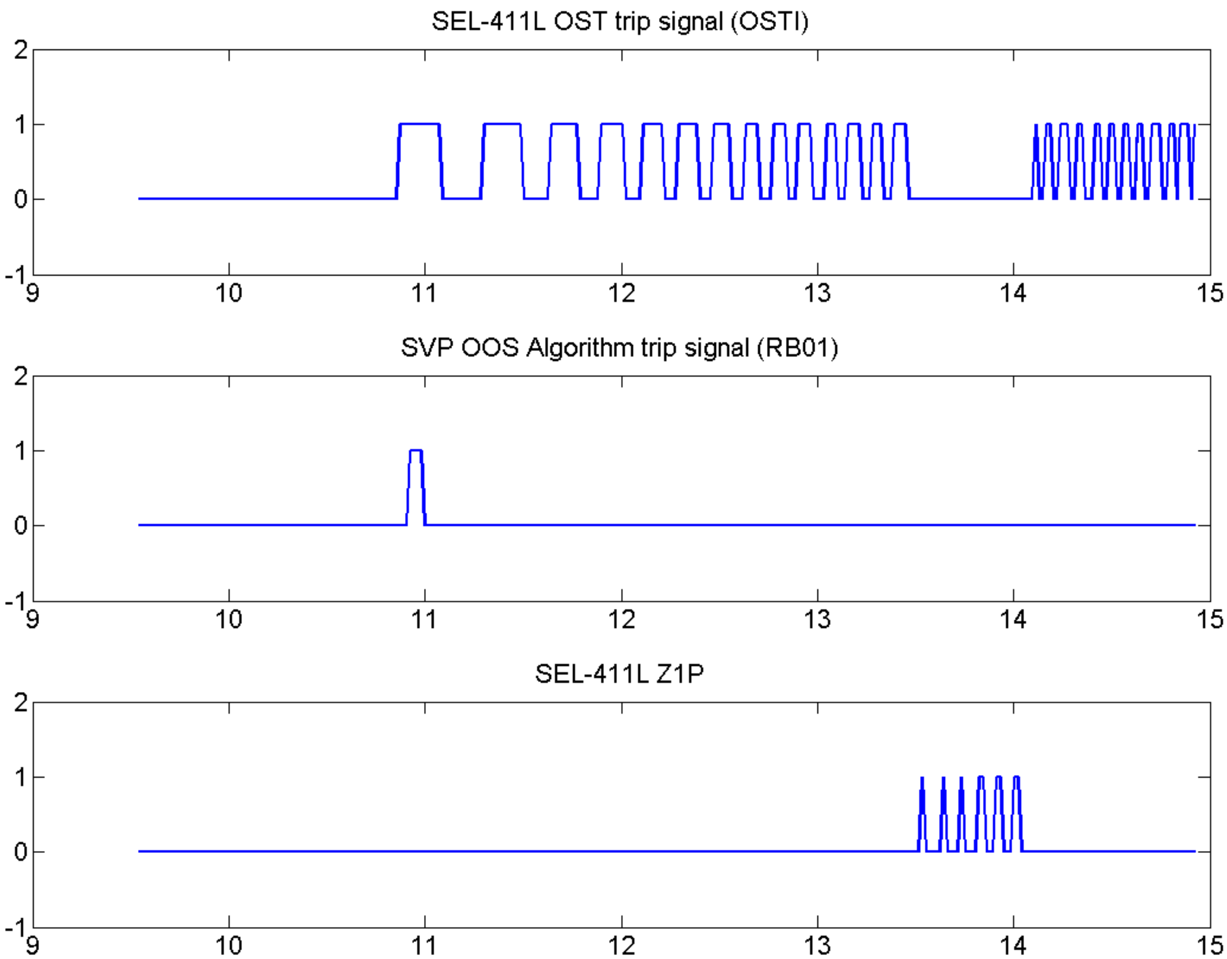


Figure 4.12 The 411L and the SVP trip signals (top, middle) in Case-6.

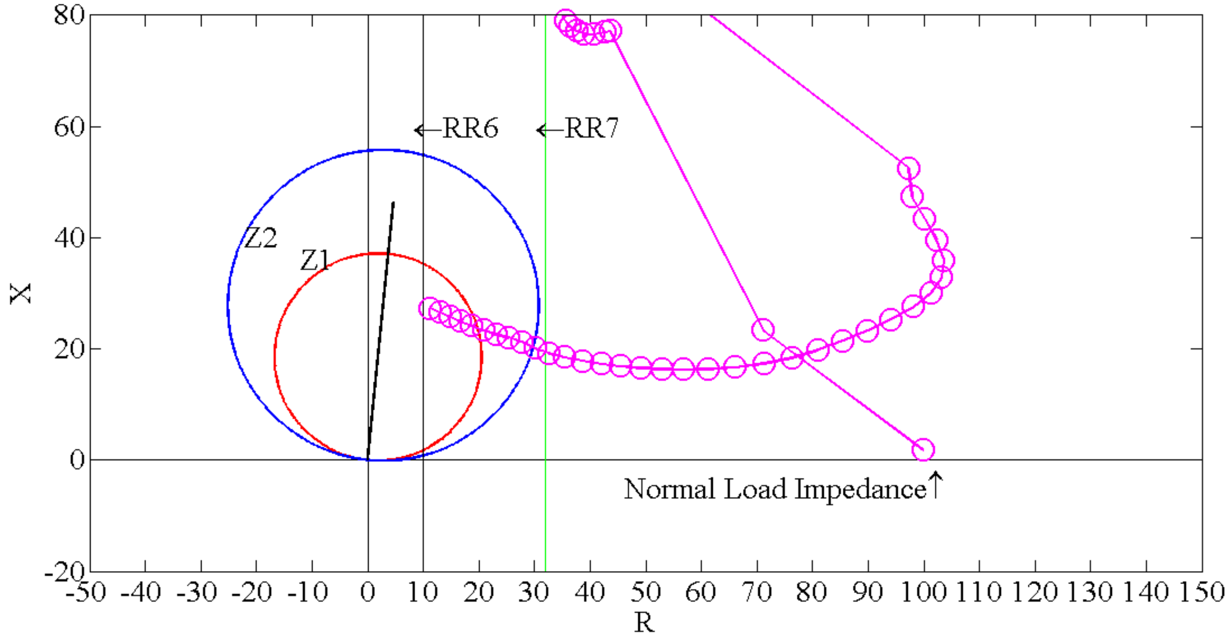


Figure 4.13 The impedance trajectory when the 411L tripped in Case-6.

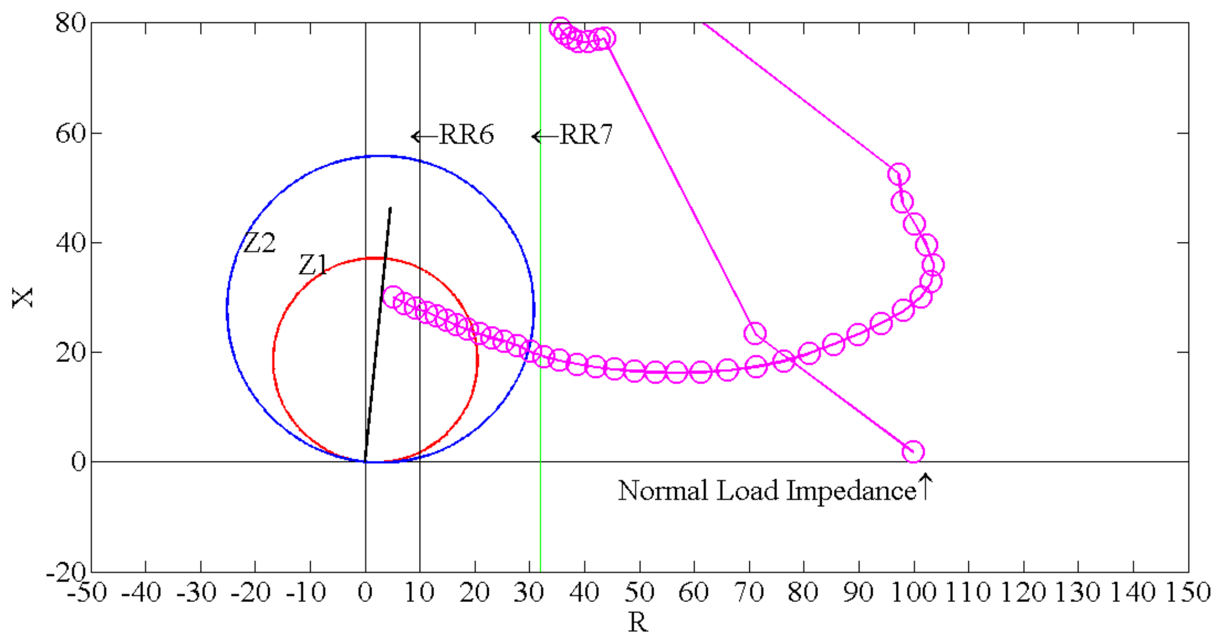


Figure 4.14 The impedance trajectory when the SVP tripped in Case-6.

4.1.7 Case-7

Case-7 was an unplanned outage of GN1. This disturbance created a stable swing, and the power system moved to another steady state operating point, with Area-1 importing power from Area-2 instead of exporting. The impedance trajectory is shown in Figure 4.15.

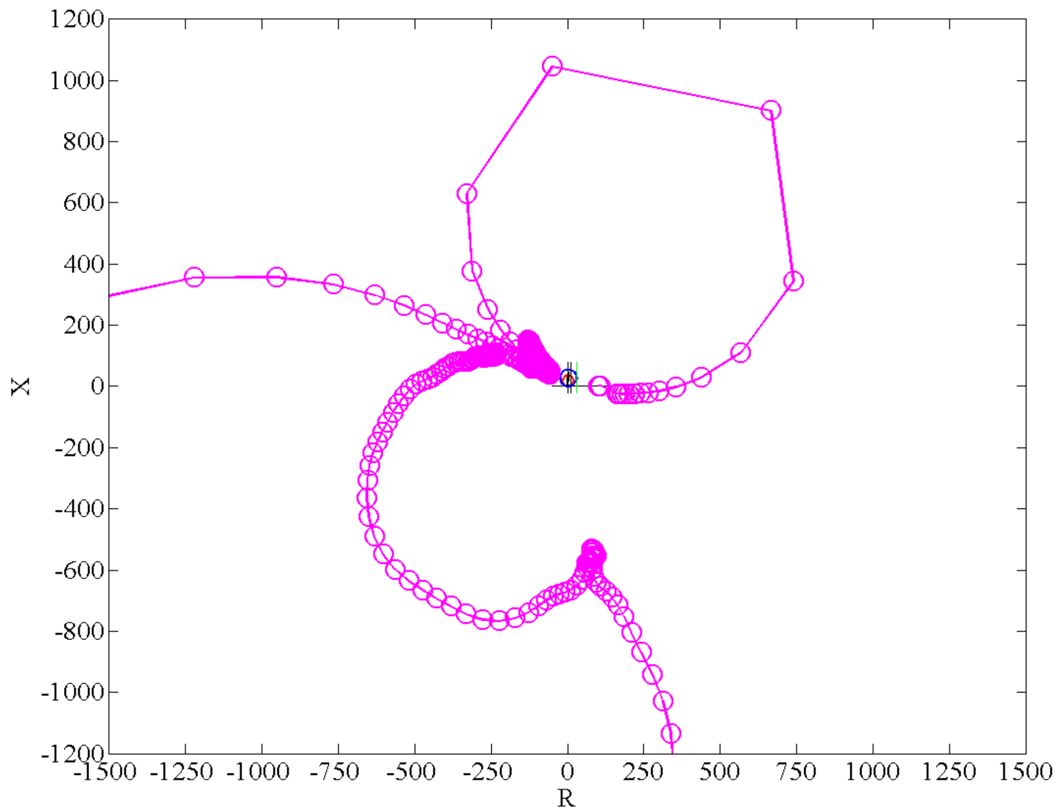


Figure 4.15 The impedance trajectory after GN1 outage (Case-7).

4.1.8 Case-8

Case-8 was an unplanned outage of GN3. This disturbance created an unstable swing. The 411L relay tripped before the SVP as shown in Figures 4.16,also the Impedance trajectory at each tripping moment is shown in Figure 4.17 and Figure 4.18.

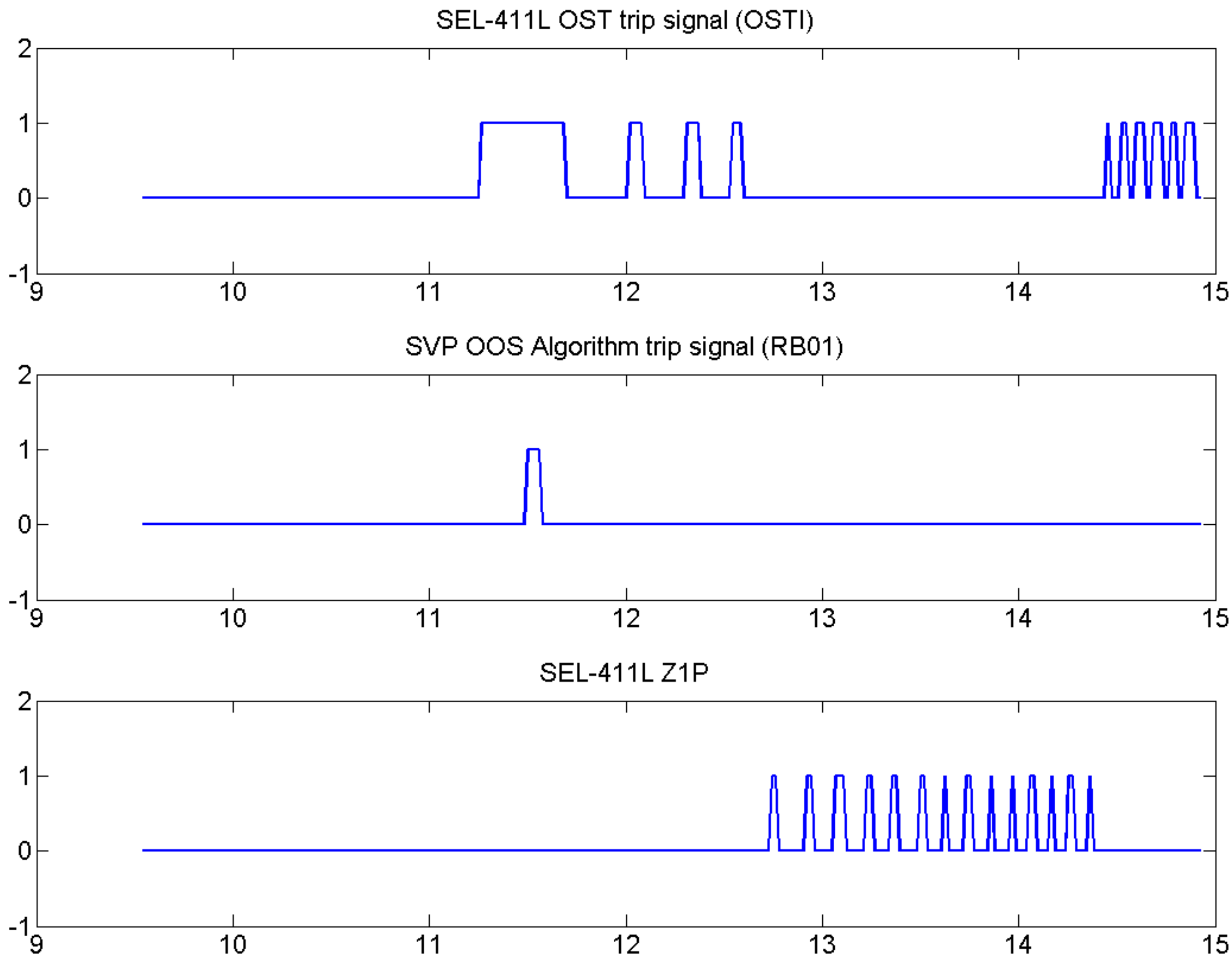


Figure 4.16 The 411L and the SVP trip signals (top, middle) in Case-8.

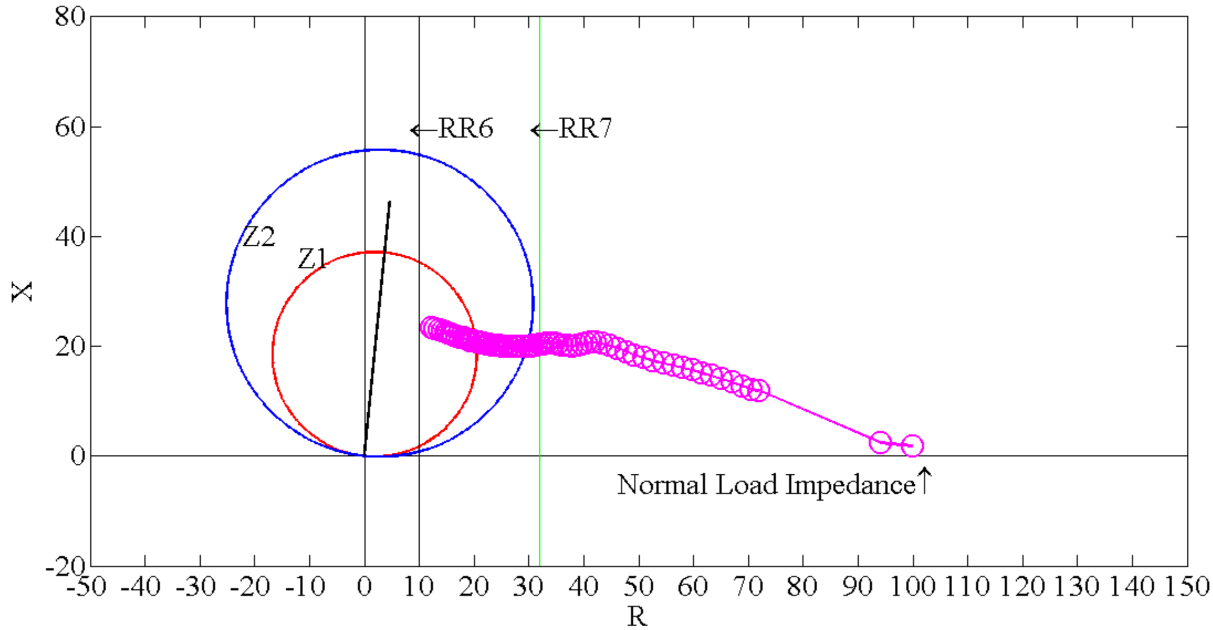


Figure 4.17 The impedance trajectory when the 411L tripped in Case-8.

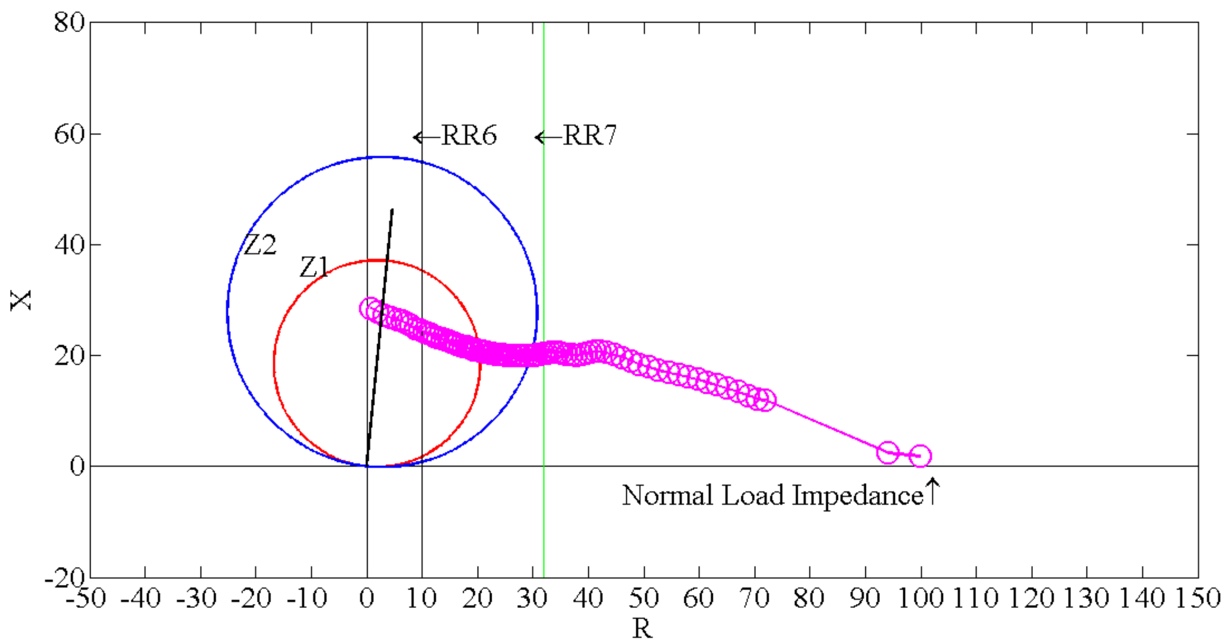


Figure 4.18 The impedance trajectory when the SVP tripped in Case-8.

4.1.9 Case-9

Case-9 was a TPH fault on Area-1's 10Km line, 20 Km from Station-A. The fault was cleared after five cycles; Tieline-2 was reclosed after twenty five cycles. This disturbance created an unstable swing. The 411L relay tripped before the SVP as shown in Figures 4.19, also the Impedance trajectory at each tripping moment is shown in Figure 4.20 and Figure 4.21.

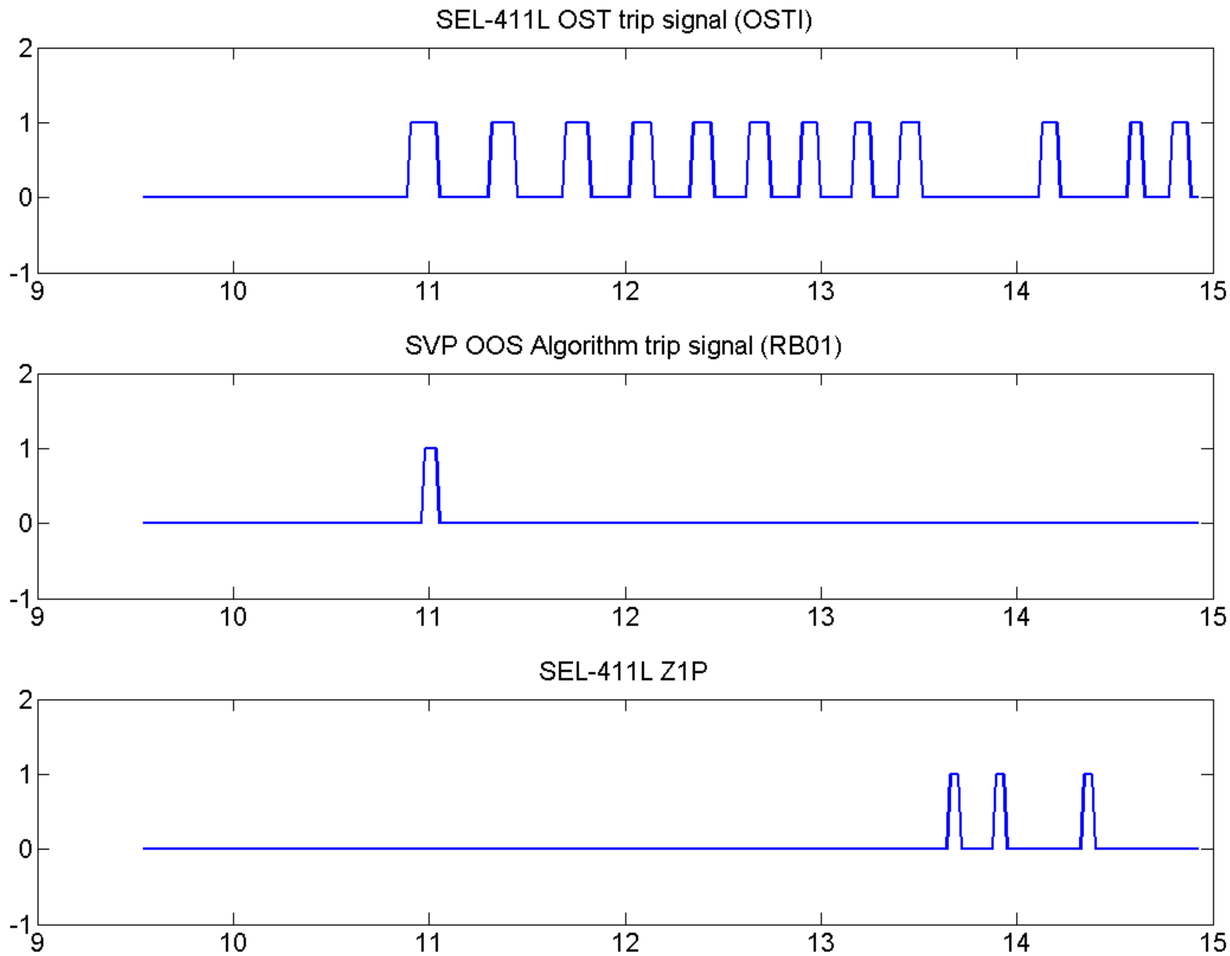


Figure 4.19 The 411L and the SVP trip signals (top, middle) in Case-9.

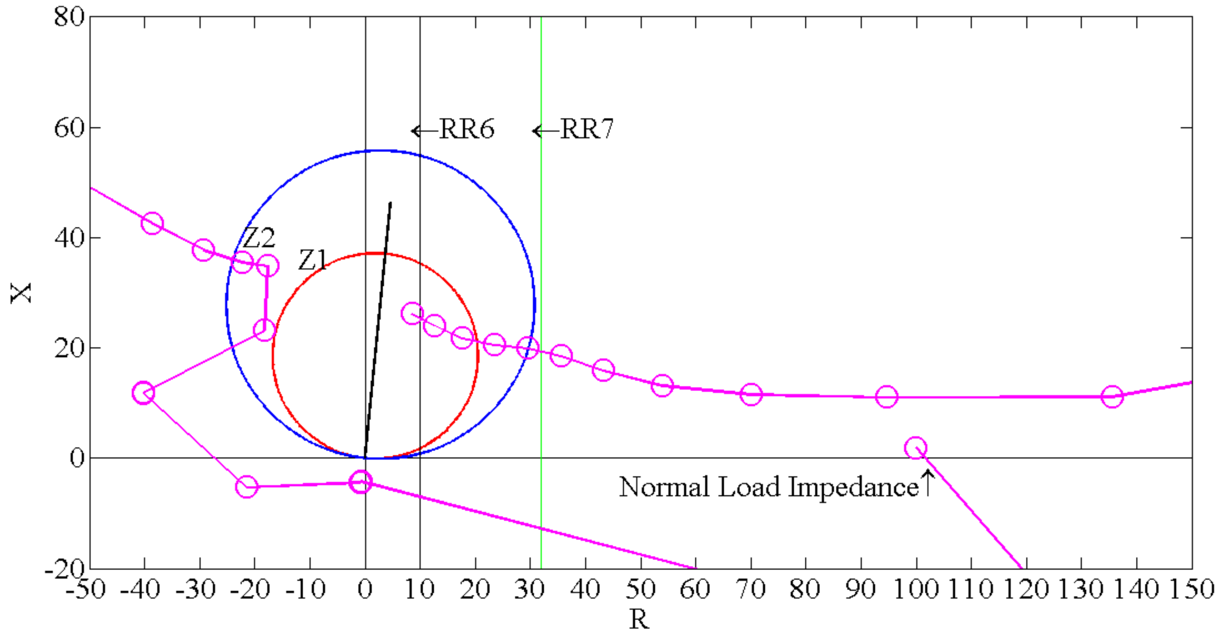


Figure 4.20 The impedance trajectory when the 411L tripped in Case-9.

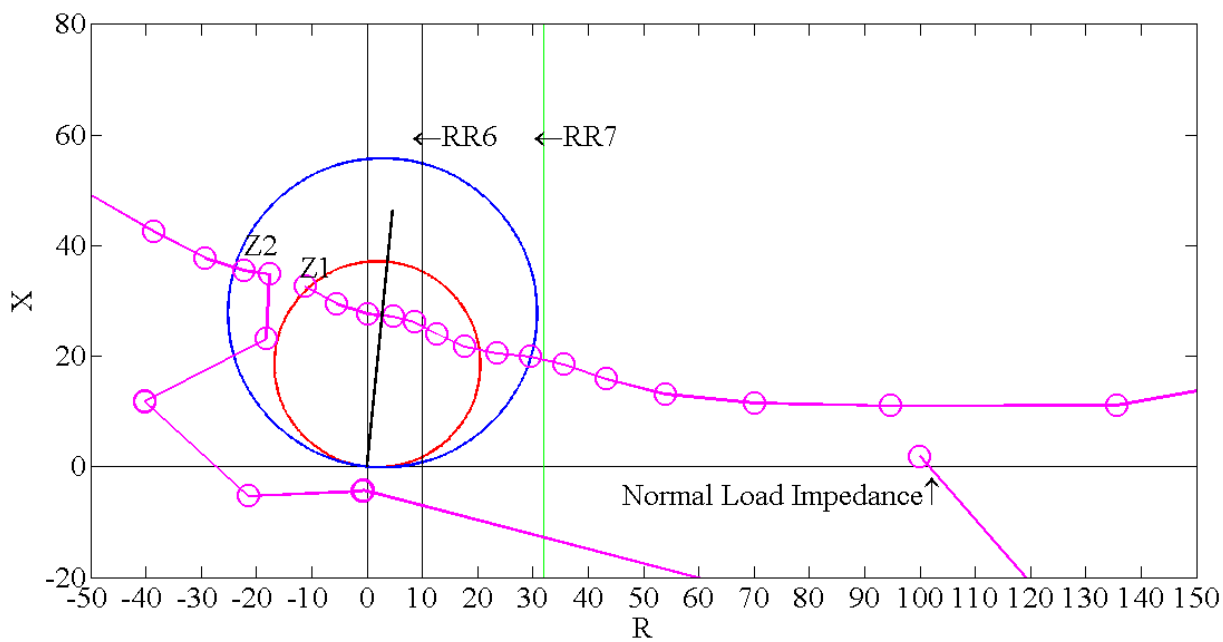


Figure 4.21 The impedance trajectory when the SVP tripped in Case-9.

4.1.10 Case-10

Case-10 was a TPH close-in fault on Area-1's10 Km line. The fault was cleared after fifteen cycles; and the Tieline-2 was reclosed after twenty five cycles. This disturbance created an unstable swing. The 411L relay tripped before the SVP as shown in Figures 4.22, also the Impedance trajectory at each tripping moment is shown in Figure 4.23 and Figure 4.24.

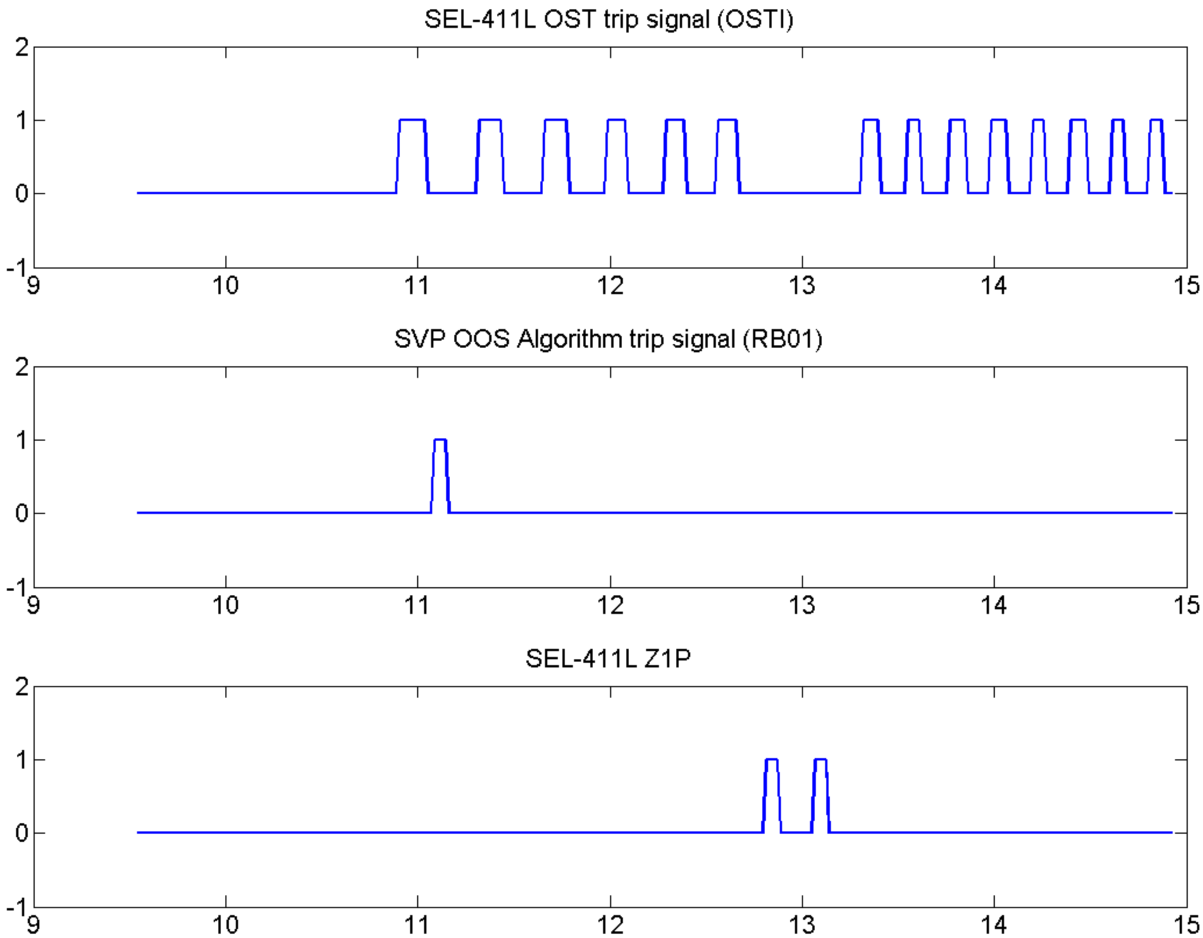


Figure 4.22 The 411L and the SVP trip signals (top, middle) in Case-10.

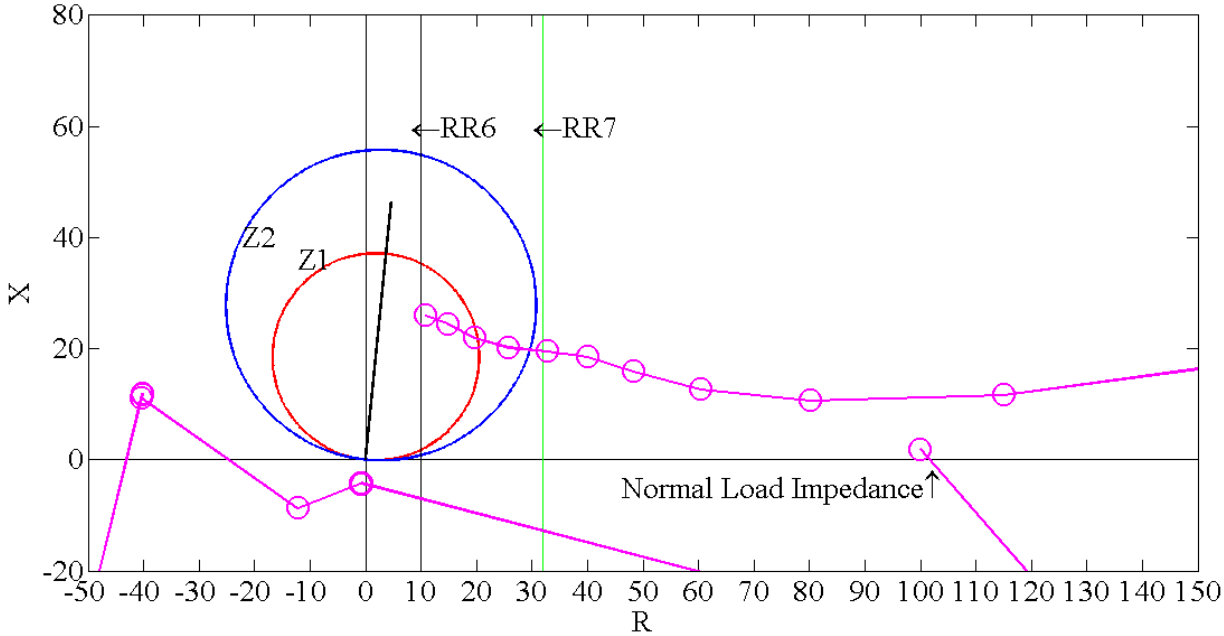


Figure 4.23 The impedance trajectory when the 411L tripped in Case-10.

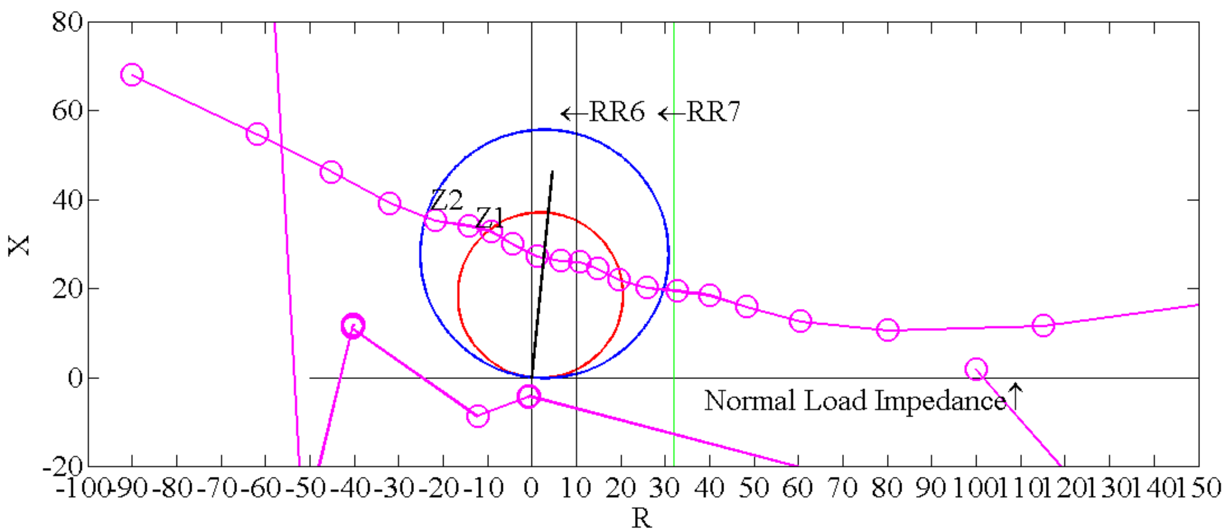


Figure 4.24 The impedance trajectory when the SVP tripped in Case-10.

4.1.11 Case-11

Case-11 was a TPH fault on Tieline-2, 20 Km from Station-A. The fault was cleared after five cycles, and the Tieline-2 was reclosed after twenty five cycles. This disturbance created a stable swing, no OOS trip was issued. Figure 4.25the impedance trajectory during this disturbance.

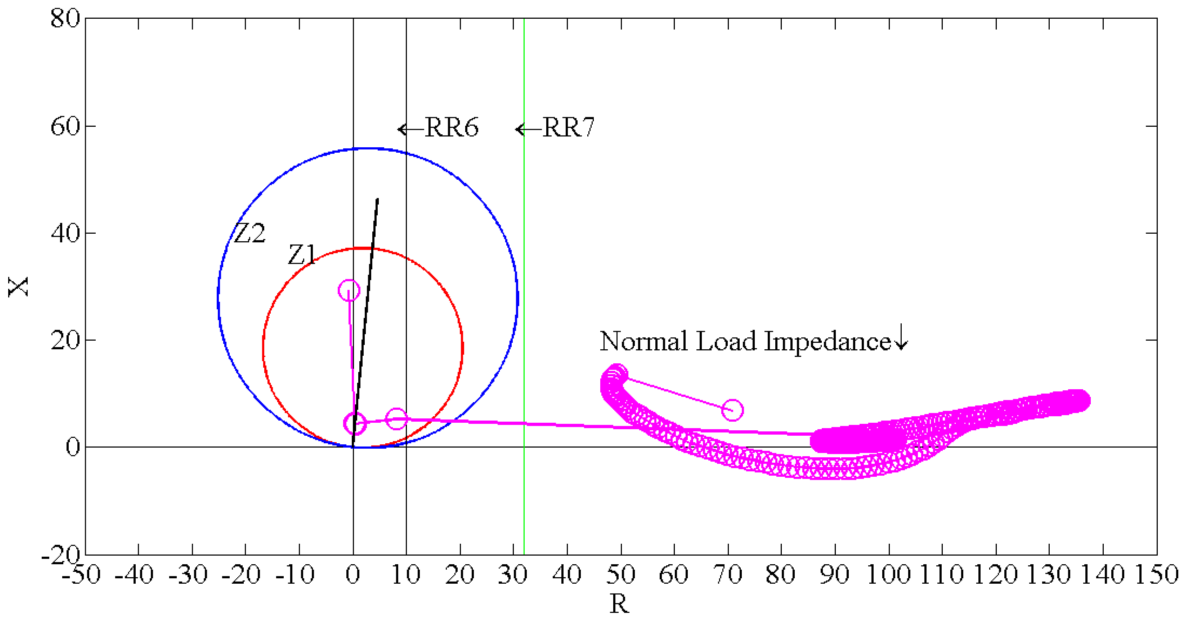


Figure 4.25 The impedance trajectory during Case-11.

4.1.12 Case-12

Case-12 was a TPH fault on Tieline-2, 20 Km from Station-A. The fault was cleared after fifteen cycles, and the Tieline-2 was reclosed after twenty five cycles. This disturbance created a stable swing, no OOS trip was issued. Figure 4.26 shows the impedance trajectory during this disturbance.

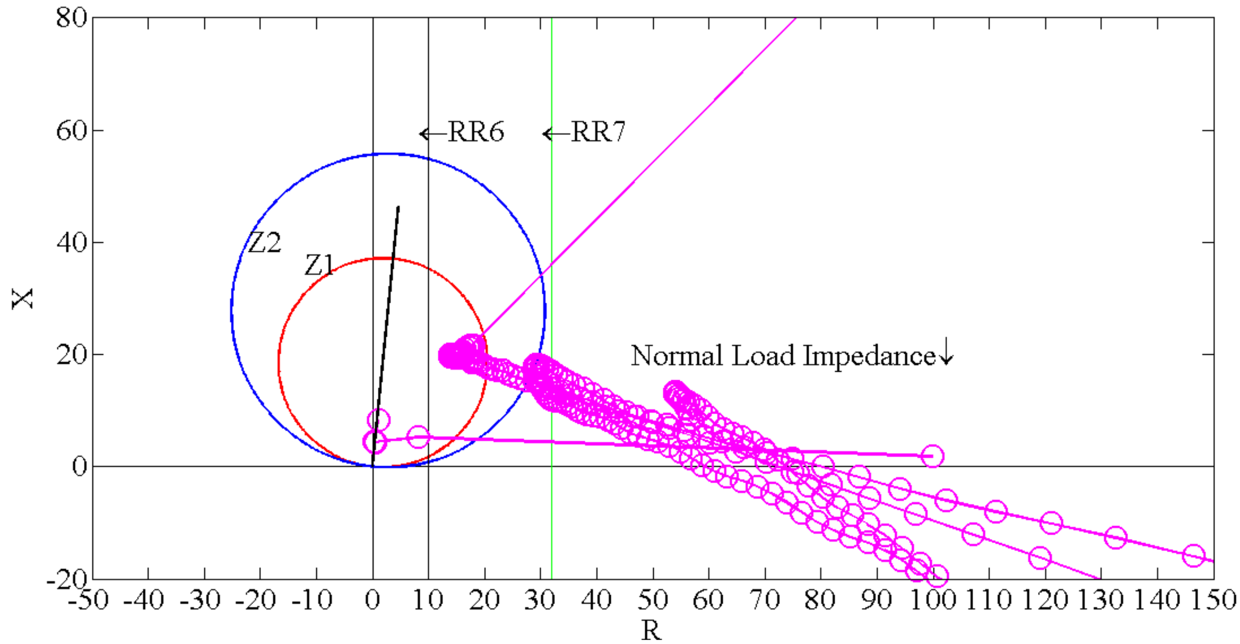


Figure 4.26 The impedance trajectory during Case-12.

4.1.13 Case-13

Case-13 was a TPH fault on Tieline-2, 20 Km from Station-A. The fault was cleared after five cycles. The Tieline-2was reclosed after twenty five cycles, and the PSSs were off. This disturbance created an unstable swing. The SVP tripped before the 411L relay as shown in Figures 4.27;also the Impedance trajectory at each tripping moment is shown in Figure 4.28 and Figure 4.29.

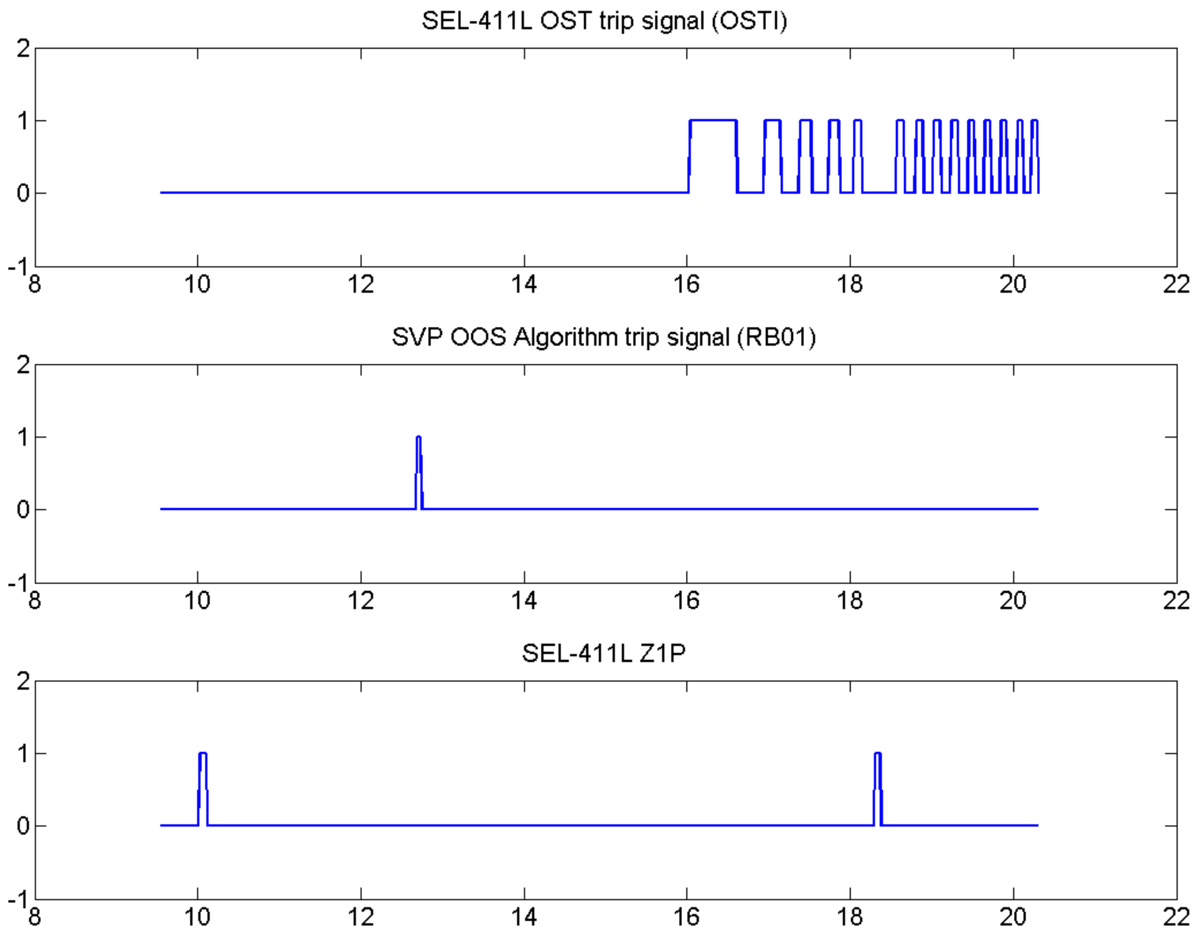


Figure 4.27 The OOS trip signals: 411L (top), SVP (middle) and Z1P trip in Case-13.

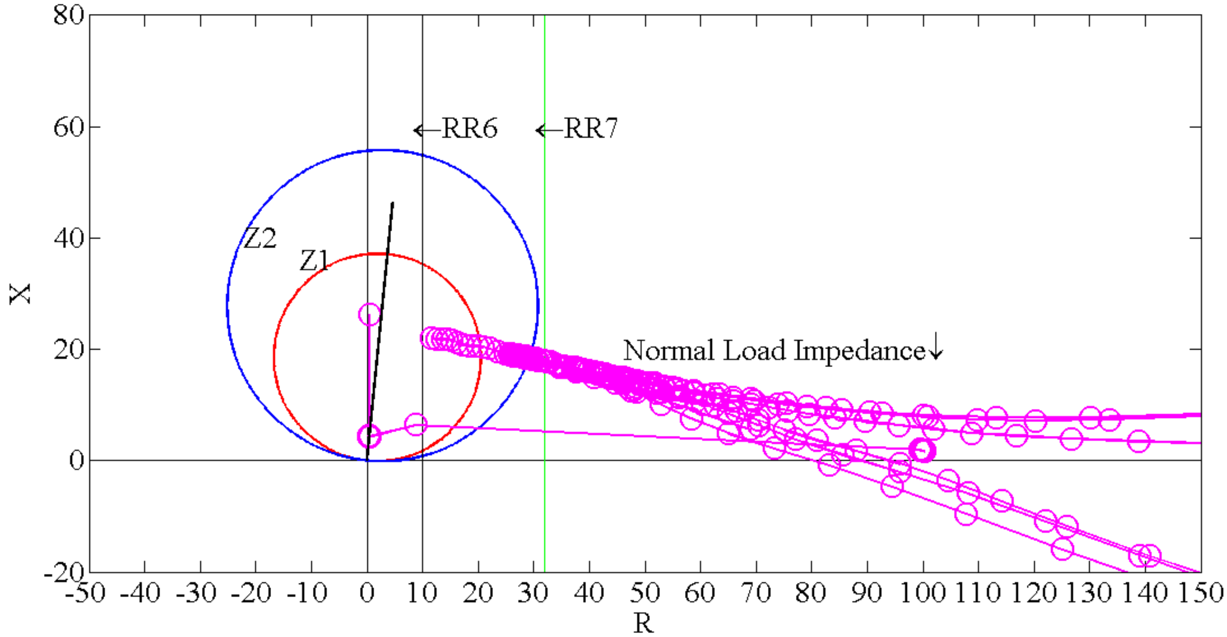


Figure 4.28 The impedance trajectory when the SVP tripped in Case-13.

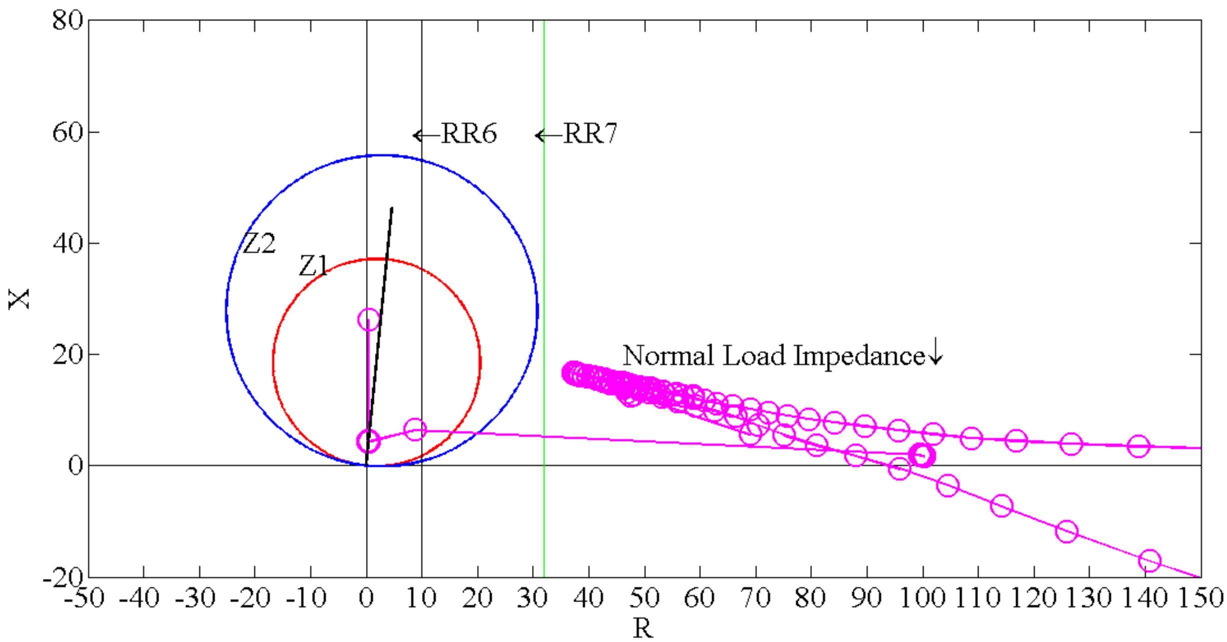


Figure 4.29 The impedance trajectory when the 411L tripped in Case-13.

4.2 Results Discussion

Out of thirteen simulated disturbances, five disturbances have caused stable power swings, and both OOS functions didn't trip, which indicates that the functions were set securely. The other eight disturbances have caused unstable power swings and trip decisions were received as expected from both IEDs. 411L Dual-Blinder function tripped faster than the SVPOOS function in five cases. The SVP tripped faster in three occasions. Table 4.1 shows the tripping time—in seconds—of each function in every case. Disturbances started ten seconds after the simulation began.

Table 4.1 Tripping time of each function in the simulated disturbances.

	Case- 3	Case-4	Case- 5	Case- 6	Case- 8	Case- 9	Case-10	Case- 13
411L	12.348	16.038	11.034	10.872	11.268	10.908	10.908	16.038
SVP	13.122	15.840	10.944	10.926	11.502	10.980	11.088	12.690

There were two cases (Case-4 and Case-13) where the effect of utilizing the first and the second derivatives of the voltage phase angle difference had led to an early prediction of the OOS situations. In these cases, the system was suffering from damping problems, which resulted in a growing angular separation and eventually an OOS condition. The trajectory of the slip versus acceleration started near the origin and grew in the way out of the stable region. Figure 4.32 and Figure 4.33 show the two cases of the undamped power swing, the figures also depict the tripping moment in each case.

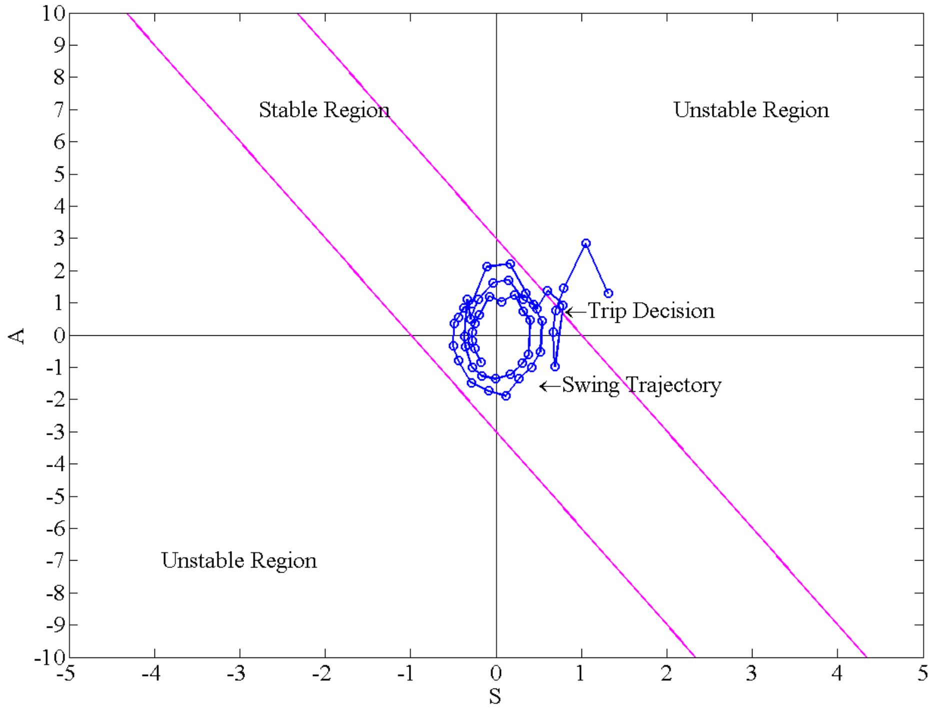


Figure 4.30 Slip versus acceleration for Case-4.

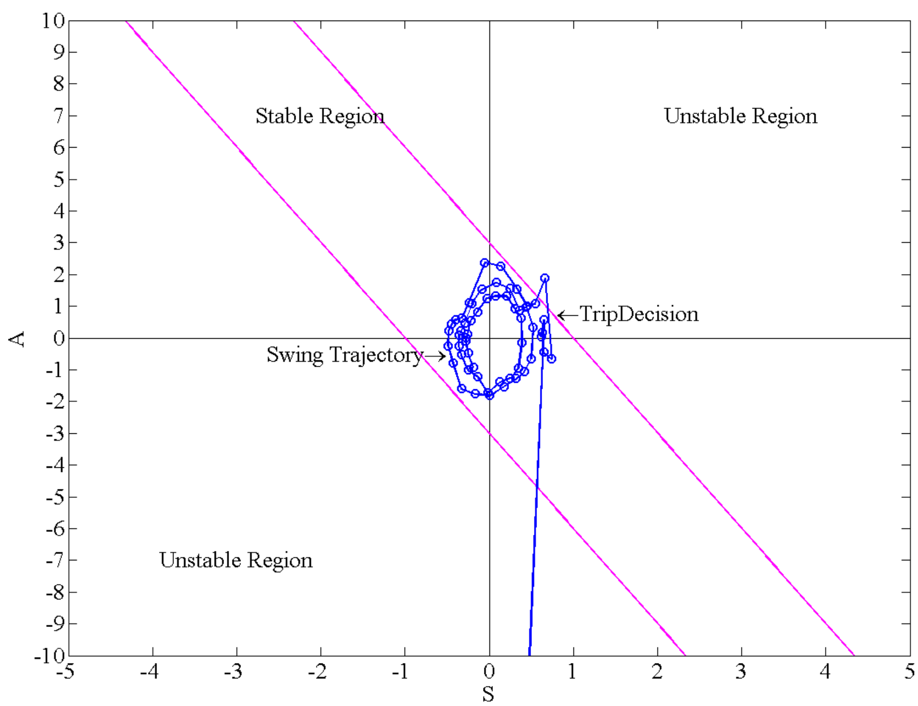


Figure 4.31 Slip versus acceleration for Case-13.

In the cases where the 411L Dual-Blinder OOS function tripped faster than the SVP Phasor-Based OOS function, more investigation, using the SVP recording arrays, shows that the SVP function tripped as soon as the trip signal became unblocked. Figure 4.34 and Figure 3.35 show the slip versus acceleration plots for Case-6 and Case-9 respectively. The algorithm is not allowed to trip during disturbances (switching, reclosing, and faults) due to the spontaneous spikes in the slip and acceleration (discussed in section 3.2.4.2). Figure 4.36 and Figure 4.37show how the SVP tripped in Case-6 and Case-9 just after the blocking signal became true (the blocking signal goes into an AND gate with the trip signal). Below is a description of the SVP variables that are shown in Figure 4.36 and Figure 4.37:

FRFNTRIP is the algorithm trip decision

FRBLK is the spikes blocking

FRUPTRIP trajectory is on the upper unstable region

FRLOWTRIP trajectory is on the lower unstable region.

If the time delay (0.75 seconds) was set shorter, the SVP would have tripped faster; however, this delay was chosen to account for the slowest clearing time of 15 cycles, which was chosen to simulate a time delayed trip by a Z2 element. The 0.75 seconds delay accounts also for the assumed reclosing dead time of twenty five cycles.

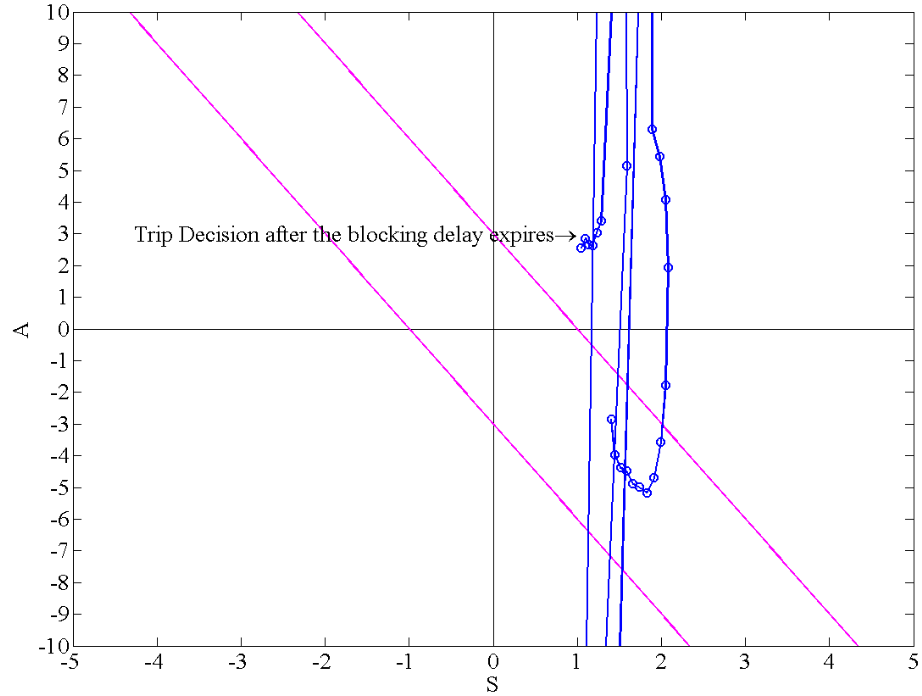


Figure 4.32 Slip versus acceleration for Case-6.

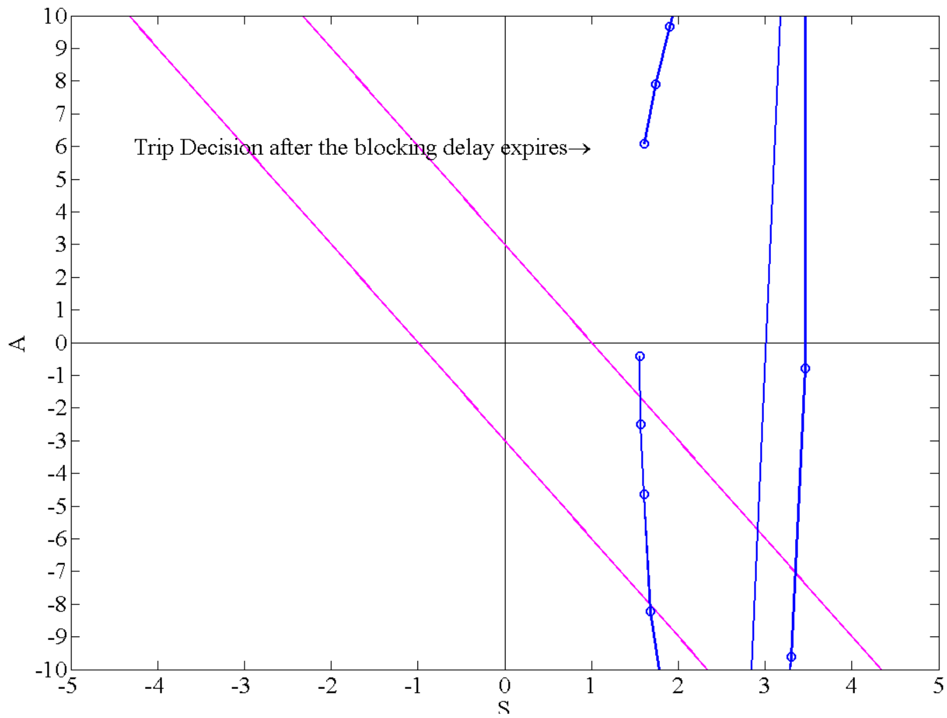


Figure 4.33 Slip versus acceleration for Case-9.

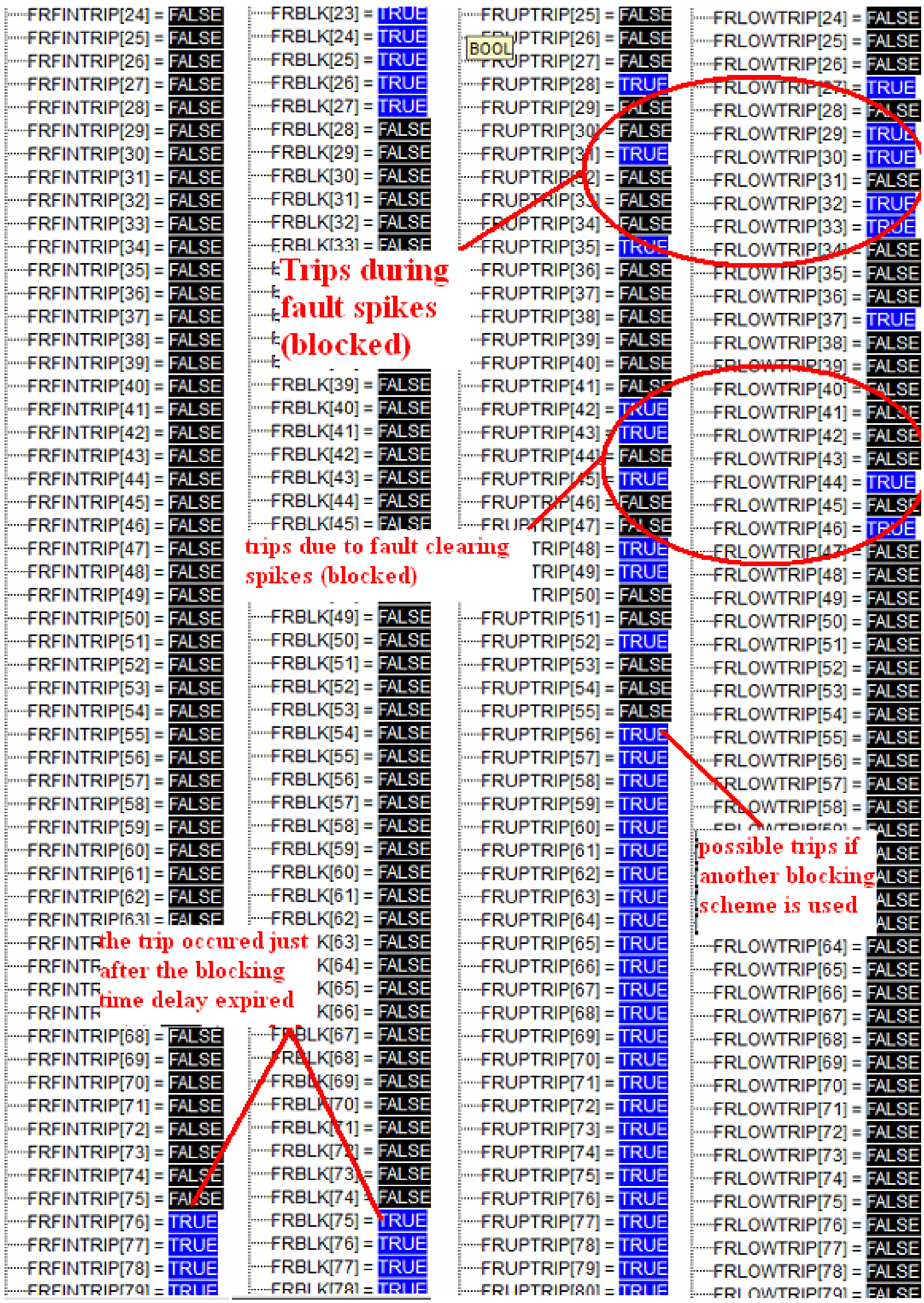


Figure 4.34 SVP variables in Case-6

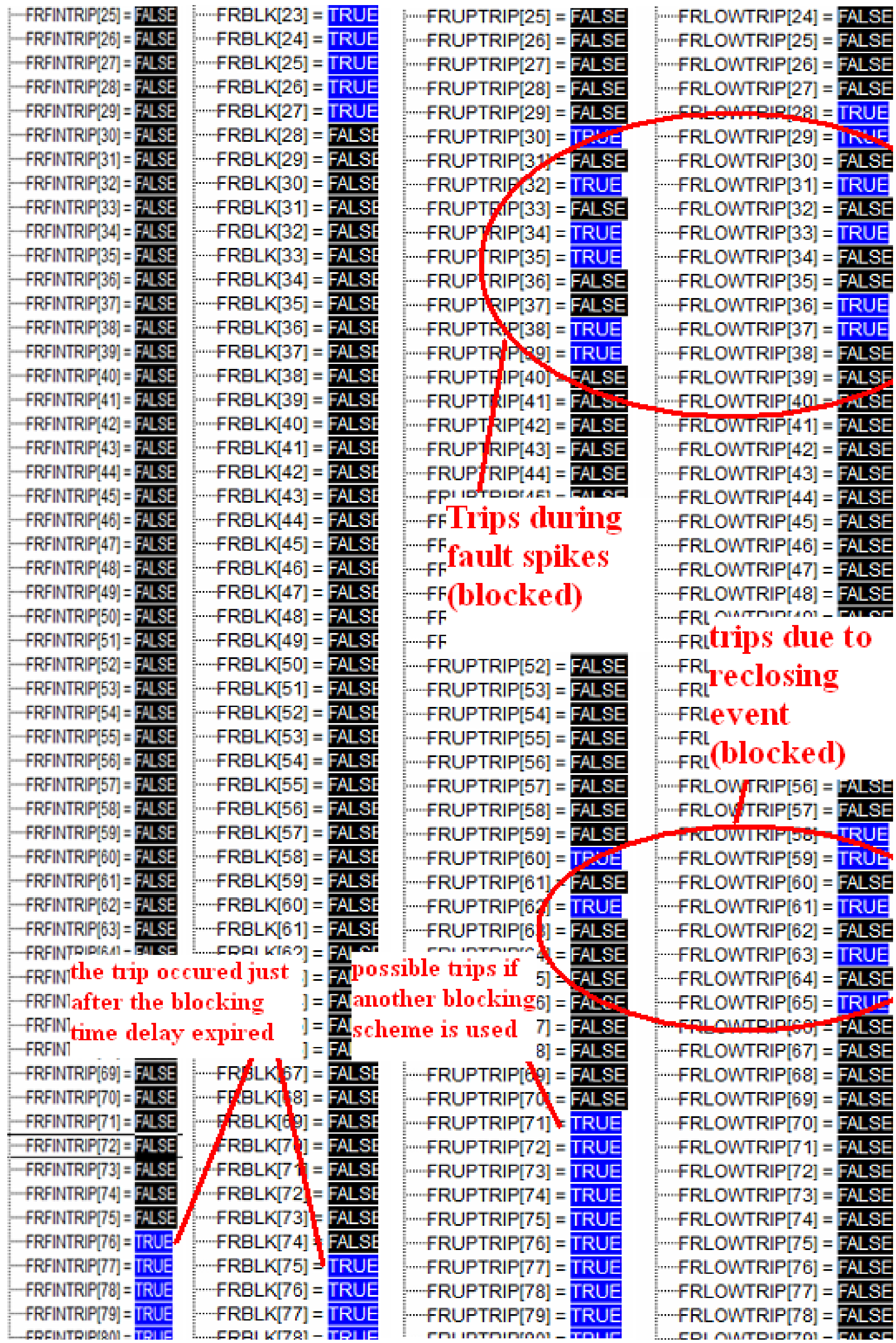


Figure 4.35 SVP variables in Case- 9.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Conclusions

The objective of this study was to compare the performance between the widely used Dual-Blinder OOS function and the Phasor-Based OOS function, which utilizes the phasor measurements from the tieline terminals. It could be concluded from the results presented in the previous chapter that each function has its advantages and disadvantages. The Dual-Blinder is a reliable and secure method, and it doesn't trip unless the impedance locus crosses the RR6 blinder. The Dual-Blinder OOS function uses the local measurements and it doesn't affect by any communication failure. However, this method, and by not considering the speed or the acceleration of the angular difference, it doesn't address the nature or the behavior of the power swing. Thus, it cannot be used for purposes other than tripping for an OOS condition (e.g. diagnosis). On the Other side, phasor measurements become a powerful tool to visualize the power systems and also to diagnose power system problems. Using phasor measurements in real-time applications brings up challenges like GPS signal reliability and phasor data alignment. The synchronization between all the devices should always be maintained. However, implementing a critical function such as the OOS has its unique challenges too. Security of this function is of a great concern since the separation should only be made if an OOS condition is about to happen. Otherwise the separation could jeopardize the whole power system and may lead to more catastrophic consequences.

Implementing the SVP Phasor-Based OOS function can be a useful tool to detect damping problems. Also with the appropriate settings, the function can perform faster and could be used as a backup for the Dual-Blinder function implemented in the relays.

5.2 Recommendations for Future Work

The Phasor-Based OOS function is prone to misoperate during disturbance. Disturbances cause spikes in the slip and acceleration as discussed earlier. Avoiding misoperation is one of the challenges that should be tackled before implementing this function. In this study a time delay blocking has been used to perform this task, and any rise in the acceleration value (>10 Hz/s) is considered a disturbance situation, and the algorithm starts the 0.75 second blocking period, which allows the protection functions in the protective relays to clear the fault and attempt reclosing . Other ideas could be implemented such as sending a blocking signal from the relays to the SVP when any relay detects a disturbance; relays have better access to the status of the power system (e.g. breakers positions, CTs and VTs) and can inform the SVP if there is a fault or a switching event to block the OOS algorithm accordingly.

The SVP execution cycle could be set only in millisecond units, and the program developed in this research has been set to a 17ms execution cycle. Phasor data were sent every 16.6667 milliseconds, 60 messages/second, which is the maximum rate available in the PMUs used, and the difference between the execution cycle and message rate results in the loss of one phasor message every 51 messages. In the Matlab model of the same OOS algorithm, both the message rate and execution cycles are 16.65 milliseconds, and the Matlab model results have shown how this difference can change the trip decision, especially when it comes to the calculation of the first and the second derivatives. Allowing the compatibility between the message rate and the execution cycle by the hardware manufacturers will result in a better functionality.

The conclusions and the results obtained from the performance comparison carried out in this research are not final, and other comparisons may show different results. However, for undamped swings, the SVP Phasor-Based OOS function would still trip faster. Parameters such as the system impedance, the transferred power, and the disturbance type will affect the performance of each method. Future work on other test-beds, preferably with bigger systems, systems, is recommended.

REFERENCES

[1] Power System Relaying Comittee, "WG D6 power swing and out-of-step considerations on transmission lines," 2005.

[2] J. L. Blackburn and T. J. Domin, *Protective relaying principles and applications*. CRC press, 2006.

[3] E. O. Scheitzer, A. Guzman, H. J. Altuve, D. A. Tziiouvaras, and J. Needs, "Real-time synchrophasor application in power system control and protection," in *Development in Power Systems Protection (DPSP 2010). Managing the Change, 10th EIT International Conference on, IET.*, 2010, pp. 1-5.

[4] E. O. Scheitzer, D. E. Whitehead, A. Guzman, Y. Gong, and M. Donolo, "Advanced real-time synchrophasor application," in *35th Annual Western Protective Relay Conference*, Spokane, WA, 2008.

[5] D. Hou, S. Chen, and S. Turner, "SEL-321-5 relay out of step logic," SchweitzerEngineering Laboratories, Inc Application Guide AG97-13, 23, 1997.

[6] N. Fischer, et al., "Tutorial on power swing and out of step tripping," Schwietzer Engineering Laboratories, Inc. Technical Paper 201220911, 2012.

[7] G. Benmouyal, D. Hou, and D. Tziouvaras, "Zero-setting power swing blocking protection," in *31th Annual Werstern Protective Relay Conference*, Spokane, WA, 2004.

[8] R. Franco, C. Sena, G. Taranto, and A. Giusto, "Using synchrophasors for controlled islanding-A prospective application for the Urguayan power system," *IEEE transactions on Power Systems*, vol. 28, no. 2, pp. 2016-2024, 2013.

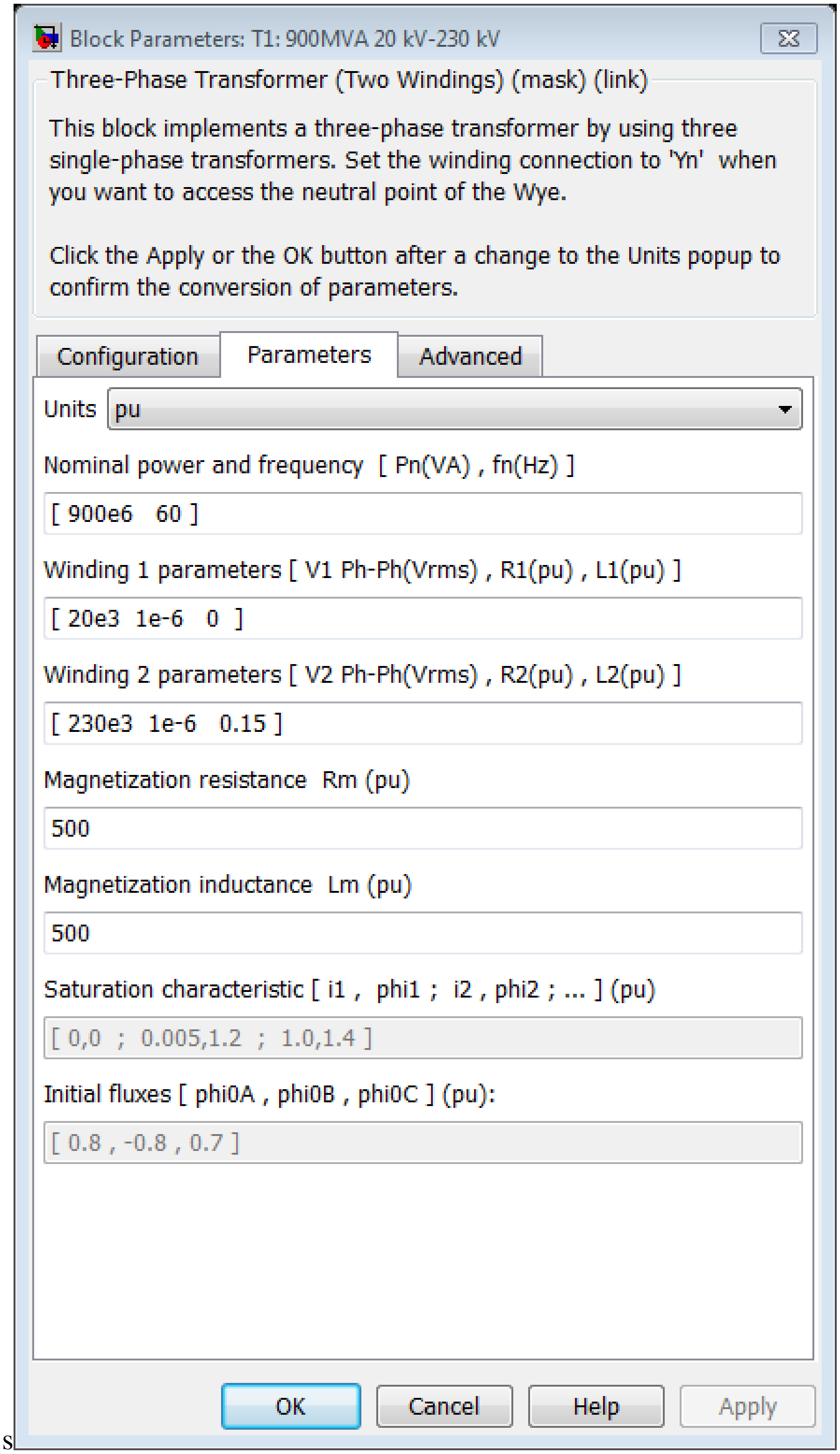
[9] P. Kundur, *Power system control and stability*. McGraw-hill, 1994.

.

APPENDIX A

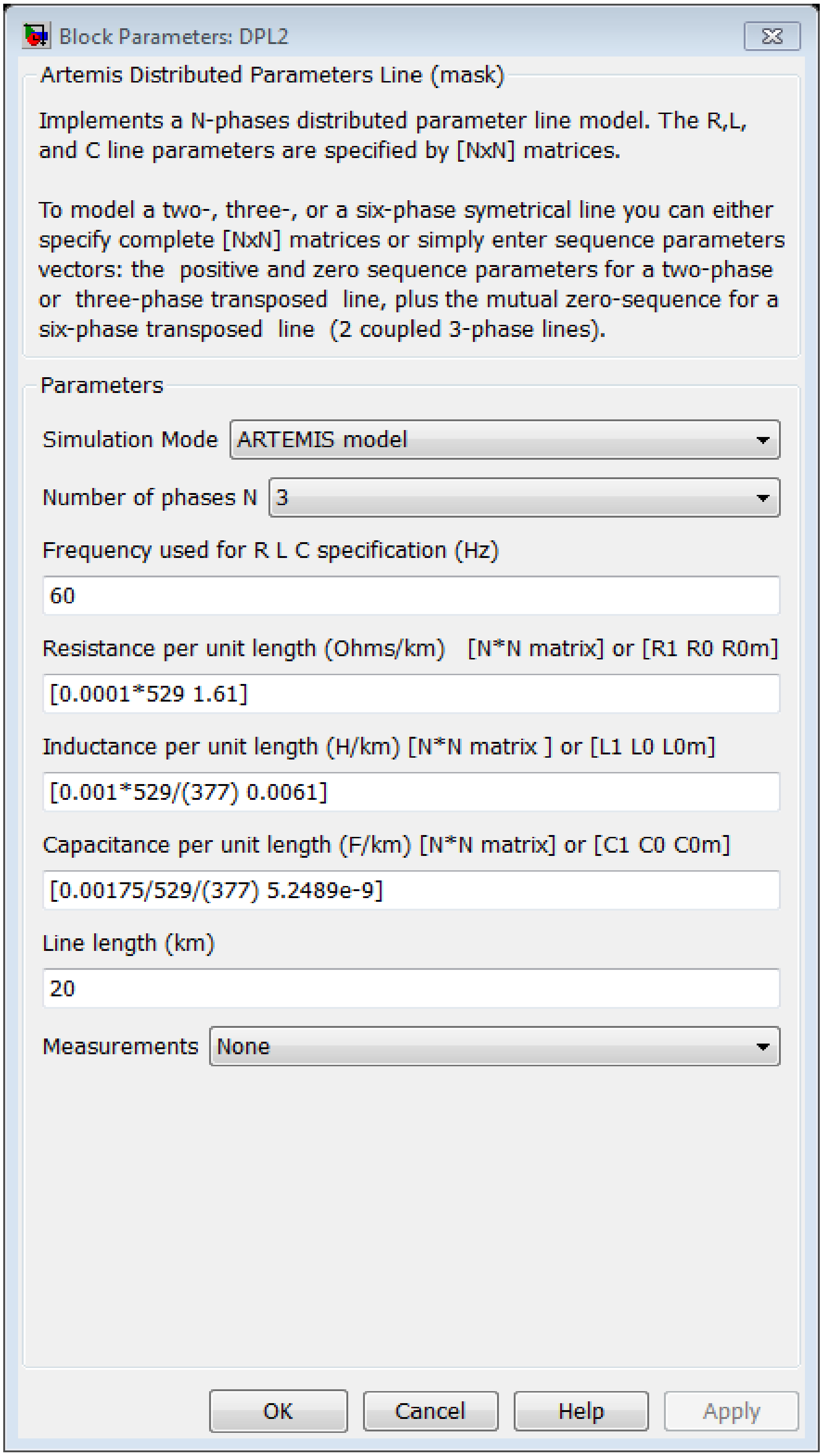
SYSTEM DATA

Transformer parameters (for all transformers)

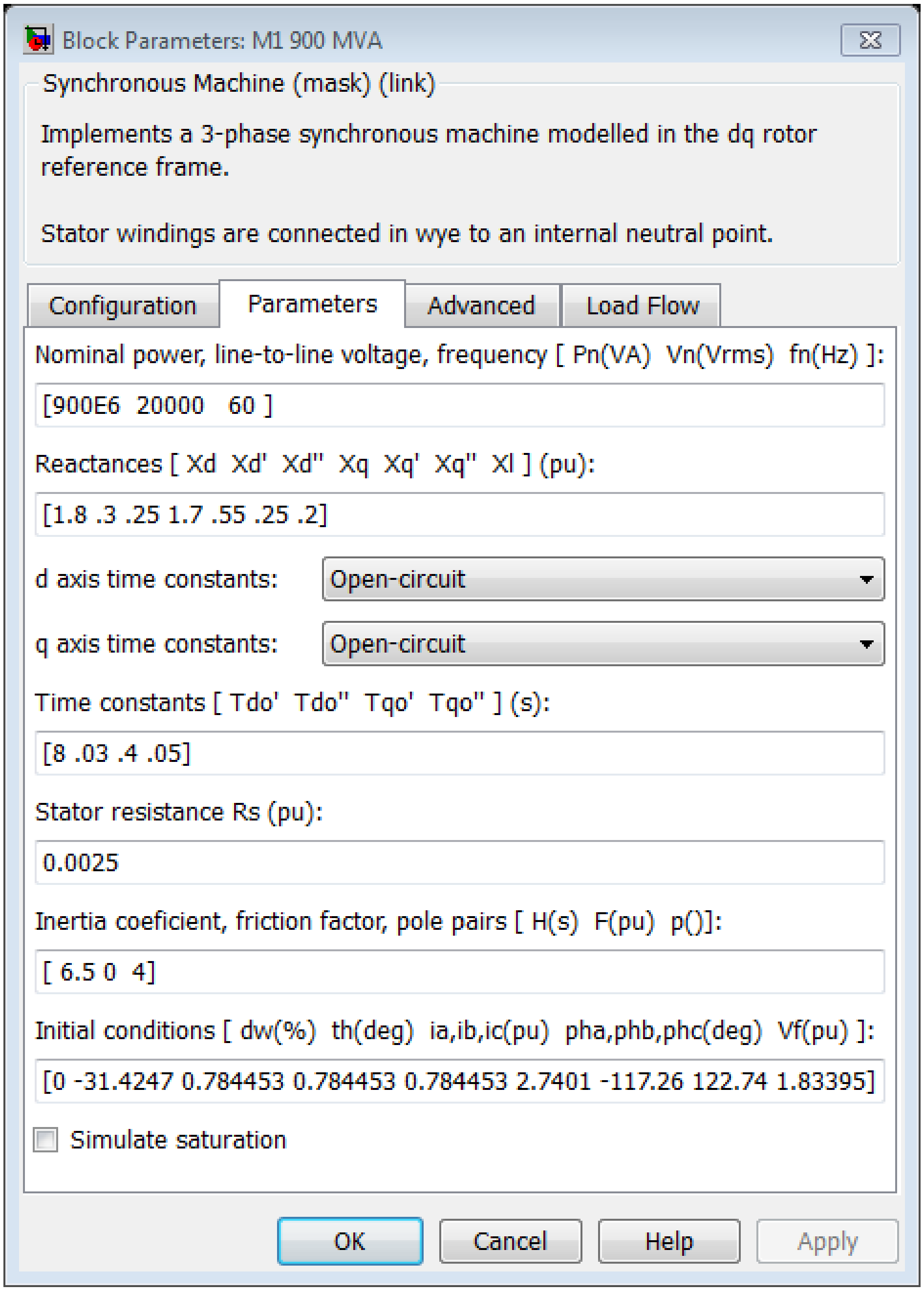


s

Transmission line impedance (all lines have the same Z/km value)

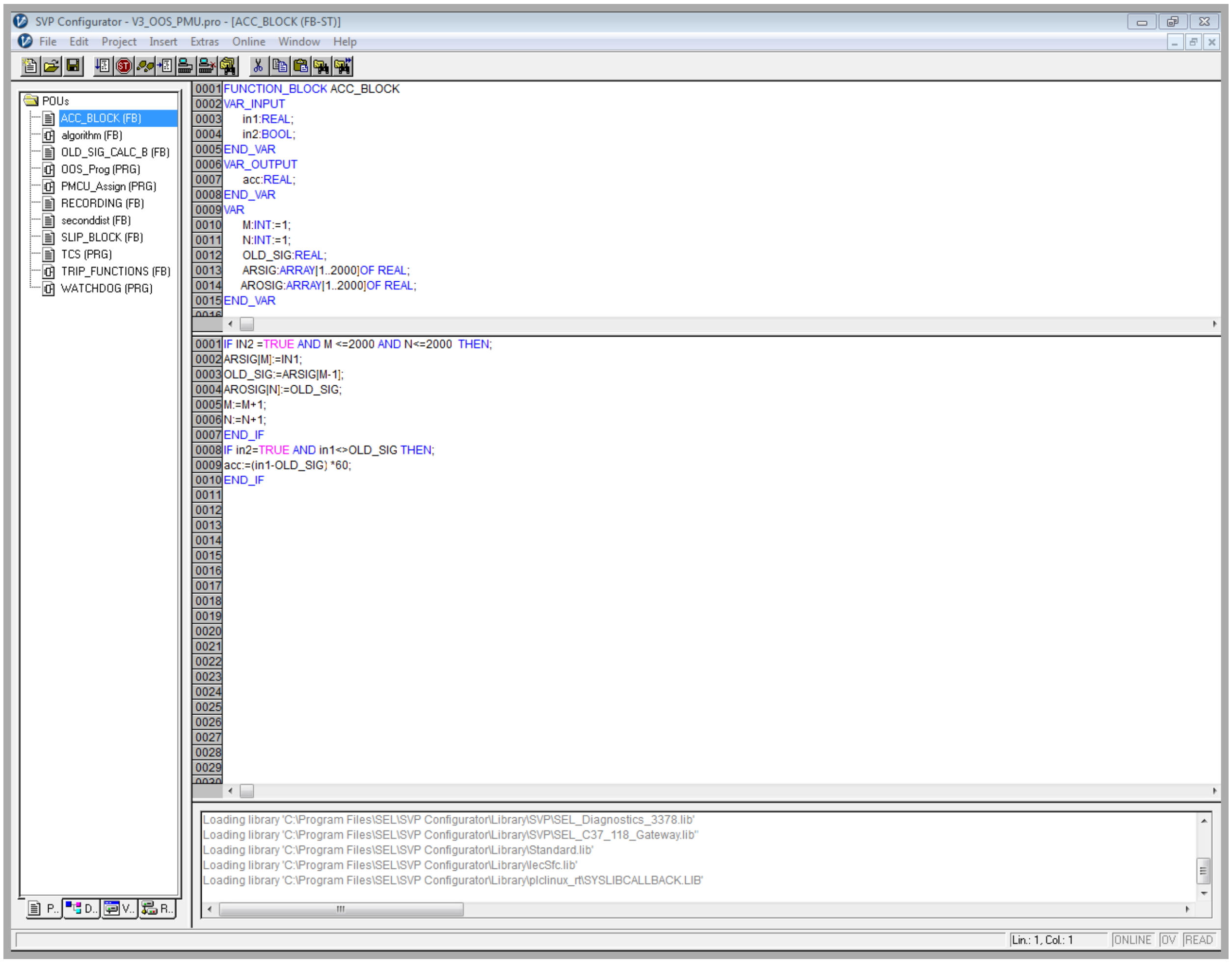


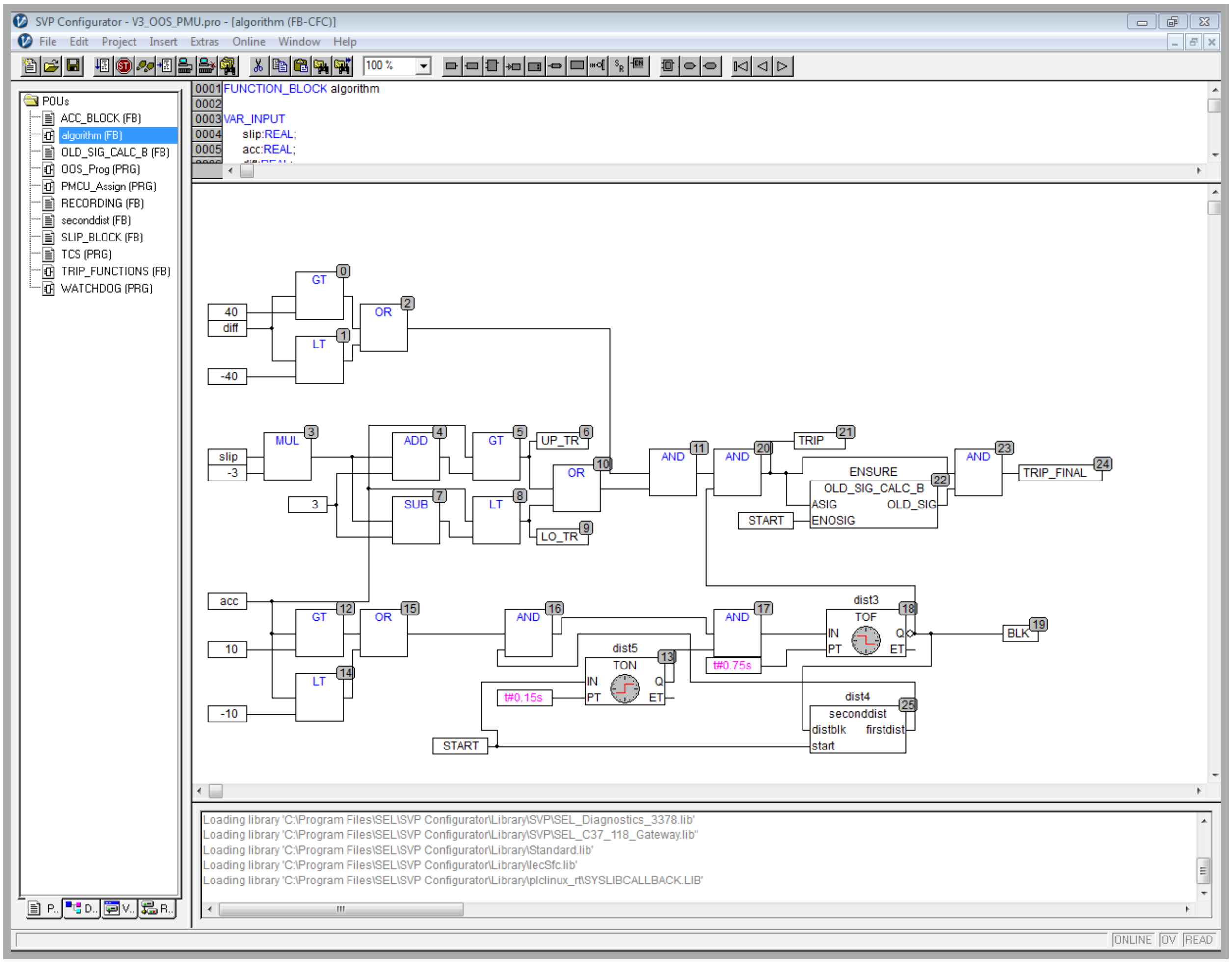
Machine data, only one machine is shown since all the machines are identical except for inertia (H) constant; H is 6.5 for GN1, GN2 and 6.175 for GN3, GN4.

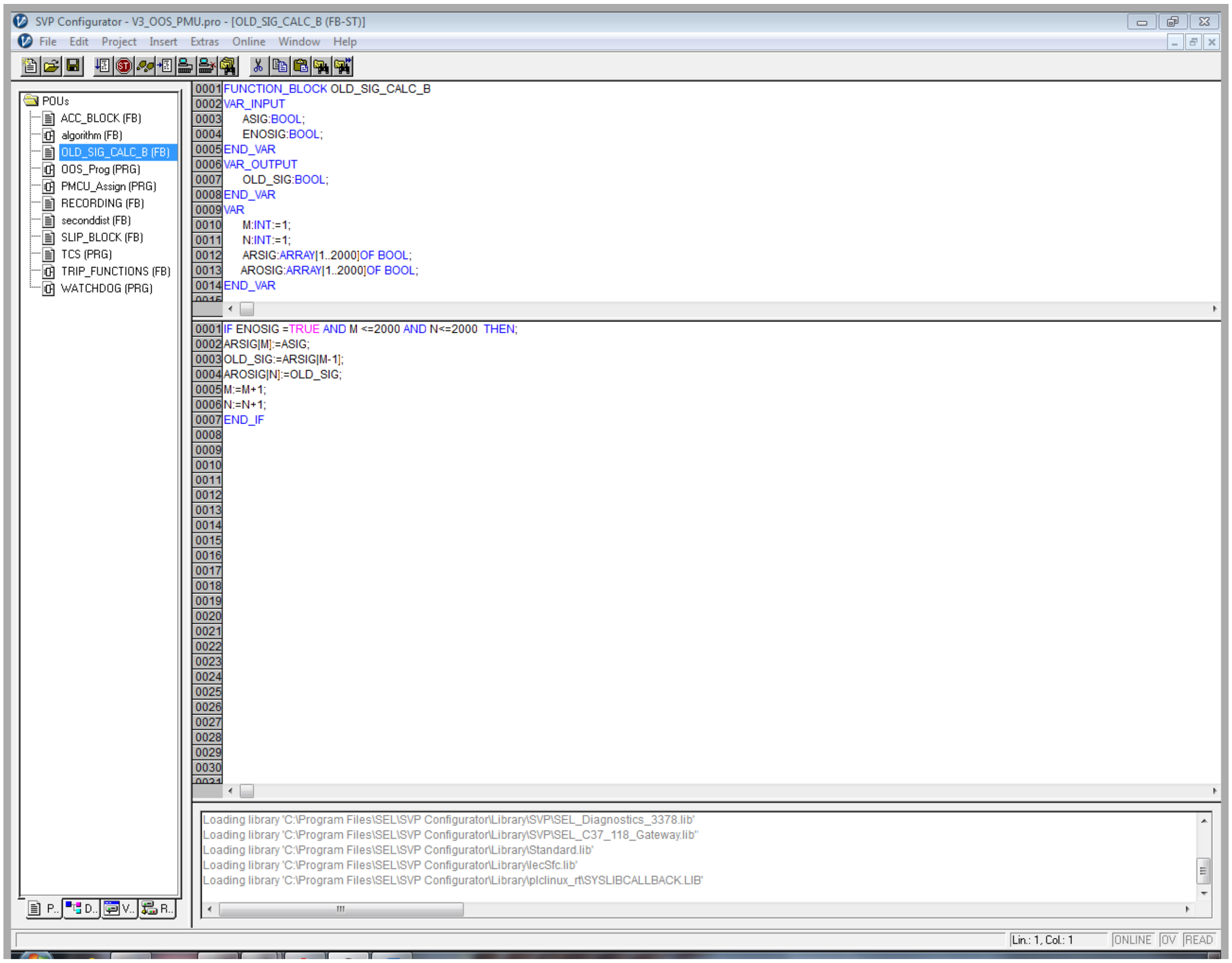


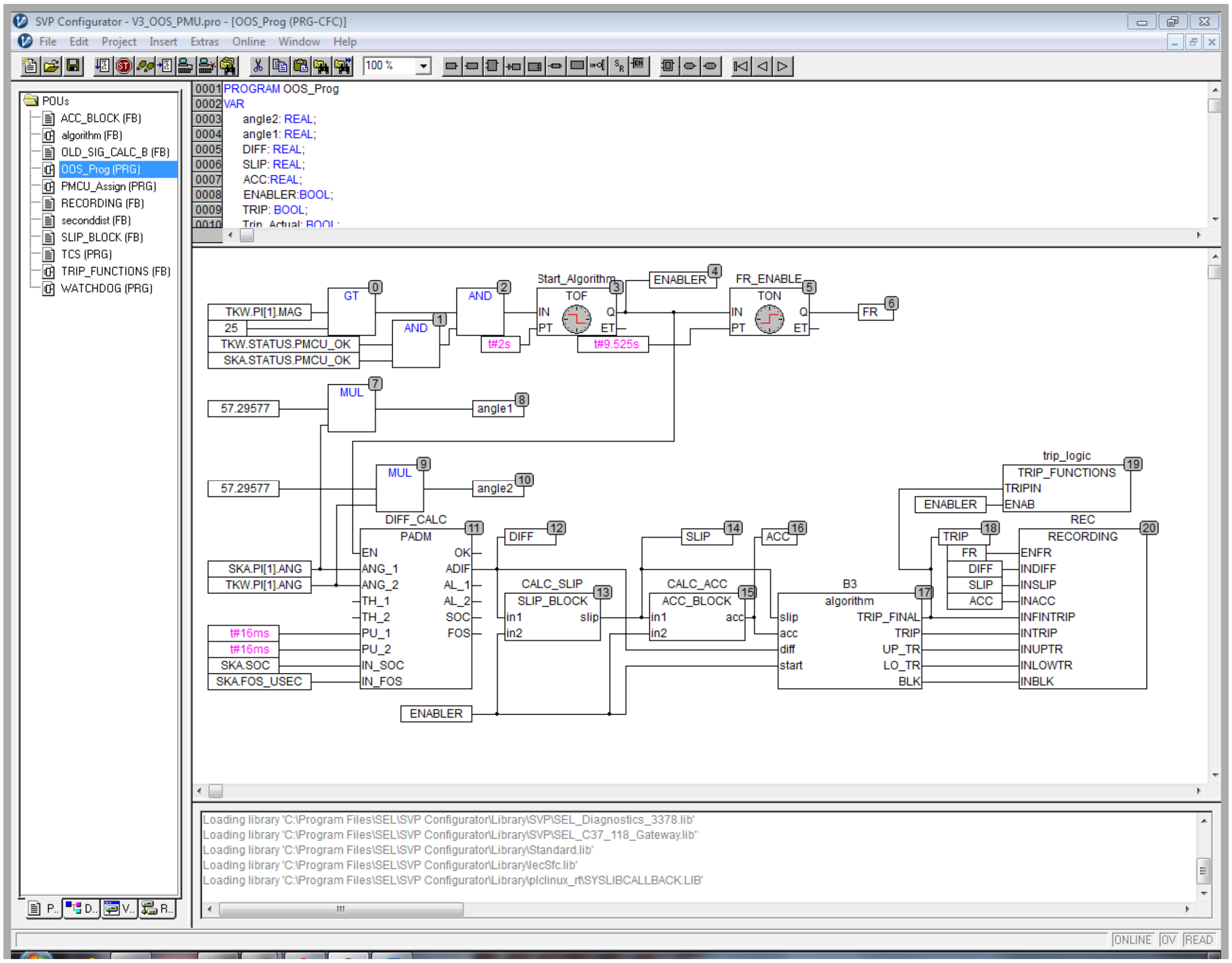
APPENDIX B

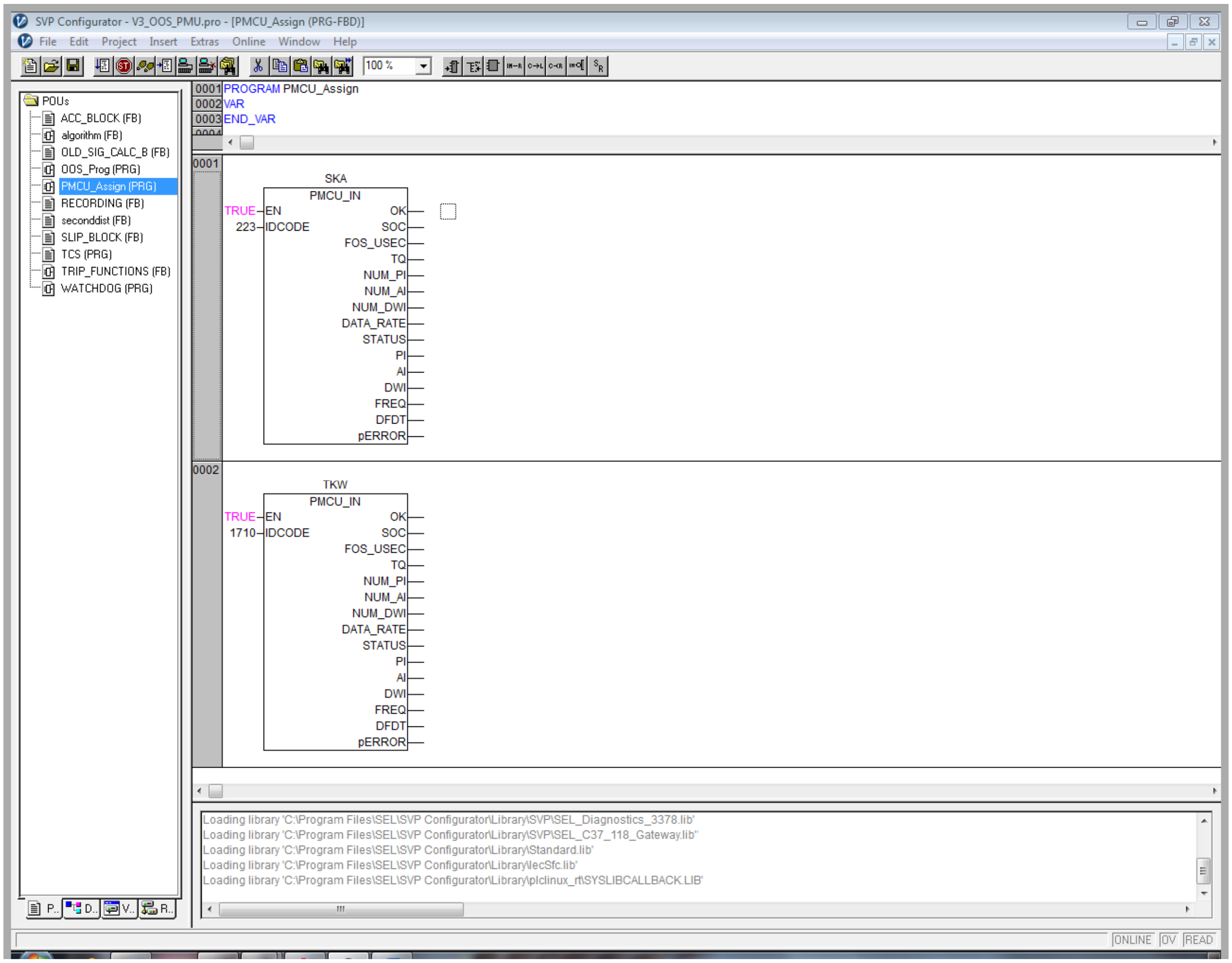
SVP OOS PROGRAM (V3_OOS_PMU) CODE

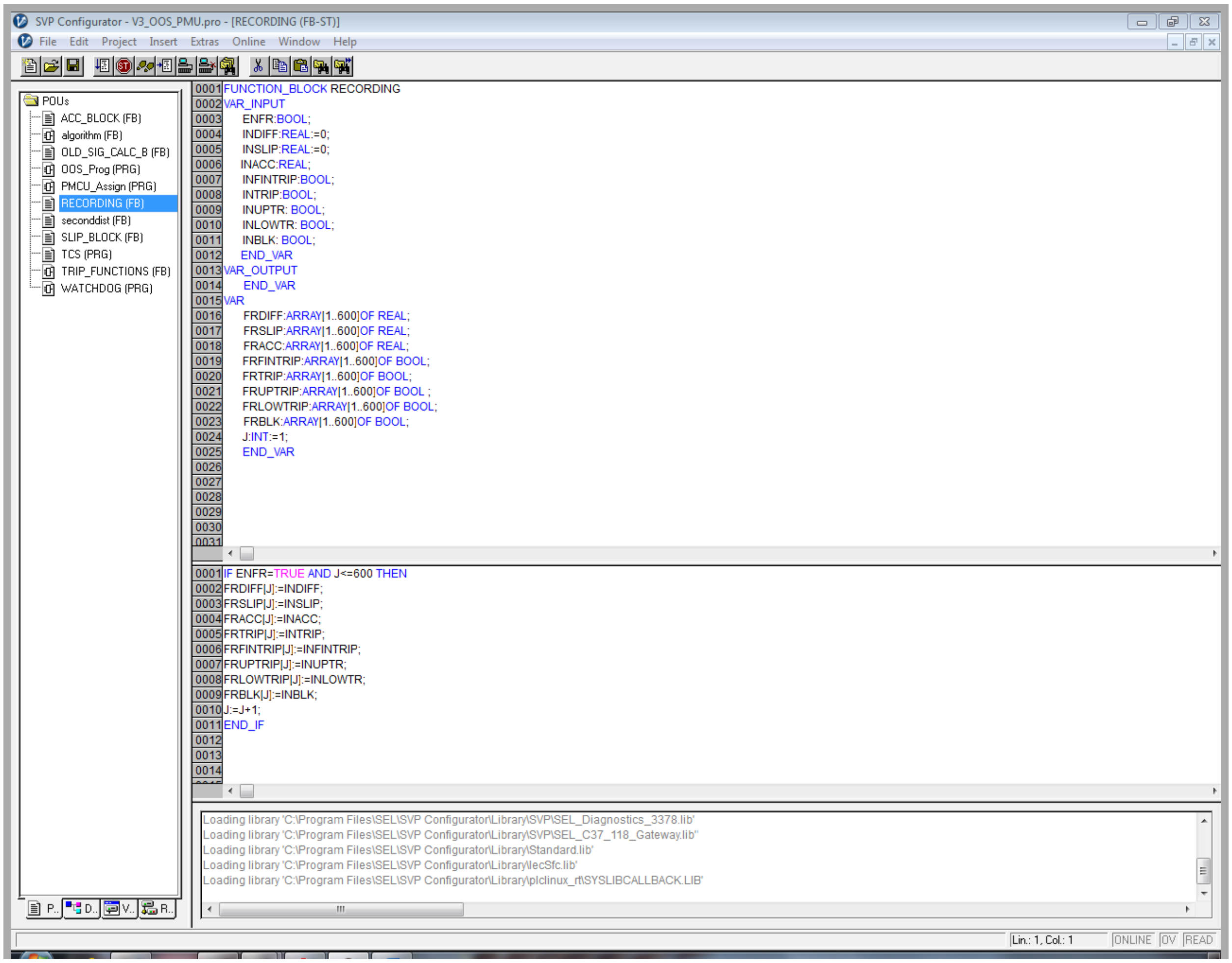

SVP Configurator - V3_OOS_PMU.pro - [ACC_BLOCK (FB-ST)]
File Edit Project Insert Extras Online Window Help
POUs
ACC_BLOCK (FB)
algorithm (FB)
OLD_SIG_CALC_B (FB)
OOS_Prog (PRG)
PMCU_Assign (PRG)
RECORDING (FB)
seconddist (FB)
SLIP_BLOCK (FB)
TCS (PRG)
TRIP_FUNCTIONS (FB)
WATCHDOG (PRG)
FUNCTION_BLOCK ACC_BLOCK
VAR_INPUT
in1:REAL;
in2:BOOL;
END_VAR
VAR_OUTPUT
acc:REAL;
END_VAR
VAR
M:INT:=1;
N:INT:=1;
OLD_SIG:REAL;
ARSIG:ARRAY[1..2000]OF REAL;
AROSIG:ARRAY[1..2000]OF REAL;
END_VAR
IF IN2 =TRUE AND M <=2000 AND N<=2000 THEN;
ARSIG[M]:=IN1;
OLD_SIG:=ARSIG[M-1];
AROSIG[N]:=OLD_SIG;
M:=M+1;
N:=N+1;
END_IF
IF in2=TRUE AND in1<>OLD_SIG THEN;
acc:=(in1-OLD_SIG) *60;
END_IF
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_Diagnostics_3378.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_C37_118_Gateway.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\Standard.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\IecSfc.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\plclinux_rt\SYSLIBCALLBACK.LIB'
Lin.: 1, Col.: 1
ONLINE
OV
READ

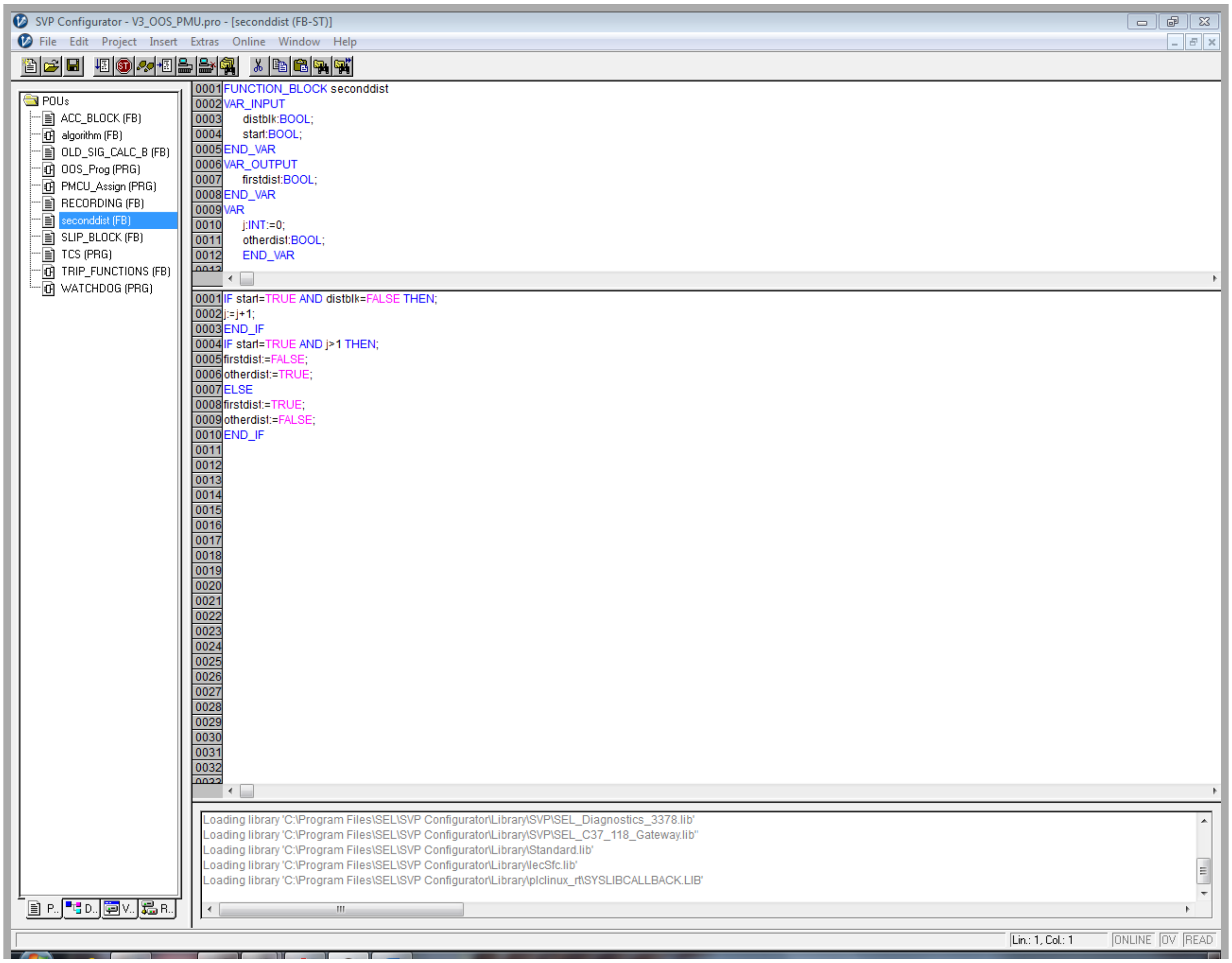

SVP Configurator - V3_OOS_PMU.pro - [algorithm (FB-CFC)]
File Edit Project Insert Extras Online Window Help
POUs
ACC_BLOCK (FB)
algorithm (FB)
OLD_SIG_CALC_B (FB)
OOS_Prog (PRG)
PMCU_Assign (PRG)
RECORDING (FB)
seconddist (FB)
SLIP_BLOCK (FB)
TCS (PRG)
TRIP_FUNCTIONS (FB)
WATCHDOG (PRG)
0001 FUNCTION_BLOCK algorithm
0002
0003 VAR_INPUT
0004 slip:REAL;
0005 acc:REAL;
GT
LT
OR
MUL
ADD
SUB
AND
TRIP
ENSURE
OLD_SIG_CALC_B
ASIG
OLD_SIG
ENOSIG
START
TRIP_FINAL
UP_TR
LO_TR
slip
acc
diff
dist3
TOF
dist5
TON
t#0.75s
t#0.15s
BLK
dist4
seconddist
distblk
firstdist
start
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_Diagnostics_3378.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_C37_118_Gateway.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\Standard.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\IecSfc.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\plclinux_rt\SYSLIBCALLBACK.LIB'
ONLINE OV READ

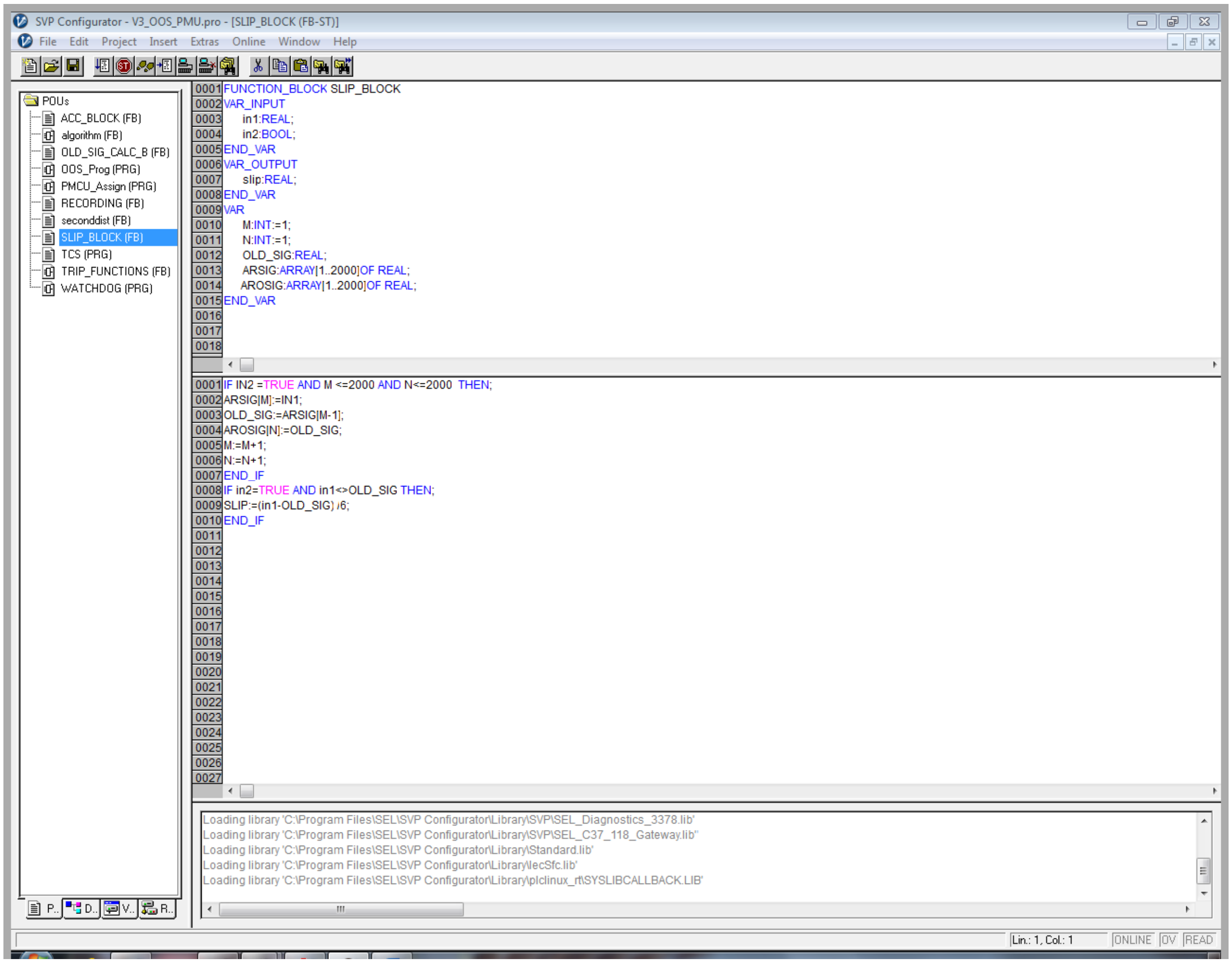

SVP Configurator - V3_OOS_PMU.pro - [OLD_SIG_CALC_B (FB-ST)]
File Edit Project Insert Extras Online Window Help
POUs
ACC_BLOCK (FB)
algorithm (FB)
OLD_SIG_CALC_B (FB)
OOS_Prog (PRG)
PMCU_Assign (PRG)
RECORDING (FB)
seconddist (FB)
SLIP_BLOCK (FB)
TCS (PRG)
TRIP_FUNCTIONS (FB)
WATCHDOG (PRG)
FUNCTION_BLOCK OLD_SIG_CALC_B
VAR_INPUT
ASIG:BOOL;
ENOSIG:BOOL;
END_VAR
VAR_OUTPUT
OLD_SIG:BOOL;
END_VAR
VAR
M:INT:=1;
N:INT:=1;
ARSIG:ARRAY[1..2000]OF BOOL;
AROSIG:ARRAY[1..2000]OF BOOL;
END_VAR
IF ENOSIG =TRUE AND M <=2000 AND N<=2000 THEN;
ARSIG[M]:=ASIG;
OLD_SIG:=ARSIG[M-1];
AROSIG[N]:=OLD_SIG;
M:=M+1;
N:=N+1;
END_IF
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_Diagnostics_3378.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_C37_118_Gateway.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\Standard.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\IecSfc.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\plclinux_rt\SYSLIBCALLBACK.LIB'
Lin.: 1, Col.: 1
ONLINE
OV
READ

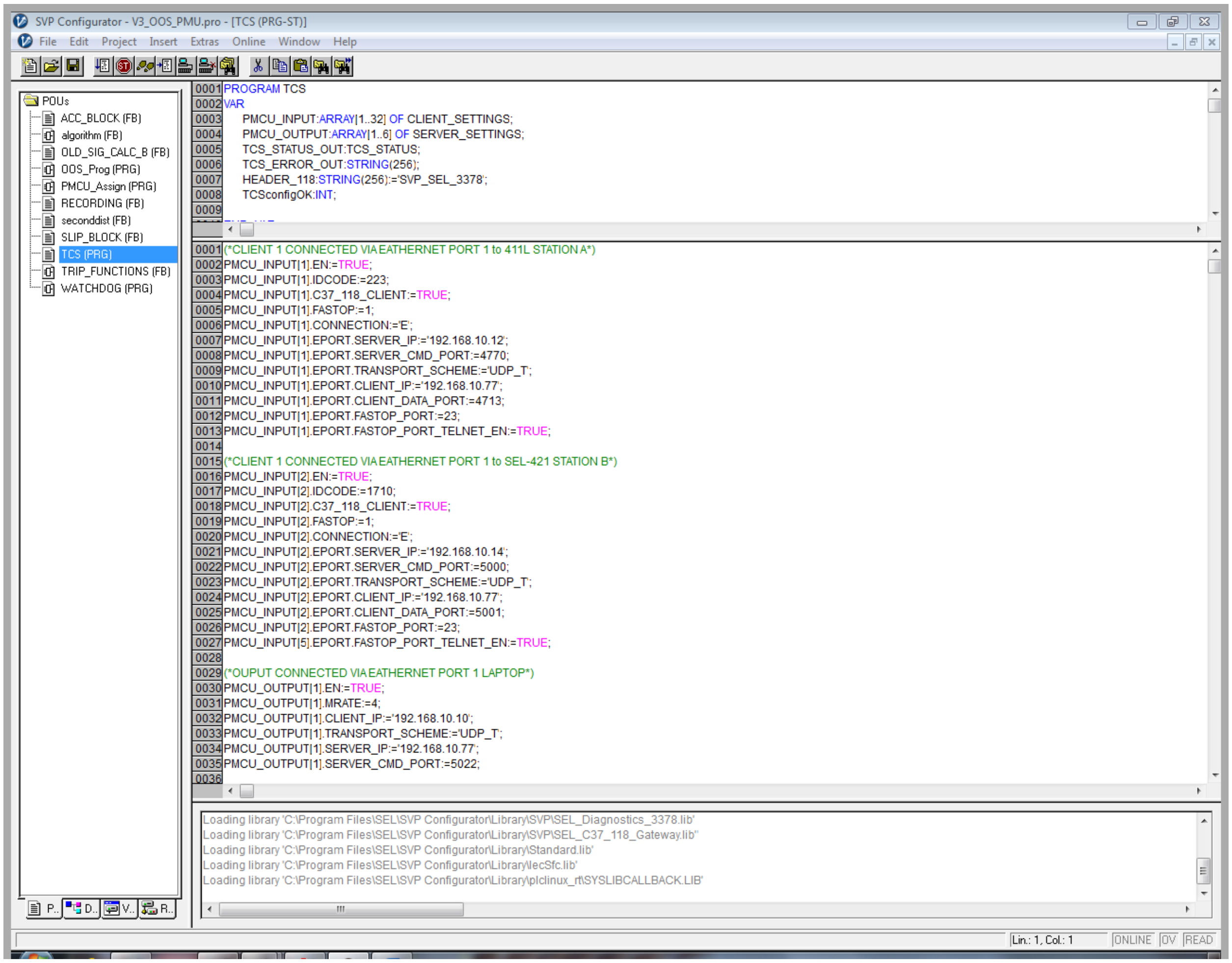

SVP Configurator - V3_OOS_PMU.pro - [OOS_Prog (PRG-CFC)]
PROGRAM OOS_Prog
VAR
angle2: REAL;
angle1: REAL;
DIFF: REAL;
SLIP: REAL;
ACC:REAL;
ENABLER:BOOL;
TRIP: BOOL;
POUs
ACC_BLOCK (FB)
algorithm (FB)
OLD_SIG_CALC_B (FB)
OOS_Prog (PRG)
PMCU_Assign (PRG)
RECORDING (FB)
seconddist (FB)
SLIP_BLOCK (FB)
TCS (PRG)
TRIP_FUNCTIONS (FB)
WATCHDOG (PRG)
TKW.PI[1].MAG
25
TKW.STATUS.PMCU_OK
SKA.STATUS.PMCU_OK
GT
AND
Start_Algorithm
TOF
t#2s
t#9.525s
ENABLER
FR_ENABLE
TON
FR
57.29577
MUL
angle1
angle2
DIFF_CALC
PADM
SKA.PI[1].ANG
TKW.PI[1].ANG
t#16ms
SKA.SOC
SKA.FOS_USEC
CALC_SLIP
SLIP_BLOCK
CALC_ACC
ACC_BLOCK
SLIP
ACC
B3
algorithm
trip_logic
TRIP_FUNCTIONS
REC
RECORDING
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_Diagnostics_3378.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_C37_118_Gateway.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\Standard.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\IecSfc.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\plclinux_rt\SYSLIBCALLBACK.LIB'

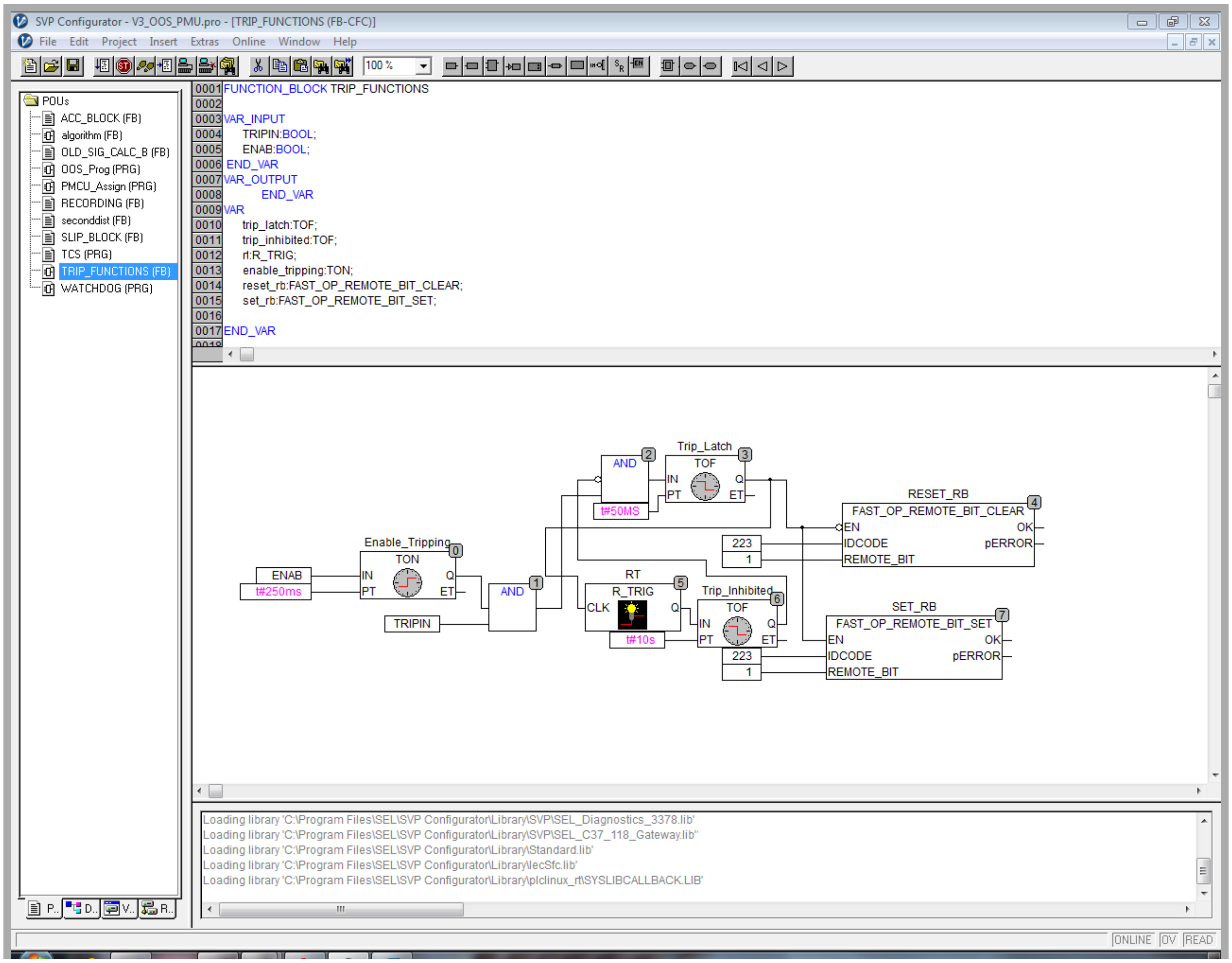

SVP Configurator - V3_OOS_PMU.pro - [PMCU_Assign (PRG-FBD)]
File Edit Project Insert Extras Online Window Help
POUs
ACC_BLOCK (FB)
algorithm (FB)
OLD_SIG_CALC_B (FB)
OOS_Prog (PRG)
PMCU_Assign (PRG)
RECORDING (FB)
seconddist (FB)
SLIP_BLOCK (FB)
TCS (PRG)
TRIP_FUNCTIONS (FB)
WATCHDOG (PRG)
0001 PROGRAM PMCU_Assign
0002 VAR
0003 END_VAR
SKA
PMCU_IN
TRUE EN
223 IDCODE
OK SOC FOS_USEC TQ NUM_PI NUM_AI NUM_DWI DATA_RATE STATUS PI AI DWI FREQ DFDT pERROR
TKW
PMCU_IN
TRUE EN
1710 IDCODE
OK SOC FOS_USEC TQ NUM_PI NUM_AI NUM_DWI DATA_RATE STATUS PI AI DWI FREQ DFDT pERROR
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_Diagnostics_3378.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_C37_118_Gateway.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\Standard.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\IecSfc.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\plclinux_rt\SYSLIBCALLBACK.LIB'
ONLINE OV READ

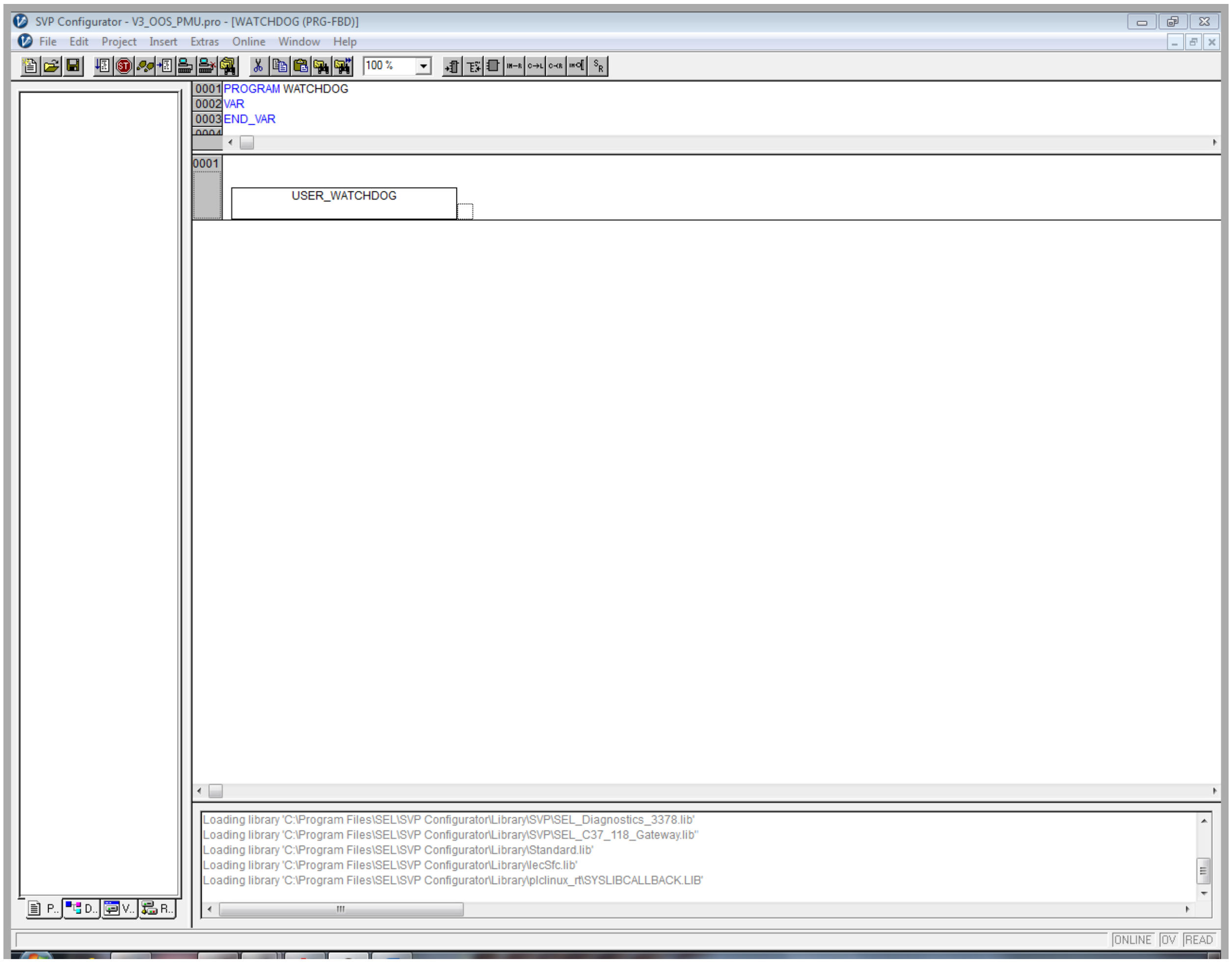

SVP Configurator - V3_OOS_PMU.pro - [RECORDING (FB-ST)]
File Edit Project Insert Extras Online Window Help
POUs
ACC_BLOCK (FB)
algorithm (FB)
OLD_SIG_CALC_B (FB)
OOS_Prog (PRG)
PMCU_Assign (PRG)
RECORDING (FB)
seconddist (FB)
SLIP_BLOCK (FB)
TCS (PRG)
TRIP_FUNCTIONS (FB)
WATCHDOG (PRG)
FUNCTION_BLOCK RECORDING
VAR_INPUT
ENFR:BOOL;
INDIFF:REAL:=0;
INSLIP:REAL:=0;
INACC:REAL;
INFINTRIP:BOOL;
INTRIP:BOOL;
INUPTR: BOOL;
INLOWTR: BOOL;
INBLK: BOOL;
END_VAR
VAR_OUTPUT
END_VAR
VAR
FRDIFF:ARRAY[1..600]OF REAL;
FRSLIP:ARRAY[1..600]OF REAL;
FRACC:ARRAY[1..600]OF REAL;
FRFINTRIP:ARRAY[1..600]OF BOOL;
FRTRIP:ARRAY[1..600]OF BOOL;
FRUPTRIP:ARRAY[1..600]OF BOOL ;
FRLOWTRIP:ARRAY[1..600]OF BOOL;
FRBLK:ARRAY[1..600]OF BOOL;
J:INT:=1;
END_VAR
IF ENFR=TRUE AND J<=600 THEN
FRDIFF[J]:=INDIFF;
FRSLIP[J]:=INSLIP;
FRACC[J]:=INACC;
FRTRIP[J]:=INTRIP;
FRFINTRIP[J]:=INFINTRIP;
FRUPTRIP[J]:=INUPTR;
FRLOWTRIP[J]:=INLOWTR;
FRBLK[J]:=INBLK;
J:=J+1;
END_IF
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_Diagnostics_3378.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_C37_118_Gateway.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\Standard.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\IecSfc.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\plclinux_rt\SYSLIBCALLBACK.LIB'
Lin.: 1, Col.: 1
ONLINE OV READ




SVP Configurator - V3_OOS_PMU.pro - [SLIP_BLOCK (FB-ST)]
File Edit Project Insert Extras Online Window Help
POUs
ACC_BLOCK (FB)
algorithm (FB)
OLD_SIG_CALC_B (FB)
OOS_Prog (PRG)
PMCU_Assign (PRG)
RECORDING (FB)
seconddist (FB)
SLIP_BLOCK (FB)
TCS (PRG)
TRIP_FUNCTIONS (FB)
WATCHDOG (PRG)
FUNCTION_BLOCK SLIP_BLOCK
VAR_INPUT
in1:REAL;
in2:BOOL;
END_VAR
VAR_OUTPUT
slip:REAL;
END_VAR
VAR
M:INT:=1;
N:INT:=1;
OLD_SIG:REAL;
ARSIG:ARRAY[1..2000]OF REAL;
AROSIG:ARRAY[1..2000]OF REAL;
END_VAR
IF IN2 =TRUE AND M <=2000 AND N<=2000 THEN;
ARSIG[M]:=IN1;
OLD_SIG:=ARSIG[M-1];
AROSIG[N]:=OLD_SIG;
M:=M+1;
N:=N+1;
END_IF
IF in2=TRUE AND in1<>OLD_SIG THEN;
SLIP:=(in1-OLD_SIG) /6;
END_IF
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_Diagnostics_3378.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_C37_118_Gateway.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\Standard.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\IecSfc.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\plclinux_rt\SYSLIBCALLBACK.LIB'
Lin.: 1, Col.: 1
ONLINE
OV
READ


SVP Configurator - V3_OOS_PMU.pro - [TCS (PRG-ST)]
File Edit Project Insert Extras Online Window Help
POUs
ACC_BLOCK (FB)
algorithm (FB)
OLD_SIG_CALC_B (FB)
OOS_Prog (PRG)
PMCU_Assign (PRG)
RECORDING (FB)
seconddist (FB)
SLIP_BLOCK (FB)
TCS (PRG)
TRIP_FUNCTIONS (FB)
WATCHDOG (PRG)
0001 PROGRAM TCS
0002 VAR
0003 PMCU_INPUT:ARRAY[1..32] OF CLIENT_SETTINGS;
0004 PMCU_OUTPUT:ARRAY[1..6] OF SERVER_SETTINGS;
0005 TCS_STATUS_OUT:TCS_STATUS;
0006 TCS_ERROR_OUT:STRING(256);
0007 HEADER_118:STRING(256):='SVP_SEL_3378';
0008 TCSconfigOK:INT;
0009
0001 (*CLIENT 1 CONNECTED VIA EATHERNET PORT 1 to 411L STATION A*)
0002 PMCU_INPUT[1].EN:=TRUE;
0003 PMCU_INPUT[1].IDCODE:=223;
0004 PMCU_INPUT[1].C37_118_CLIENT:=TRUE;
0005 PMCU_INPUT[1].FASTOP:=1;
0006 PMCU_INPUT[1].CONNECTION:='E';
0007 PMCU_INPUT[1].EPORT.SERVER_IP:='192.168.10.12';
0008 PMCU_INPUT[1].EPORT.SERVER_CMD_PORT:=4770;
0009 PMCU_INPUT[1].EPORT.TRANSPORT_SCHEME:='UDP_T';
0010 PMCU_INPUT[1].EPORT.CLIENT_IP:='192.168.10.77';
0011 PMCU_INPUT[1].EPORT.CLIENT_DATA_PORT:=4713;
0012 PMCU_INPUT[1].EPORT.FASTOP_PORT:=23;
0013 PMCU_INPUT[1].EPORT.FASTOP_PORT_TELNET_EN:=TRUE;
0014
0015 (*CLIENT 1 CONNECTED VIA EATHERNET PORT 1 to SEL-421 STATION B*)
0016 PMCU_INPUT[2].EN:=TRUE;
0017 PMCU_INPUT[2].IDCODE:=1710;
0018 PMCU_INPUT[2].C37_118_CLIENT:=TRUE;
0019 PMCU_INPUT[2].FASTOP:=1;
0020 PMCU_INPUT[2].CONNECTION:='E';
0021 PMCU_INPUT[2].EPORT.SERVER_IP:='192.168.10.14';
0022 PMCU_INPUT[2].EPORT.SERVER_CMD_PORT:=5000;
0023 PMCU_INPUT[2].EPORT.TRANSPORT_SCHEME:='UDP_T';
0024 PMCU_INPUT[2].EPORT.CLIENT_IP:='192.168.10.77';
0025 PMCU_INPUT[2].EPORT.CLIENT_DATA_PORT:=5001;
0026 PMCU_INPUT[2].EPORT.FASTOP_PORT:=23;
0027 PMCU_INPUT[5].EPORT.FASTOP_PORT_TELNET_EN:=TRUE;
0028
0029 (*OUPUT CONNECTED VIA EATHERNET PORT 1 LAPTOP*)
0030 PMCU_OUTPUT[1].EN:=TRUE;
0031 PMCU_OUTPUT[1].MRATE:=4;
0032 PMCU_OUTPUT[1].CLIENT_IP:='192.168.10.10';
0033 PMCU_OUTPUT[1].TRANSPORT_SCHEME:='UDP_T';
0034 PMCU_OUTPUT[1].SERVER_IP:='192.168.10.77';
0035 PMCU_OUTPUT[1].SERVER_CMD_PORT:=5022;
0036
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_Diagnostics_3378.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_C37_118_Gateway.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\Standard.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\IecSfc.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\plclinux_rt\SYSLIBCALLBACK.LIB'
Lin.: 1, Col.: 1
ONLINE OV READ

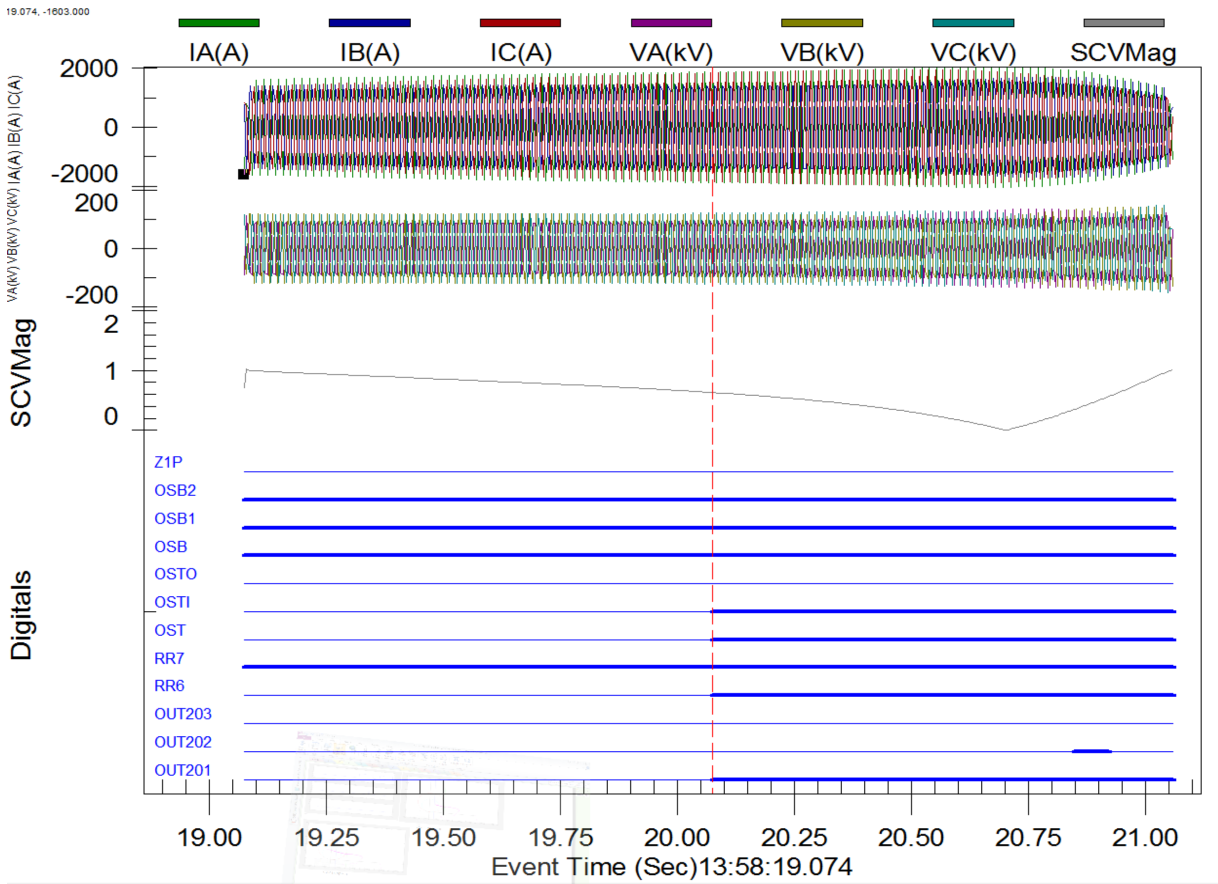

SVP Configurator - V3_OOS_PMU.pro - [TRIP_FUNCTIONS (FB-CFC)]
File Edit Project Insert Extras Online Window Help
POUs
ACC_BLOCK (FB)
algorithm (FB)
OLD_SIG_CALC_B (FB)
OOS_Prog (PRG)
PMCU_Assign (PRG)
RECORDING (FB)
seconddist (FB)
SLIP_BLOCK (FB)
TCS (PRG)
TRIP_FUNCTIONS (FB)
WATCHDOG (PRG)
FUNCTION_BLOCK TRIP_FUNCTIONS
VAR_INPUT
TRIPIN:BOOL;
ENAB:BOOL;
END_VAR
VAR_OUTPUT
END_VAR
VAR
trip_latch:TOF;
trip_inhibited:TOF;
rl:R_TRIG;
enable_tripping:TON;
reset_rb:FAST_OP_REMOTE_BIT_CLEAR;
set_rb:FAST_OP_REMOTE_BIT_SET;
END_VAR
Trip_Latch
TOF
t#50MS
RESET_RB
FAST_OP_REMOTE_BIT_CLEAR
EN
IDCODE
REMOTE_BIT
OK
pERROR
223
1
Enable_Tripping
TON
ENAB
t#250ms
TRIPIN
AND
RT
R_TRIG
CLK
t#10s
Trip_Inhibited
TOF
SET_RB
FAST_OP_REMOTE_BIT_SET
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_Diagnostics_3378.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_C37_118_Gateway.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\Standard.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\IecSfc.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\plclinux_rt\SYSLIBCALLBACK.LIB'
ONLINE OV READ


SVP Configurator - V3_OOS_PMU.pro - [WATCHDOG (PRG-FBD)]
File Edit Project Insert Extras Online Window Help
100 %
0001 PROGRAM WATCHDOG
0002 VAR
0003 END_VAR
0001
USER_WATCHDOG
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_Diagnostics_3378.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\SVP\SEL_C37_118_Gateway.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\Standard.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\IecSfc.lib'
Loading library 'C:\Program Files\SEL\SVP Configurator\Library\plclinux_rt\SYSLIBCALLBACK.LIB'
ONLINE OV READ

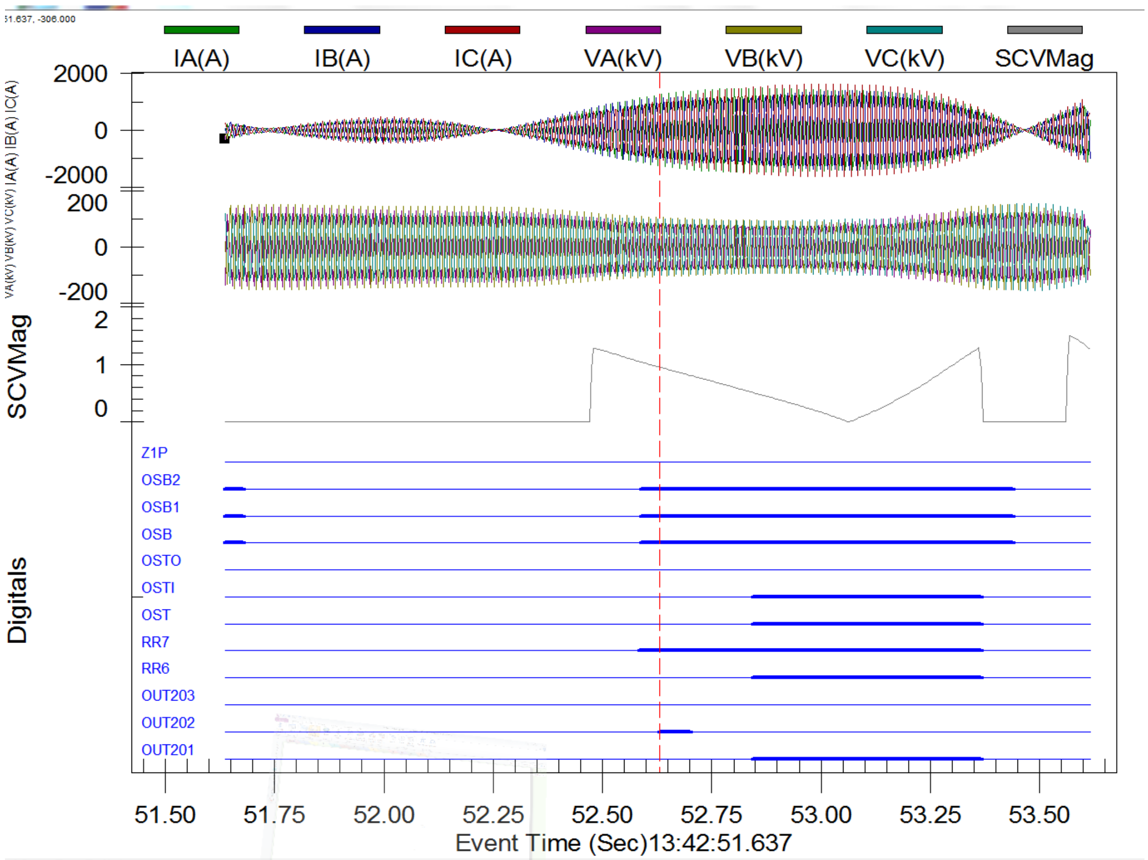
APPENDIX C

STATION_A'S RELAY EVENT FILES

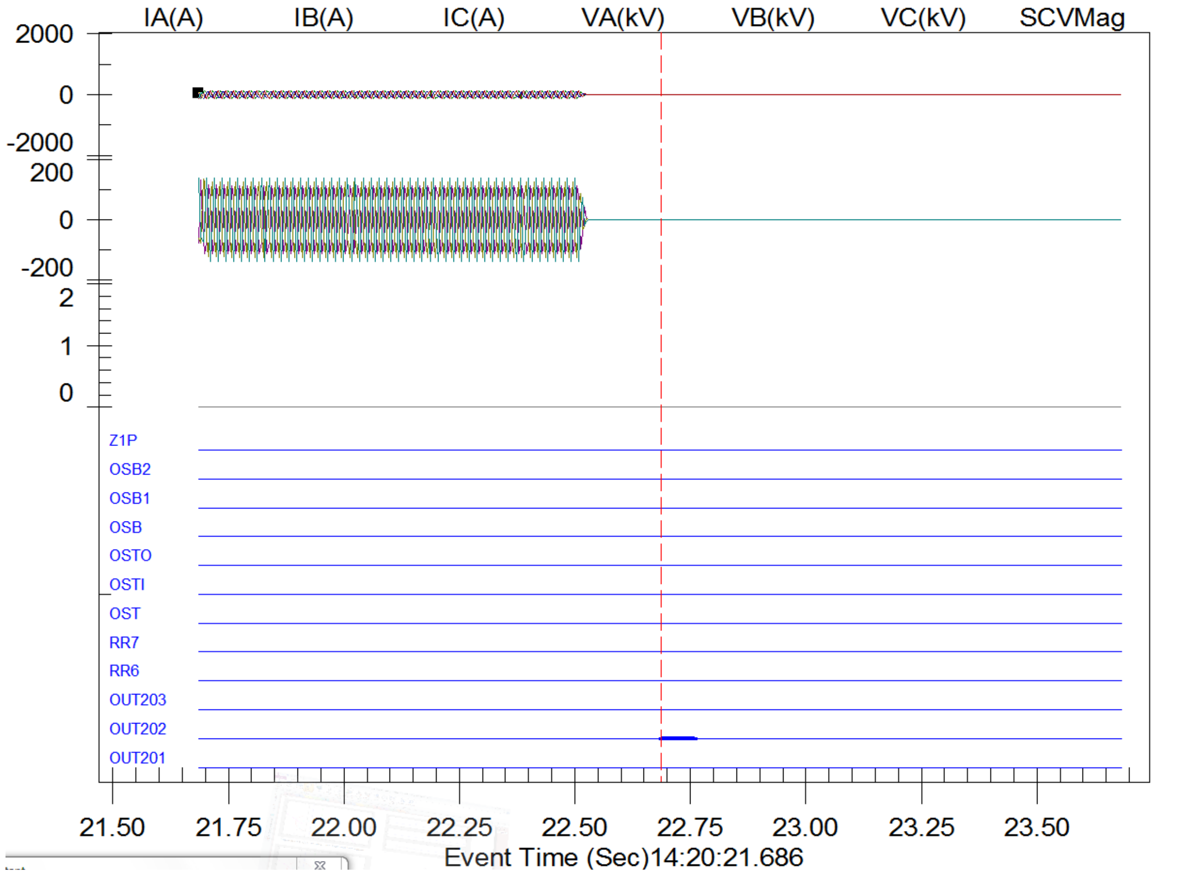
Case-3


19.074, -1603.000
IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
2000
0
-2000
200
0
-200
2
1
0
VA(kV) VB(kV) VC(kV) IA(A) IB(A) IC(A)
SCVMag
Digitals
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
19.00
19.25
19.50
19.75
20.00
20.25
20.50
20.75
21.00
Event Time (Sec)13:58:19.074

Case-4

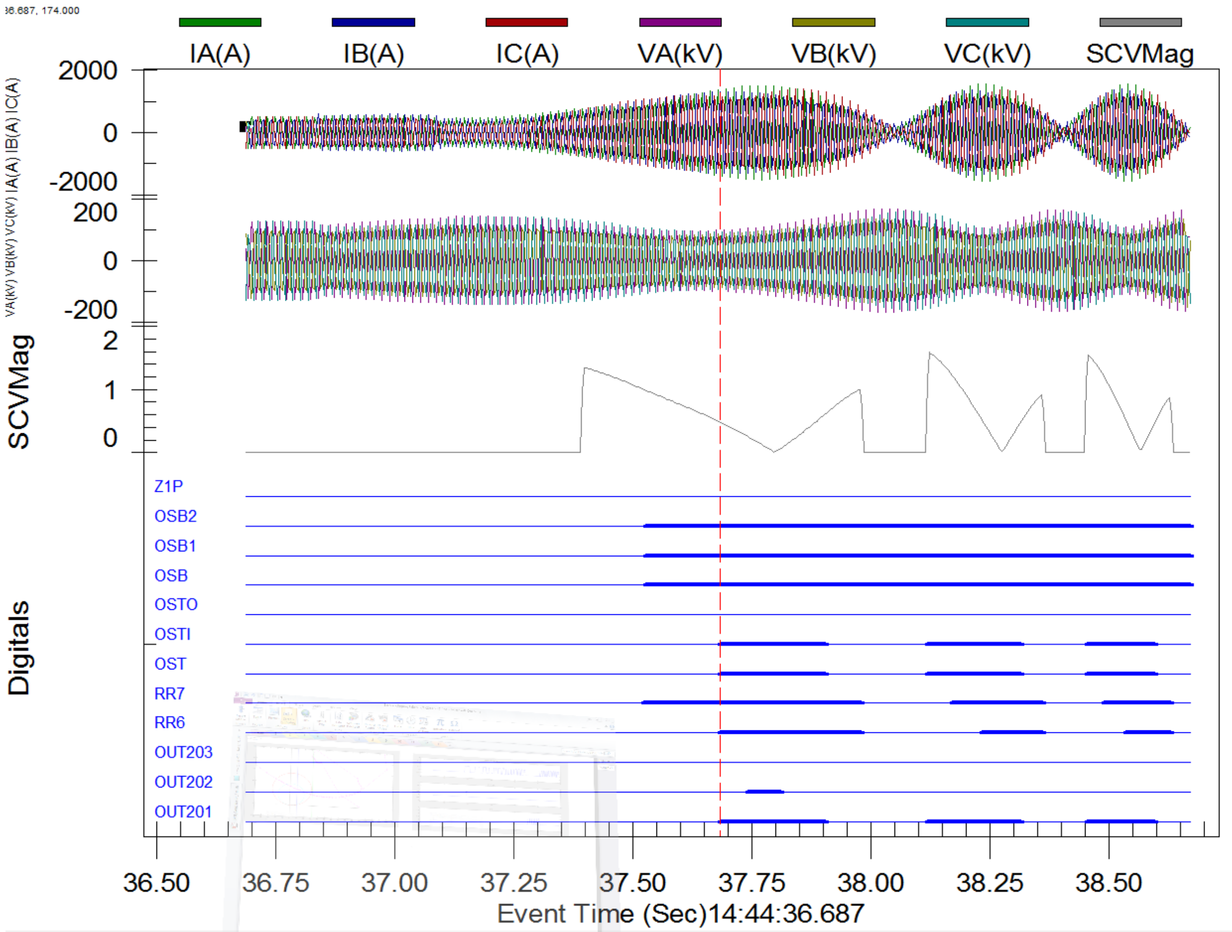

51.637, -306.000
IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
2000
0
-2000
200
0
-200
2
1
0
VA(kV) VB(kV) VC(kV) IA(A) IB(A) IC(A)
SCVMag
Digitals
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
51.50
51.75
52.00
52.25
52.50
52.75
53.00
53.25
53.50
Event Time (Sec)13:42:51.637

Case-5



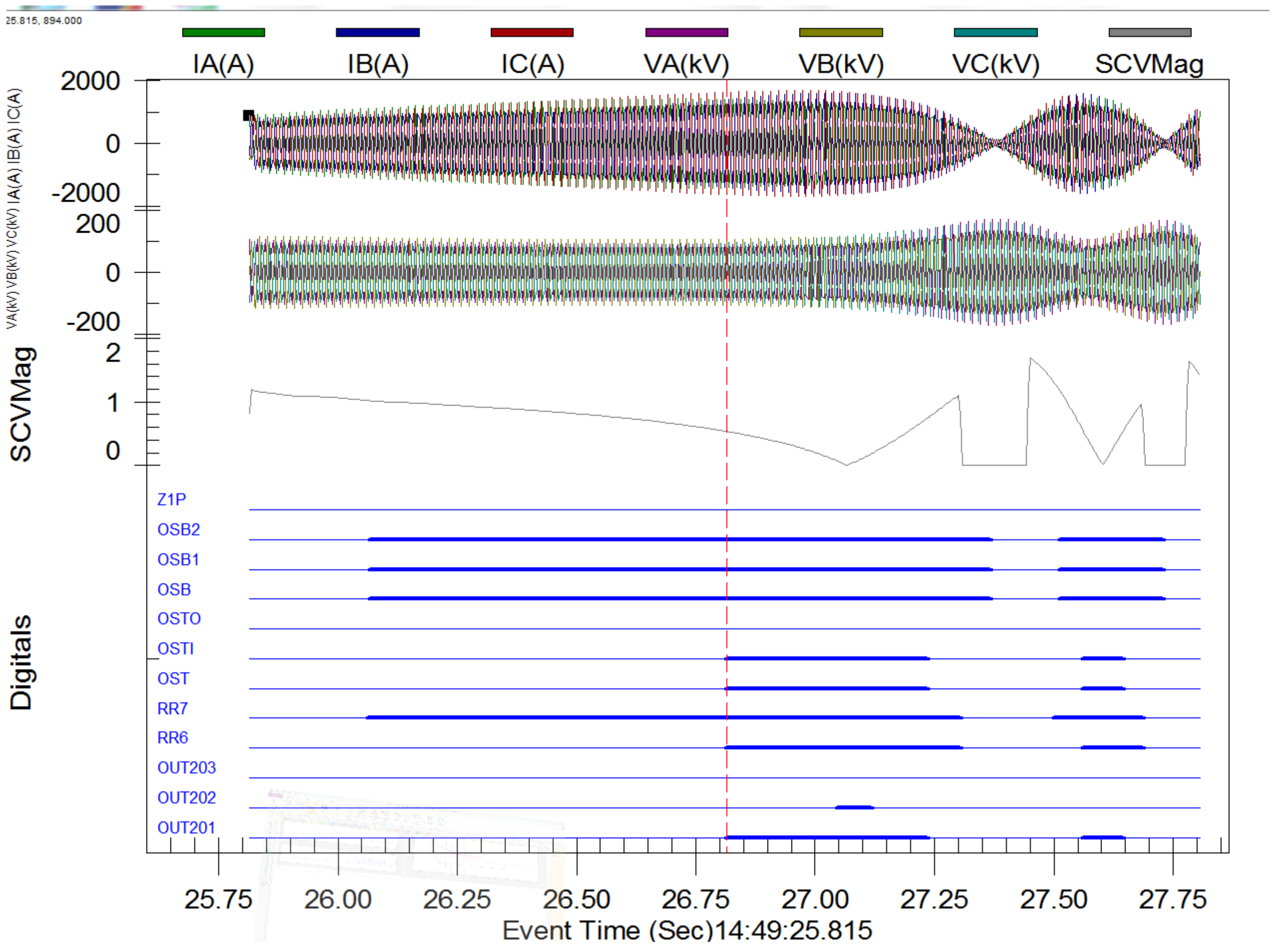
IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
2000
0
-2000
200
0
-200
2
1
0
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
21.50
21.75
22.00
22.25
22.50
22.75
23.00
23.25
23.50
Event Time (Sec)14:20:21.686

Case-6

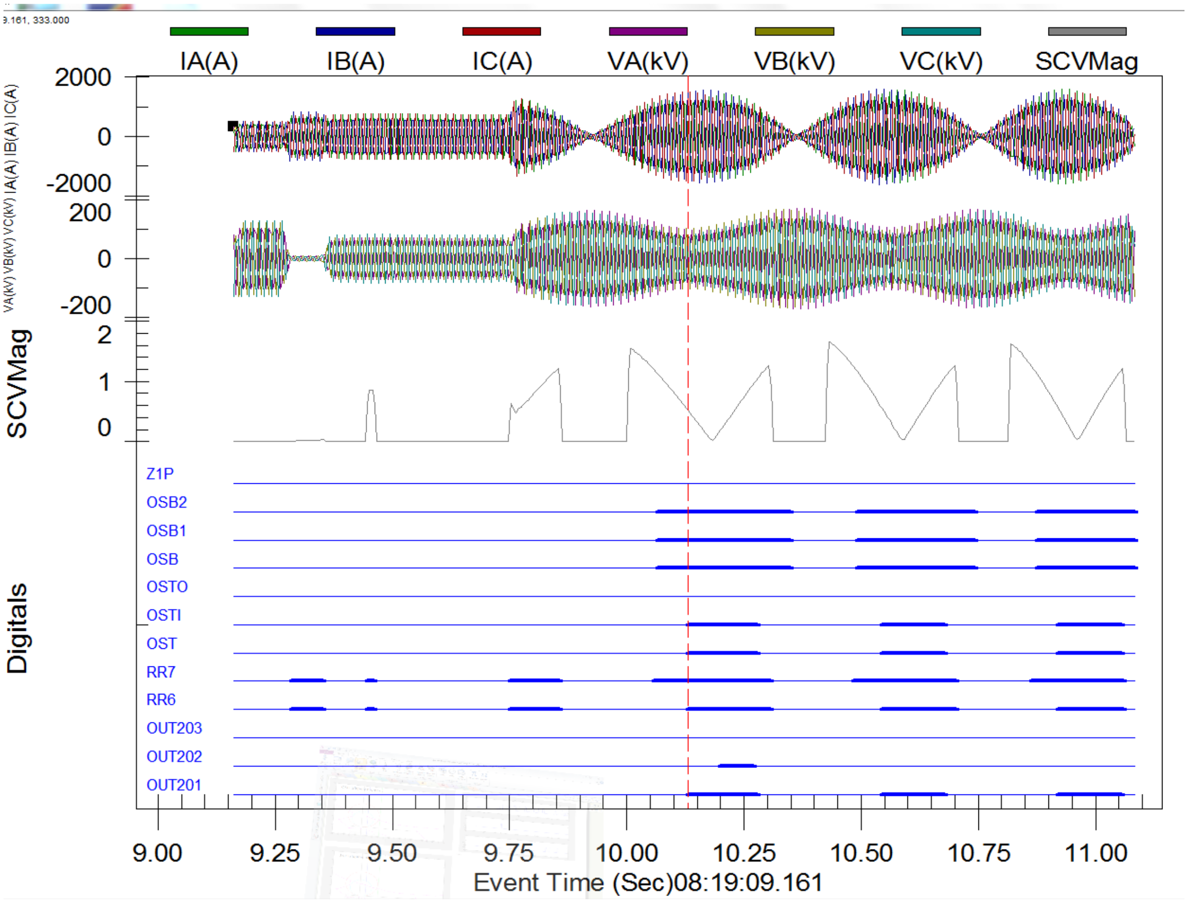


IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
2000
0
-2000
200
0
-200
2
1
0
SCVMag
Digitals
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
36.50
36.75
37.00
37.25
37.50
37.75
38.00
38.25
38.50
Event Time (Sec)14:44:36.687

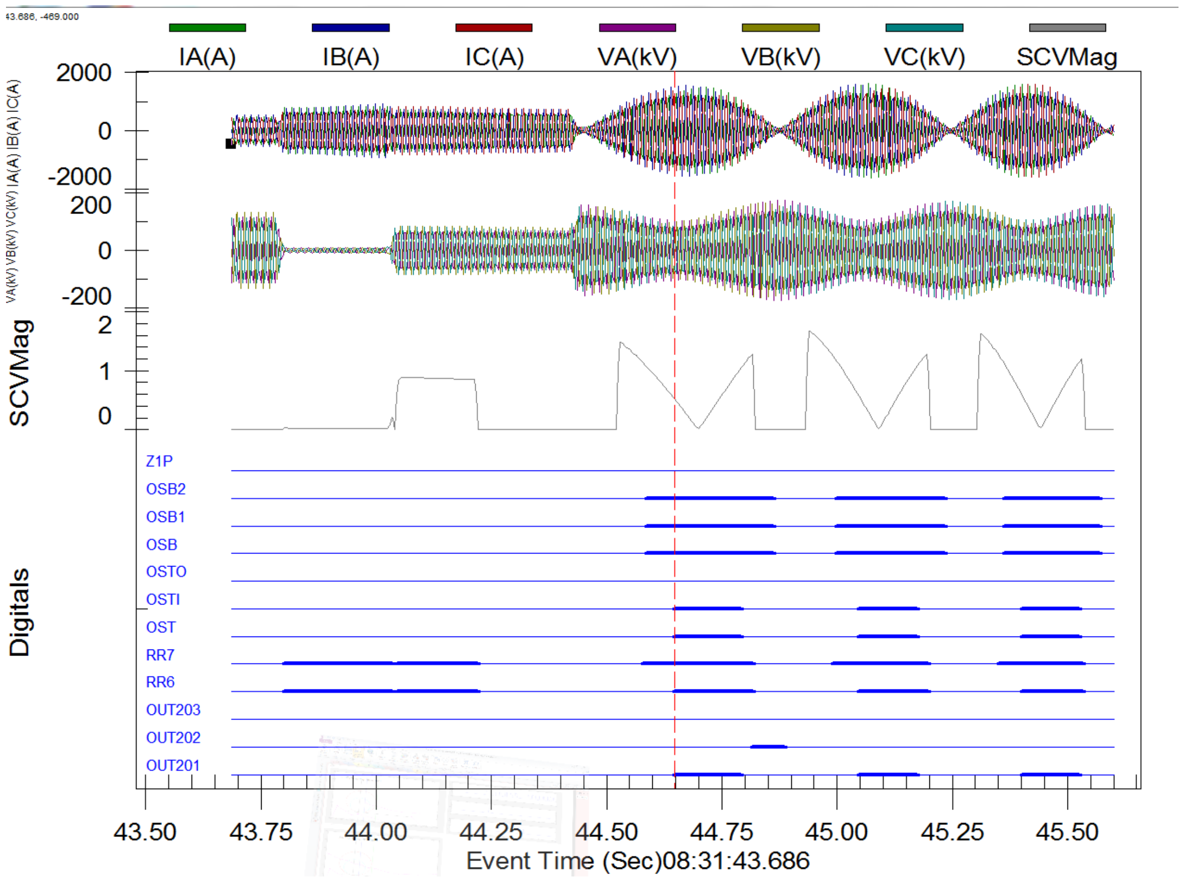
Case-8


25.815, 894.000
IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
2000
0
-2000
200
0
-200
2
1
0
VA(kV) VB(kV) VC(kV) IA(A) IB(A) IC(A)
SCVMag
Digitals
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
25.75
26.00
26.25
26.50
26.75
27.00
27.25
27.50
27.75
Event Time (Sec)14:49:25.815

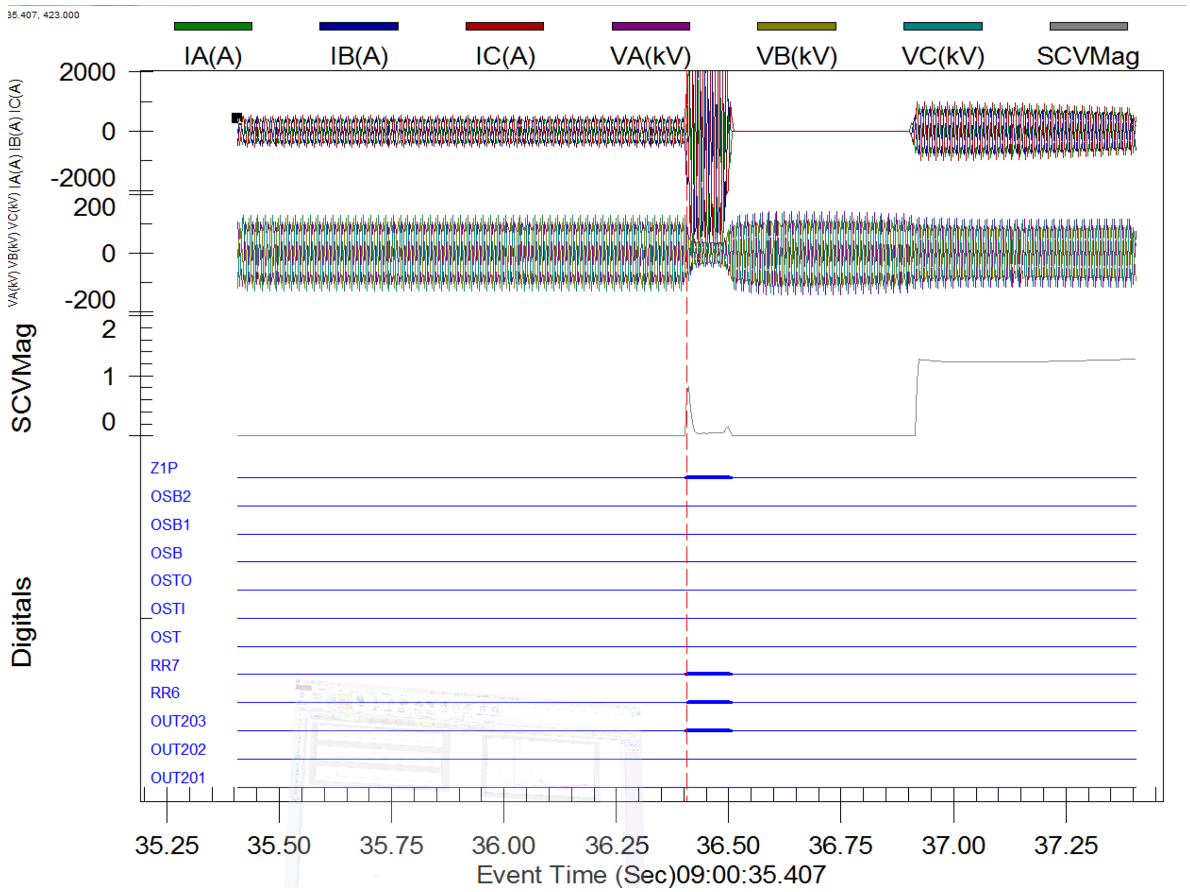
Case-9


IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
2000
0
-2000
200
0
-200
VA(kV) VB(kV) VC(kV) IA(A) IB(A) IC(A)
2
1
0
SCVMag
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
Digitals
9.00
9.25
9.50
9.75
10.00
10.25
10.50
10.75
11.00
Event Time (Sec)08:19:09.161

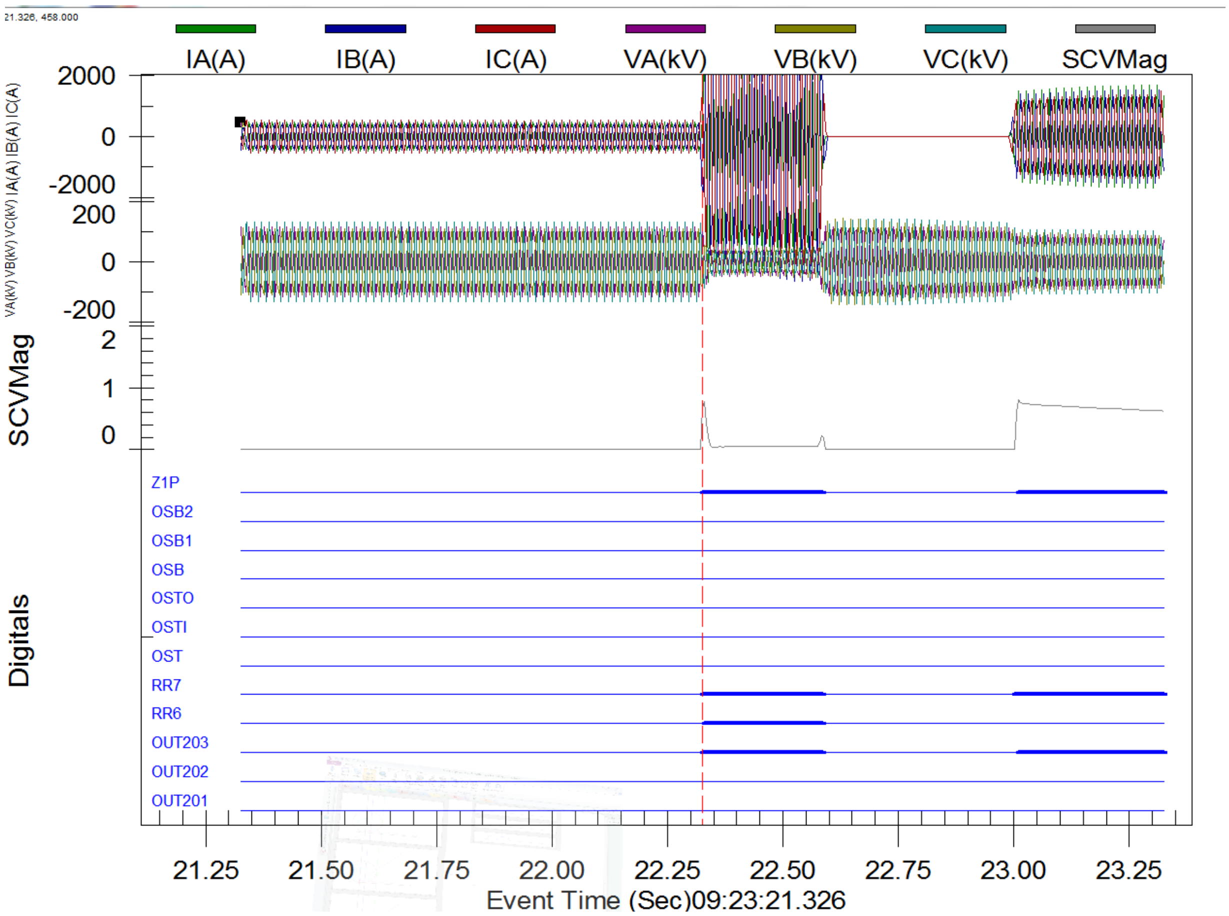
Case-10


43.686, -469.000
IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
2000
0
-2000
200
0
-200
2
1
0
VA(kV) VB(kV) VC(kV) IA(A) IB(A) IC(A)
SCVMag
Digitals
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
43.50
43.75
44.00
44.25
44.50
44.75
45.00
45.25
45.50
Event Time (Sec)08:31:43.686

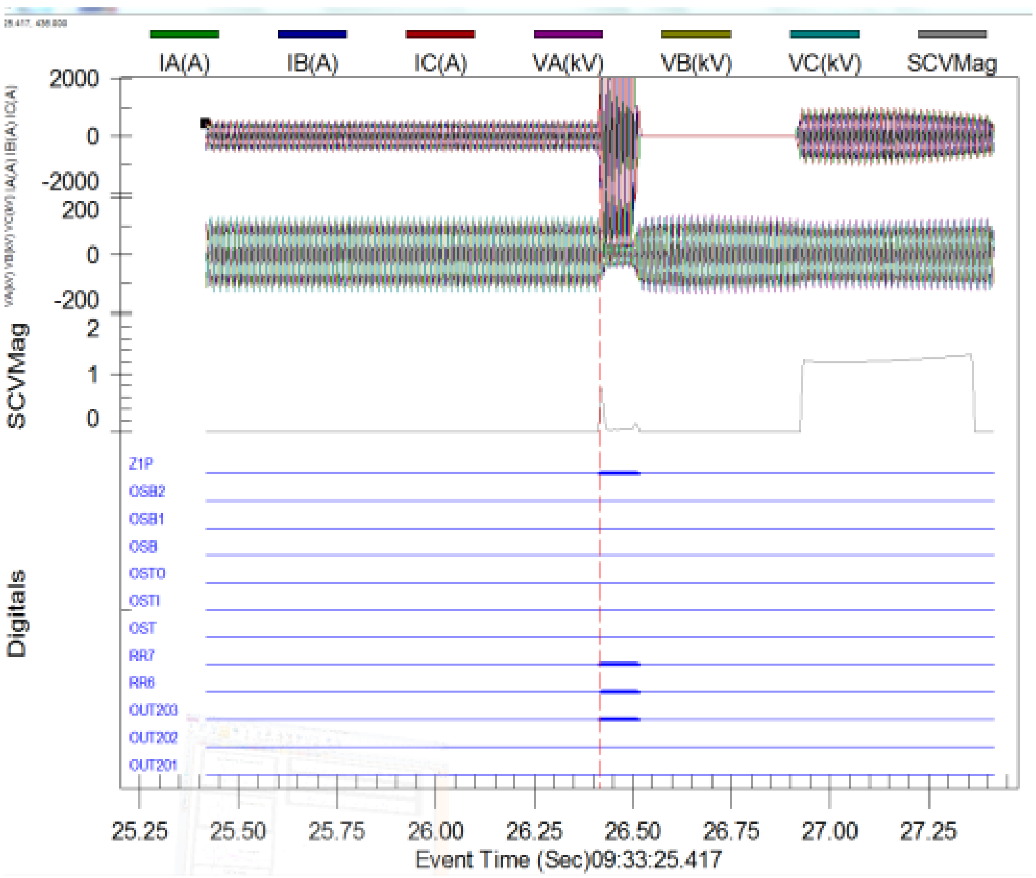
Case-11


35.407, 423.000
IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
VA(kV) VB(kV) VC(kV) IA(A) IB(A) IC(A)
2000
0
-2000
200
0
-200
SCVMag
2
1
0
Digitals
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
35.25
35.50
35.75
36.00
36.25
36.50
36.75
37.00
37.25
Event Time (Sec)09:00:35.407

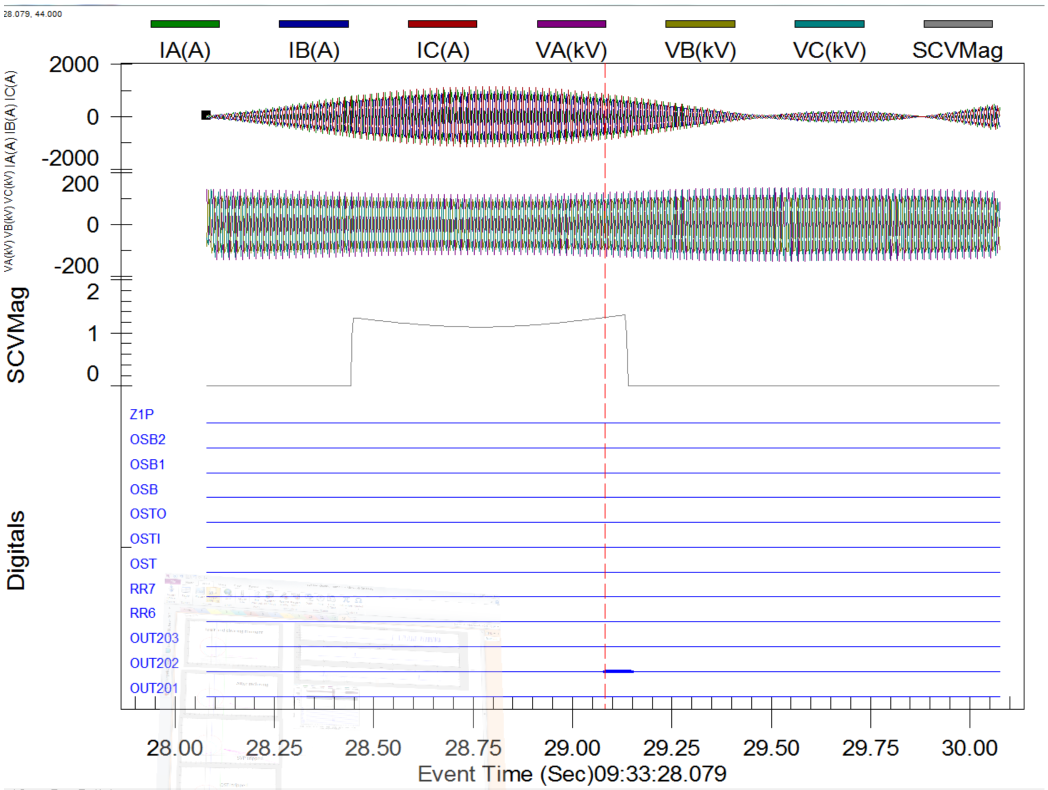
Case-12

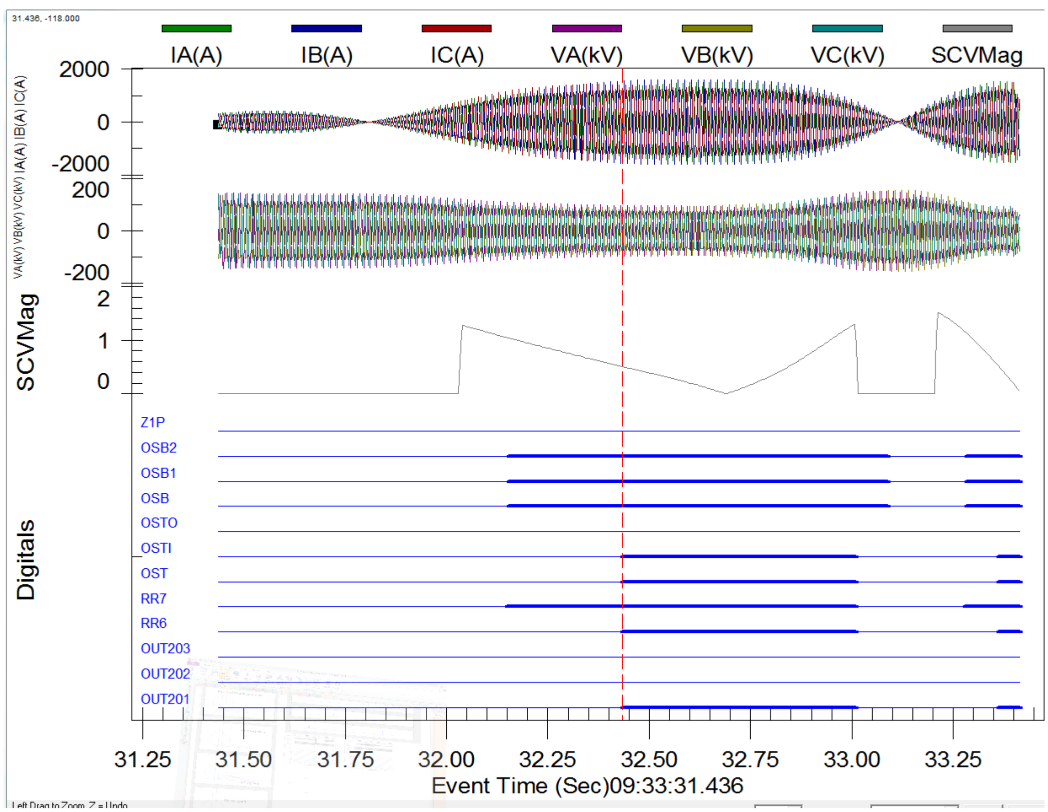

21.326, 458.000
IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
VA(kV) VB(kV) VC(kV) IA(A) IB(A) IC(A)
2000
0
-2000
200
0
-200
SCVMag
2
1
0
Digitals
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
21.25
21.50
21.75
22.00
22.25
22.50
22.75
23.00
23.25
Event Time (Sec)09:23:21.326

Case-13



IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
2000
0
-2000
200
0
-200
2
1
0
SCVMag
Digitals
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
25.25
25.50
25.75
26.00
26.25
26.50
26.75
27.00
27.25
Event Time (Sec)09:33:25.417


28.079, 44.000
IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
2000
0
-2000
200
0
-200
2
1
0
VA(kV) VB(kV) VC(kV) IA(A) IB(A) IC(A)
SCVMag
Digitals
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
28.00
28.25
28.50
28.75
29.00
29.25
29.50
29.75
30.00
Event Time (Sec)09:33:28.079

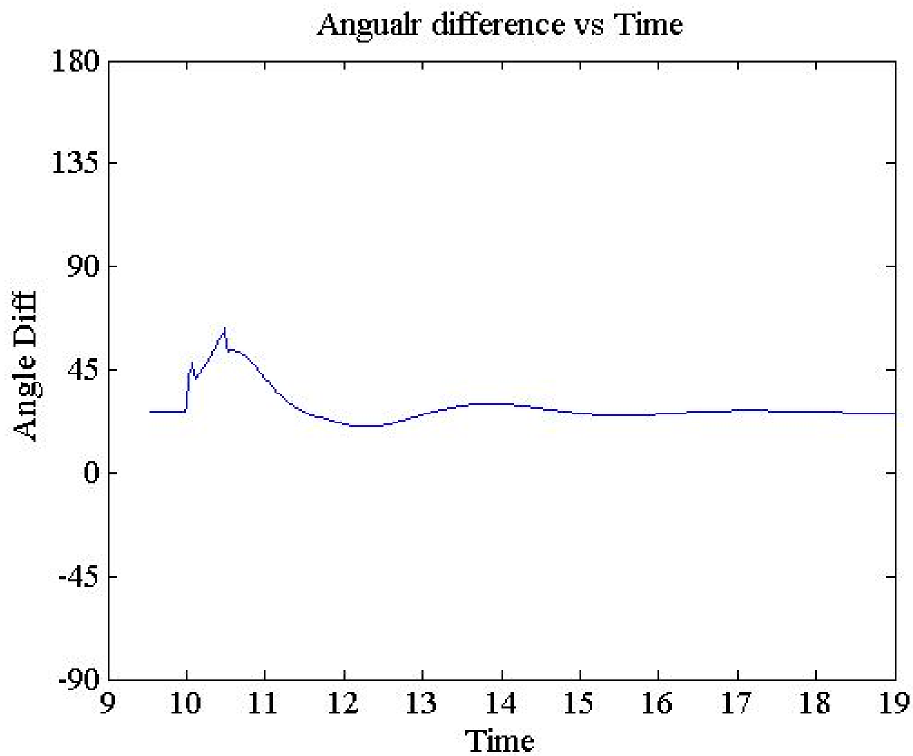

31.436, -118.000
IA(A)
IB(A)
IC(A)
VA(kV)
VB(kV)
VC(kV)
SCVMag
2000
0
-2000
200
0
-200
2
1
0
VA(kV) VB(kV) VC(kV) IA(A) IB(A) IC(A)
SCVMag
Digitals
Z1P
OSB2
OSB1
OSB
OSTO
OSTI
OST
RR7
RR6
OUT203
OUT202
OUT201
31.25
31.50
31.75
32.00
32.25
32.50
32.75
33.00
33.25
Event Time (Sec)09:33:31.436

APPENDIX D

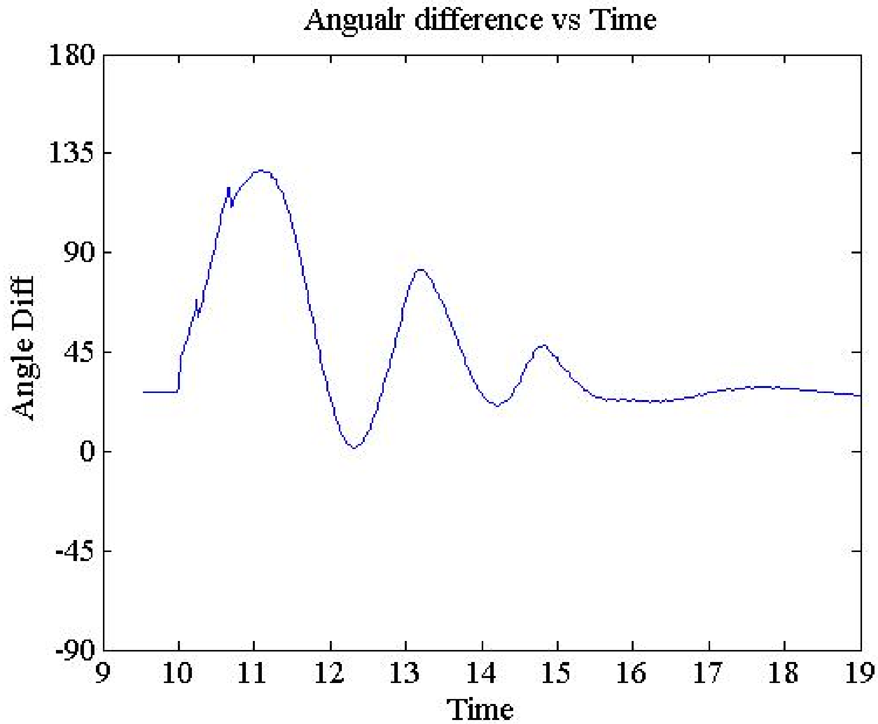
AREAS’ PHASE DIFFERENCE DURING DISTURBANCES

In this appendix, the angular difference between the two areas during each disturbance is presented. The trip signals receieved at the real time digital simulator from the OOS functions of both of the 411L relay and the SVP were only recorded for comparison purposes and they were not connected to the tieline breakers, and this why in the OOS situations the angular difference between the areas reaches to 180º and above regardless of the received trip signals.

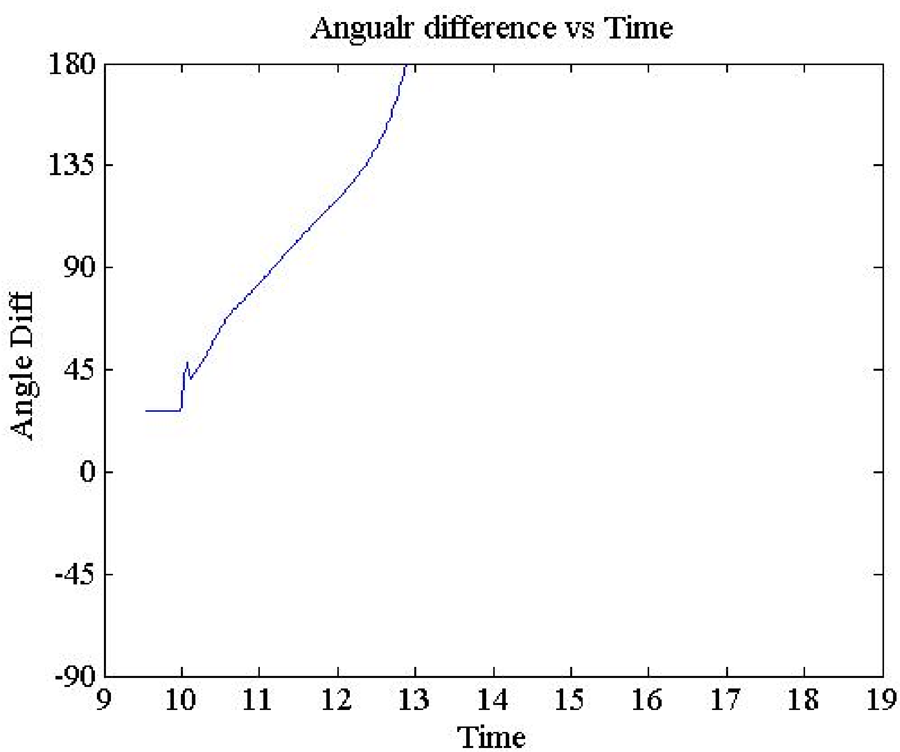
Case-1



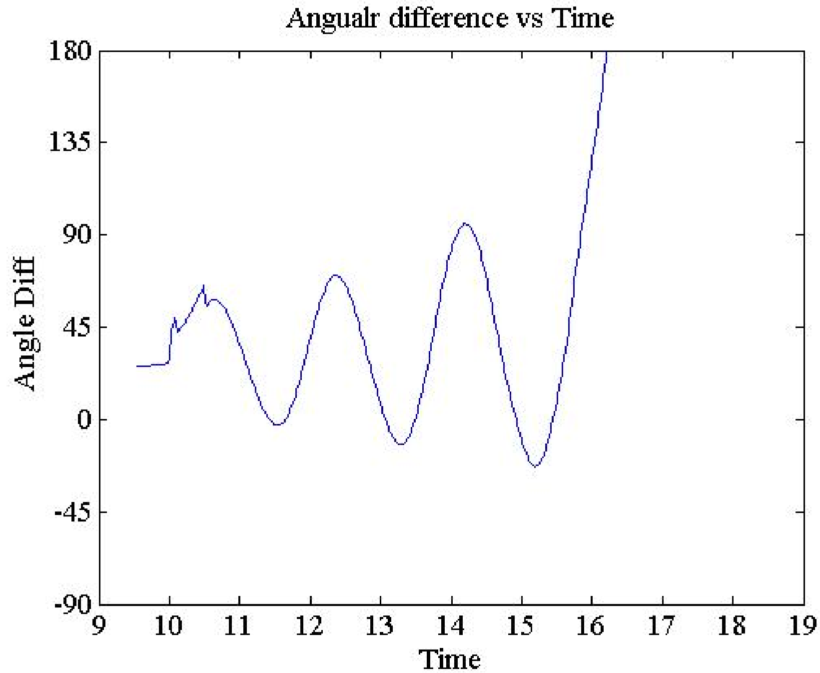
Case-2


Angualr difference vs Time
Angle Diff
Time
180
135
90
45
0
-45
-90
9
10
11
12
13
14
15
16
17
18
19

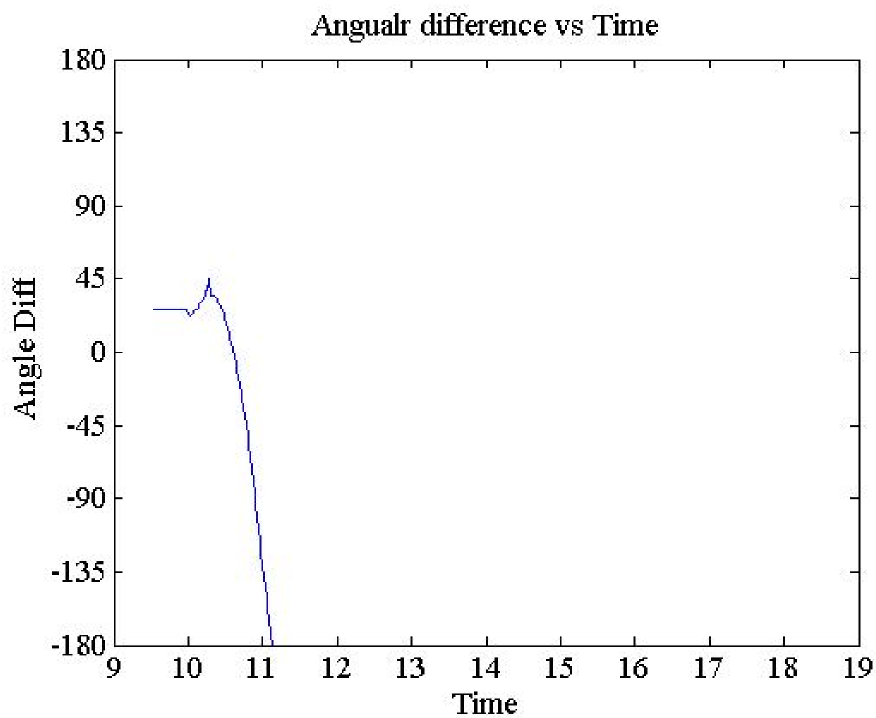
Case-3


Angualr difference vs Time
Angle Diff
Time
180
135
90
45
0
-45
-90
9
10
11
12
13
14
15
16
17
18
19

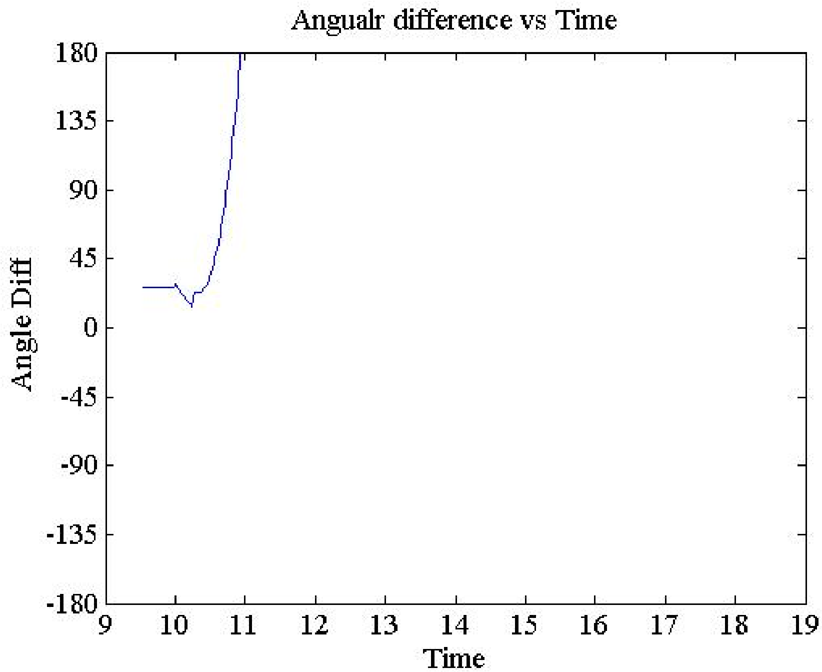
Case-4


Angualr difference vs Time
180
135
90
45
0
-45
-90
Angle Diff
9 10 11 12 13 14 15 16 17 18 19
Time

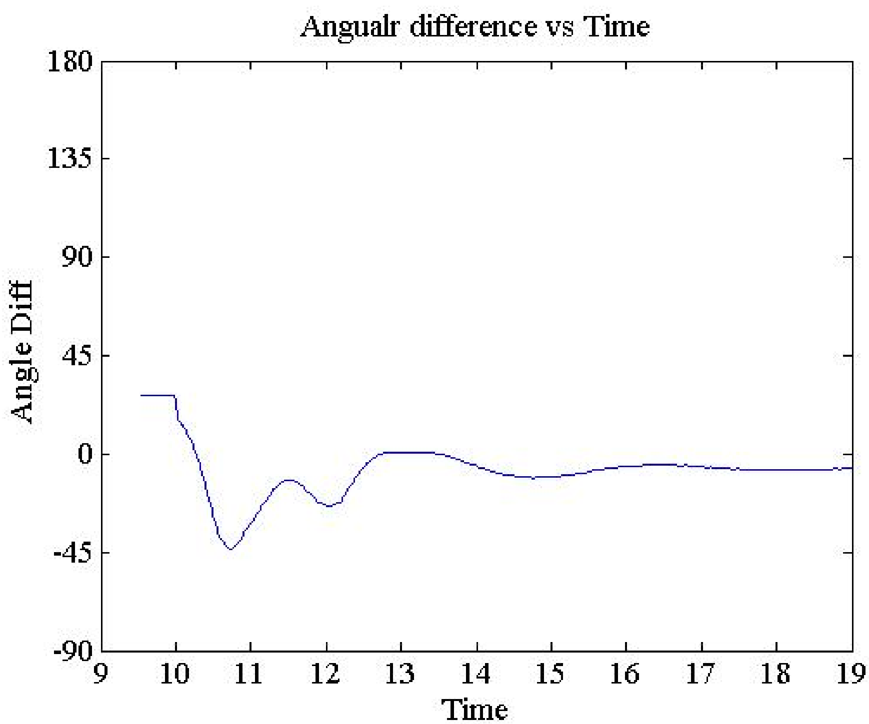
Case-5


Angualr difference vs Time
180
135
90
45
0
-45
-90
-135
-180
Angle Diff
9 10 11 12 13 14 15 16 17 18 19
Time

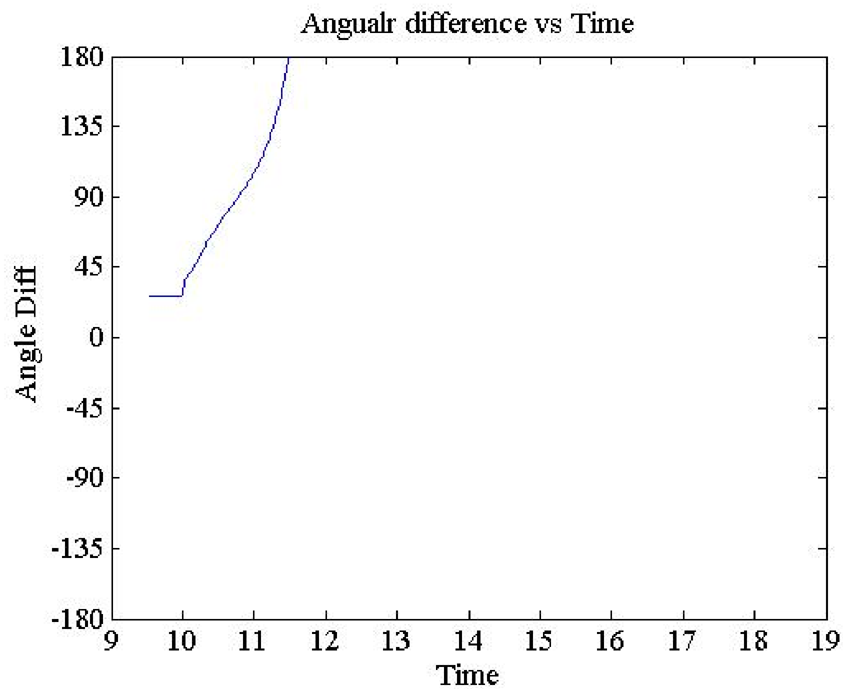
Case-6


Angualr difference vs Time
Angle Diff
Time
180
135
90
45
0
-45
-90
-135
-180
9
10
11
12
13
14
15
16
17
18
19

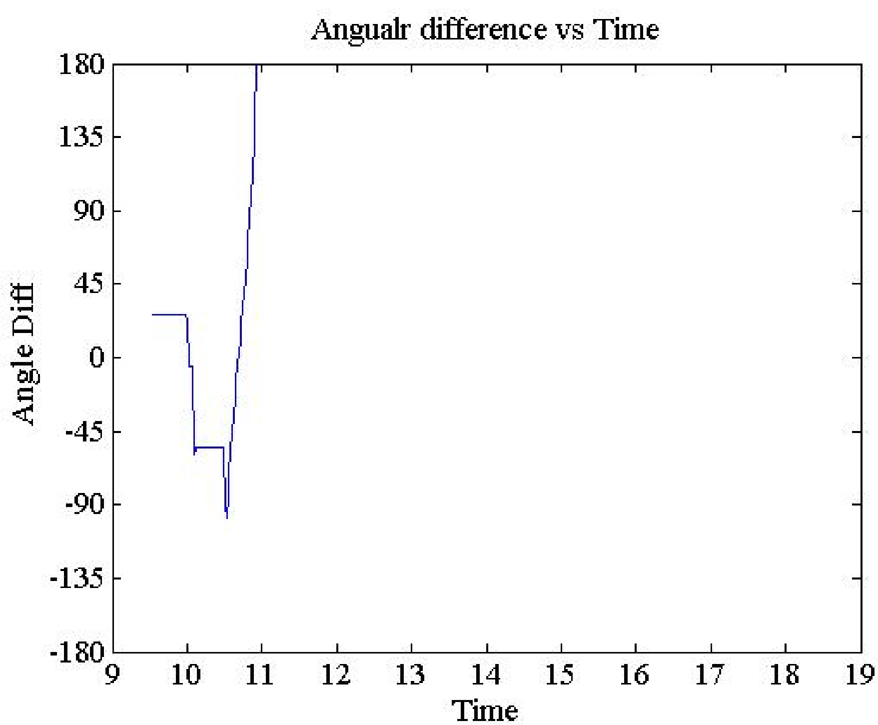
Case-7


Angualr difference vs Time
Angle Diff
Time
180
135
90
45
0
-45
-90
9
10
11
12
13
14
15
16
17
18
19

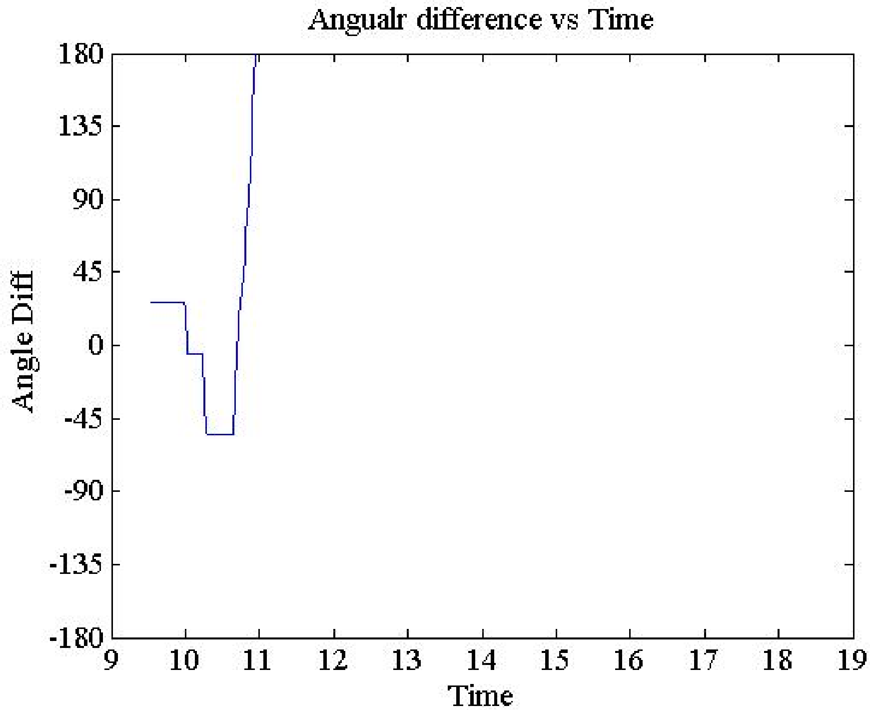
Case-8


Angualr difference vs Time
180
135
90
45
0
-45
-90
-135
-180
Angle Diff
9
10
11
12
13
14
15
16
17
18
19
Time

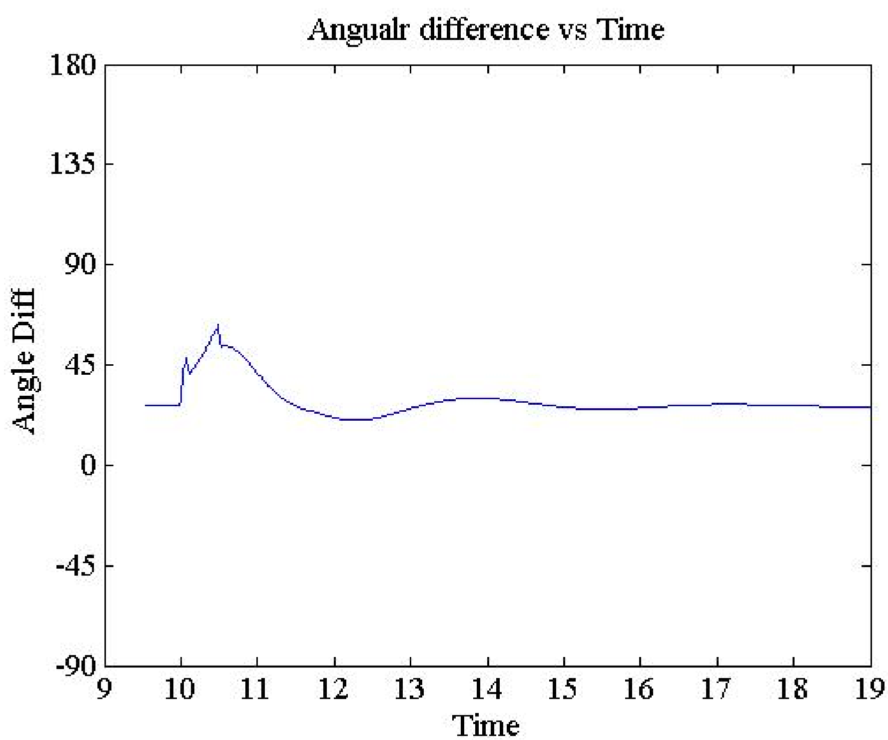
Case-9


Angualr difference vs Time
180
135
90
45
0
-45
-90
-135
-180
Angle Diff
9
10
11
12
13
14
15
16
17
18
19
Time

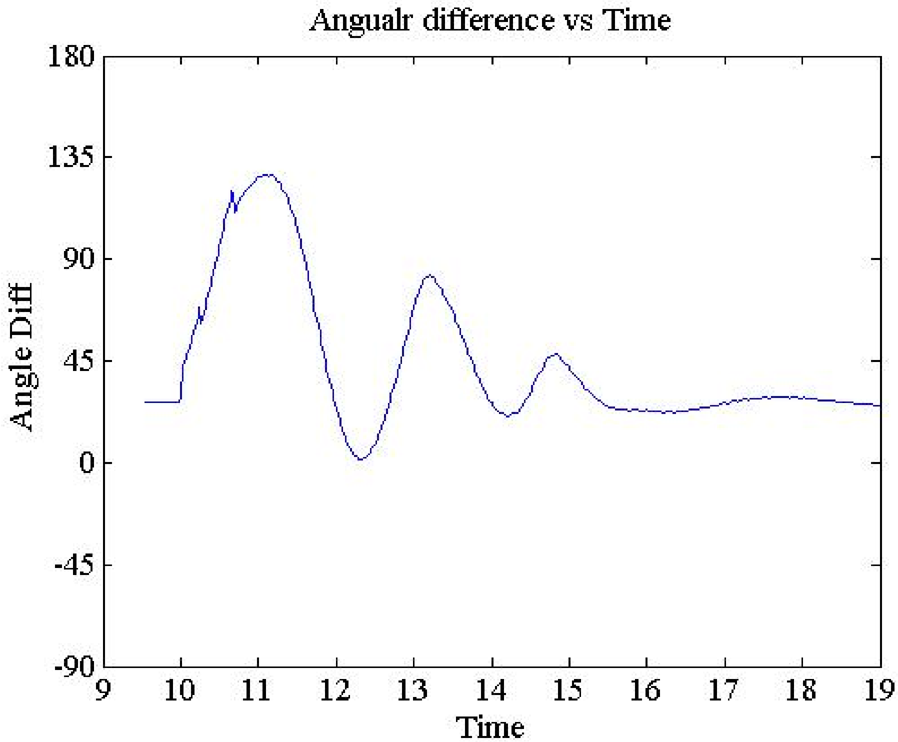
Case-10



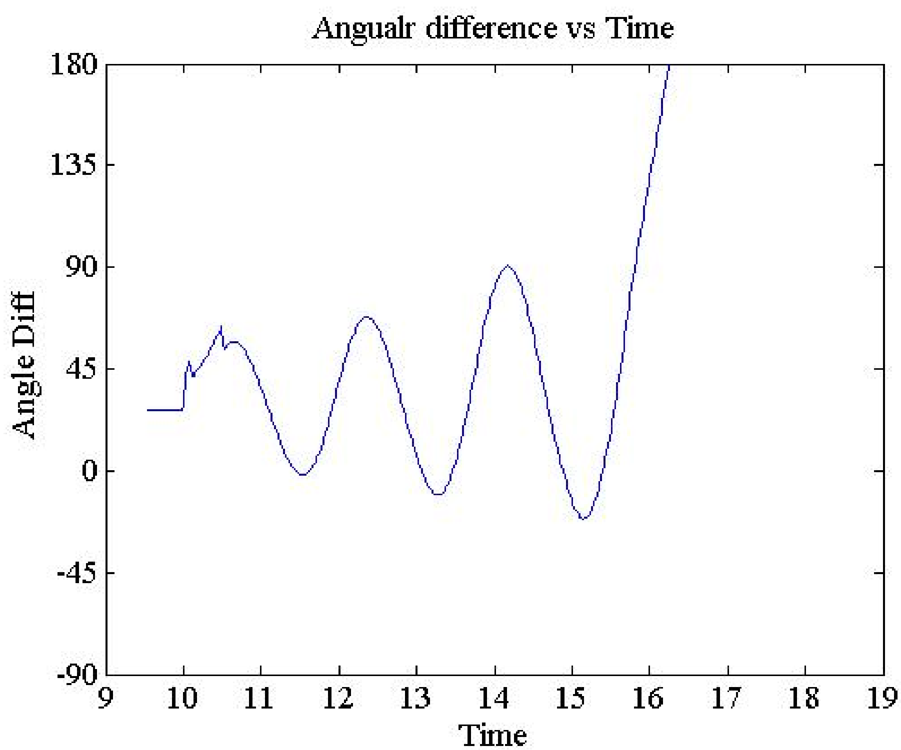
Case-11



Case-12



Case-13



VITA

Mustafa Saad was born in Omdurman, Sudan, to the parents of Amir Mustafa and Najwa Altayeb. He is the oldest of six children. Mustafa completed elementary and high school in Omdurman, and he was one of the best 100 students in Sudan when he graduated from the high school in April 2002. Mustafa was accepted to attend the University of Khartoum in Khartoum, Sudan, and he graduated in August 2007 with a Bachelor of Science in Electrical Engineering. After graduation, Mustafa had worked for five years in the energy automation sector before he was offered a graduate research assistantship under the Department of Energy grant for Workforce Training for the Electric Power Sector to pursue the Master of Science in Electrical Engineering in the University of Tennessee at Chattanooga.