Improving Stability by Enhancing Critical Fault Clearing Time

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by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Electrical Engineering
Department of Electrical Engineering
College of Engineering
University of South Florida

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Date of Approval:
June 21, 2019

Keywords: Breaker Failure, Instability, 3 phase fault, Extreme event, Gang Operated breaker, Independent Pole Operated breaker

DEDICATION

I dedicate this thesis to my parents for their infinite support towards my education, my fiancé Syed Talha Masood and my friend/colleague Aasha Ishtiaq for their constant motivation towards my higher education.

I dedicate this work to my Professor, Dr. Ralph Fehr, for his endless trust in my abilities and continuous support towards my professional and educational growth.

ACKNOWLEDGEMENTS

I am thankful to my professors Dr. Wilfrido A. Moreno and Dr. Lee Stefanakos for their support. I am grateful to Jim Howard, David Miller and Hanna K. Georgos for enabling me with technical support.

I can't thank enough my mentors, Mr. Larry Watt and Mr. Dave Darden, for their tremendous technical and emotional support during the period when I needed it the most. I am thankful to them from the core of my heart.

I am grateful to USEFP and IIE for giving me the opportunity to pursue higher education in the U.S.

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ABSTRACT

The Bulk Electric System (BES) in the United States includes transmission lines of 100kV and above, transformers of 100kV and above on Low Voltage (LV) side and generating units that step up to 100 kV and above. The BES is a power network that connects different states and utility companies via tie lines for exchange of Power. [1]

To maintain the integrity of power systems, it is very important to keep the BES intact and for that the regulatory authority, North American Electric Reliability Corporation (NERC), has developed over 100s of reliability standards and is responsible to enforce them.

During the past several years, the U.S has experienced power system instability events in which a fault occurred on one part of a system and travelled through the entire interconnection. Some of the extreme events are a major concern for power systems in the U.S that consists of Cascading, Uncontrolled Separation and natural disasters damaging the transmission circuits.

Protection System plays important role towards the stability of power systems, but most important aspect of protection system is the Critical Fault Clearing Time. This case study focused on the Critical Fault Clearing Time enhancement by making a comparison between a Gang Operated (GO) and Independent Pole Operated (IPO) Breaker. An extreme event was considered as a fault scenario for the case study that consisted of three phase fault followed by breaker failure scenario.

PSS®E 33.9 software was used to perform dynamic study on three different power plants to show the comparison between GO breaker and IPO breaker. A tremendous improvement was achieved using IPO breaker with more than 100% increase in Critical Fault Clearing Time.

CHAPTER 1

INTRODUCTION

1.1 Overview of Power Systems in the United States

Power systems in The United States are very complex and reliable. North American Electric Reliability Corporation (NERC) is an International regulatory authority in the U.S to enforce reliability standards on all the Transmission owners, Generator owners, Transmission Service Providers, Distribution providers, Reliability coordinators, Balancing Authorities and other functional entities in the United States and Canada for the reliability and security of Bulk Electric System (BES). Bulk Electric System comprises of all the transmission circuits (100 kV and above), transformers (LV winding of 100 kV or above) and generators connected to 100 kV and above. All NERC standards are enforceable on BES equipment. [1]

There are three major interconnections in the U.S which are made up of interconnected grids in certain geographical areas. They are mentioned below.

- Eastern Interconnection.
- ERCOT (The Electric Reliability Council of Texas) Interconnection.
- Western Interconnection.[2]

These major interconnections work independently but limited power can be transferred from one major interconnection to the other. Every utility company in an interconnection are connected to the other within the same interconnection via tie lines for transfer of power. This type of interconnected power system is very rigid and efficient but there is a possibility that if a fault occurs on one part of the system, it might cause instability problems in some other parts of the system, which leads to extreme events causing Instability, Uncontrolled separation or Cascading. In order to avoid uncontrolled separation, system instability and cascading, the protection system has to be very substantial.

1.2 Instability Event that Occurred in the State of Florida

The state of Florida has experienced major instability events in the past which resulted in loss of generation/load. The following event is described briefly to give an overview of stability issues under consideration.

As per Florida Reliability Coordinating Council (FRCC) report on System Disturbance and Under Frequency Load Shed (UFLS) Event on February 26, 2008, a fault was developed at 138 kV switch located at one of Miami's Substations in Florida. The fault propagated due to long fault clearing time of 1.7 seconds, triggering the Under-Frequency Load Shedding (UFLS)scheme and shed a load of 2273 MW in the state of Florida. Due to this fault, suppressed voltages caused two nearby generating units tripped, resulting in generation unit's loss of 2500 MW and additional 1800 MW generation loss in the rest of the state.

This whole situation took 10 seconds during which the whole state of Florida experienced severe Frequency, voltage and power surges. The frequency was swinging between 59.38 Hz to 60.4 Hz causing power system disturbance and instability [3].

CHAPTER 2

PROCESS OF ENHANCING CRITICAL FAULT CLEARING TIME

2.1 Introduction

This chapter explains the process of enhancing Critical Fault Clearing (CFC) time and why it is important to do so. Power systems stability can be improved tremendously by considering system improvements in it. The scope of this thesis includes extreme events that consists of three-phase fault on a 230 kV transmission circuit, connected to a 230 kV bus which is connected to a generation substation, followed by breaker failure situation which makes this fault scenario an extreme event as per TPL-001 standard of NERC. Due to extreme event, the power system could face catastrophic instability issues. The major instabilities under observation during the simulations are explained in the next section.

2.2 Types of System Instabilities

In order to assess the system instability, this thesis will focus on instability, uncontrolled separation and cascading which are major instability issues described below.

2.2.1 Instability

As per NERC proposed glossary of terms for IROLs, Instability is defined as,

"The inability of Elements of Bulk Power System, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a Disturbance".[4]

In order to assess instability during PSS®E simulations considering extreme event condition, the following parameters will be observed.

- Load/Generation loss.
- Rotor angle instability causing any generator to lose synchronism.
- The number of BES transmission circuits tripped during the offline study.
- The type of load tripped (e.g. sensitive load or nuclear plants).
- The Under Frequency Load Shed (UFLS) post fault.

2.2.2 Uncontrolled Separation

As per NERC proposed glossary of terms for IROLs, Uncontrolled Separation is defined as, "The unintended islanding of a portion of the Bulk Power System that includes generation or load".[4]

In order to assess uncontrolled separation during dynamic simulations, the following parameters will be assessed.

i. Uncontrolled separation refers to islanding of a portion of Bulk power system that includes generation or load which is separated due to the mis-operation of protection system.
ii. The frequency and voltage of the BES busses will be monitored against severe frequency and voltage dips caused by transient instability.

2.2.3 Cascading

As per NERC proposed glossary of terms for IROLs, cascading is defined as,

"The uncontrolled successive loss of Bulk Power System Elements triggered by a Disturbance".[4]

There are two types of cascading explained in the NERC Reliability guideline,

i. Bounded Cascading

It is a type of cascading that stops after removing certain number elements from the system. This type of cascading brings no harm to the rest of the Bulk Power System but a small load pocket or some generation is removed from the system and the system readjusts itself to the steady state condition.

ii. Unbounded Cascading

It is a type of cascading that cannot stop the subsequent removing of elements from the Bulk Power System. The system enters into an unstable condition in which the fault escalates to a certain point after removing tremendous number of elements from Bulk Power System.

2.3 Critical Fault Clearing Time

The critical fault clearing time is the total time, during which if a system is subject to disturbance and the fault is cleared within that that time duration, the system will remain stable once the fault is isolated. If the fault is isolated beyond the critical fault clearing time, it could lead to system instabilities in the form of generation/load loss. The total fault clearing time is different for different parts of power systems. It mainly depends on the protection settings and type of protection system used. For transmission substation with no generating unit directly connected to it, the critical fault clearing time is usually longer than it is at a generation substation. The following figure explains Total Fault Clearing Time.[5]

In this thesis, "~" sign has been used to show electrical cycles.

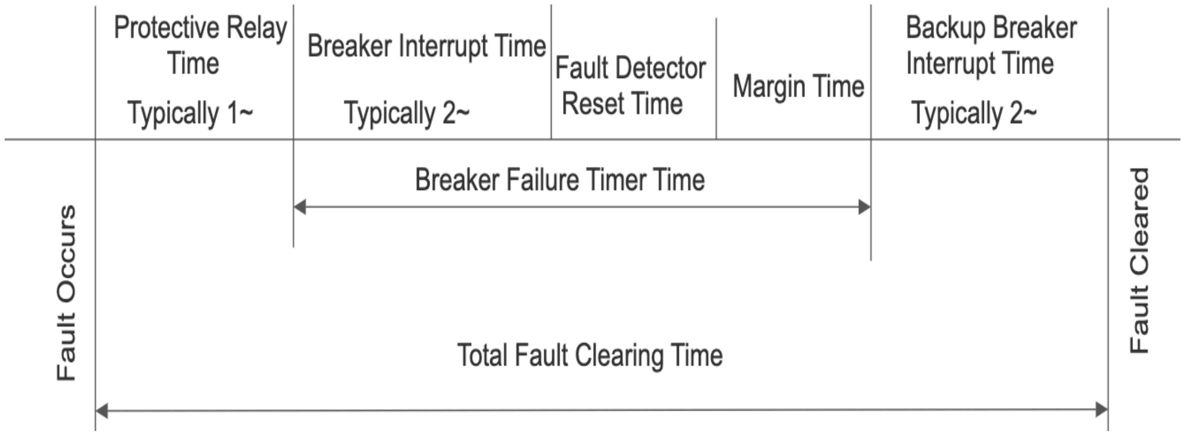

Figure 1 Total clearing time diagram

* This figure has been modified and taken from conference paper "Experience with Local Breaker Failure Relay Protection" by Albert N. Darlington and Thomas W. Patrick at page 3.

Considering fast protection system, the above figure shows the protection settings for local breaker failure scenario. When a fault occurs, it typically takes 1~ for a protective relay to detect the fault. It typically takes 2~ for a circuit breaker at the power plant substation to operate, while for transmission (non-generation) substation, the circuit breaker interrupt time is typically 3~. When the relay senses the fault, it sends trip command to the circuit breakers in its zone of protection and at the same time, the breaker failure timer starts. At the end of breaker failure timer time, if current is still flowing through any of the local breakers, a breaker failure has occurred. In order to clear the fault, the breaker failure relay sends trip commands to all backup breakers. The fault detector reset time is set based on the slowest breaker interrupt time of the substation. The total fault clearing time for breaker failure might be longer for a transmission (non-generation) substation.[6]

2.4 Components of Normal Fault Clearing Time

The typical time components for relay, transfer trip and circuit breaker assumed for running the simulations are given below.

Table 1 Normal Fault Clearing Time

Protection System	Local End (cycles)	Remote End (cycles)
Relay Time	1~	1~ (at local end)
Transfer Trip Time	Not Applicable	1~
Circuit Breaker Interrupt Time	2~	3~
Total (Normal Fault Clearing Time)	3~	5~

The normal fault clearing time at local end is 3~ as the fault occurs in its zone 1. At the remote end, as the fault is not in its zone, the local end relay time (1~) is counted towards clearing the fault from remote end. The normal fault clearing time at remote end is 5~ which includes 1~ relay time at local end, 1~ transfer trip time and 3~ remote end circuit breaker interrupt time. As the remote end is a non generation substation, the circuit breaker interrupt time considered is 3~.

2.5 System Operating Limits

The System Operating Limits (SOL) for each BES facility in the United States are established following the NERC Standard FAC-008-3. The SOLs are established mainly by considering the facility ratings of generators, transmission circuits, protection system and transformers for a particular facility. The most limiting element is set up as System Operating Limit for that facility.[7]

2.5.1 Voltage Limits

The protection settings against off nominal voltage considered for this thesis are explained in the voltage ride through curve below. The curve is designed for 60 Hz frequency.

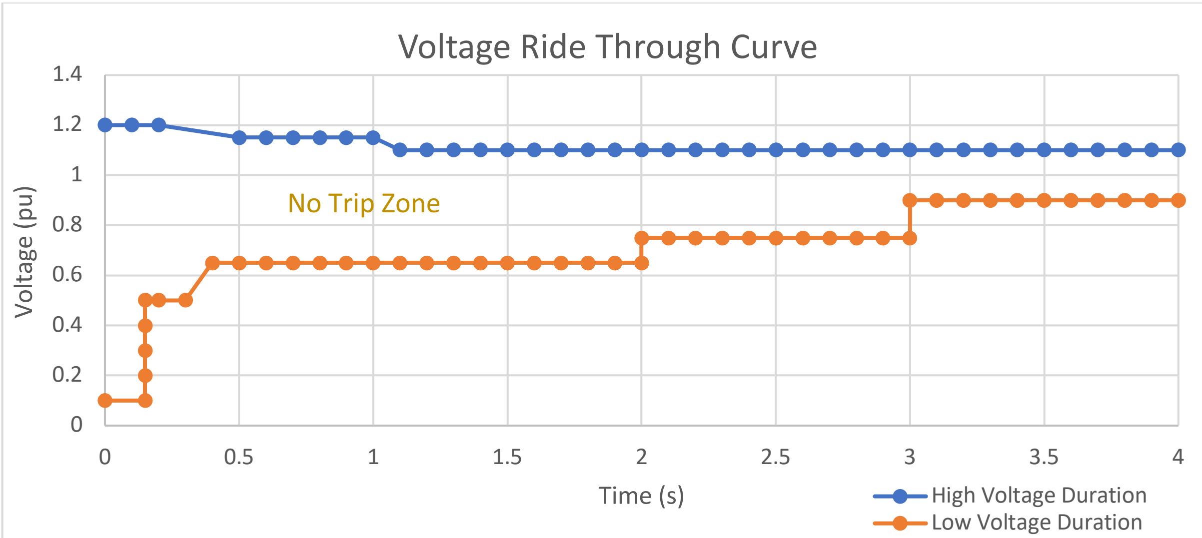

Figure 2 Voltage ride through curve

* This figure has been modified and originally taken from NERC's Standard PRC-024-2 "Generator Frequency and Voltage Protection Relay Settings" at page 8.

The blue curve shows high voltage duration while the orange curve shows low voltage duration. This curve considers cumulative time of the voltage excursion limits (upper and lower limits) which means if for instance the voltage is 0.85pu for less than 3 seconds, it is forbidden to trip. If the cumulative time of the voltage excursion falls outside the curve, it is allowed to trip.

2.5.2 Frequency Stability Limits

For the simulations, there is an Under-Frequency Load Shedding (UFLS) program, which operates its first step of shedding load when the frequency drops down to 59.6 Hz to mitigate the under-frequency condition. If the frequency continues to drop down, further Load Shedding steps will be activated and will shed more load to mitigate the under-frequency condition.

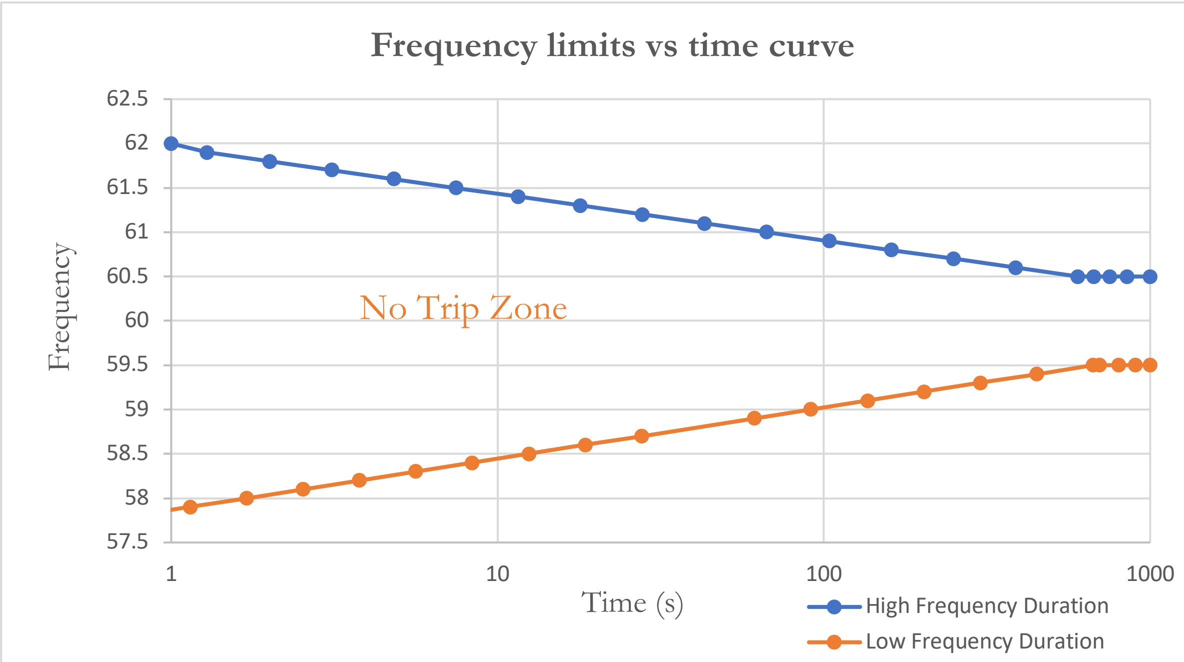

Figure 3 Frequency limits vs time curve

* This figure has been modified and originally taken from NERC's Standard PRC-024-2 "Generator Frequency and Voltage Protection Relay Settings" at page 10.

The blue curve shows high frequency duration for generating units while the orange curve shows low frequency duration for generators. If the frequency goes beyond its standard limits (high or low) for a time duration that will make it fall outside the curve, it is allowed to trip the generating unit. As long as any generating unit frequency limit for certain period of time stays inside the curve, it is forbidden to trip.

CHAPTER 3

SETTING UP PSS®E SOFTWARE FOR DYNAMIC SIMULATIONS

3.1 Overview

To run dynamic study simulations, PSS®E 33.9 by SIEMENS software is used in this thesis to achieve the objective.

Many Utility companies in the United States use PSS®E software to run steady state and dynamic simulations. To set up PSS®E 33.9 software base case, all the utility companies have to follow NERC Standard MOD-032-1. The purpose of MOD-032-1, as defined in the standard, is, "To establish consistent modelling data requirements and reporting procedures for development of planning horizon cases necessary to support analysis of the reliability of the interconnected transmission system".[8]

In this chapter, a step by step process of PSS®E set up, simulations and results retrieval is briefly explained. To set up a base case for PSS®E, a wide range of data is required as per NERC MOD-032-1 standard.

3.2 Setting Up the Base Case for Simulations

The base case is set up using the existing sample cases in the PSS®E library. Modifications are made to the sample cases by altering or adding necessary data to it. The base case is set up following the requirement R1 of the NERC standard MOD-032-1 which explains the details to be included in the model that is data format, level of detail to which equipment shall be modelled and case types or scenarios to be modelled.[8]

The PSS®E 33.9 GUI Users Guide gives instructions on how to set up the base case. [9]

3.2.1 Types of Database

There are mainly two types of databases used for Dynamic simulations. The two types are briefly explained below.

i. Network Data

Network data is used for power flow studies. It contains the data of whole network which includes transmission (impedance, voltages (peak and off peak), loading (normal and emergency), length of line, operational status of circuit), generation (active power, reactive power, voltage (peak and off peak)), load (MW and MVAR), fixed shunt, switched shunt and transformers (2-windings and 3-windings). The Network data saved file has an extension of (.sav).

ii. Dynamic Data

Dynamic data contains detailed data of generators which includes type of generator (Salient pole or round rotor), exciter, turbine governor and stabilizer. It also contains the UFLS (Under Frequency Load Shed) program and some line relay models. The dynamic data file is called a snapshot file and is saved with an extension (.snp).

3.3 Sequence Thevenin Impedance Data

To perform dynamic simulations for GO and IPO breaker, the sequence Thevenin impedance data is required. The fault study under consideration for dynamic simulations is three phase fault which is a balanced fault and requires positive sequence Thevenin impedance only. A high inductance shunt is used at the point of three phase fault. As IPO breaker has separate operating mechanism for each pole, the assumptions used for simulations for a breaker failure is that only one pole fails to operate. In this situation, three-phase fault is converted into a single line to ground fault due to one stuck pole. As single line to ground fault is an unbalanced fault, it requires positive, negative and zero sequence Thevenin impedance data.

To calculate Thevenin sequence impedance, a short circuit data bank case is used to run automatic sequencing fault calculation in PSS®E which provides fault current and sequence Thevenin impedance. The busses under consideration are selected. The following settings are selected.

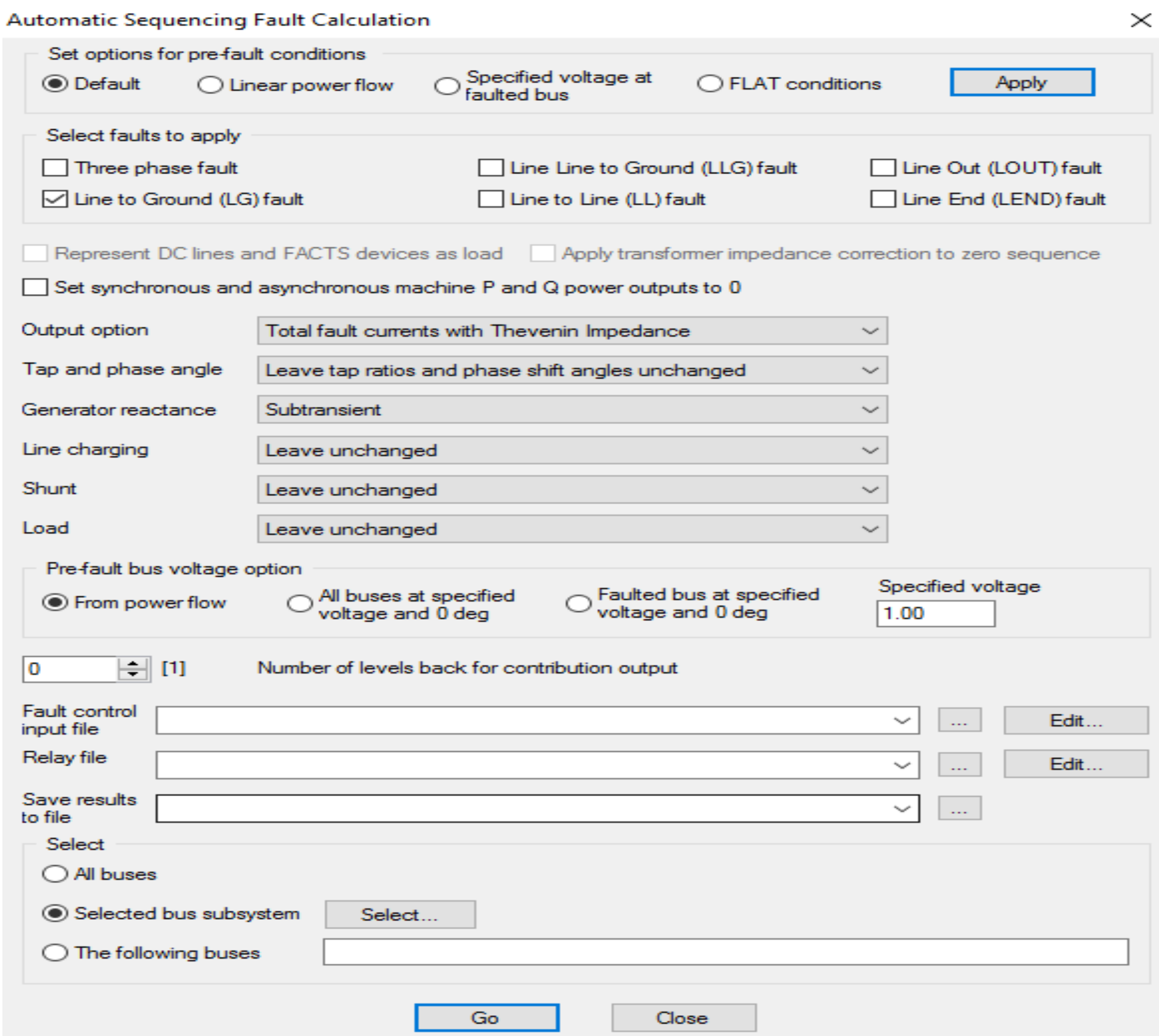

Figure 4 Automatic sequence fault calculation settings

The sum of negative and zero sequence resistance and reactance are converted into per unit values with 100 MVA base as shown in formula.

$$R\ (pu) = (100MVA/230kV^2) * R\ (ohms)$$

The per unit values of resistance and reactance are converted into MW and MVAR respectively to be used as shunt at the point of single line to ground fault in the simulations using the following formula.

$$G = (100MVA/\sqrt{R^2+X^2})* \cos(\tan^{-1}\frac{X}{R})\ MW$$

$$B = -(100MVA/\sqrt{R^2+X^2})* \sin(\tan^{-1}\frac{X}{R})\ MVAR$$

The value of B is negative because negative value of MVARs show inductance. The following table shows negative and zero sequence Thevenin impedance for the three busses under consideration for simulation.

Table 2 Sequence Thevenin impedance data

Substation		**Negative Sequence Thevenin Impedance**		**Zero Sequence Thevenin Impedance**		**Negative + Zero Sequence Thevenin Impedance**		**SLG Shunt (MVA)**	
Bus Name	(kV)	R (Ohms)	X (Ohms)	R (Ohms)	X (Ohms)	R (pu)	X (pu)	G (MW)	B (MVAR)
Pakistan	230	0.22417	2.65899	0.14818	2.21734	0.0007039	0.0092180	824	-10785
GoBulls	230	0.17642	2.26732	0.17957	1.91255	0.0006729	0.0079015	1070	-12565
Bravo	230	0.18602	2.60588	0.25393	3.06702	0.0008317	0.0107238	719	-9269

3.4 Procedure to Run Dynamic Simulations

The step by step procedure followed to perform simulations for this thesis is as follows.

3.4.1 Loading the Base Case and Setting Up the Channels Wizard

The network saved case (.sav) is loaded first and then dynamic data is loaded by opening the snap file (.snp).

Channel wizard is set up before dynamic simulations are run. The channel contains the parameters selected for output channel. The parameters (Rotor angle, Bus Voltage, Bus frequency, Load (MW and MVAR), Generator Terminal Voltage, Generator mechanical power, speed of rotor) and the selected busses that will be monitored during simulations. All 230 kV transmission lines and BES generators will be monitored for any type of instability. The Channel wizard set up is shown below.

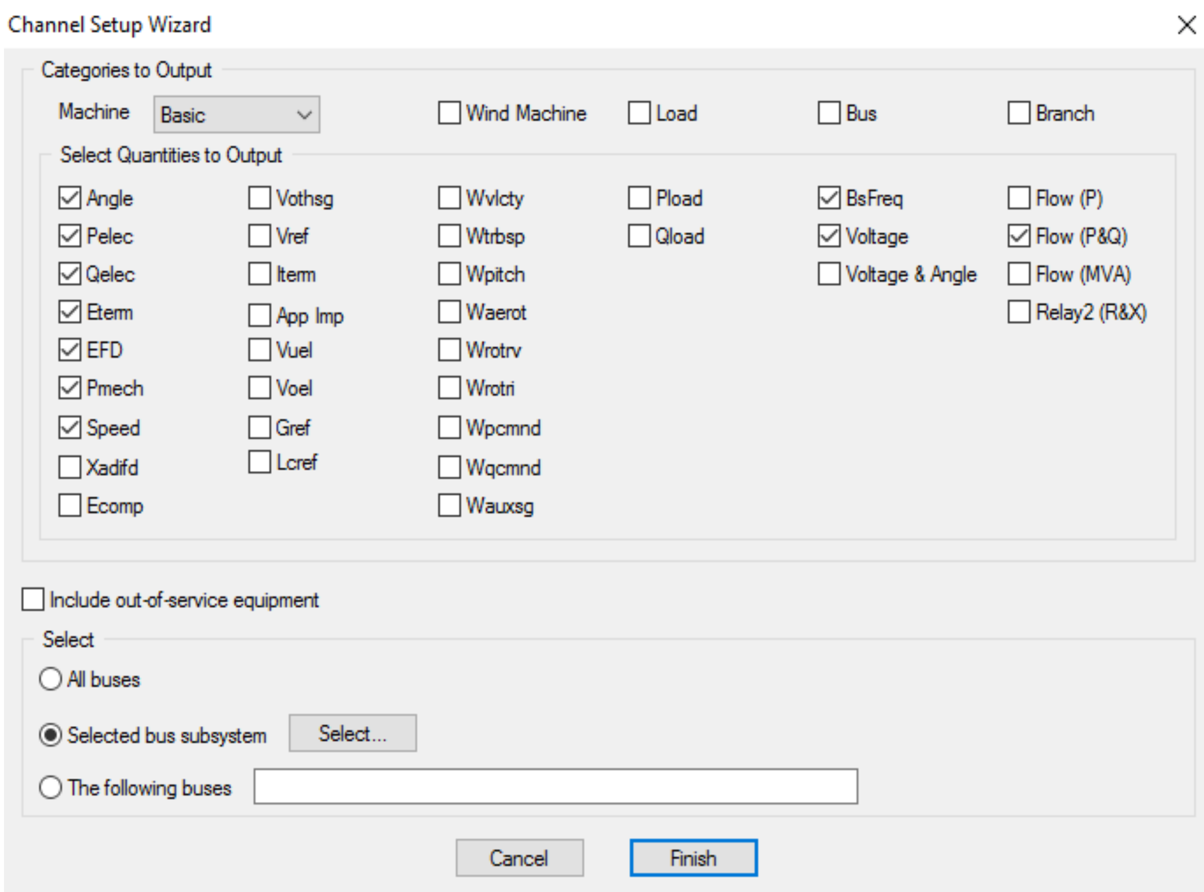

Figure 5 Channel wizard settings

3.4.2 Setting Up Dynamic Simulations Options

The dynamic simulation options are set up before the simulations are run, keeping in mind the parameters discussed in this thesis to monitor instability. The four main parameters to be monitored for instability are rotor angle, electrical power, frequency and voltage. The settings for dynamic simulation options are shown in the figure below.

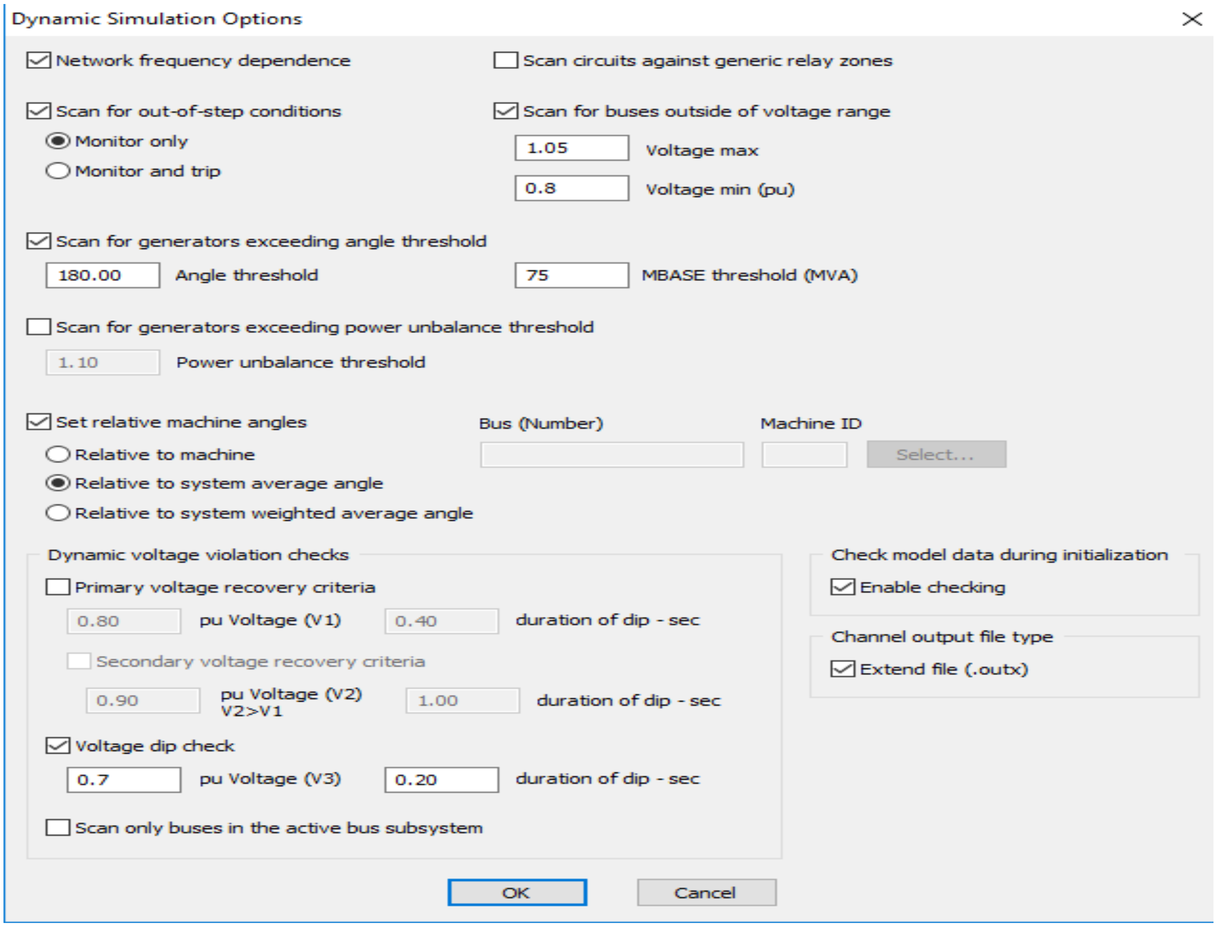

Figure 6 Dynamic simulation settings

3.4.3 Performing Dynamic Simulations

The network and dynamic data files are loaded. The channel output file is created and then the system is initialized and run to 6~ to ensure flat pre-disturbance conditions. A fault is applied at 6~ (0.1s) for all the simulation cases. Depending on the case, different fault duration is applied to the cases until the critical fault clearing time is found after multiple simulations run. The total simulation run time is 5 seconds. A log file is created which contains informational messages from the simulation. An output file is generated which contains all the quantities for different channels. The dynamic simulation settings are shown below.

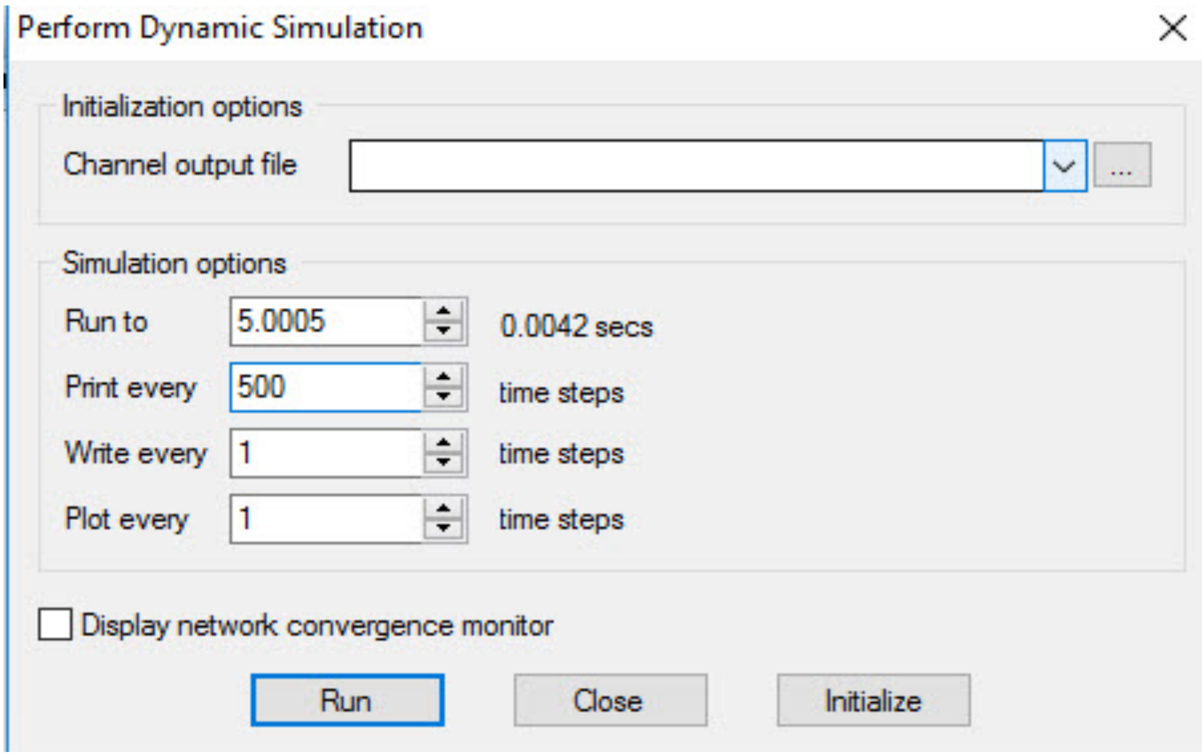

Figure 7 Performing dynamic simulations settings

CHAPTER 4

CASES AND SIMULATION RESULTS

4.1 Overview

The process discussed in Chapter 2 is implemented in this chapter to find instability, uncontrolled separation and cascading. This chapter is based on the results of simulations. Three power plants are considered with different generating units, excitation systems, protection settings and different network to which they are connected. An extreme event (as per TPL-001 standard by NERC) is considered for all the three power plants in which a three-phase fault occurs at one of the transmission circuits connected to a 230 kV generation substation, followed by a breaker failure.

There are several cases explained in this chapter in the following sections to show tremendous improvement in power system stability by enhancing Critical Fault Clearing Time.

4.2 Types of Approaches Used for Simulations

There are two main approaches used. In first approach, a GO (Gang Operated) breaker is used while in the second approach IPO (Independent Pole Operated) breaker is used.

4.2.1 Approach 1

The first approach used is based on Gang Operated (GO) circuit breakers. In GO circuit breaker, one operating mechanism is used for all the three poles. A GO circuit breaker is considered to run dynamic simulations after a three-phase fault occurs on 230 kV transmission circuit followed by breaker failure. The critical fault clearing time would be found by running the simulations for multiple fault durations (1~ increments) while monitoring the log and output files for any loss of synchronism.

4.2.2 Approach 2

The second approach used is based on Independent Pole Operated (IPO) circuit breakers. IPO breakers have separate operating mechanism for every pole. It means that if a three phase fault occurs on a transmission circuit followed by breaker failure (with only one pole stuck assumption), only one pole would fail to operate while the other two poles would operate normally. The separate mechanism for each pole operates every pole independently from the other. In this approach, three phase fault occurs on 230 kV transmission circuit followed by breaker failure scenario (one stuck pole assumption). Due to IPO breaker, the three phase fault is converted to a single line to ground fault right after the normal fault clearing time at the local end. The critical fault clearing time would be found by running the simulations for multiple fault durations (1~ increments) while monitoring the log and output files for any loss of synchronism.

4.3 Cases and Results

4.3.1 Case 1 – Fulbright Power Plant

Consider a Power Plant called "Fulbright" which is connected to a 230 kV Substation Pakistan via GSU (Generation Step Up) transformer. The generation capacity of power plant is 1632 MW. The two ST (Steam Turbine) units have IEEET1 exciter system while the CTs (Combustion Turbines) have ESST4B exciter system. All the CTs have active Turbine Governor and Stabilizer features as well.

The unit details are given in the following table.

Table 3 Fulbright power plant unit details

Fulbright Power Plant					
Unit	Type of Turbine	Power (MW)	Name Plate		Inertia (s)
			(MVA)	Terminal (kV)	
FB_1ST	Steam	236	256	20	3.76
FB_2ST	Steam	308	495	22	3.11
FB_CT1A	Combustion	152	211	18	5.26
FB_CT1B	Combustion	152	211	18	5.26
FB_CT1C	Combustion	152	211	18	5.26
FB_CT2A	Combustion	158	211	18	5.26
FB_CT2B	Combustion	158	211	18	5.26
FB_CT2C	Combustion	158	211	18	5.26
FB_CT2D	Combustion	158	211	18	5.26
Total		1632	2228		

The power plant is connected to a 230 kV substation called "Pakistan" that has total eighteen 230 kV transmission circuits. There are nine transmission circuits capable of exporting power to the grid.

The bus/branch diagram from PSS®E is given below.

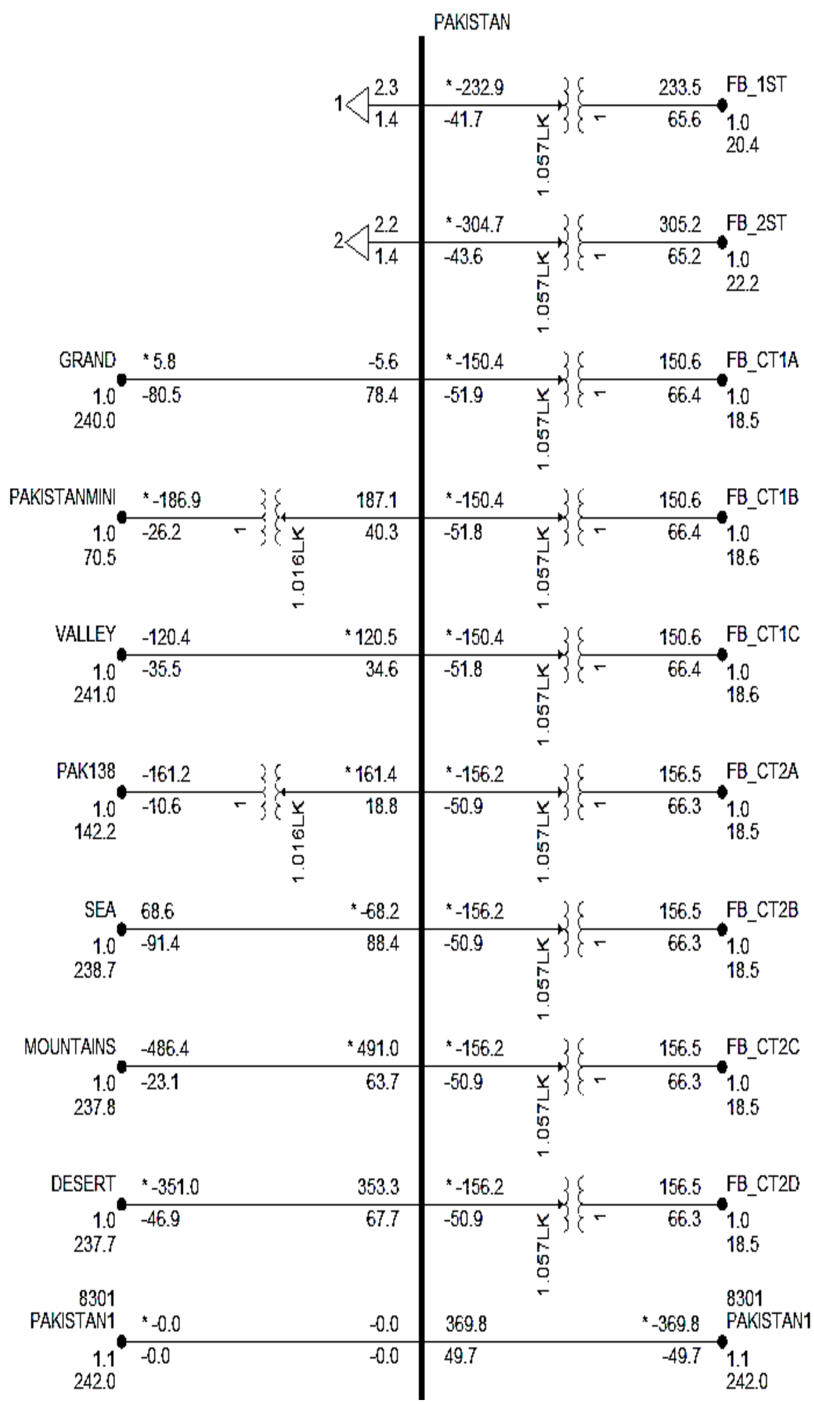

Figure 8 Bus/Branch diagram of 230 kV Pakistan substation

This power plant has the station service load connected to the LV (Low Voltage) bus of GSU (Generator Step Up) transformer as shown in the bus/branch diagram of one of the units.

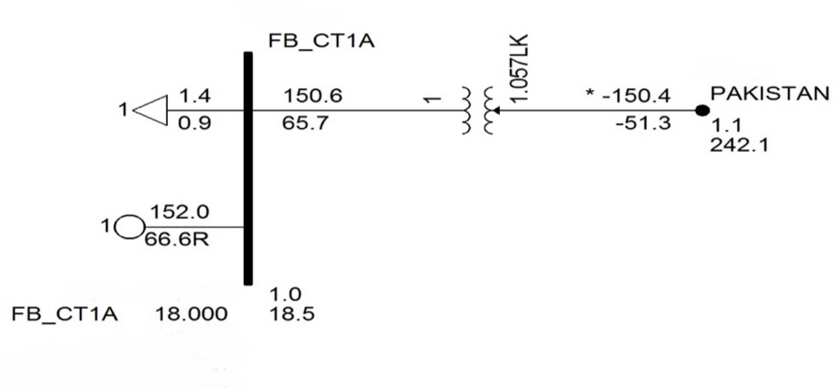

Figure 9 LV (Low Voltage) bus of Fulbright power plant

The 230 kV circuit (Pakistan – Mountain) carried the maximum load of 491 MVA. A three-phase fault occurred on this circuit followed by breaker failure.

The bus/branch diagram showing the fault is given below.

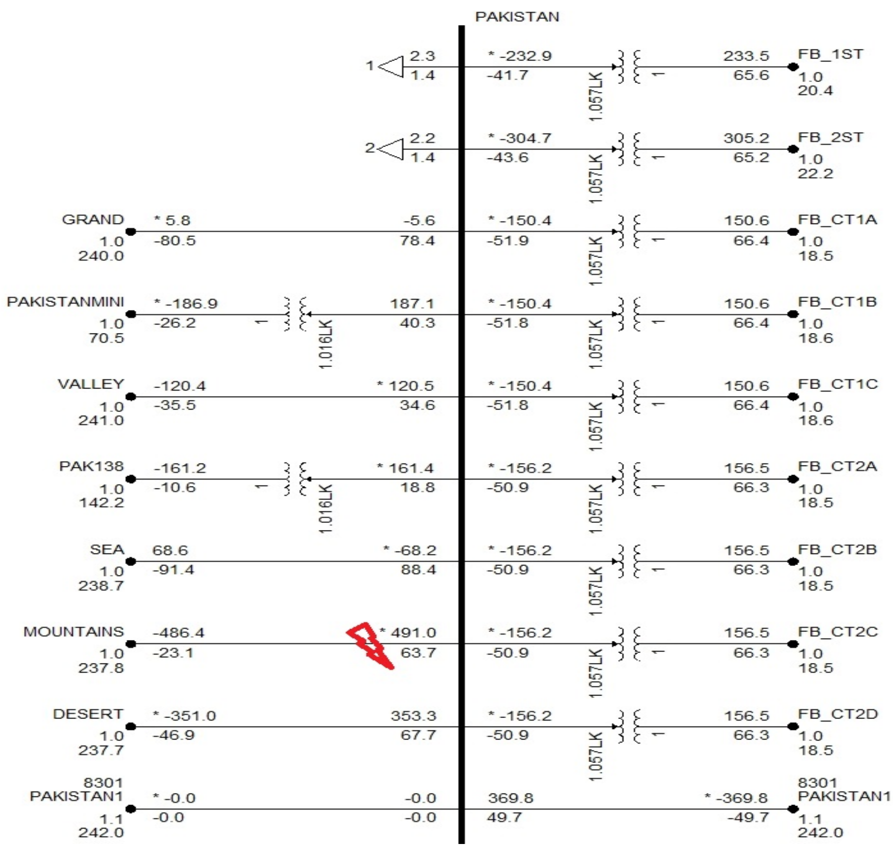

Figure 10 Bus/Branch diagram of 230 kV Pakistan substation with three phase fault

4.3.1.1 Critical Fault Clearing Time Using Approach 1 for Case 1

A three-phase fault occurred at 230 kV Pakistan-Mountains circuit right outside the fence of 230 kV Pakistan substation. The fault location was very close to the 230-kV Pakistan bus. As the fault was in zone 1 of 230 kV Pakistan bus, it took 1~ for the relay to sense the fault and 2~ for the breakers to operate. The remote end (230 kV Mountain) breaker operated in 5~. The GO breaker at Pakistan end failed to operate. But in order to clear the fault from local end, the breaker failure relay sent trip signal to back up breakers. It was observed that for a total fault clearing time of 14~, all units remained in synchronism as shown in Figure 11.

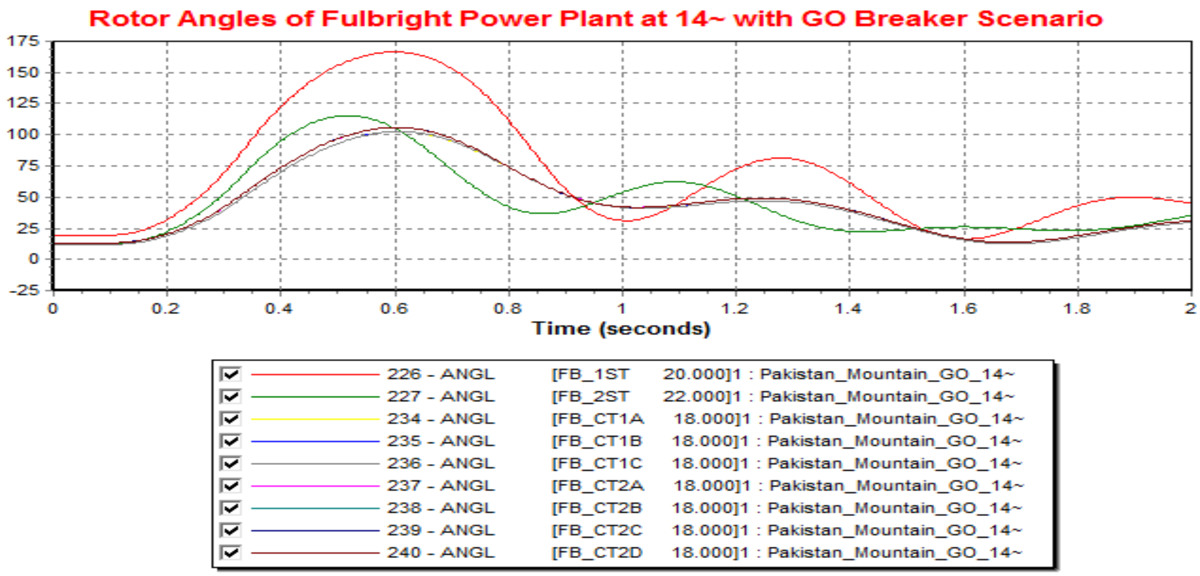

Figure 11 Rotor angles of Fulbright power plant units with GO breaker at 14~

For a total fault clearing time of 15~, Fulbright 1ST lost synchronism as shown in Figure 12.

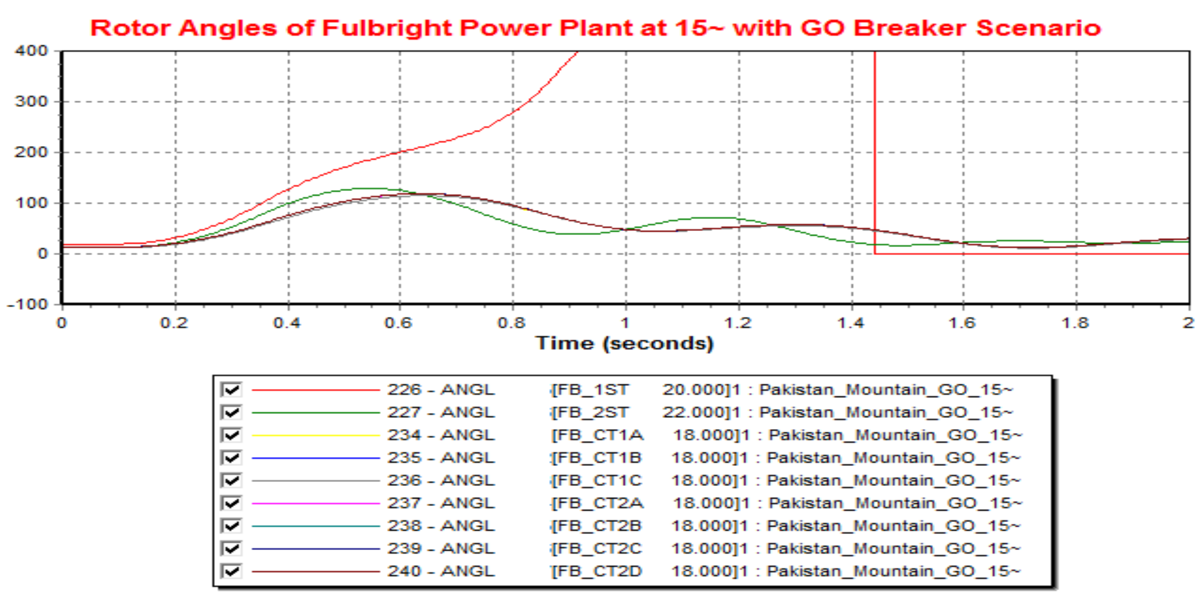

Figure 12 Rotor angles of Fulbright power plant with GO breaker at 15~

The rotor angles comparison of Fulbright 1ST for a total fault clearing time of 14~ and 15~ is given below.

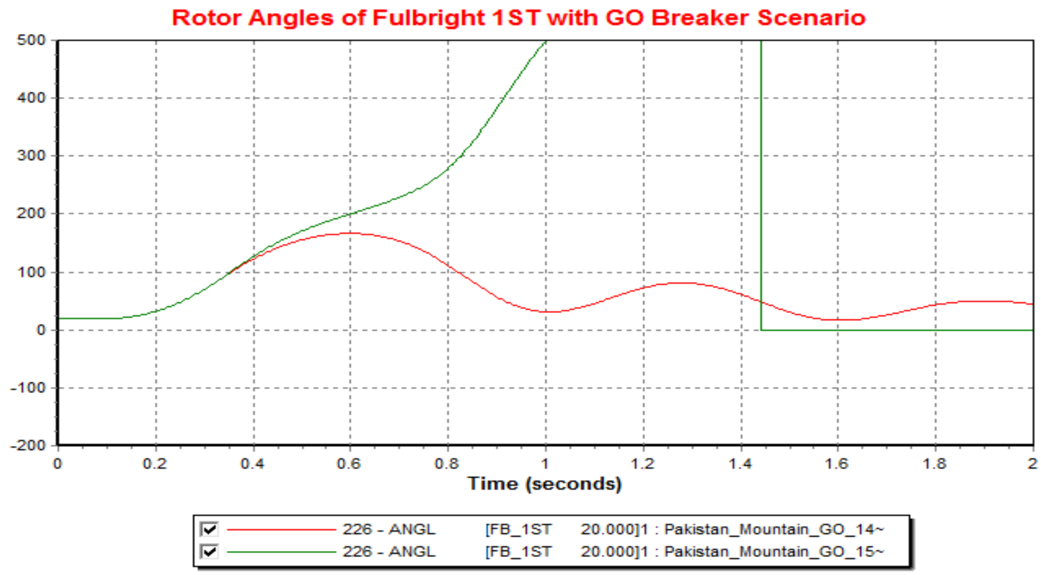

Figure 13 Rotor angles comparison of Fulbright 1ST with GO breaker scenario

The electrical power comparison for total fault clearing time of 14~ and 15~ is given below. If the fault stays on the system for 15~, Fulbright 1ST loses synchronism.

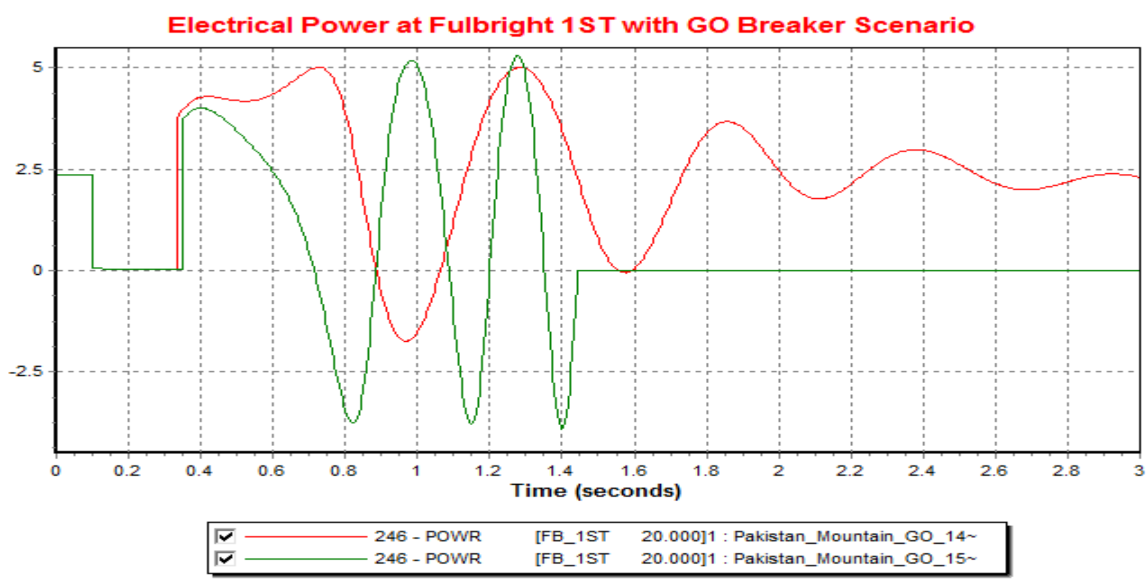

Figure 14 Electrical power comparison at Fulbright 1ST Unit with GO breaker scenario

The voltage at 230kV Pakistan bus for total fault clearing time of 14~ and 15~ with GO breaker is given below.

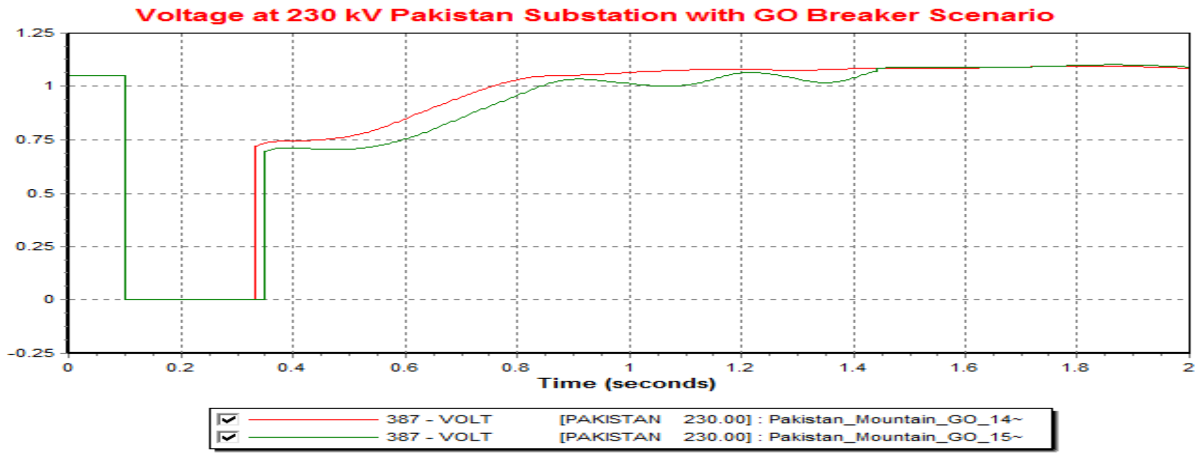

Figure 15 Voltage at 230 kV Pakistan substation with GO breaker scenario

The frequency at 230 kV Pakistan Substation for total fault clearing time of 14~ and 15~ with GO breaker is given below. According to this graph, the frequency does not drop down to 59.6 Hz to trigger UFLS (Under Frequency Load Shed).

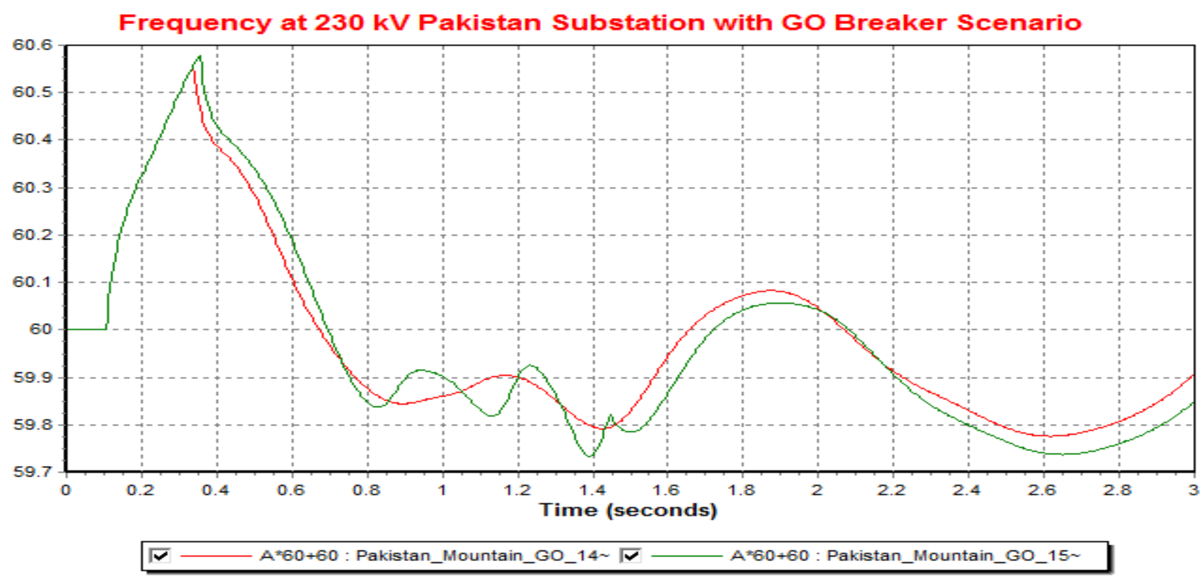

Figure 16 Frequency at 230 kV Pakistan substation with GO breaker scenario

4.3.1.2 Critical Fault Clearing Time Using Approach 2 for Case 1

A three-phase fault occurred at 230 kV Pakistan-Mountains circuit right outside the fence of 230 kV Pakistan substation. The fault location was very close to the 230 kV Pakistan bus. The fault was followed by breaker failure situation but in this case only one pole of the breaker failed to operate while the other two poles of the phases operated normally. It took 1~ for the relay to detect fault, 2 ~ for the circuit breaker to operate in its zone 1. It took 5~ to clear the fault from remote end which is 230 kV Mountains substation. In the case of an IPO breaker, the three-phase fault is converted to a single line to ground fault due to one stuck pole and none of the units lost synchronism due to single line to ground fault as shown in Figure 17.

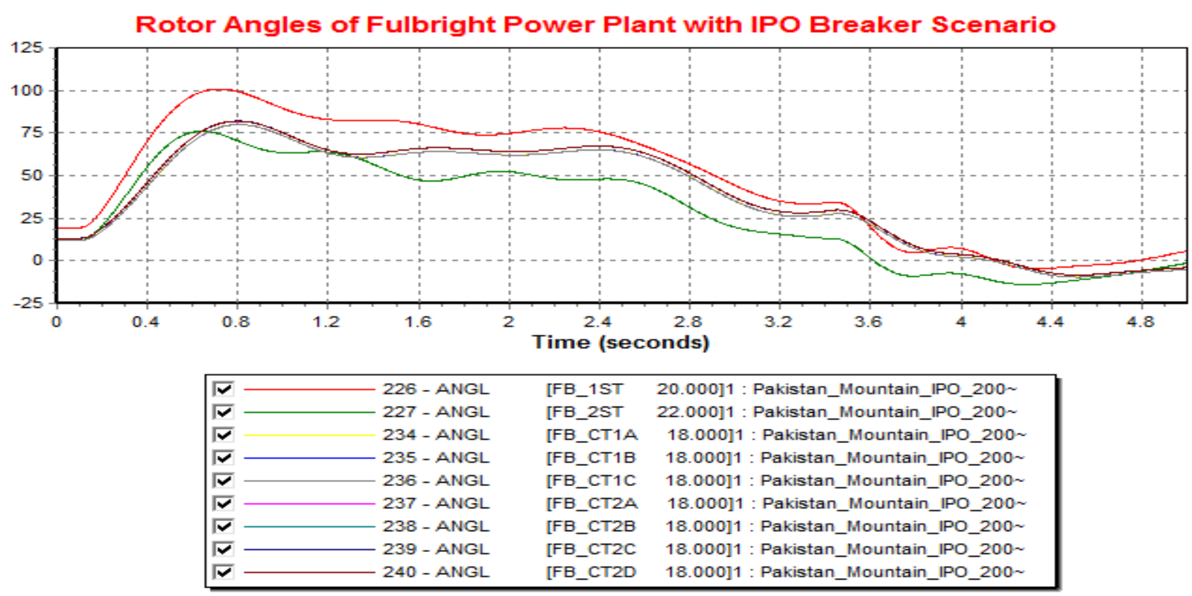

Figure 17 Rotor angles of Fulbright power plant units with IPO breaker at 200~

The electrical power at Fulbright 1ST unit is given below. The electrical power curve of Fulbright ST1 curve is shown because it is the least stable unit and lost synchronism in case of GO breaker failure. The single line to ground fault stayed on the system for 200~ and none of the units lost synchronism. When the fault was applied, the electrical power dropped down to almost zero. A small amount of electrical power from the generator was fed to the auxiliary load and GSU losses during the fault. At 200~, the fault was cleared and there was 60% increase in the electrical power.

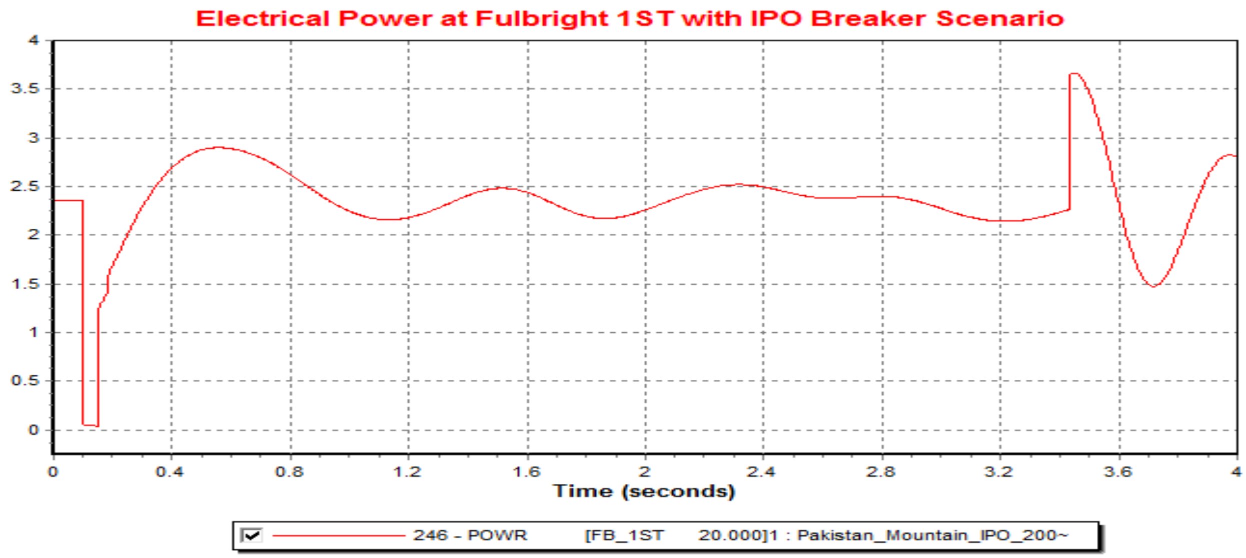

Figure 18 Electrical power at Fulbright 1ST with IPO breaker at 200~

The voltage at 230kV Pakistan bus is given below. When the three phase fault occurred, the positive sequence voltage went down to zero. An IPO breaker with one stuck pole clears two phases of the fault from local end which brings the positive sequence voltage from zero up to 0.63 pu. With a single line to ground fault remaining on the system for 200~, none of the units lost synchronism.

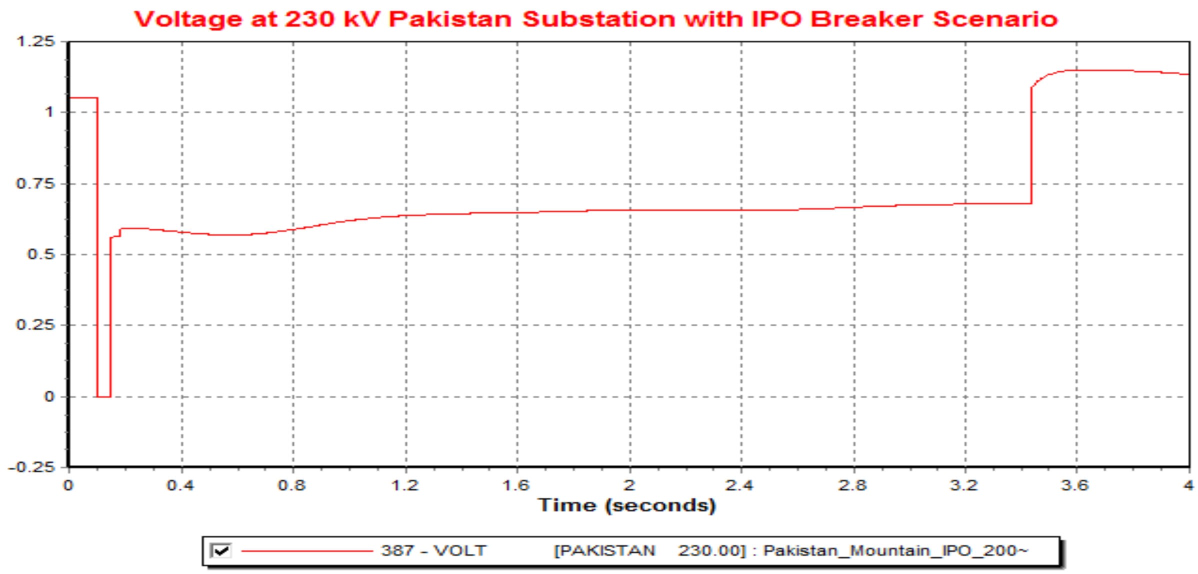

Figure 19 Voltage at 230 kV Pakistan substation with IPO breaker at 200~

The frequency at 230 kV Pakistan substation with IPO breaker is given below. The frequency did not drop down to 59.6 Hz to trigger UFLS.

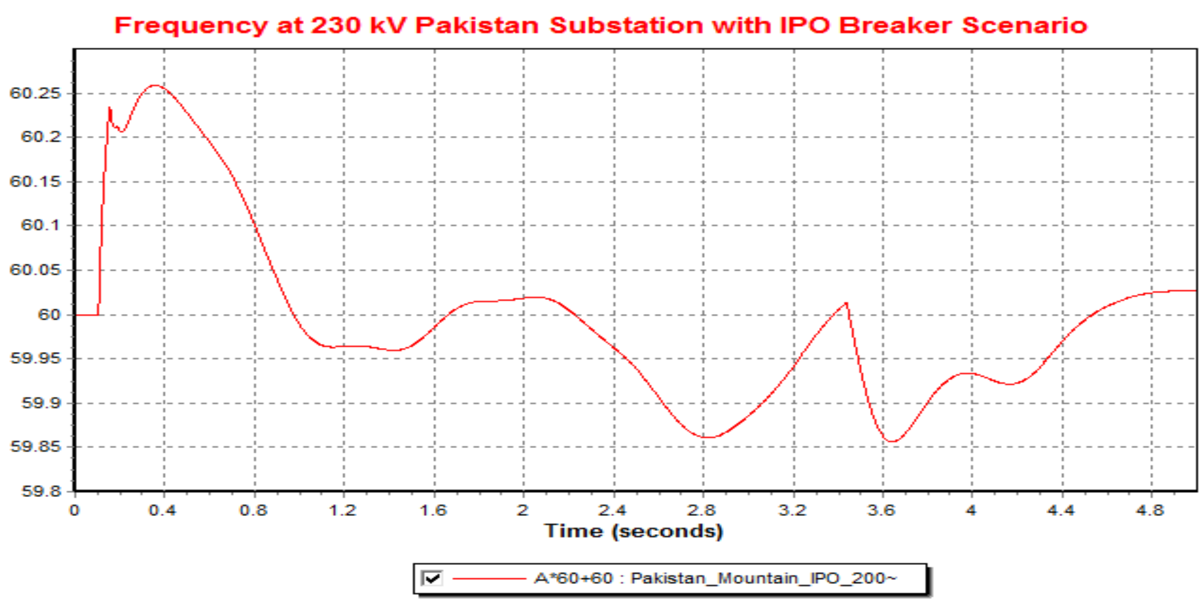

Figure 20 Frequency at 230 kV Pakistan substation with IPO breaker at 200~

4.3.2 Results for Case 1

The results for GO and IPO breakers were compared for 230 kV Pakistan substation, and IPO breakers gave the best results. The comparison is shown below.

Table 4 Comparison of GO and IPO breaker for 230 kV Pakistan substation

Gang Operated Breakers	**Independent Pole Operated Breakers**
Critical Fault Clearing Time = 14 ~	Critical Fault Clearing Time = >200~
At 15 ~, Fulbright 1ST lost synchronism	At 200~, none of the units lost synchronism

4.3.3 Case 2 – GoBulls Power Plant

Consider a Power Plant called "GoBulls" which is connected to a 230 kV Substation GoBulls. The generation capacity of power plant is 1767 MW. It consists of four STs (Steam Turbines) and one CT (Combustion Turbine). The four ST units have IEEET1 Exciter system while the CT has AC exciter system. The turbine governor feature is active for unit GoBulls 1 & 2 while the others do not have that feature. None of the units have Stabilizer feature active. The unit details are given in the following table.

Table 5 GoBulls Power Plant unit details

GoBulls Power Plant					
Units	Type of Turbine	Power (MW)	Power (MVA)	Terminal Voltage (kV)	Inertia (s)
GoBulls 1	Steam	410	495	24	2.94
GoBulls 2	Steam	410	495	24	2.94
GoBulls 3	Steam	420	495	22	2.74
GoBulls 4	Steam	470	540	22	2.30
GoBulls CT4	Combustion	57	82	13.8	1.55
Total		1767	2107		

The power plant is connected to a 230-kV substation called "GoBulls" which has fourteen 230 kV transmission circuits. There are five circuits which are directly connected to the GoBulls Power Plant while the other nine are 230 kV transmission circuits capable of exporting power to the grid. The PSS®E bus/branch diagram is given below.

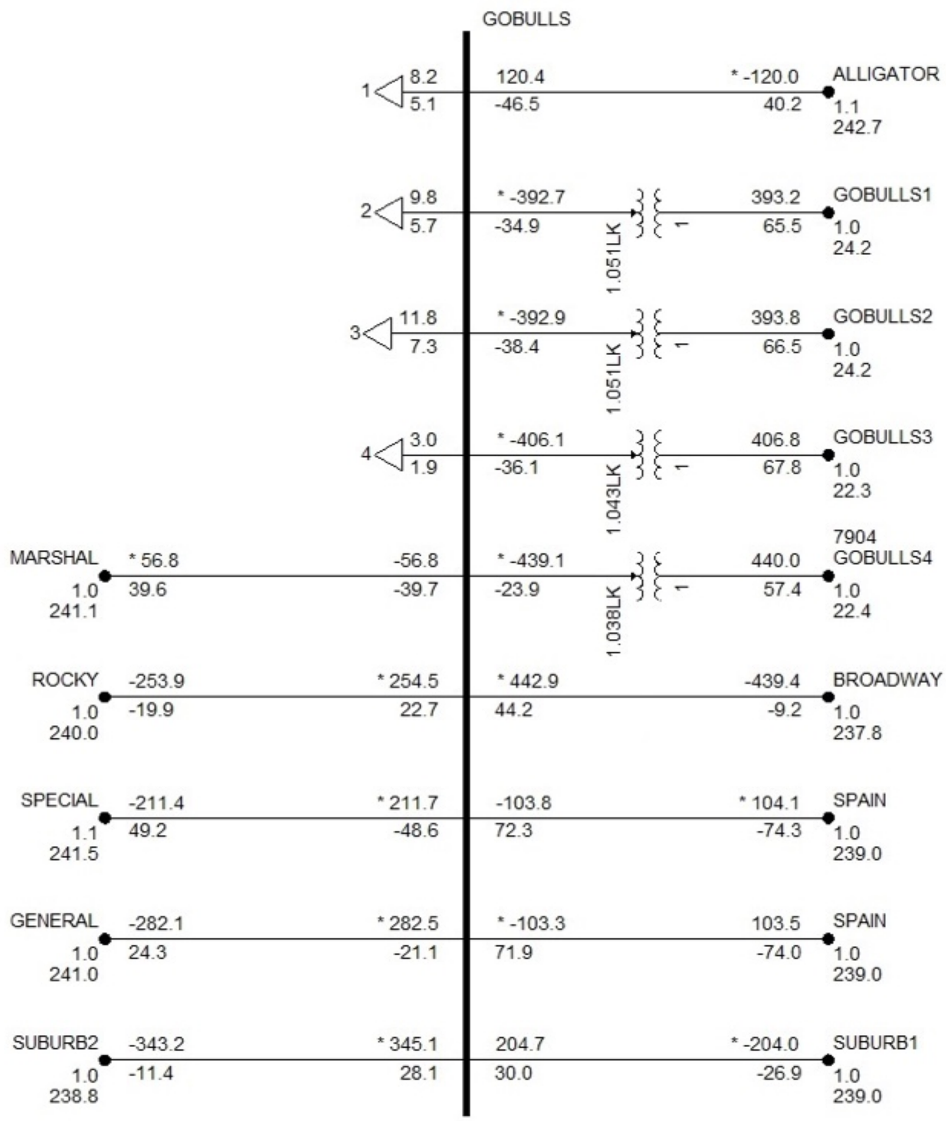

Figure 21 Bus/Branch diagram of 230 kV GoBulls substation

This power plant has the station service load connected to the LV (Low Voltage) bus of GSU (Generator Step Up) transformer as shown in the diagram of one of the units.

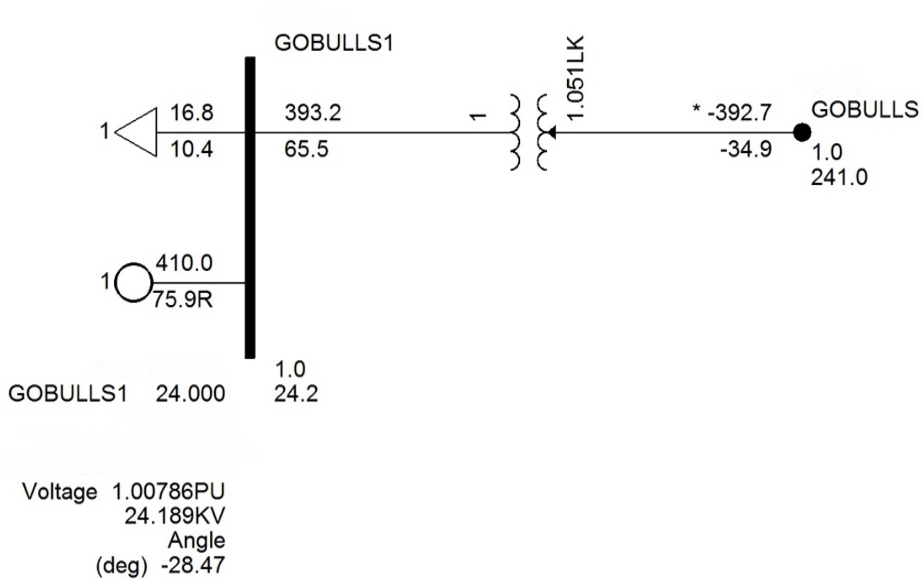

Figure 22 LV bus of GoBulls power plant

The 230 kV circuit (GoBulls – Broadway) carried the maximum load of 439 MVA. A three-phase fault occurred on this circuit followed by breaker failure. The bus/branch diagram showing the fault is given below.

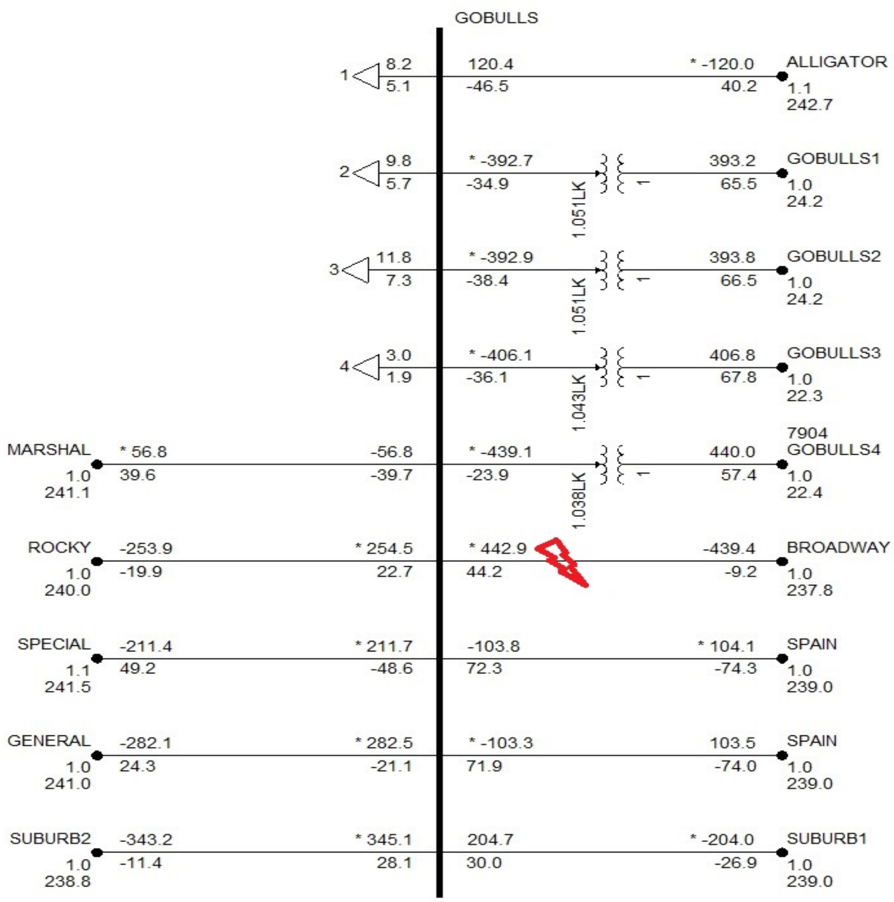

Figure 23 Bus/Branch diagram of 230 kV GoBulls substation with 3 phase fault

4.3.3.1 Critical Fault Clearing Time Using Approach 1 for Case 2

A three-phase fault occurred at 230 kV GoBulls-Broadway circuit right outside the fence of 230 kV GoBulls substation. The fault location was very close to the 230-kV GoBulls bus. As the fault was in zone one of 230 kV GoBulls bus, it took 1~ for the relay to sense the fault and 2~ for the breaker to operate. The remote end (230 kV Mountain) breaker operated in 5~. The GO breaker at GoBulls end failed to operate. But in order to clear the fault from local end, the relay sent trip signal to back up breakers. It was observed that at 11~ total fault clearing time, all units remained in synchronism as shown in figure 24.

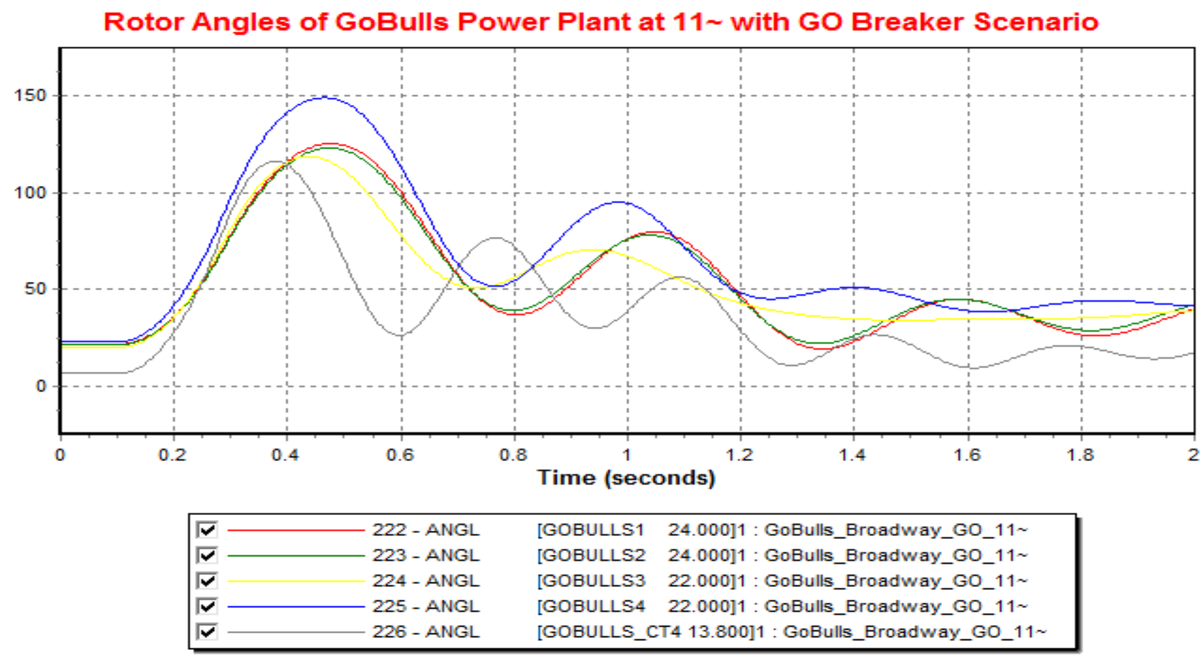

Figure 24 Rotor angles of GoBulls power plant units with GO breaker at 11~

At 12~ total fault clearing time, GoBulls 4 unit lost synchronism. The rotor angles for total fault clearing time of 12~ are shown below.

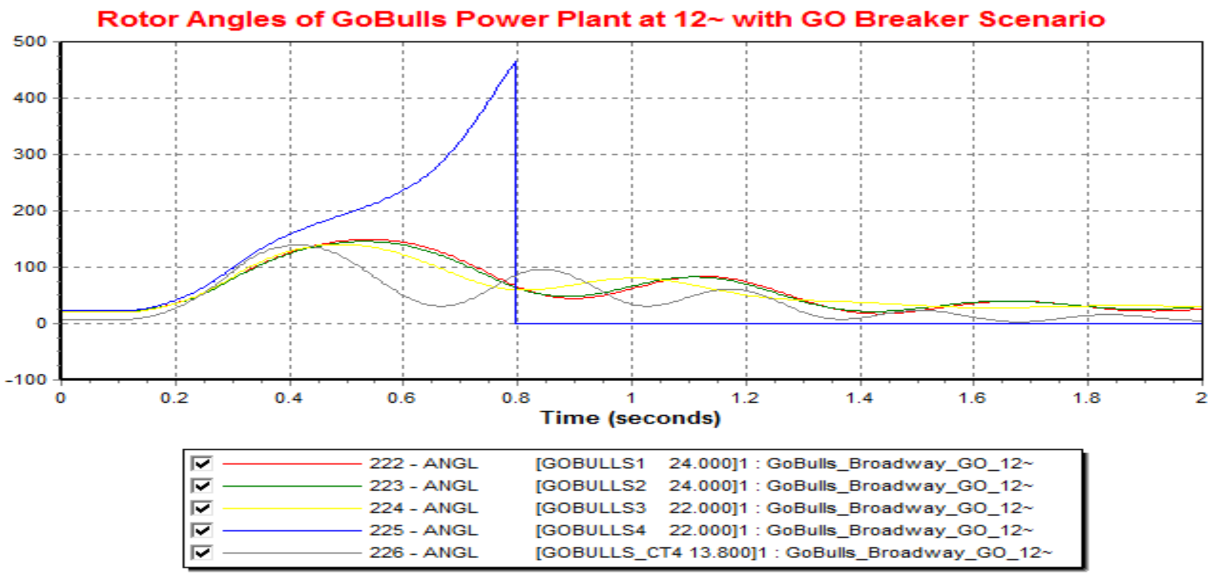

Figure 25 Rotor angles of GoBulls power plant with GO breaker at 12~

The rotor angles comparison of GoBulls 4 unit for total fault clearing time of 11~ and 12~ are given below.

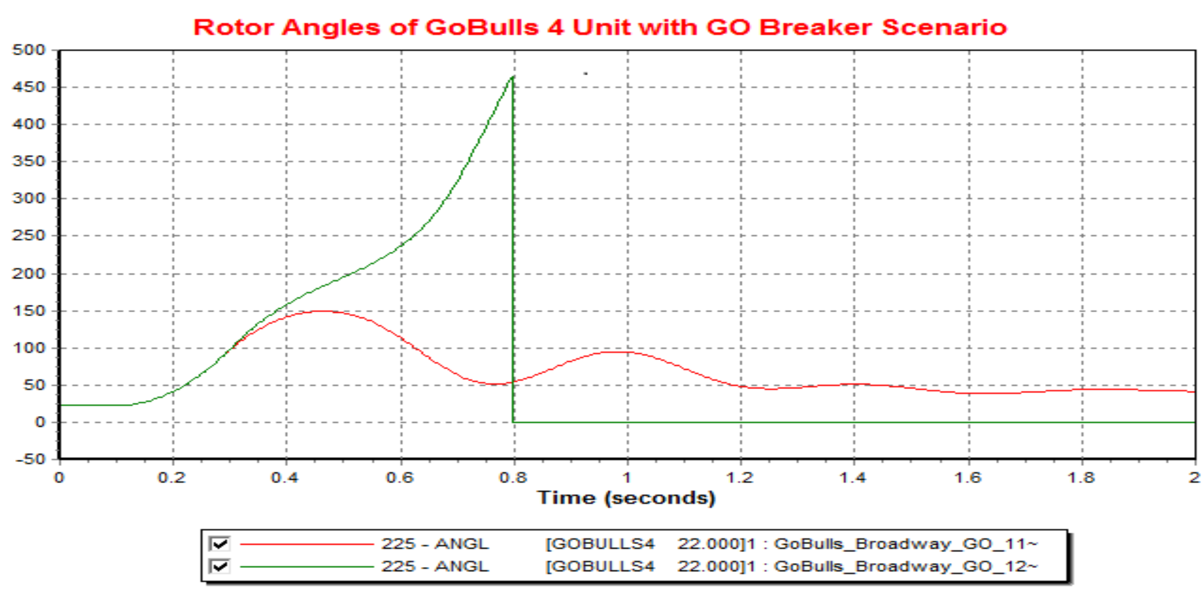

Figure 26 Rotor angles comparison of GoBulls 4 unit with GO breaker scenario

The electrical power comparison for 11~ and 12~ total fault clearing time is given below. If the fault stays on the system for 12~, GoBulls 4 unit loses synchronism along with 907.2 MW of UFLS.

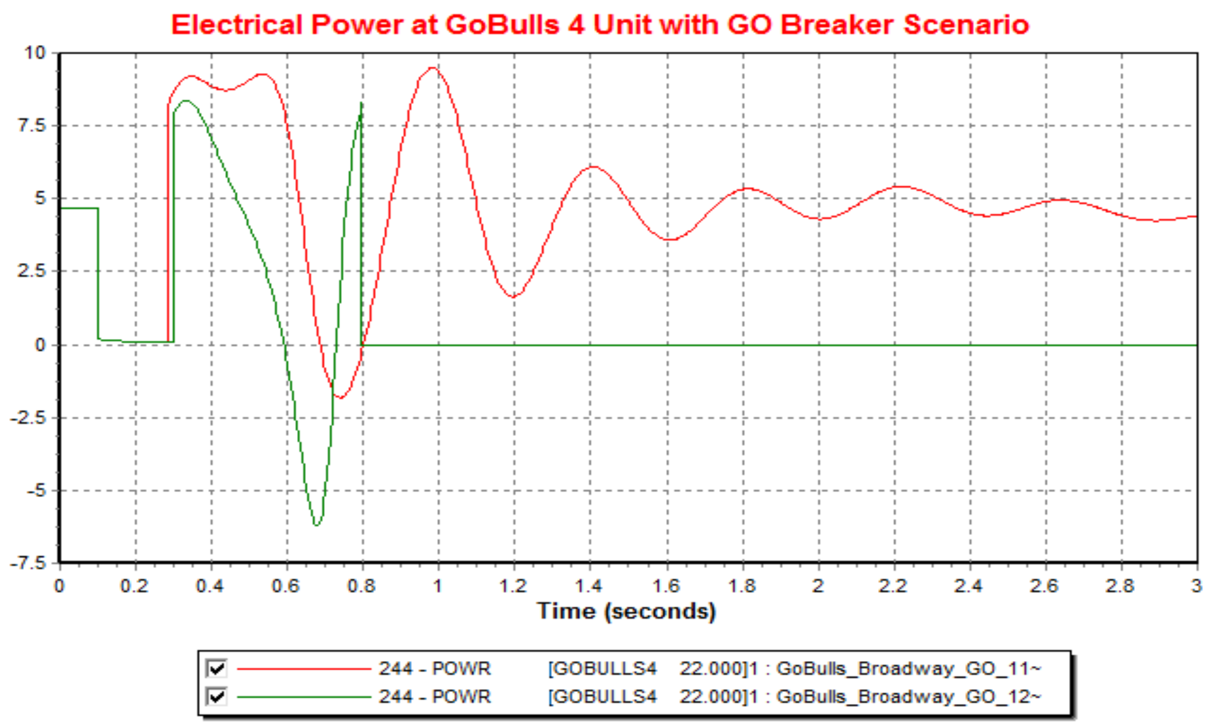

Figure 27 Electrical power comparison of GoBulls 4 unit with GO breaker scenario

The voltage at 230kV GoBulls bus for total fault clearing time of 11~ and 12~ is given below.

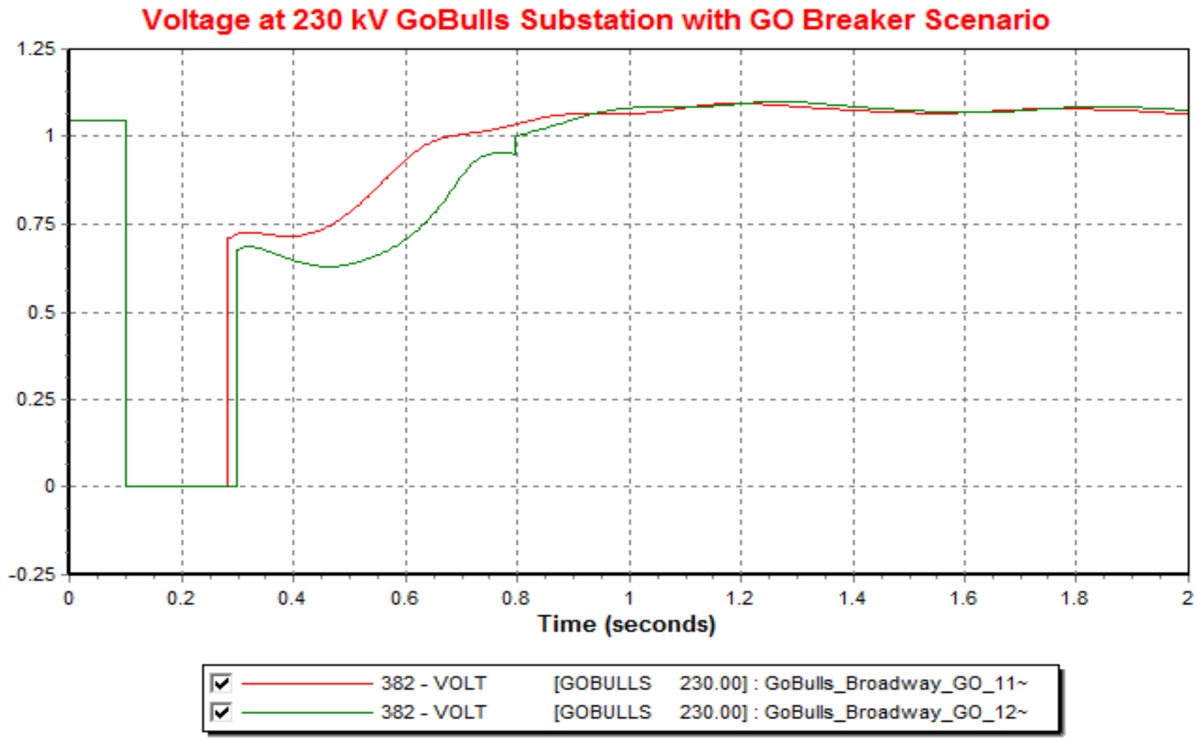

Figure 28 Voltage at 230 kV GoBulls substation with GO breaker scenario

The frequency at various distribution substation went below 59.6 Hz triggering stage 1 of UFLS program, shedding a load of 907.2 MW. However, the frequency at GoBulls substation went down to 59.7 Hz as shown below.

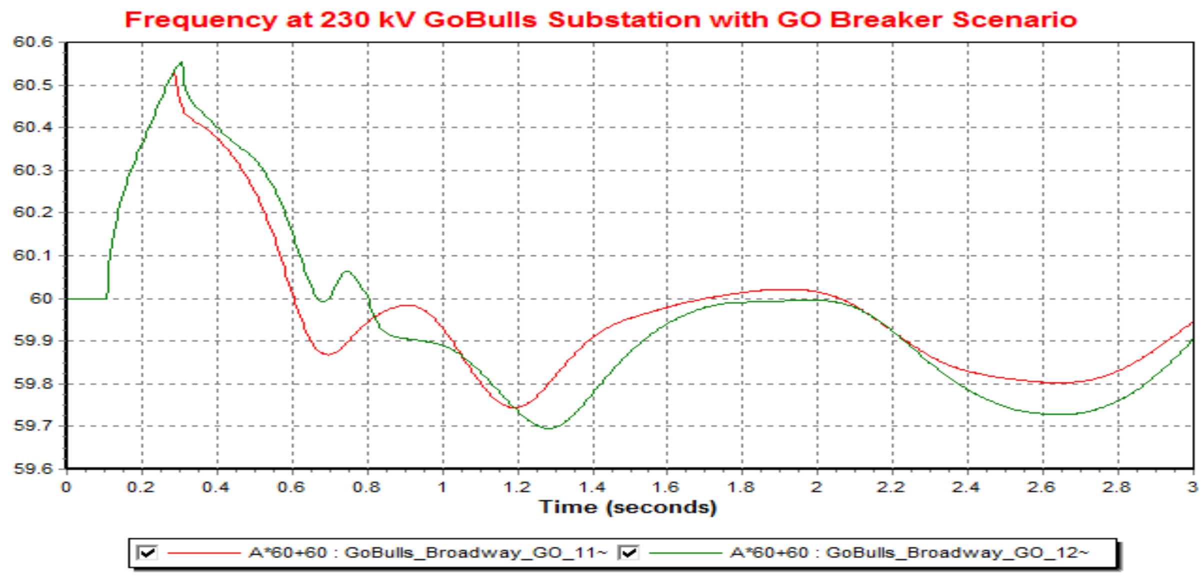

Figure 29 Frequency at 230 kV GoBulls substation with GO breaker scenario

4.3.3.2 Critical Fault Clearing Time Using Approach 2 for Case 2

A three-phase fault occurred at 230kV GoBulls-Broadway circuit right outside the fence of 230 kV GoBulls substation. The fault location was very close to the 230 kV GoBulls bus. The fault was followed by breaker failure situation but in this case only one pole of the breaker failed to operate while the other two poles of the phases operated. It took 1~ for the relay to detect fault, 2~ for the circuit breaker to operate in its zone 1. It took 5~ to clear the fault from remote end which is 230 kV Broadway substation.

In the case of an IPO breaker, the three-phase fault is converted to a single line to ground fault due to one stuck pole and none of the units lost synchronism due to single line to ground fault as shown in Figure 30.

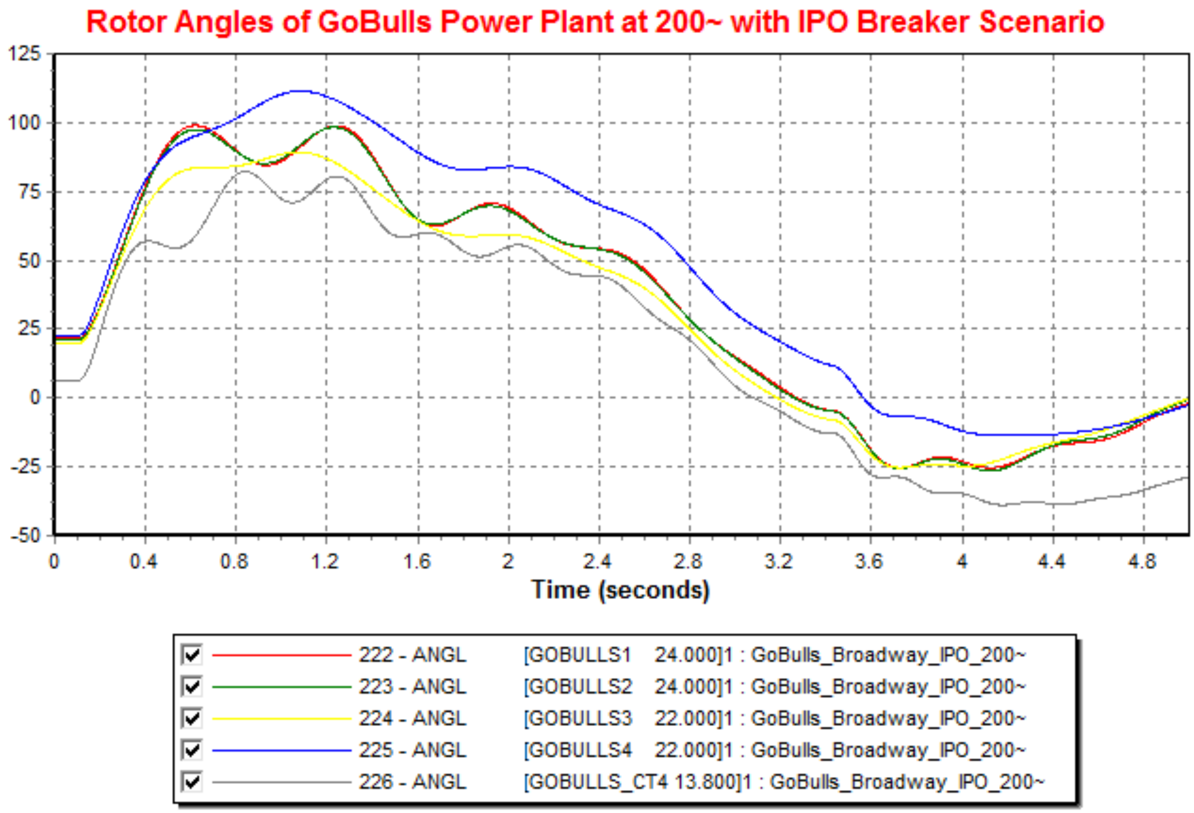

Figure 30 Rotor angles of GoBulls power plant units with IPO breaker at 200~

The electrical power of GoBulls 4 unit is given below. The electrical power of GoBulls 4 is shown because it is the least stable unit as compared to others and lost synchronism in the case of GO breaker. When the fault occurred, the electrical power dropped down to almost zero. A small amount of electrical power from the generator was fed to the auxiliary load and GSU losses during the fault. At 200~, the fault was cleared and there was 60% increase in the electrical power.

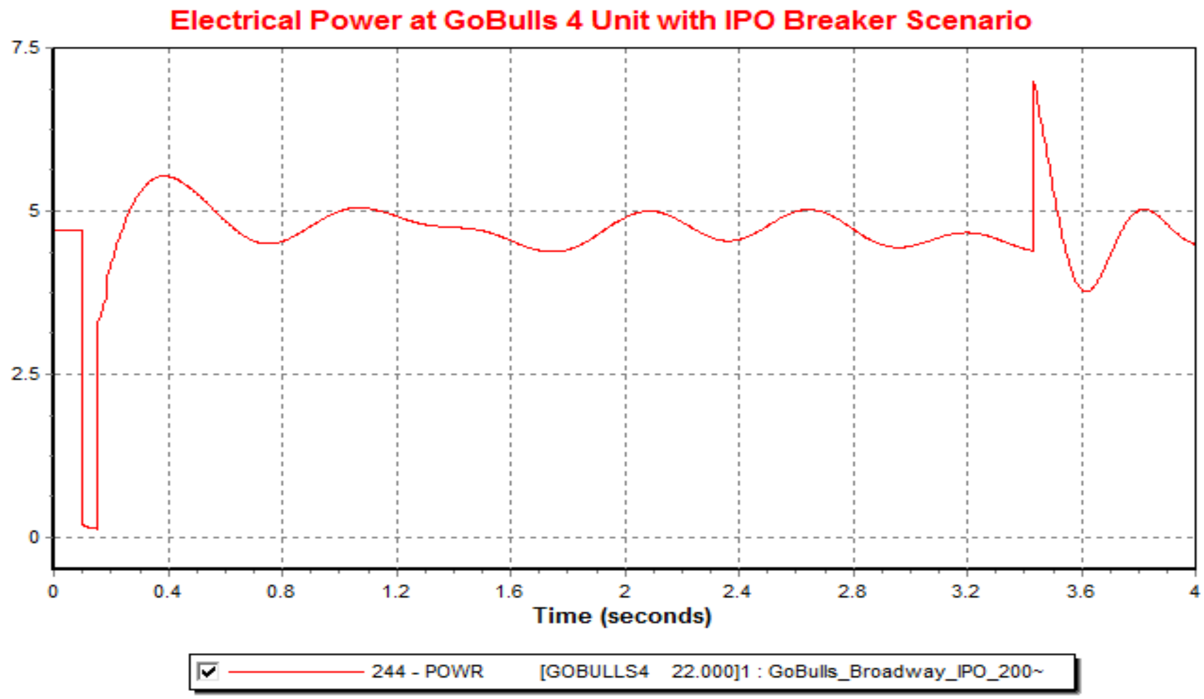

Figure 31 Electrical power at GoBulls 4 unit with IPO breaker at 200~

The voltage at 230kV GoBulls bus is given below. When the three phase fault occurred, the positive sequence voltage went down to zero. An IPO breaker with one stuck pole clears two phases of the fault from local end which brings the positive sequence voltage from zero up to 0.63 pu. With a single line to ground fault remaining on the system for 200~, none of the units lost synchronism.

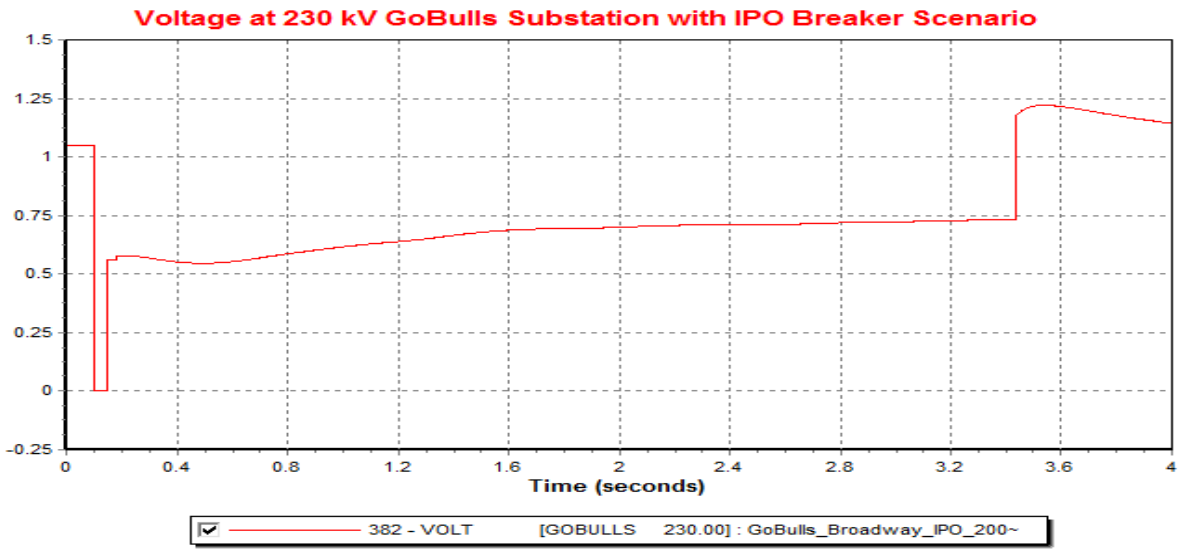

Figure 32 Voltage at 230 kV GoBulls substation with IPO breaker at 200~

The frequency at 230 kV GoBulls substation is given below. There was not any UFLS observed during simulations as the frequency dip went to 59.8 Hz.

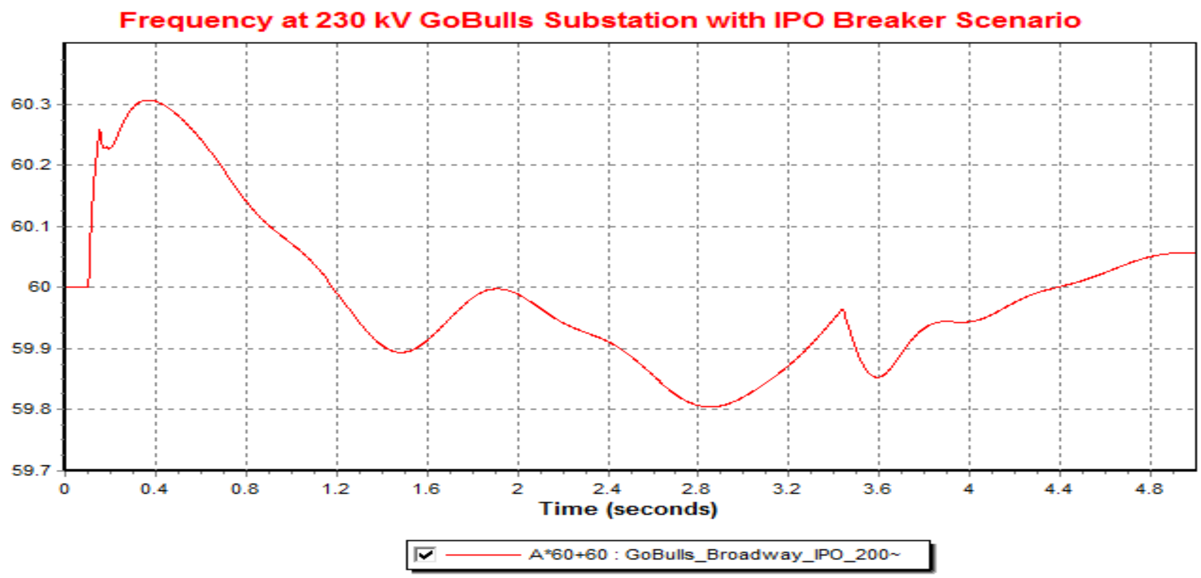

Figure 33 Frequency at 230 kV GoBulls substation with IPO breaker at 200~

4.3.4 Results for Case 2

The results for GO and IPO breakers were compared for 230 kV GoBulls Substation and IPO breakers gave the best results. The comparison is shown below.

Table 6 Comparison of GO and IPO breaker for 230 kV GoBulls substation

Gang Operated Breakers	**Independent Pole Operated Breakers**
Critical Fault Clearing Time = 11~	Critical Fault Clearing Time >200~
At 12~, GoBulls 4 unit tripped with 907.2 MW Load Shed	At 200~, none of the units lost synchronism

4.3.5 Case 3 – Bravo Power Plant

Consider a Power Plant called "Bravo" which is connected to 230kV Bravo Substation. The generation capacity of this Power Plant is 1401 MW. It consists of five Combustion Turbine (CT) units and two Steam Turbine (ST) units. Bravo CT1, CT2, CT3 and ST1 has same exciter system of EXST1 with no active turbine governor and stabilizer feature. Bravo CT4 has an exciter system of EXST1 with no active Turbine governor and Stabilizer feature. Bravo ST2 has an exciter system of ESST1A with active Stabilizer feature and no Turbine governor feature. The details of each unit are given in the following table.

Table 7 Bravo power plant unit details

Bravo Power Plant					
Unit	Type of Turbine	Power (MW)	Power (MVA)	Terminal Voltage (kV)	Inertia (s)
Bravo CT1	Combustion	170	229	18	4.8
Bravo ST1	Steam	120	154	13.8	3.5
Bravo CT2	Combustion	152	195	18	5.8
Bravo CT3	Combustion	152	195	18	5.94
Bravo CT4	Combustion	152	234	18	4.83
Bravo CT5	Combustion	152	234	18	4.83
Bravo ST2	Steam	503	570	24	3.8
Total		1401	1811		

The power plant is connected to a 230-kV substation called "Bravo" which has twelve (12) 230 kV circuits. There are seven circuits connected to Bravo Power Plant, while the other five are transmission circuits capable of exporting power to the grid.

The bus/branch diagram is given below.

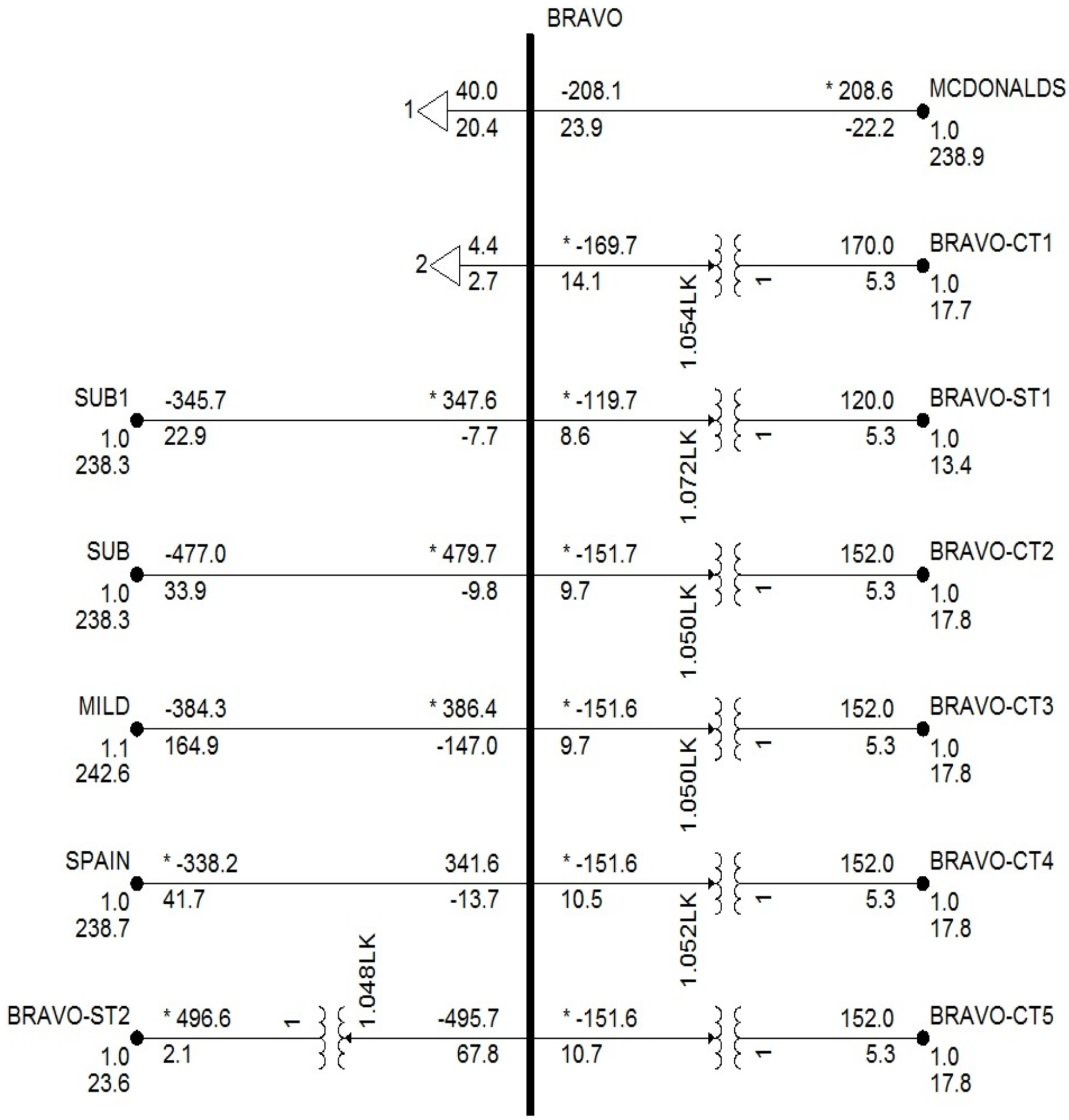

Figure 34 Bus/Branch diagram of 230 kV Bravo substation

This power plant does not have station service load connected to the LV (Low Voltage) bus of GSU transformer as shown in the bus/branch diagram of one of the units.

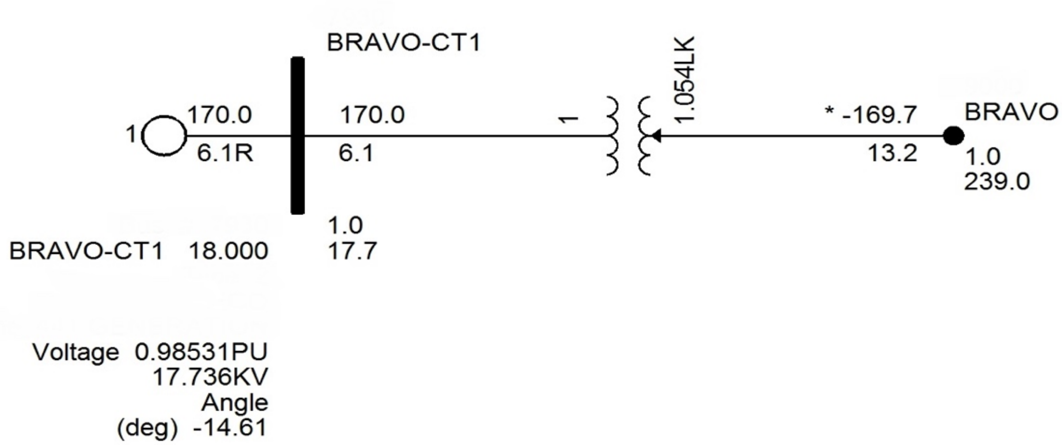

Figure 35 LV bus of Bravo power plant

The 230 kV circuit (Bravo – Spain) carried the load of 341 MVA. A three-phase fault occurred on this circuit followed by breaker failure. The bus/branch diagram showing the fault is given below.

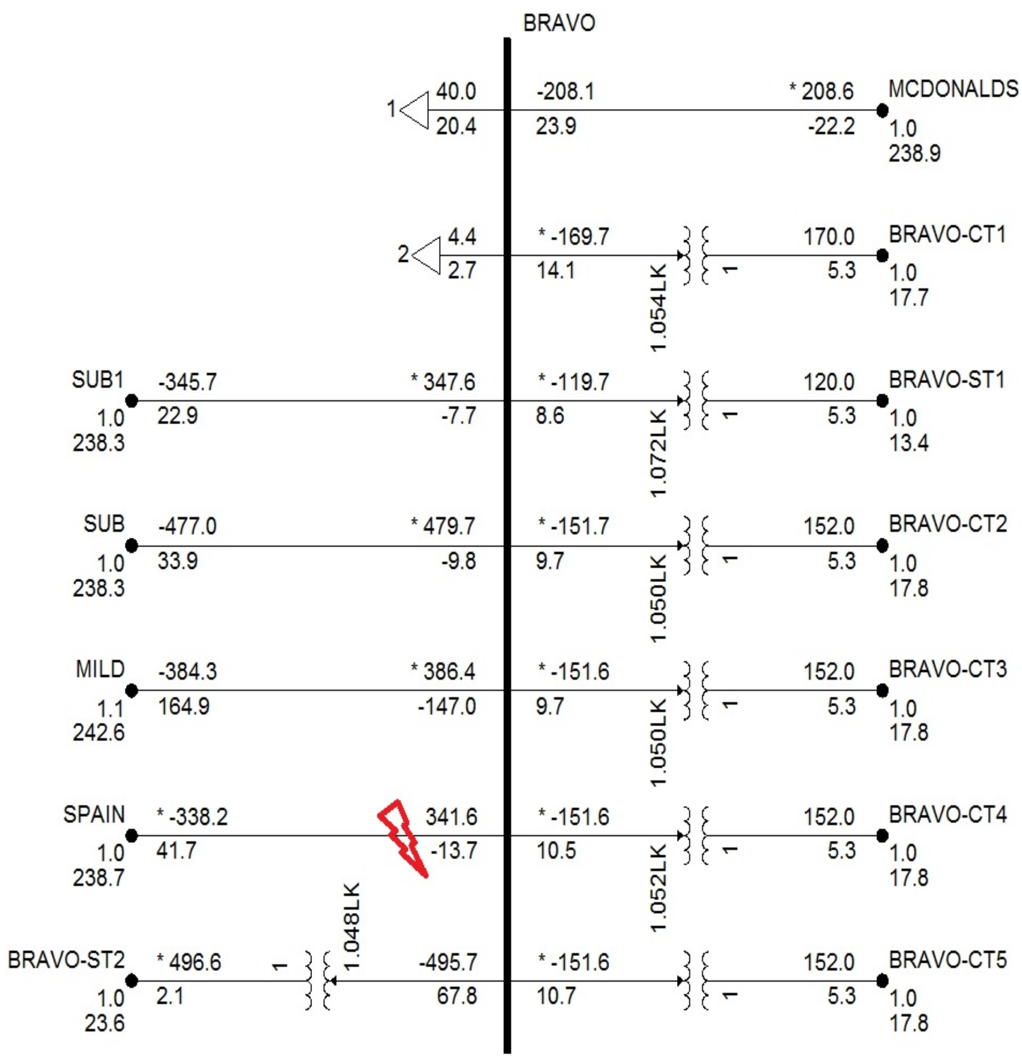

Figure 36 Bus/Branch diagram of 230 kV Bravo substation with fault

4.3.5.1 Critical Fault Clearing Time Using Approach 1 for Case 3

A three-phase fault occurred at 230 kV Bravo-Spain circuit right outside the fence of 230 kV Bravo substation. The fault location was very close to the 230-kV Bravo bus. As the fault was in zone one of 230 kV Bravo bus, it took 1~ for the relay to sense the fault and 2~for the breaker to operate. The remote end (230 kV Spain) breaker operated in 5~. The GO breaker at Bravo end failed to operate. But in order to clear the fault from local end, the relay sent trip signal to back up breakers to clear the fault. It was observed that for a total fault clearing time of 10~, all units remained in synchronism as shown in figure 37.

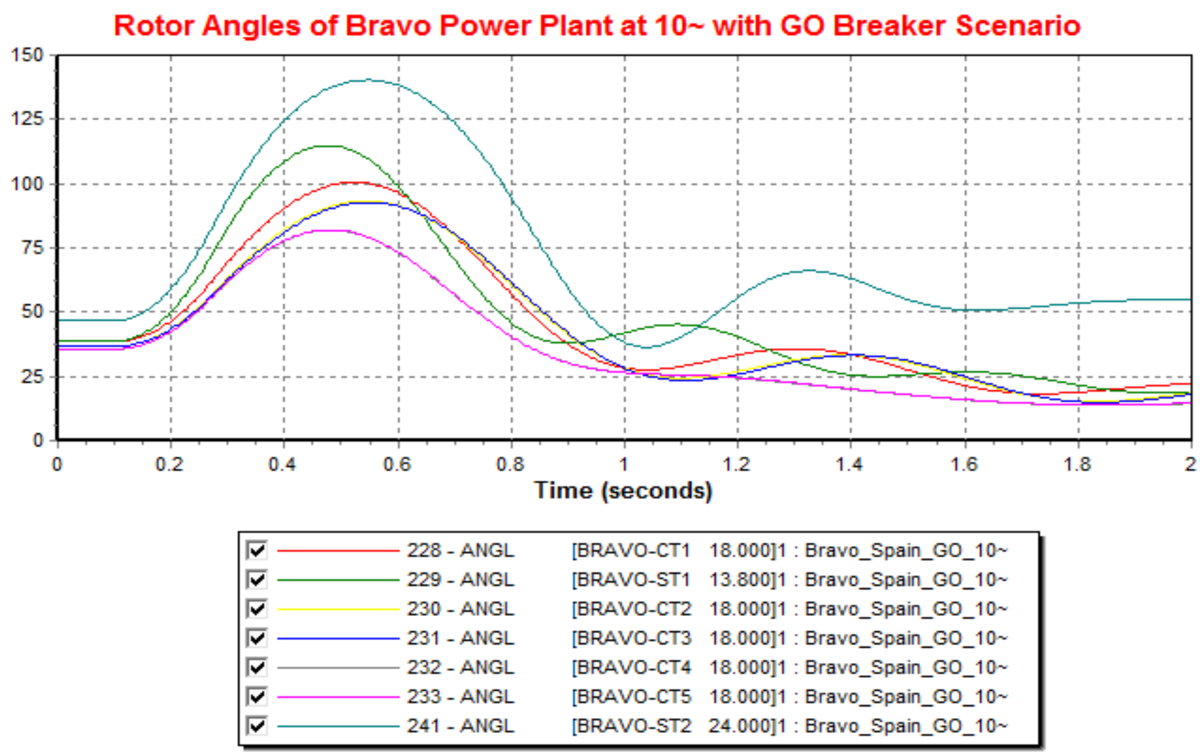

Figure 37 Rotor angles of Bravo power plant units with GO breaker at 10~

For a total fault clearing time of 11~, Bravo ST2 unit lost synchronism as shown below.

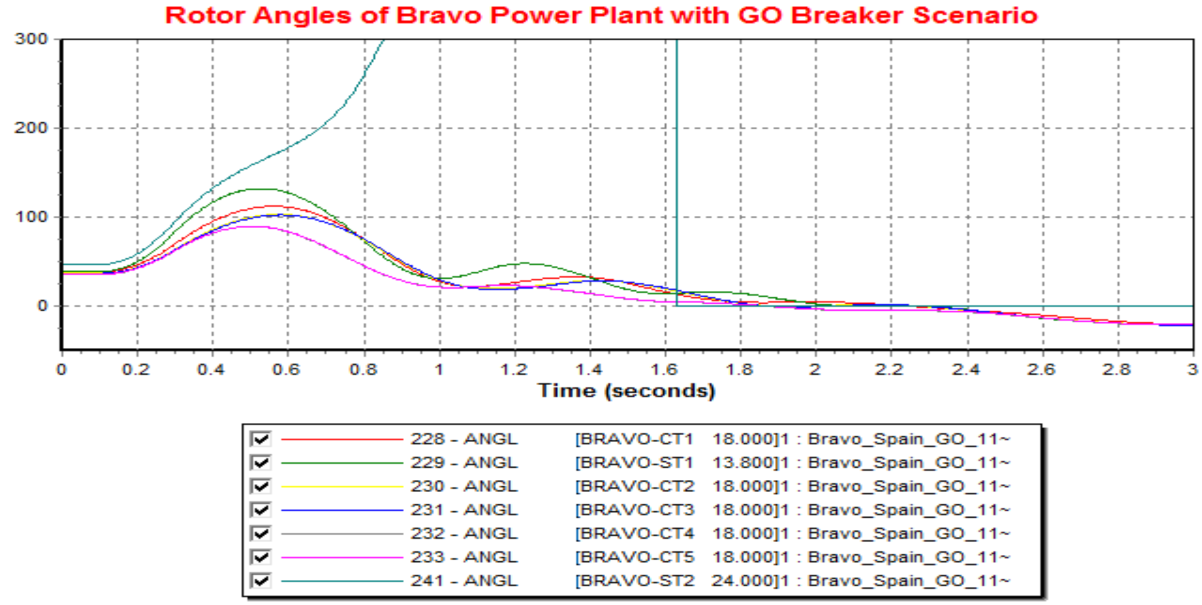

Figure 38 Rotor angles of Bravo power plant with GO breaker at 11~

The rotor angle comparison for Bravo ST2 unit is given below for a total fault clearing time of 10~ and 11~.

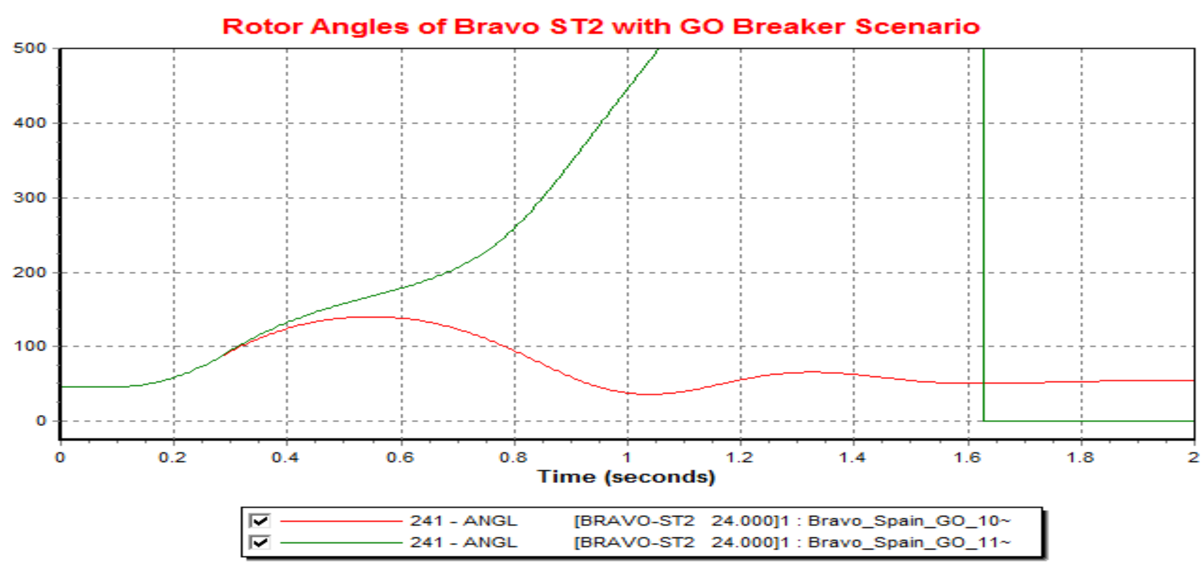

Figure 39 Rotor angles comparison of Bravo ST2 unit with GO breaker scenario

The electrical power comparison of Bravo ST2 unit for a total fault clearing time for 10~ and 11~is given below.

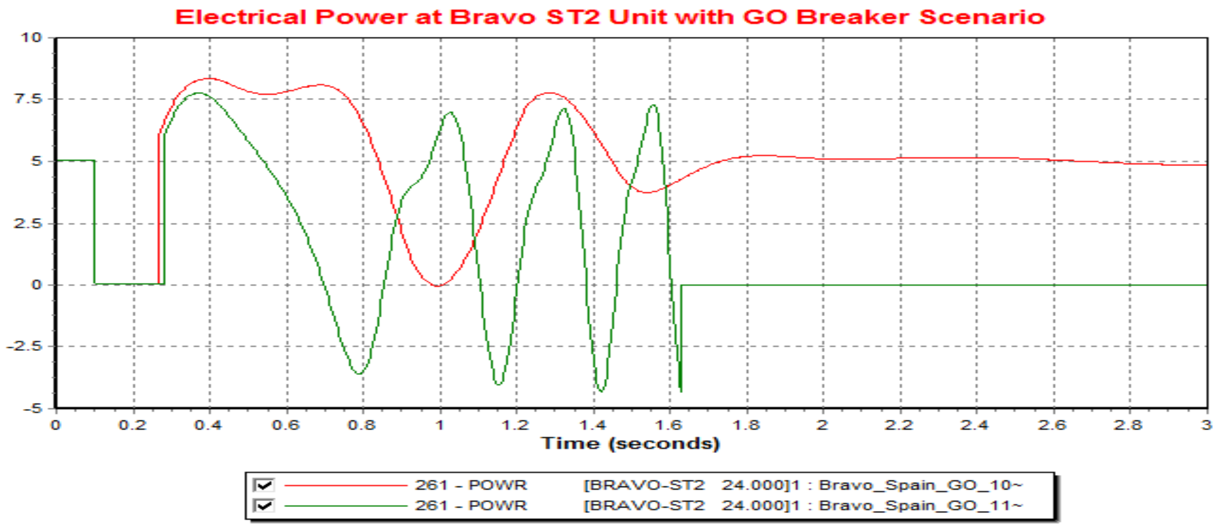

Figure 40 Electrical power comparison of Bravo ST2 with GO breaker scenario

The voltage at 230kV Bravo bus is given below for a total fault clearing time of 10~ and 11~.

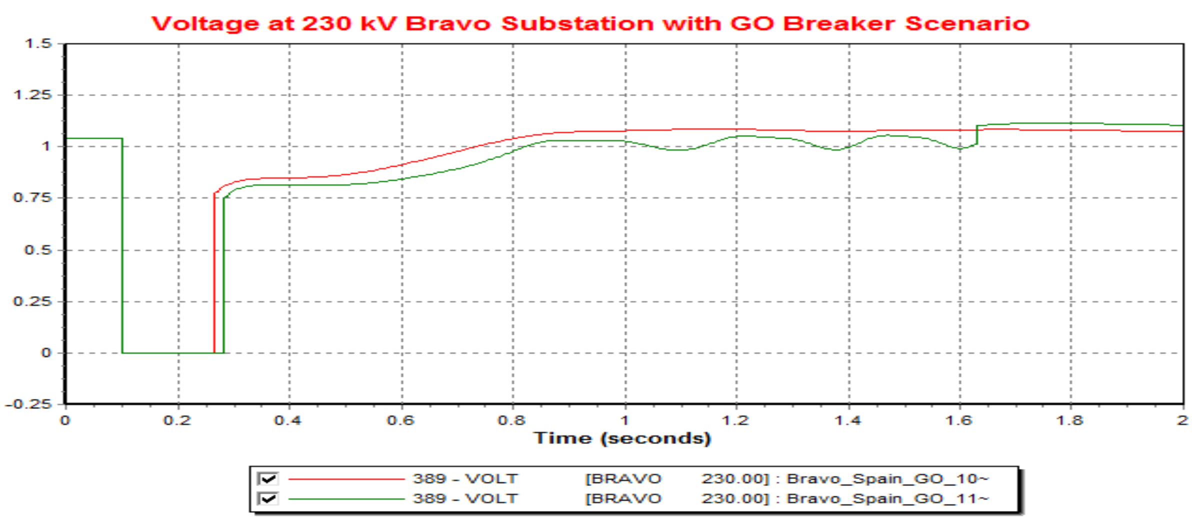

Figure 41 Voltage at 230 kV Bravo substation with GO breaker scenario

The frequency at 230 kV Bravo substation for the total fault clearing time of 10~ and 11~ is given below.

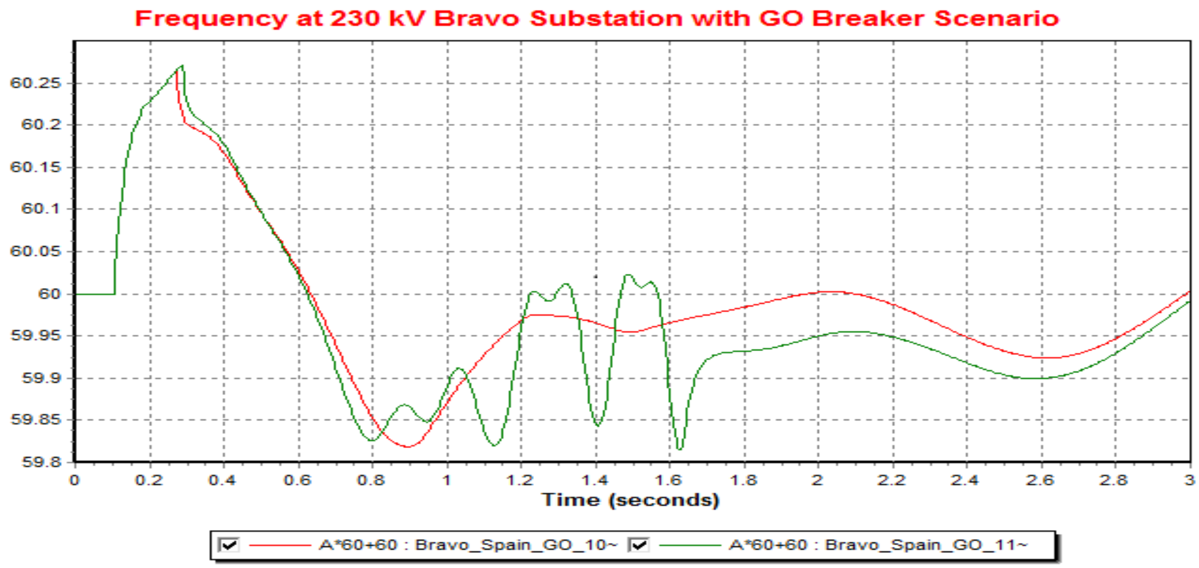

Figure 42 Frequency at 230 kV substation Bravo with GO breaker scenario

4.3.5.2 Critical Fault Clearing Time Using Approach 2 for Case 3

A three-phase fault occurred at 230kV Bravo-Spain circuit right outside the fence of 230 kV Bravo substation. The fault location was very close to the 230-kV Bravo bus. The fault was followed by breaker failure situation but in this case only one pole of the breaker failed to operate while the other two poles of the phases were normal. It took 1~ for the relay to detect fault, 2~ for the circuit breaker to operate but one of the poles did not operate. It took 5~ to clear the fault from remote end which is 230 kV Spain substation. In the case of an IPO breaker, the three-phase fault is converted to a single line to ground fault due to one stuck pole and none of the units lost synchronism due to single line to ground fault. It was observed that for a total fault clearing time of 35~, all units remained in synchronism as shown in figure 43.

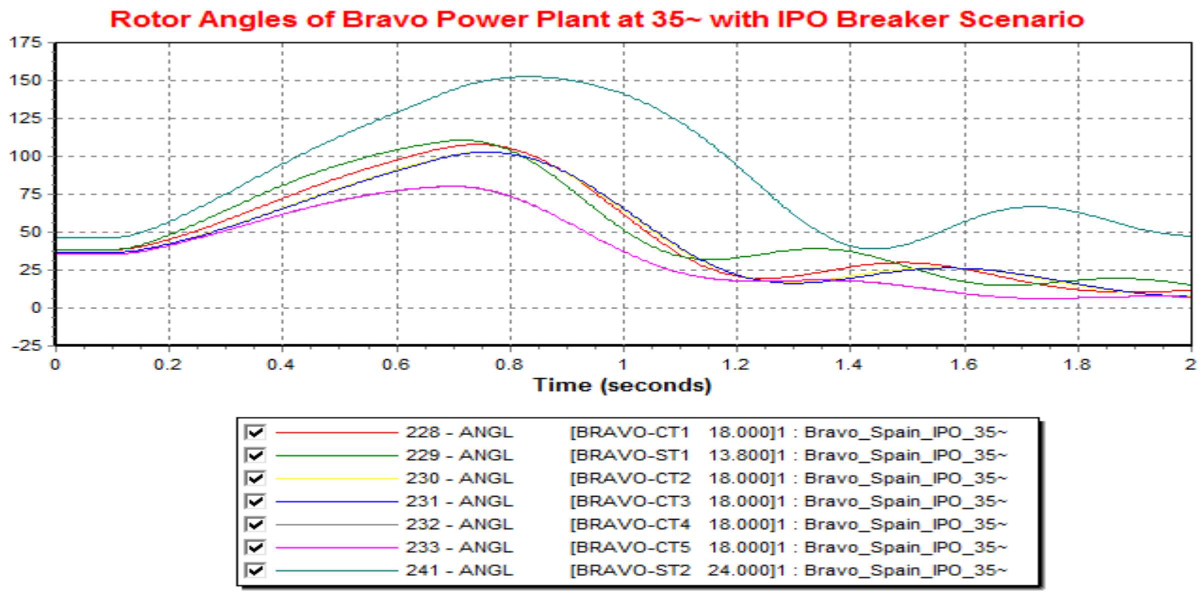

Figure 43 Rotor angles of Bravo power plant units with IPO breaker at 35~

The rotor angles of Bravo power plant for a total fault clearing time of 36~ are given below. For a total fault clearing time of 36~. Bravo ST2 unit lost synchronism. It is the least stable unit as compared to the others.

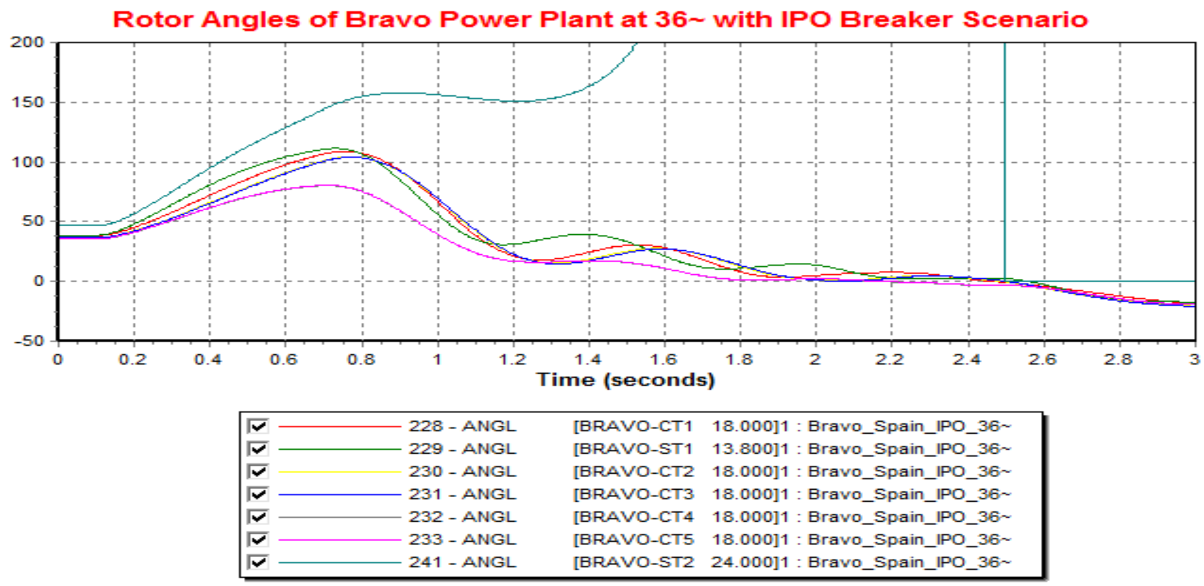

Figure 44 Rotor angles of Bravo power plant with IPO breaker at 36~

The rotor angle comparison of Bravo ST2 unit for 35~ and 36~ is shown below.

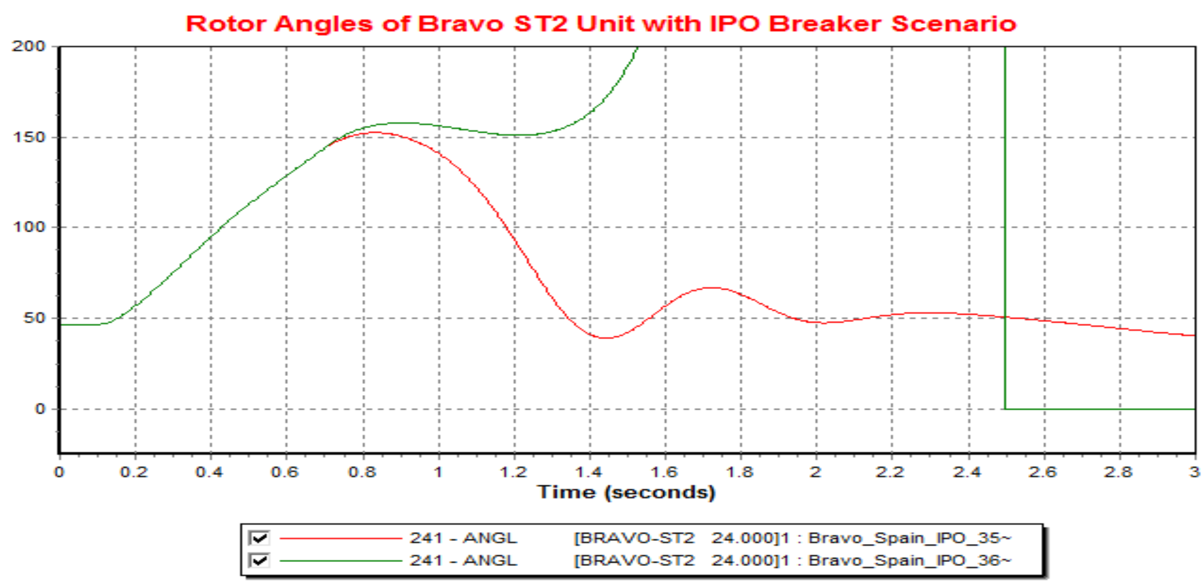

Figure 45 Rotor angles of Bravo ST2 unit with IPO breaker scenario

The electrical power comparison of Bravo ST2 unit for 35~ and 36~ is given below. The electrical power restored quickly when the fault was cleared from remote end.

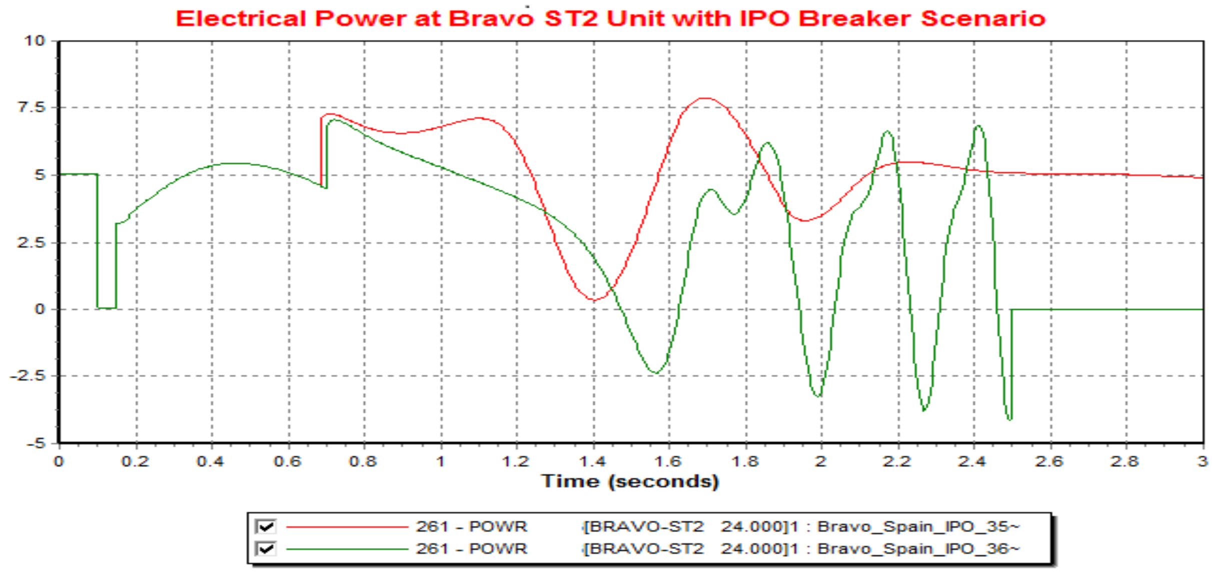

Figure 46 Electrical power comparison of Bravo ST2 unit with IPO breaker scenario

The voltage at 230kV Bravo bus is given below. When the three phase fault occurred, the positive sequence voltage went down to zero. An IPO breaker with one stuck pole clears two phases of the fault from local end which brings the positive sequence voltage from zero up to 0.63 pu. With a single line to ground fault remaining on the system for 35~, none of the units lost synchronism.

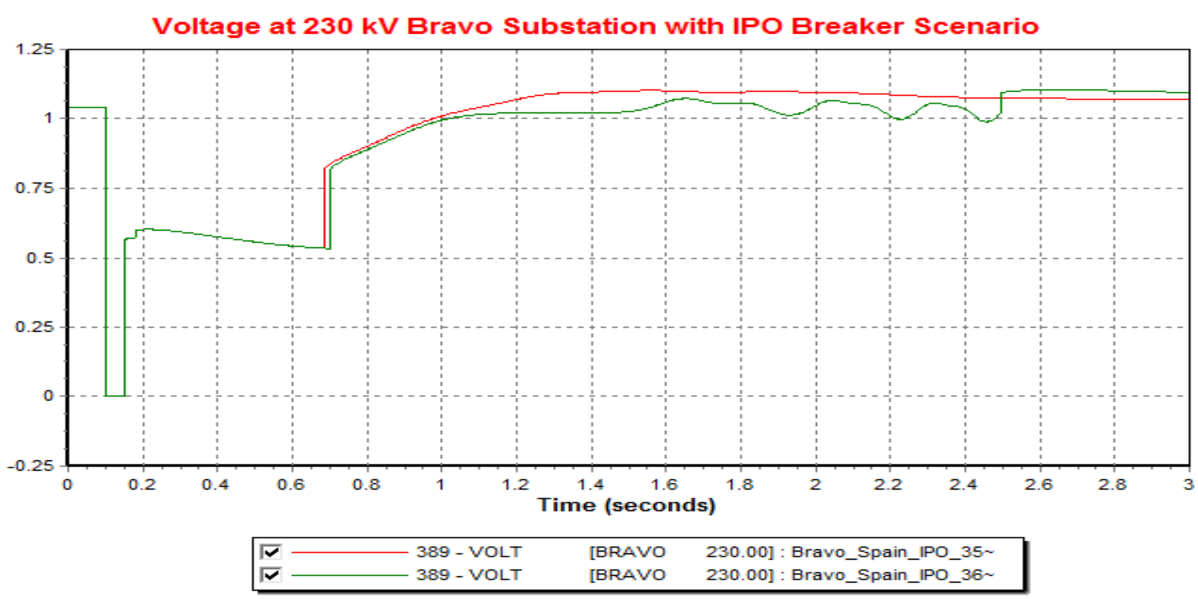

Figure 47 Voltage at 230 kV Bravo substation with IPO breaker scenario

The frequency at 230 kV Bravo substation is given below. The frequency does not go beyond 59.6 Hz to trigger UFLS.

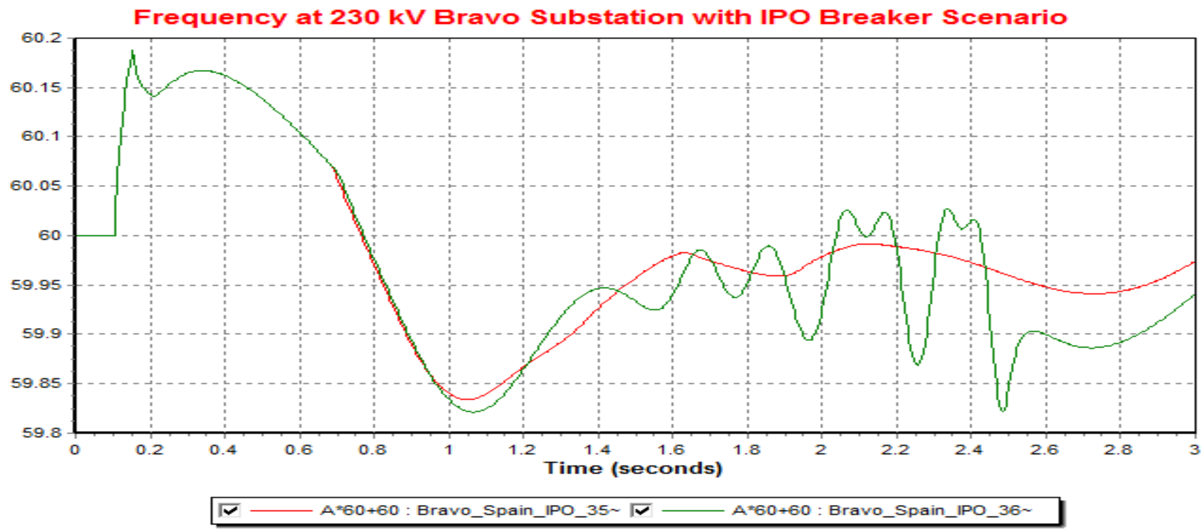

Figure 48 Frequency at 230 kV Bravo substation with IPO breaker scenario

4.3.6 Results for Case 3

The results for GO and IPO breakers for 230 kV Bravo Substation were compared and IPO breakers gave the best results. Bravo Power plant is less stable as compared to the other two cases because it has less transmission circuits capable of exporting power. The comparison is shown below.

Table 8 Comparison of GO and IPO breaker for Bravo power plant

Gang Operated Breakers	**Independent Pole Operated Breakers**
Critical Fault Clearing Time = 10 EC	Critical Fault Clearing Time = 35 EC
At 11 EC, Bravo ST2 lost synchronism	At 36 EC, Bravo ST2 lost synchronism
Total Improvement in Stability: Critical Clearing Time Enhanced from 10~ to 35~ = **250%** **Enhancement in Critical Clearing Time**	

CHAPTER 5

CONCLUSION

The Bulk Electric System has a very dense network of 230 kV transmission circuits. This thesis was based on a study to make comparison between Gang Operated and Independent Pole Operated circuit breakers using extreme event scenario. An extreme event condition was considered to analyze the power system stability during worst case scenarios. Three different power plants were considered for simulations using PSS®E software. The power plants had different units with different types of excitation system and power network to which they were connected to see the variation in results.

PSS®E software was used to perform dynamic study. The extreme condition considered was a three phase fault on a transmission circuit, very close to the 230 kV substation directly connected to the power plant, followed by breaker failure situation. The same fault was applied to those three different power plants to determine the critical fault clearing time for GO and IPO breakers. A comparison was made between the results simulated for GO and IPO breakers to show improvement in stability.

Depending on the characteristics of generating units and the network they are connected to, all the three power plants showed different results. In the three simulation cases, Independent Pole Operated breakers showed tremendous improvement in stability when compared with Gang Operated breakers.

5.1 Recommendation

Independent Pole Operated (IPO) breakers showed outstanding improvement in enhancing critical fault clearing time. It is highly recommended that if any new breaker is installed in a generation substation, it should be an IPO breaker for better stability results. Also, if any Gang Operated (GO) breaker needs to be replaced at a generation substation due to increased available fault current, it should be replaced with an IPO breaker for better stability results.

REFERENCES

[1] North American Electric Reliability Corporation (NERC), 3353 Peachtree Road, NE Suite 600 North Tower, Atlanta, GA 30326 https://www.nerc.com/pa/Stand/2018%20Bulk%20Electric%20System%20Definition%20Reference/BES_Reference_Doc_08_08_2018_Clean_for_Posting.pdf

[2] U.S. Energy Information Administration, 1000 Independence Ave, SW Washington, DC 20585 https://www.eia.gov/todayinenergy/detail.php?id=27152 Dated: 06/01/2019

[3] Florida Reliability Coordinating Council Inc.(FRCC), 3000 Bayport Drive, Suite 600, Tampa, Florida, 33607-8410. www.frcc.com/Reliability/Shared%20Documents/FRCC%20Event%20Analysis/FEAT%202-26-08/00%20-%20FRCC%20System%20Disturbance%20and%20UFLS%20Event%20Report%202-26-08%20.pdf dated 06/03/2019

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