ANALYSIS ON THE IMPACT OF LOAD INCREMENT TO POWER SYSTEM STABILITY AND MITIGATION TECHNIQUES

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Master of Electrical Engineering

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DECLARATION

I hereby declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently submitted for any other degree at Universiti Tenaga Nasional or at any other institutions. This thesis may be made available within the university library and may be photocopies and loaned to other libraries for the purpose of consultation.

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ABSTRACT

Power System Stability is essentially recognized as an important problem for secure system operation and to prevent major blackouts. The complexity of power systems is continually increasing because of the growth in interconnection and new technology. The nature of load characteristics and increased in load demand due to complexity of the power system is one of the major area in Power System Stability. When the system is operating at steady state and dynamic stability conditions, it should be operating at its optimized condition in meeting the customers demand in terms of quantity and quality with all parameters such as frequency and voltage are within the acceptable limits and generators are operating at synchronism. With variable load growth in the system and at the same time to ensure stability of the power system, it is important to know the impact of load increment to the power system stability. This research work is to analyse the impact of load increment to power system stability by monitoring generator performance with respect to generator capability curve and bus voltage with respect to Voltage Stability Indices (VSI). In addition, injection of PV and installation Static Var Compensator (SVC) is also included in this research work as mitigation technique to improve power system instability. IEEE 30 Bus Test System is modelled and tested using PSS®E 34 software and three (3) scenarios are simulated to achieve the research objectives. The strongest and weakest lines in the system are determined using two (2) VSI which are Fast Voltage Stability Indices (FVSI) and Line Stability Factor (LQP). Many papers have been published on voltage stability focused on the changes of reactive load at the weakest bus. Some of the researcher have discussed the impact of reactive load increment on selected buses to achieve their research objectives. However, no works have been published on analysing voltage stability with respect to active and reactive load increment at all buses, sending and receiving ends of weakest and strongest lines. Furthermore, there is no research done to study the impact of load increment to generators performance with respect to generators capability curve. The relationship between generators performance with respect to generators capability curve, and voltage stability with respect voltage stability indices is also investigated to achieve the research objectives.

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In the name of Allah, Most Gracious, Most Merciful

"It is He Who created for you all the things that are on earth; then He turned to heaven and made them into seven firmaments and of all things He hath perfect knowledge."

(Al Quran, 2: 29)

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DEDICATION

This dissertation is dedicated to:

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who lead me with light of hope and support,

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who encourage and taught me the spirit of life,

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Who encourage me to complete this dissertation as soon as possible,

I hope this dissertation will be a motivation for all of you to achieve
your dreams in future

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LIST OF SYMBOLS

θ	Angle between apparent power (S) and active power (P)
P	Active power
Q	Reactive power
S	Apparent power
V	Voltage
Z	Impedance
I	Current
R	Resistance
X	Reactance
V_S	Sending end voltage
V_R	Receiving end voltage
δ_s	Phase angle of the sending end voltage
δ_r	Phase angle of the receiving end voltage
Ps	Active power at sending end
G1	Generator No 1
TX1	Transformer No 1
V1	Voltage at Bus 1

LIST OF ABBREVIATIONS

VSI	Voltage Stability Indices
FVSI	Fast Voltage Stability Index
LQP	Line Stability Factor
SVC	Static Voltage Compensator
PV	Solar Photovoltaic
IEEE	Institute of Electrical and Electronics Engineers
PSS®E	Power System Simulator for Engineering
AC	Alternating current
DC	Direct current
AVR	Automatic Voltage Regulator
MVA	Mega Volt Ampere –unit for apparent power

CHAPTER 1

INTRODUCTION

1.1 Research Motivation

Power System Stability is essentially recognised as an important problem for secure system operation and to prevent major blackouts. The complexity of power systems is continually increasing because of the growth in interconnections and use of new technologies. At the same time, financial and regulatory constraints have forced utilities to operate the systems nearly at stability limits [1]. The instability of the power system is subjected to wide range of disturbance such as loss of synchronism due to loss of generator or load, or loss of a tie line between two sub-systems, short circuit on the transmission lines and changes in load demand depending on the individual load characteristics.

Power system must be designed and operated to meet continual changing in active and reactive power of load demand. Increased load in the system and various load characteristics are one of the key areas in power systems to maintain power system stability. The imbalance between load demand and generation is one of the power system disruptions that leads to system instability. The motivation to conduct this research work is to analyse the impact of load increment to power system stability and mitigation techniques. The generators performance with respect to generators capability curve and voltage stability with respect to Voltage Stability Indices (VSI) are investigated to achieve the research objectives. In addition, the injection of solar photovoltaic (PV) and installation of Static Var Compensator (SVC) are used as mitigation techniques to improve power system instability. The results before and after PV and SVC installations are compared to investigate the contribution of PV and SVC in maintaining power system stability due to load increment respectively.

1.2 Problem Statement

Load increment gives an impact to the performance of generators and voltage stability in the power system. Generator is a main voltage source of a power system and is significant important towards maintaining voltage stability. An increase in load is an increase in the real and/or reactive power drawn from the generators. The imbalance between load demand and generation is one of the power system disruptions that leads to power system instability. Thus, power system becomes unstable if the real and/or reactive power supplied by the generators is insufficient to meet the load demand. With variable load increment in the system and at the same time to ensure stability of the power system, it is important to know the impact of load increment to power system stability since increase in load demand may lead to voltage instability, which further causes voltage collapse and blackout. Hence, the impact of load increment to power system stability needs to be investigated.

This research work is to analyse the impact of load increment to power system stability including injection of solar photovoltaic (PV) and installation of Static Var Compensator (SVC) as mitigation techniques to improve power system instability. Many papers have been published on voltage stability focusing on the changes of reactive load at the weakest bus. Some of the researchers have discussed the impact of reactive load increment on selected buses to achieve their research objectives. However, no work has been published on analysing voltage stability with respect to active and reactive load increment at all buses, sending and receiving ends of weakest and strongest lines. Furthermore, there is no research done to study the impact of load increment to generators performance with respect to generators capability curve. In this research work, the relationship between generators performance with respect to generators capability curve, and voltage stability with respect voltage stability indices are also investigated to achieve the research objectives.

1.3 Research Objectives

The objectives of this dissertation are: -

a) To investigate the impact of load increment to power system stability.

b) To analyse: -

   i. Voltage stability with respect Voltage Stability Indices

   ii. Generators' performance with respect to generator capability curve.

c) To investigate the contribution of PV and SVC in maintaining power system stability due to load increment.

1.4 Research Scope

The scope of this research work is to investigate the impact of load increment to power system stability by analysing generator performance with respect to generator capability limits and voltage stability with respect to Voltage Stability Indices (VSI). IEEE 30 Bus Test System is modelled using PSS®E 34 software, and power flow and dynamic simulations are performed. Power flow simulation is performed for load increment scenarios while dynamic simulation is performed for PV injection and SVC installation. Base case condition is simulated without any additional load, and without any PV and SVC integration. Furthermore, various loads with different amount of active and reactive power are added by staged at all buses, sending and receiving end of the weakest and strongest buses. There are three (3) scenarios are being simulated to achieve the research objectives as listed below: -

- Scenario 1: Load increment at all buses
- Scenario 2: Load increment at the sending and receiving ends of the weakest line
- Scenario 3: Load increment at the sending and receiving ends of the strongest line

PV and SVC are introduced at scenarios 2 and 3 for one selected load increment to evaluate its contribution and effectiveness in the system to improve power system stability. The generator power factor and bus voltage are monitored, and VSI is calculated at base case condition and every simulated scenario.

1.5 Research Outline

This research work is divided into five (5) chapters with references and appendices at the end.

Chapter 1 : This chapter presents an overview of research motivation, problem statement, research objectives, scope of research works and research outline

Chapter 2 : This chapter discusses on the literature review, which consists of introduction to power system stability, classification of power system stability, voltage stability including voltage stability indices, excitation system of synchronous generators including generator capability curve and classification of electrical loads and loads characteristics. This chapter also deliberates PV and SVC as mitigation techniques to improve power system stability.

Chapter 3 : This chapter describes the research methodology used to analyse on the impact of load increment to power system stability. This chapter also explains in detail the data used in IEEE 30 Bus Test System as modelled to achieve the research objectives.

Chapter 4 : This chapter presents the analysis on power system stability focusing on generator power factor, bus voltage and voltage stability indices with respect to load increment. In addition, the contribution of PV injection and SVC installation to improve power system stability is also being investigated.

Chapter 5 : This chapter summarises all findings based on simulations results and ends with recommendation for future works.

CHAPTER 2

INTRODUCTION

2.1 Introduction to Power System Stability

Power system stability may be broadly defined as the property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [1]. The instability of the power system is subjected to wide range of disturbance such as loss of synchronism due to loss of generator, loss of load, loss of a tie line between two sub-systems, short circuit on the transmission lines, and changes in load demand depending on the individual load characteristic. In addition, while the system response to abnormal system condition, the network topology will be changed due to changes in the power flow. Thus, there will be variation in voltage and frequency since the rotor of the synchronous machine will deviate from the normal steady state condition. The complexity of power systems is continually increasing due to system expansion such as penetration of distributed generation (DG), expansion of new technologies and increase in load demand depending on individual load characteristics.

The quality of supply depends on voltage, frequency and power factor operated within the acceptable limits with regards to any disturbance occurred in the system. The control system should be able to respond accordingly in order to maintain these key parameters within the acceptable limits. Voltage is governed by reactive power control while frequency is governed by active power control of the generator. Reactive power is control through generator excitation system while active power is control through governor system of the synchronous generator. Renewable energy such as PV, biomass, and wind also new source of alternative generation in the system should also meet the increase in load demand. The consistency of voltage and frequency are important in ensuring the quality of supply, thus preventing the system from instability that will lead to voltage collapse.

Nowadays, the increase of the reactive power loading has resulted the power system to operate closer to its point of collapse. Most of the load demand involves reactive power rather than the real power, and the effects lead to motor stalling, transformer and generator outages [2]. This causes power system to be in stress and led to voltage collapse. Loads are the main root cause of voltage instability. Power system becomes unstable when the system encountered either an increase in load demand, change in operating condition, a disturbance like outage, or major equipment such as generator, transformer or transmission line [3]. This causes a surge of reactive power demand which concludes to the deterioration of voltage levels at one or more buses in the power system [3].

2.2 Classification of Power System Stability

There are various forms of instabilities that a power system may undergo and effectively dealt due to complexity of stability problems. Figure 2.1 shows an overall classification of power system stability based on analysis of stability problems [1].

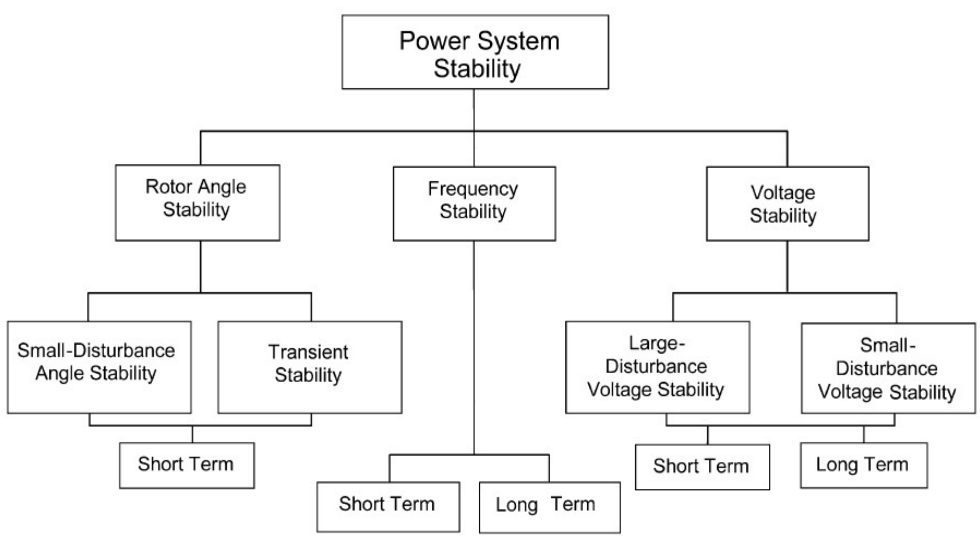


Figure 2.1: Classification of Power System Stability [1]

Power system stability are classified into three (3) categories which are rotor angle stability, frequency stability and voltage stability. Rotor angle stability refers to the ability of the synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance [1]. It depends between mechanical input and electromagnetic output torque balance each of the synchronous machine in the system, while the speed remains constant. Instability that may occurs in the form of increasing angular swings of some generators leading to their loss of synchronism with other generator [1]. Loss of synchronism can occur between one machine to the rest of the system, or between groups of machines, with synchronism maintained within each group after being separating from each other. Rotor angle stability are categorised into two subcategories which are small disturbance stability and transient stability. Small disturbance rotor angle stability is concerned with the ability of the power system to maintain synchronism under small disturbance such as changes in load continuously and also influence by load characteristic. The system shall be automatically respond to the changing conditions by itself. Transient stability is commonly referred to the ability of the power system to maintain synchronism when subject to a severe disturbance such as fault on a transmission lines, loss of generation and loss of large load. The response of power system towards transient disturbance involves large excursion of generator rotor angle, power flows and bus voltage. Both subcategories are categorised as short term phenomena.

Frequency stability refers to the ability of a power system to maintain steady frequency as a result of imbalance between the generation and load demand. It depends on the stability to maintain or restore equilibrium between system generation and load demand, with minimal unintentional loss of load [1]. Instability may occur due to tripping of generators units or loss of loads. Frequency stability may be occurred as short-term or long term phenomenon. Short term frequency instability such as frequency decays rapidly causing blackout of the island within a few seconds due to insufficient of under frequency load shedding operations. During frequency excursions, the percentage of voltage magnitude changes may be higher compared with magnitude of frequency changes. High voltage may cause undesirable generator tripping while low voltage may cause undesirable operation of impedance relays for an overloaded system.

Voltage stability is defined as the ability of a power system to maintain steady acceptable voltages at all busses in the system after under normal operating conditions and after being subjected to a disturbance [3]. In facts, voltage stability depends on the relationship with reactive power supply and demand. Insufficient reactive power supply will lead to voltage stability issues. Voltage stability is one of the major constraints in planning and operations of power systems to ensure secure and reliability of the power supply. Voltage stability is a local problem, normally occur in heavily stressed system which leads the system to operate close to their limits.

2.3 Voltage Stability

As explained in 2.2, voltage stability is defined as the ability of power system to maintain steady stage voltage at all busses in the system after being subjected to a disturbance from a given initial operating condition [3]. With continuous load growth in a power system, the reactive power absorption increases leading to drop in voltage magnitude [4]. A point is reached when the power system is unable to meet the reactive power demand and further caused an accelerated reduction in voltage magnitude. At that condition, the power system is considered to be voltage unstable which may lead to voltage instability. Voltage instability is defined as inability of power system to maintain steady state voltage at all buses following a disturbance such as increased in load demand [5]. Voltage instability has played a key role in some of the blackout all over the world [6]. Voltage instability can have occurred in both short and long term depending on the time frame. The time frame for long term stability analysis could be several minutes to hours while for short term study, it is only for few second [6]. Previously, several methods have been proposed in conducting voltage stability analysis such as P-V and Q-V curves, modal analysis, artificial neural networks, neuro-fuzzy network, reduced Jocobian determinant, energy function methods and sensitivity analysis [7]. P-V and Q-V curves leads to proximity to voltage collapse while others developed voltage stability indices as indicator [7]. Various static voltage stability indices such as VCPrI, L-index, extended L-index, LCPI, VCPI, LQP, FVSI, Lmn and SVSI are developed to identify voltage stability of a system [4].

2.3.1 Voltage Stability Indices

Voltage Stability Indices (VSI) is an indicator to measure and evaluate the voltage stability limits of the power system. It can be used for the prediction to detect proximity to voltage instability condition. The stability indices depict how close a system towards instability. With growing loads in the system, the system voltage will decrease. Any minor load increment at any bus close to its stability limits may also contribute to voltage instability. The information on load increment at each bus that the system can handle without heading for instability is important to helps the operator to take necessary steps to avoid possibility of instability.

The point of voltage instability in this research works are calculated using two (2) indices which are Fast Voltage Stability Index (FVSI) and Line Stability Factor (LQP). Two indices are used as comparison or verification between each other. The results are expected in close agreement.

The indices are derived and formulate using power flow concept between two buses in a transmission system. Figure 2.2 show the two bus network that used to derive and formulate VSI [3].

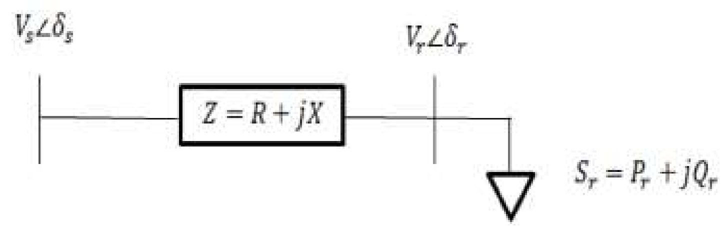


Figure 2.2: Two bus network [3]

Where: -

V_s = Sending end voltage
V_r = Receiving end voltage
δ_s = Phase angle of the sending end voltage
δ_r = Phase angle of the receiving end voltage
Z = Line impedance
R = Line resistance
X = Line reactance
θ = Line impedance angle
Q_r = Reactive power at receiving end
Pr = Active power at the receiving end

The constant parameters are line impedance (Z), resistance (R), reactance (X) and line impedance angle (θ) while the variable parameters are phase angle different between sending and receiving bus voltage (δ).

FVSI referred to a line which is capable in determining the points of voltage collapse maximum permissible load, weak bus in the system and the most critical line in an inter-connected system [7]. The trend of voltage and index profiles were study with gradually increase reactive power loading in stages until the load flow solution fails to give any results. Therefore, as shown in equation 2.1, the FVSI values is proportional with reactive power loading at receiving end (Q_r): -

$$\text{FVSI} = \frac{4\,Z^2\,Qr}{Vs^2 X} < 1 \qquad \text{Equation 2.1}$$

LQP is an indicator of proximity to static voltage collapse [8]. The trend of voltage and index profiles were study with gradually increase active and reactive power loading in stages until the load flow diverges. Therefore, as shown in equation 2.2, LQP formula is includes the influence of active power at sending end (P_r) and reactive power on the receiving end (Q_r): -

$$\text{LQP} = 4\left(\frac{X}{Vs^2}\right)\left(\frac{X}{Vs^2}Ps^2 + Qr\right) \leq 1 \qquad \text{Equation 2.2}$$

In this research work, FVSI and LQP are calculated to determine the strongest and weakest lines in the system at base case condition and as indication of voltage stability. The trend of generator power factor, bus voltage and index profiles are study with gradually increase reactive and active power loading for each simulated scenario.

Both indices are depending on line reactance (X), sending end voltage (V_s) and reactive power at receiving end (Q_r). However, LQP has additional parameter which is active power at sending end (P_s). Thus, the value of FVSI might be slightly lower as compared with LQP. This is because LQP is depends with active power at the sending end (P_s) and reactive power at receiving end (Q_r) while FVSI is purely depends only on reactive power at receiving end (Q_r).

2.4 Excitation System of Synchronous Generators

Synchronous generators or alternators are synchronous machines used to convert mechanical power to Alternating current (AC) of electrical power [9]. Synchronous generator is a main voltage source of a power system and is significant important towards maintaining voltage stability. Excitation System of synchronous generator is function to regulate generator voltage and to regulate reactive power output by provided Direct Current (DC) to synchronous generator field winding. The excitation system also performs control and protective functions by controlling field voltage and thereby control the field current to maintain the terminal voltage. This means, excitation system enhances the system stability by control of voltage and reactive power flow to the system. It should be capable to respond rapidly to a disturbance to avoid power system instability.

Since excitation system functions as reactive power output of synchronous generators, the insufficient reactive power supplied by a synchronous generator may lead to the voltage stability issues in situations when the load increases drastically. This will increase reactive power needed to maintain voltage stability. If a synchronous generators reached their reactive power limits, it may not be able to contribute reactive power to the system. If synchronous generators connected in parallel, some generators may produce significantly more reactive power than others in relation to their size. This will cause overloaded condition that will shorten generators life span which may lead to higher maintenance cost.

2.4.1 Generator Capability Curve

The operation of synchronous generators is determined by its capability curve which explained the operation constraints of a synchronous generators [10]. The capability curve defines the machine permissible operating region for a given terminal voltage [11]. The synchronous generator is rated in terms of maximum apparent power (MVA) output and power factor at a specified voltage. The power factor usually is in between 0.85 to 0.9 lagging. Generators' reactive power capabilities play a crucial role in maintaining system voltage stability as they can cause the system to lose its structural stability within a very short period, leading to voltage collapse. Power system voltage stability can impact significantly when one or more generators hits the Var limits. This paper aims to investigate generators performance with respect to generator capability curve subjected to active and reactive load increment at all buses, sending and receiving ends of the weakest and strongest lines.

Figure 2.3 shows the generator capability curve that gives the basic information regarding the limiting zones of operation so that limiters can be set/commissioned suitably for safe operation of the units [10]. It also explained the boundaries of reactive power output capability or supplies to the system continuously without overheating. The reactive power output capability of a synchronous generator can deliver continuously without overheating is governed by three factors which are armature current limit or stator winding limited, field current limit or rotor winding limited and end region heating limits or stator end iron limited.

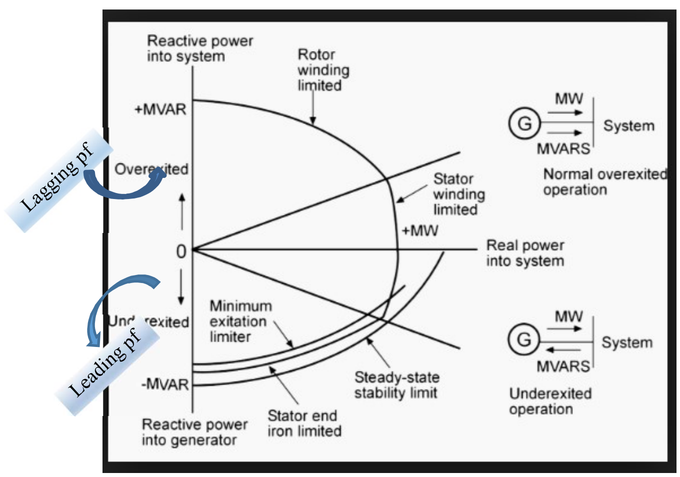


Figure 2.3: Generator capability curve [10]

The armature current limit or stator winding limited is the maximum current that the stator winding can withstand without overheating. The field current limit or rotor winding limited is the maximum of field current is imposed to the rotor winding without overheating. End region heating limit is the maximum reactive power that the synchronous generator can supplied under leading power factor condition or under excited condition. The field current will increase to meet the required working flux. This will cause more end flux in the synchronous generator that will lead to stator lamination and cause eddy current heating.

Generator Capability Curve can explain about heating of different parts of synchronous generator. The generator shall always be operated within their capability curve to avoid damage due to overheating. Under lagging load condition, the synchronous generator must be operated at overexcited region to avoid armature and field heating limits while under leading load condition, the synchronous generator must be operated at under excited region to avoid end region heating that will lead to stator lamination that cause eddy current heating.

2.5 Classification of electrical loads and loads characteristics

Loads are the main root cause of voltage instability. Load stability also known as voltage stability [5]. A power system becomes unstable when the system encountered an increase in load demand which results changes in reactive power demand. This will further contribute to voltage drop on one bus or other buses in the system. This is because, an increase in load is an increase in the real and/or reactive power drawn from the generator.

Electrical loads are classified into 3 categories which are loads operated with unity, lagging or leading power factor. The nature of electrical loads is resistive, inductive, capacitive or combination of them. The resistive load such as lamp and heater resist the flow of electrical energy in the circuit. Resistive load converts electrical energy into thermal energy. The current and voltage of the resistive loads are in phase, thus cause unity power factor. The inductive loads such as generators, transformer and motor has a coil which converts electrical current into a magnetic field to deliver the works. An inductive reactance resists the change of current, which caused the current to lag voltage waveform. Thus, reactive loads cause lagging power factor. The capacitive load such as capacitor bank resists the change of voltage which cause the current to lead voltage waveform. Hence, capacitive load cause leading power factor. Capacitive loads allowing reactive power to be supplied to the system and contribute to power factor improvement. Figure 2.4 shows the characteristics of voltage and current for electrical loads in the system.

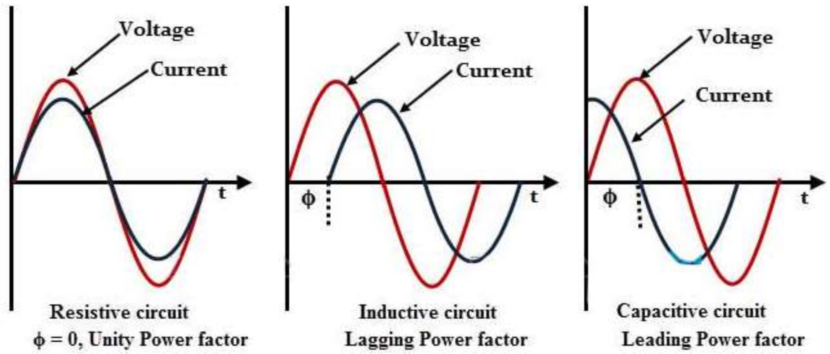


Figure 2.4: The characteristics of voltage and current for electrical loads [12]

Power system loads are classified into 3 categories which are static, dynamic or composite load. The static load is defined as characteristics of the load at any instant of time while dynamic load is defined as changes of the load characteristics with respect to time. The types of load contributes to the power system stability and its depends either the load are voltage or frequency dependency. Voltage dependency are present by constant impedance (Z), constany current (I) and constant power (P) while frequency dependency is present by frequency deviation and reactive power (Q) of the loads. Loads that are located at load concentration zone are expected to have lower voltage as compare loads that are placed near to generators or voltage regulator. In this research works, simulations are done using static loads. The active and reactive power are vary to investigate the impact of load increment on voltage stability and generators performance with respect to generators capability curve.

2.6 Static Var Compensator (SVC)

Static Var compensator is a set of electrical instruments for providing fast acting reactive power on high voltage electricity transmission networks [13]. SVCs are part of the Flexible AC transmission system device family, regulating voltage, power factor, harmonics and stabilizing the system [13]. The SVC is an automated impedance matching device, designed to bring the system closer to unity power factor. Following are the benefits of SVC in the system: -

a) Voltage support and regulation
b) Transient stability improvement
c) Power system oscillation damping
d) Reactive power compensation
e) Increase in power transfer capability

SVC control only one of these parameters i.e. voltage, impedance and phase angle that determine the power flow in the AC Power system. An increase in load causes active and reactive power shortage, which further causes voltage drop in the system. The SVC regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. SVC reacts as a reactive power compensator for bus voltage regulation. SVC is only compensated the reactive power and unable to exchange the active power from the system. SVC can work as both capacitive and reactive power compensation by absorbs reactive power (inductive) when the system voltage is over the limits and generates reactive power (capacitive) when system voltage is under the limit.

2.7 Solar Photovoltaic (PV)

The need for clean and affordable energy due to the concern of climate change and increasing energy demand has been leading the power system towards renewable. Among the renewable energy sources, PV systems are recognised as one of the most important energy sources due to its availability and low maintenance cost [6]. With the rapid increasing integration of PV power generation, the influence of PV power generation on voltage of power system has attracted more and more attention. The voltage stability may decrease especially in case of a weak power grid, such as remote areas far from load centre. Usually PV system are designed to transfer the maximum power from the PV panels to the Grid. Depending on the necessity of the grid, the PV systems will supply active power or reactive power with a balanced or unbalanced profile [14]. In this research work, the PV is used as active power support to mitigate power system stability issues after the system experience load increment.

2.8 Summary of Chapter 2

This chapter discusses on the literature review, which consists of introduction to power system stability, classification of power system stability, voltage stability including voltage stability indices, excitation system of synchronous generators including generator capability curve and classification of electrical loads and loads characteristics. This chapter also deliberates Static Var compensator (SVC) and Solar Photovoltaic (PV) as mitigation techniques to improve power system stability.

Many papers have been published on voltage stability focusing on the changes of reactive load at the weakest bus. Some of the researcher have discussed the impact of reactive load increment on selected buses to achieve their research objectives. However, no work has been published on analysing voltage stability with respect to active and reactive load increment at all buses, sending and receiving ends of weakest and strongest lines. In addition, this paper also aims to investigate the impact of active and reactive load increment at all buses, sending and receiving ends of the strongest and weakest lines to generators performance with respect to generators capability curve.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes on the research methodology used to analyse the impact of load increment to power system stability including mitigation techniques. IEEE 30 Bus Test System is modelled using PSS®E 34 software and power flow and dynamic simulations are performed. The modelled system is a standard test system published by IEEE and has been used widely by researchers as their test system. Base case condition is simulated without any additional load and without any PV and SVC integration. Power flow simulation is performed for load increment scenarios while dynamic simulation is performed for PV injection and SVC installation. The various amount of loads are increased at staged values at all buses, sending and receiving ends of the weakest and strongest lines to achieve the objectives of the research work. The analysis is performed on generators performance with subject to Generator Capability Limits and voltage stability with subject to Voltage Stability Indices (VSI). The results for each scenario is investigated and compared with the base case condition. In addition, the results before and after PV injection and SVC installation are compared to investigate the contribution of PV and SVC in maintaining power system stability due to load increment.

3.2 IEEE 30 Bus Test System

Figure 3.1 presents the schematic diagram of IEEE 30 Bus Test System. The system is modelled with 6 generators, 27 transmission lines including 7 tie-lines, 14 transformers and 21 loads and 1 fixed shunt connected to Bus 2. The generators, transformers and lines are represented by "G", "TX" and "L" respectively.

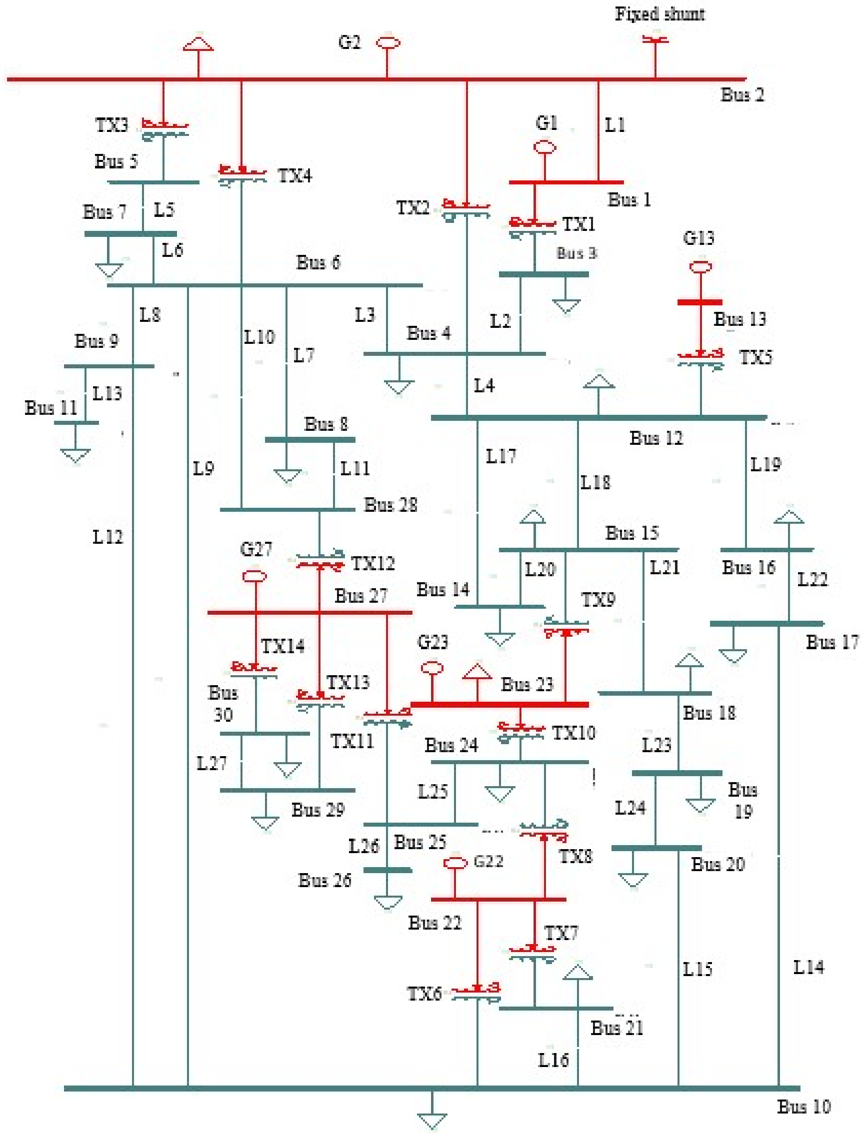


Figure 3.1: IEEE 30 Bus Test System

IEEE 30 Bus Test System is geographically divided into three areas. Table 3.1 summarises the numbers of buses, generators and loads in each respective area. The test system has a total of six generators and 21 loads. In order to maintain the voltage stability of the test system at base case condition, a fixed shunt is connected to Bus 2 as reactive power support in the system. There are 11 buses in Area 1, 10 buses in Area 2 and 30 buses in Area 3, respectively. Each area is installed with 2 generators that serve as a source of active and reactive powers at their respective areas.

Table 3.1: Description of IEEE 30 Bus Test System

Area	Bus No	Bus type	No of generator	No of load	No of fixed shunt
1	1	Slack bus	1	-	-
	2	Generator bus	1	1	1
	3	Load bus	-	1	-
	4		-	1	-
	5		-	-	-
	6		-	-	-
	7		-	1	-
	8		-	1	-
	9		-		-
	11		-	1	-
	28		-	-	-
2	13	Generator bus	1	-	-
	23		1	1	-
	12	Load bus	-	1	-
	14		-	1	-
	15		-	1	-
	16		-	1	-
	17		-	1	-
	18		-	1	-
	19		-	1	-
	20		-	1	-
3	22	Generator bus	1	-	-
	27		1	-	-
	10	Load Bus	-	1	-
	21		-	1	-
	24		-	1	-
	25		-	-	-
	26		-	1	-
	29		-	1	-
	30		-	1	-
	Total		**6**	**21**	**1**

Table 3.2 shows active and reactive powers supply per area. Area 1 has the largest active and reactive powers supply to the system with capacity of 96.85 MW and 36.75 MVAR while Area 3 has the smallest active and reactive powers supply to the system with capacity of 48.51 MW and 16.46 MVAR. The total active and reactive powers supply in the system is 195.56 MW and 109.46 MVAR.

Table 3.2: Distribution of total active and reactive powers supply per area

Generator No	Active and reactive powers supply by each generators		Area	Active and reactive powers supply by area	
	P (MW)	Q (MVAR)		P (MW)	Q (MVAR)
G1	35.87	14.92	1	96.85	36.75
G2	60.98	21.83			
G13	36.00	16.97	2	55.20	26.25
G23	19.20	9.28			
G22	21.60	9.96	3	48.51	16.46
G27	26.91	6.50			
Fixed Shunt	-5	+30	1	-5	+30
Total	**195.56**	**109.46**		**195.56**	**109.46**

Table 3.3 shows the total active and reactive powers by each load per area. Area 1 has the highest total active and reactive powers consumption of 89.5 MW and 57.4 MVAR while Area 3 has the lowest total active and reactive powers consumption of 48.5 MW and 25.8 MVA. The total active and reactive powers consumption in the system is 194.2 MW and 108.5 MVAR.

The highest active and reactive load consumption is at Bus 8 with 30 MW and 30 MVAR while the lowest load consumption is at Bus 29 with 2.4 MW and 0.9 MVAR. Bus 8 is located in Area 1 and Bus 2 is located in Area 3.

Table 3.3: Distribution of total active and reactive powers consumption per area

Area 1		
Bus	**Total Active (P) and Reactive (Q) Powers consumption**	
	P (MW)	**Q (MVAR)**
2	21.7	12.7
3	2.4	1.2
4	7.6	1.6
7	22.8	10.9
8	30.0	30.0
11	5.0	1.0
Total load area 1	**89.5**	**57.4**
Area 2		
Bus	**Total Active (P) and Reactive (Q) Powers consumption**	
	P (MW)	**Q (MVAR)**
12	11.2	7.5
14	6.2	1.6
15	8.2	2.5
16	3.5	1.8
17	9.0	5.8
18	3.2	0.9
19	9.5	3.4
20	2.2	0.7
23	3.2	1.6
Total load area 2	**56.2**	**25.8**
Area 3		
Bus	**Total Active (P) and Reactive (Q) Powers consumption**	
	P (MW)	**Q (MVAR)**
10	5.8	2.0
21	17.5	11.2
Area 3		
Bus	**Total Active (P) and Reactive (Q) Powers consumption**	
	P (MW)	**Q (MVAR)**
24	8.7	6.7
26	3.5	2.3
29	2.4	0.9
30	10.6	1.9
Total load area 3	**48.5**	**25.0**
Total overall Active (P) and Reactive (Q) Powers consumption	**194.2**	**108.2**

Table 3.4 shows list of transformers installed in the IEEE 30 Bus Test System. The system consists of 14 transformers rated at 11/132 kV. The transformers function to step up the voltage from 11 kV to 132 kV, which indicates that the power flow from generation station to the transmission lines.

Table 3.4: Distribution of 11/132 kV transformers

Low voltage level	From Bus	To Bus	Transformer No	High voltage level
11 kV	1	3	TX 1	132 kV
	2	4	TX 2	
	2	5	TX 3	
	2	6	TX 4	
	13	12	TX 5	
	22	10	TX 6	
	22	21	TX 7	
	22	24	TX 8	
	23	15	TX 9	
	23	24	TX 10	
	27	25	TX 11	
	27	28	TX 12	
	27	29	TX 13	
	27	30	TX 14	

Table 3.5 shows the list of transmission lines in the IEEE 30 Bus Test System. The system consists of 27 transmission lines with rated voltage at 132 kV.

Table 3.5: List of 132 kV transmission lines

From Bus	To Bus	Lines No
1	2	L1
3	4	L2
4	6	L3
4	12	L4
5	7	L5
6	7	L6
6	8	L7
6	9	L8
6	10	L9
6	28	L10
8	28	L11
9	10	L12
9	11	L13
10	17	L14

From Bus	To Bus	Lines No
10	20	L15
10	21	L16
12	14	L17
12	15	L18
12	16	L19
14	15	L20
15	18	L21
16	17	L22
18	19	L23
19	20	L24
24	25	L25
25	26	L26
29	30	L27

Figure 3.2 shows total active and reactive powers supply and consumption per area in IEEE 30 Bus Test System. The total active and reactive powers supply is 195.56 MW and 109.45 MVAR including additional power of 5 MW and 30 MVAR fixed shunt. Furthermore, the active and reactive powers consumption is 194.2 MW and 108.5

MVAR. In order to meet the load demand, the conventional generators supply both active and reactive powers in the system with addition power of reactive power support by the fixed shunt. The bolted green lines indicating tie-lines between the 2 Areas.

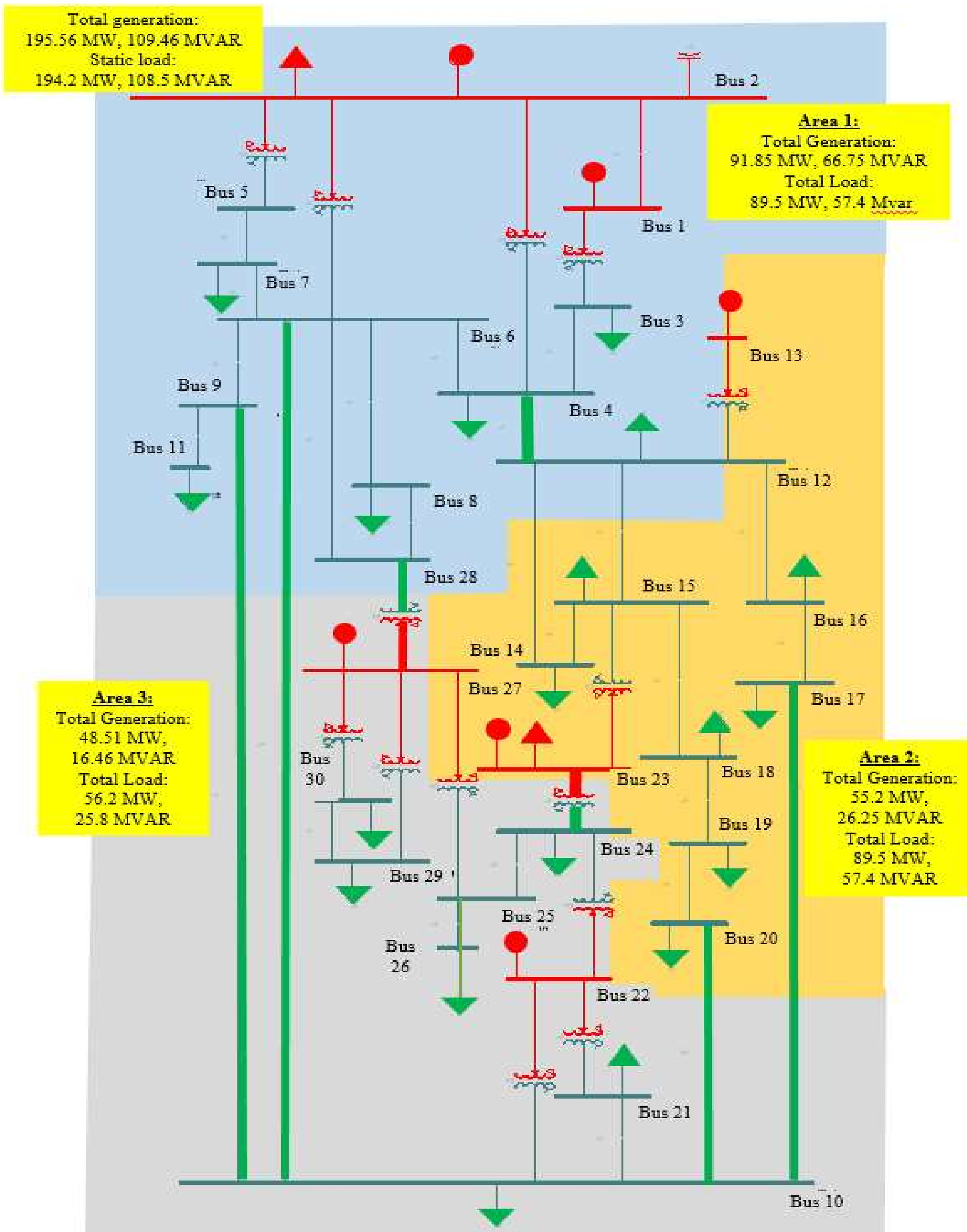


Figure 3.2: Total generation supply and total load consumption per area

Table 3.6 and Figure 3.3 shows the tie lines of IEEE 30 Bus Test System per area. The diagram shown total active and reactive powers transfer at each of the tie lines to support insufficient active and reactive powers demand at other areas. There are 7 tie-lines in IEEE 30 Bus Test System and the list of the tie-lines is below: -

Table 3.6: List of the tie-lines

Areas	**Tie-lines**	**Total active & reactive powers**	
		P (MW)	**Q (MVAR)**
1 to 2	Bus 4 to Bus 12	1.2	3.2
1 to 3	Bus 6 to Bus 10	4.1	4.0
	Bus 9 to Bus 10	3.9	6.0
	Bus 28 to Bus 29	-7.6	-0.1
2 to 3	Bus 17 to Bus 10	-2.3	-3.6
	Bus 20 to Bus 10	-5.0	-2.4
	Bus 23 to d Bus 24	7.0	5.8
Total Power transfer		**1.3**	**12.9**

The largest active and reactive powers transfer is from Area 1 to Area 3 while the lowest reactive and active powers transfer is from Area 2 to Area 3. The largest the amount of active and reactive powers generation, the higher the amount of active and power transferred. However, it is depending on the total load consumption within the Areas.

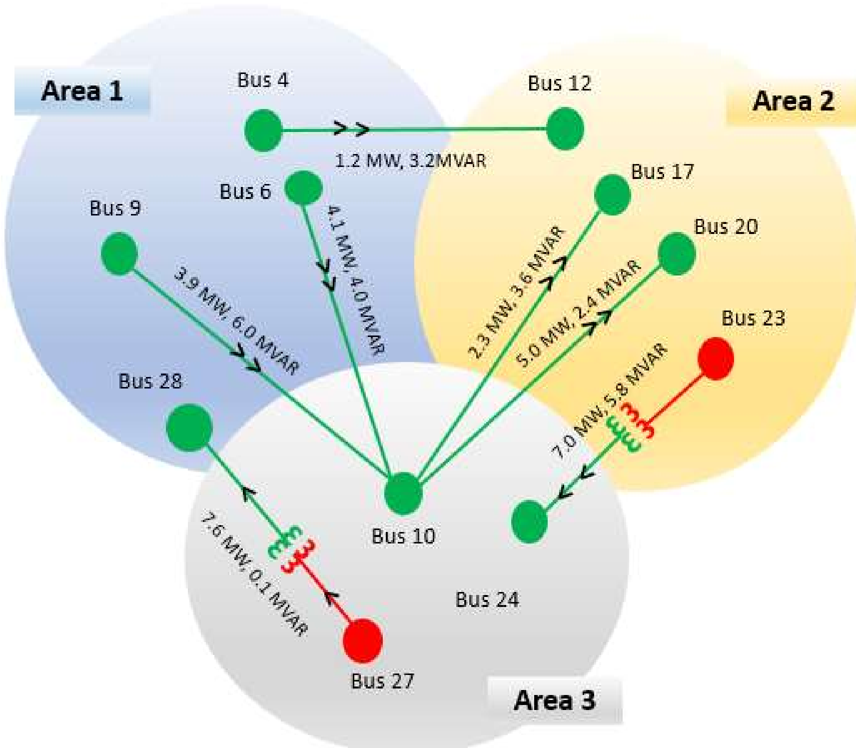
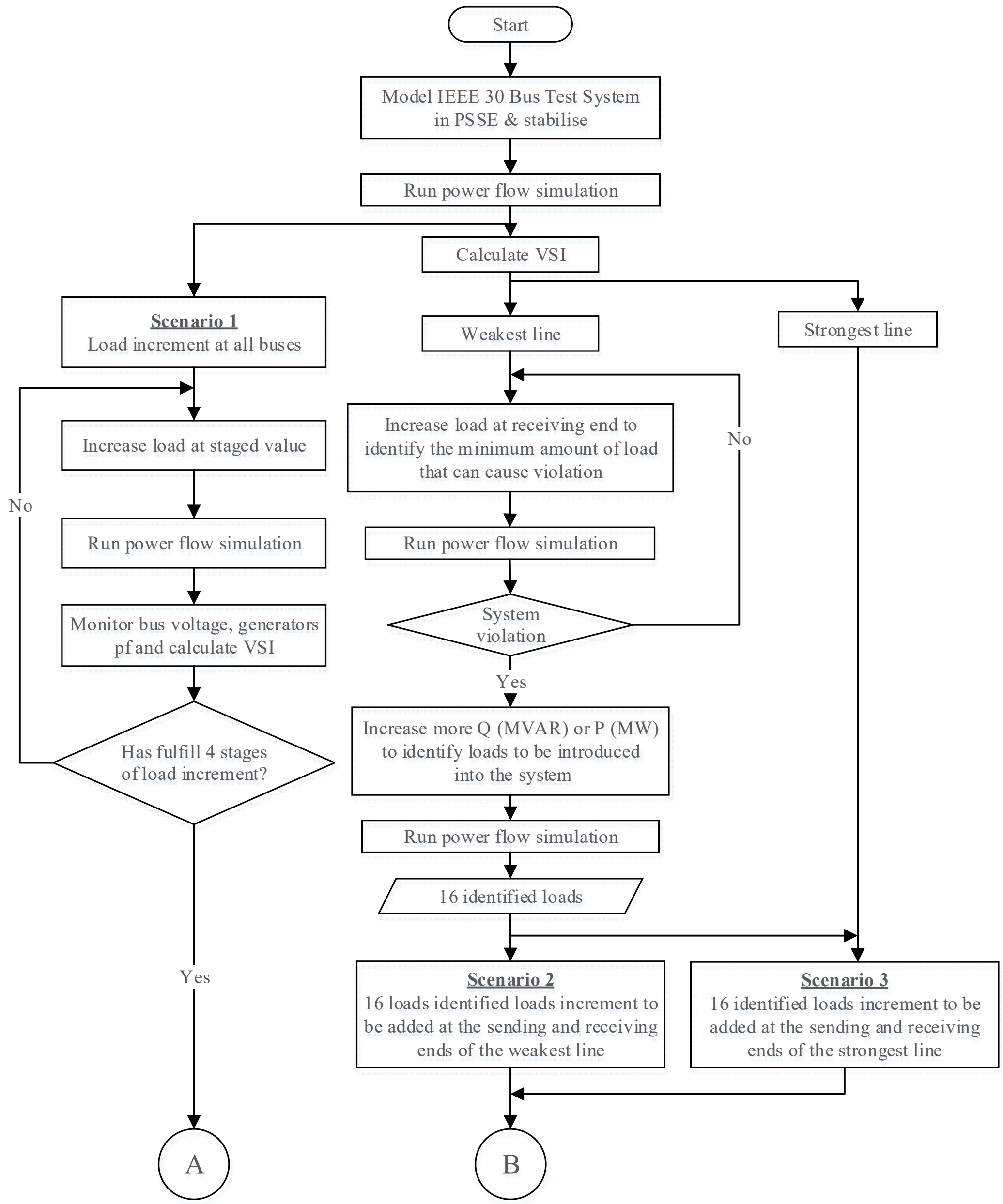


Figure 3.3: Total active and reactive powers transfer between the tie lines.

3.3 Methodology of the research work

Figure 3.4 presents the summary of research methodology of the research work.



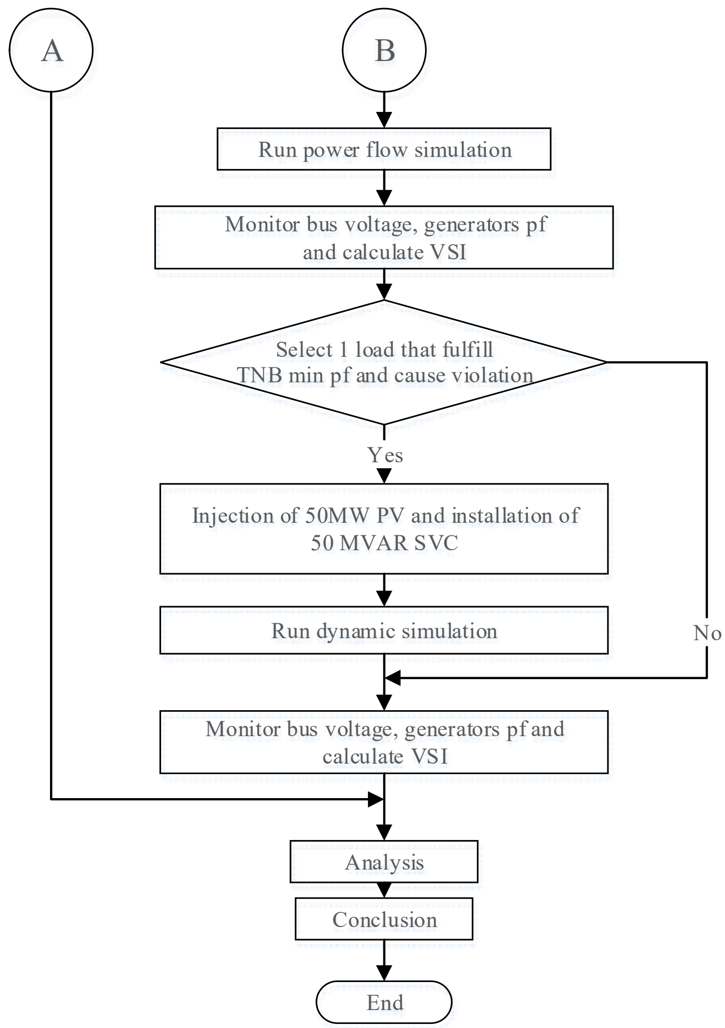


Figure 3.4: Methodology of the research work

Referring to the flow chart, the methodology starts with modelling of IEEE 30 Bus Test System, which is known as base case condition. The system is stabilised which represents by zero (0) power mismatch. It means that the system is balanced between total generation and total load plus losses. In addition, generators power factor, bus voltage, transmission lines and transformers loading are within the acceptable limits. In addition, the stability of the system is achieved based on the following conditions: -

a) Generators power factor between 0.85 – 1.00
b) Bus voltage between 0.95 to 1.05 p.u
c) VSI less than 1.00

Then, power flow simulation is performed and VSI are calculated for each of the transmission lines as indication of voltage stability and to identify the strongest and weakest lines in the system. The strongest and weakest lines in the system are determined using selected VSI which are Fast Voltage Stability Index (FVSI) and Line Stability Factor (LQP). The following are the three scenarios being simulated to achieve the research objectives: -

- Scenario 1: Load increment at all buses
- Scenario 2: Load increment at the sending and receiving ends of the weakest line
- Scenario 3: Load increment at the sending and receiving ends of the strongest line

In scenario 1, the loads are increased at all buses up to 4 stages. The loads are gradually increased at staged values as below: -

- Stage 1: 1 MW, 1 MVAR
- Stage 2: 2 MW, 2 MVAR
- Stage 3: 5 MW, 5 MVAR
- Stage 4: 10 MW, 10 MVAR

With the strongest and weakest lines identified after the VSI calculation at base case condition, scenarios 2 and 3 are simulated. Based on VSI formula as explained in Chapter 2, the determination of weakest and strongest lines in the system is proportional to the amount of powers transfer in the system. The larger the powers transfer in the system will contribute to higher VSI, which indicates the weakest line or the most sensitive/critical line in the system. The lower the powers transfer in the system will contribute to lower VSI, which indicates the strongest line or least sensitive line in the system.

The minimum amount of load that caused violation is identified by gradually increasing the load at receiving end of the weakest line. The receiving end of the weakest line is used to determine a minimum amount of load that will cause violation. This is based on the assumption that the receiving end of the weakest line will contribute to the severe impact when it is subjected to the load increment compared to the strongest line.

Furthermore, more active and reactive powers are added on top of the minimum identified load to analyse the impact of active and reactive powers increment to power system stability. As a result, 16 loads have been identified to be added to the sending and receiving ends of the weakest and strongest lines.

At each scenario, power flow simulation is performed. Generators power factor and bus voltage are monitored while VSI is calculated. In addition, the values of generators power factor, bus voltage, and VSI are compared before and after loads increment to analyse generators performance with respect to generator capability limits and voltage stability with respect to VSI.

Subsequently, one (1) load among the 16 identified loads is selected to be added to the system along with injection of PV and installation of SVC as mitigation techniques to improve power system stability. The load must fulfil TNB load power factor criteria to avoid violation to the system. The load will be placed either at the sending or receiving ends of the strongest or weakest lines depending which ends are most affected due to load increment. Based on TNB Electricity Supply Application Handbook, consumers are required to maintain their load power factor to a minimum of 0.85 for a voltage level less than 132 kV and 0.90 for a voltage level 132 kV and above [15]. The summary on TNB requirement on load power factor is as shown in Table 3.7: -

Table 3.7: Limits of TNB load power factor

No	**Voltage level**	**Power factor (pf) limits**
1	<132kV	0.85
2	>132kV	0.90

Therefore, since this research work involved loads increment at 11 kV or 132 kV buses, a minimum load power factor is specified to 0.85 and above. The injection of 50 MW PV is performed at sending and receiving ends at a time while the installation of 50 MVAR SVC is performed at the receiving end only. The amount of 50 MW PV and 50 MVAR SVC are selected randomly. The SVC is designed as reactive power support, thus it is placed only at receiving end to improve bus voltage and at the same time to reduce the VSI value. With addition of PV and SVC, dynamic simulation is performed. In this research work, the PV is set to operate at unity power factor indicating that PV only contributes to active power. In contrast, SVC is set to almost zero power factor indicating that SVC only contributes to reactive power. Again, at each placement of PV and SVC, generators performance and bus voltage are monitored while VSI is calculated. The values of generators power factor, bus voltage and VSI are compared before and after placement of PV and SVC to investigate the contribution of PV and SVC in maintaining power system stability due to load increment.

3.4 Modelling of Static Var Compensator (SVC)

Static Var Compensator (SVC) is a set of electrical instruments for providing fast acting reactive power on high voltage electricity transmission network [13]. The SVC is designed to bring the system closer to unity power factor by determining the power flow in the AC system. In this research work, SVC is connected directly to the 132 kV busbar to improve voltage stability in IEEE 30 Bus Test System by controlling the amount of reactive power injected into the system. It is expected that the bus voltage will decrease with load increment. As such, the function of introducing SVC in this research works is to provide reactive power support in improving the bus voltage.

SVC is modelled in PSS®E 34 software using automatic Switched Shunt Device and dynamic simulation is performed. Figure 3.5 shows the model of fixed shunt, switched shunt reactor and capacitors for reactive power supply to control bus voltage. The difference between fixed and switched shunts: fixed shunt is design as manual voltage control while switched shunt is designed as automatic voltage control in the system.

A fixed shunt is represented by combination of Bshunt (susceptance) and Gshunt (conductance) while a switched shunt is being represented by a general arrangement that consists up to eight block of reactive power support. A switched shunt subsystem may have both reactors and capacitors but may not be included in the same block. Reactor blocks, if present, must all be specified in the first block or block in order of which they are to be switched 'ON'. However, capacitor blocks if present, follow the reactor blocks in the order of which there are to be switch ‘ON’ [16]. Theoretically, the reactor and capacitor elements may not be ‘ON’ at the same time. The reactor block will be switched ‘ON’ when the bus voltage is over the limit while the capacitor block will be switched ‘ON’ if the bus voltage is under the limit [16].

Based on TNB Substation Guideline, shunt capacitor banks in transmission network is functioned as reactive power support to maintain system voltage. The capacitor is directly connected to the 132 kV busbar with rated capacity either 30 MVAR or 60 MVAR. In this research work, the installation of switched shunt is switched ‘ON’ as capacitor elements and fixed at 50 MVAR. Furthermore, as reactive power support into the system, SVC will always be installed at the receiving end of the strongest or weakest lines to improve the bus voltage.

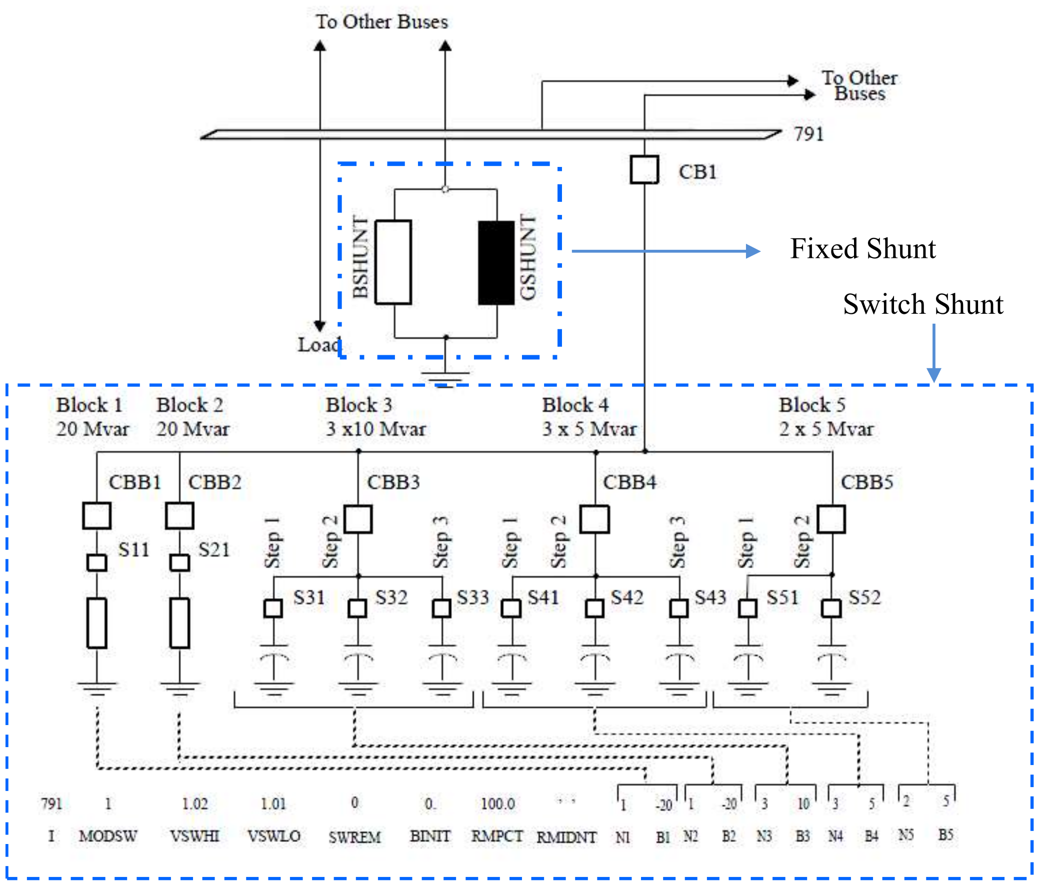


Figure 3.5: Model of Fixed Shunt, Switch Shunt for Reactive Power Support [16]

3.5 Modelling of Solar Photovoltaic (PV)

Government of Malaysia has decided to increase the use of renewable energy in Malaysia as an initiative to reduce CO_2 emission by planting up larger scale grid connected solar PV power plant [17]. With the rapid increasing integration of PV power generation, the influence of PV power generation on power system stability has attracted more attention. The power system stability may deteriorate especially in case of a weak power grid, such as remote areas far from load centre [18]. The export capacity of a plant shall not be less than 1 MW_{ac} but not more than 100 MW_{ac} [17]. Large Solar Scale (LSS) that is allowed to be connected to the Transmission Network shall have a capacity of not less than 30 MW_{ac} at one interconnection points [17].

PV unit is developed in PSS®E 34 using dynamic stability model to simulate the performance of a photovoltaic (PV) plant connected to the grid via a power converter. The model is largely based on generic type 4 wind model, WT4 with the added ability to simulate output changes due to solar irradiation. The PV generic wind model comprises of the following modules [16]: -

- PVGU: Power converter/generator module
- PVEU: Electrical control module
- PANEL: Linearized model of a panel's output curve (mechanical module)
- IRRAD: Linearized solar irradiance profile (pitch module)
-

The interaction between these 4 modules are shown in Figure 3.6: -

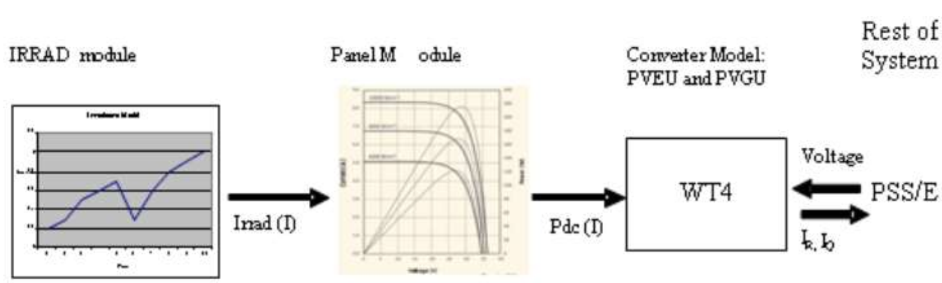


Figure 3.6: PV Model connectivity diagram in PSS®E 34 [34]

In this research work, the solar irradiance date used as an input to the PV model. Thus, for the purpose of simulation, the data are obtained from Universiti Tenaga Nasional (UNITEN) [7]. The PV power output depends on the solar irradiance and is set to operate at unity power factor indicating that PV only contributes active power in the system. The injection of PV into the system is fixed at 50 MW at a time.

3.6 Determination of weakest and strongest lines based on Voltage Stability Indices (VSI)

The strongest and weakest lines in the system are determined using selected VSI which are Fast Voltage Stability Index (FVSI) and Line Stability Factor (LQP). These 2 indices are used as indication of voltage stability by proving that these values compliment to each other.

As explained in Chapter 2 section 2.6, FVSI and LQP are proportional to the power transfer between the 2 buses. Referring to the formula, FVSI is subjected to reactive power at the receiving end while LQP is subjected to reactive power at the receiving end and active power at the sending end. The higher the power transfer in the system, the higher the indices and thus indicate that the line is the weakest line in the system. However, the smaller the power transfer in the system, the lower the indices and this indicates that the line is the strongest line in the system. The value of the voltage stability indices must be maintained less than 1.00 to maintain the security of voltage supply. If the indices values are closed to 1.00, the line is approaching towards instability condition that may lead to voltage collapse.

3.7 Determination on the amount of load increment that can cause violation.

The minimum amount of load that caused violation is identified by gradually increasing the load at the receiving end of the weakest line until the amount of load increment causes violation in terms of power factor of generators in operation and bus voltage. The receiving end of the weakest line is used to determine a minimum amount of load that will cause violation based on an assumption that the receiving end of the weakest line will contribute to severe impact with respect to the load increment compared to the strongest line.

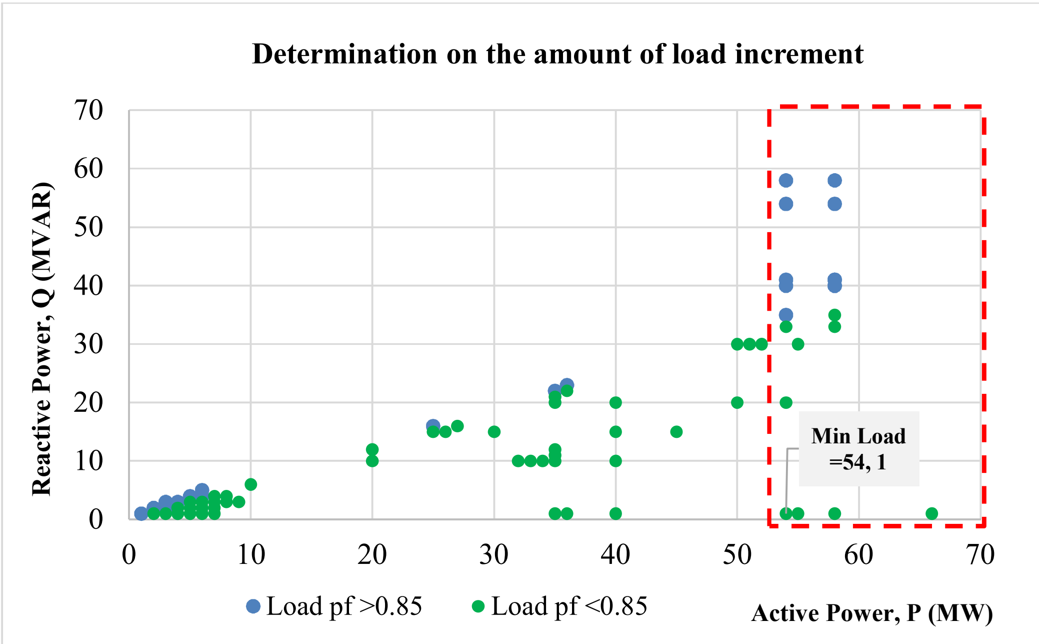


Figure 3.7: Determination on the amount of load increment

Figure 3.7 shows the distribution of various amount of load at the receiving end of the weakest line to determine the minimum amount of load that would cause violation. The distribution of load increment is divided into 2 categories which are load with power factor less than 0.85 and load with power factor more than 0.85. This is only an indication either the load meets TNB load power factor requirement with a value greater than 0.85.

The minimum of load increment that causes violation is found at 54 MW and 1 MVAR. Then, the active power is fixed at 54 MW and 58 MW while the reactive power is gradually increased to 33, 35, 40, 41, 54 and 58 MVAR to investigate the impact of reactive power increment in the system. Next, the reactive power is fixed at 1 MVAR while the active power is randomly started at 54 MW and gradually increasing to 55, 58 and 66 MW to investigate the impact of active power increment in the system. As a result, 16 loads have been identified to be added to the sending and receiving ends of the weakest and strongest lines in the system.

At each stage of load increment, generators power factor and bus voltage are monitored while VSI is calculated. In addition, the values of generators power factor, bus voltage and VSI are compared before and after load increment to analyse generators performance and voltage stability.

3.1 Summary of Chapter 3

This chapter describes on the methodology of the research work to achieve the research objectives which is to investigate the impact of load increment to power system stability by analysing generator performance with respect to generator capability curve and voltage stability with respect to VSI. The methodology used for this research work starts with modelling of the IEEE 30 Bus Test System using PSS®E 34 software. Data are then collected through power flow and dynamic simulations. Power flow simulation is performed for load increment scenarios while dynamic simulation is performed for PV injection and SVC installation. Based on the simulation, the results are analyse and tabulate in table and graph for further discussion in chapter 4.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter presents the result and discussion on the impact of load increment to power system stability by analysing generator performance with respect to generator capability limits and voltage stability with respect to VSI. As explained in Chapter 3, there are three scenarios being simulated to achieve the research objectives as below: -

- Scenario 1: Load increment at all buses
- Scenario 2: Load increment at the sending and receiving ends of the weakest line
- Scenario 3: Load increment at the sending and receiving ends of the strongest line

The results for each scenario are investigated and compared with the base case condition. PV and SVC are introduced at scenarios 2 and 3 for one selected load increment. This is to investigate the contributions of PV and SVC in maintaining power system stability due to load increment. The results before and after injection of PV and installation of SVC are compared and analysed to evaluate their contributions and effectiveness in the system.

4.2 Base Case Condition

Figure 4.1 presents the power factor of generators in operation at base case condition. In general, the power factor of all generators are within the acceptable limit. All generators operate at lagging power factor or overexcited conditions which show that all generators supply Var to the system. The generator that operates at the highest power factor of generator is G27 while generator that operates at the lowest power factor is G23.

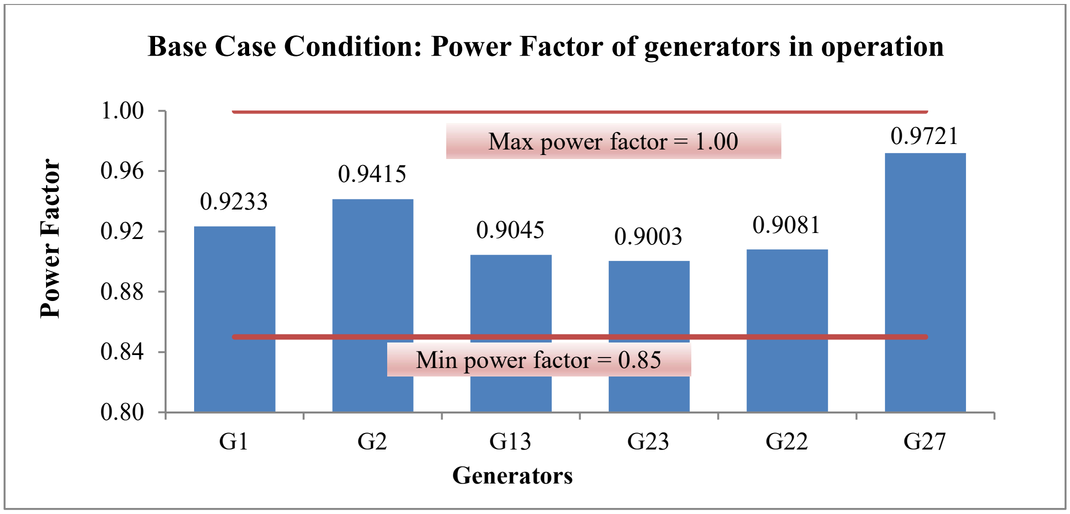


Figure 4.1: Power factor of generators in operation

The power factor of generators in operation is defines with respect to generator capability limits. The generator capability limits indicate the capability of each generator supplying active and reactive powers to the system without overheating. The angle θ, which is the angle between active and reactive powers represents the power factor angle of the synchronous generator. The larger the power factor angle, the lower will be the power factor of generators in operation. The power factor angle must be between 0º to 31º to ensure that the power factor of generators in operation is within the acceptable limits, which is between 0.85 - 1.00. This is the limit that all generators must be operated so as to be within the generator capability limit, which deliver or absorb reactive power continuously without overheating the Armature Current Limit, Field Current Limits and End Part Heating Limit. In addition, the reactive power output of the generator is controlled through generator excitation system.

Table 4.1 summaries the power factor angle and power factor of each generator in operation. Theoretically, larger angle represents the more reactive power supply into system while the smaller the angle represents less reactive power supply into the system. However, the total active and reactive power supplied need to be balanced in order to ensure that the generators are operated within the capability limits. The highest generator power factor is G27 since it has the smallest power factor angle while the lowest generator power factor is G23 since it has the largest power factor angle.

Table 4.1: Summary of the power factor angle and power factor of generators in operation

Generators No	Active Power (MW)	Reactive Power (MVAR)	Power Factor Angle, θ (degree)	Power Factor (cos θ)
G1	35.87	14.92	22.59	0.9233
G2	60.98	21.83	19.70	0.9415
G13	36.00	16.97	25.24	0.9045
G23	19.20	9.28	25.80	0.9003
G22	21.60	9.96	24.80	0.9081
G27	26.91	6.50	13.58	0.9720

Table 4.2 shows the voltage of each bus. The voltage at all buses are within acceptable limits which is within 0.95 - 1.05 p.u. The highest voltage is at Bus 1 while the lowest voltage is at Bus 19. Bus 1 is a generator bus while Bus 19 is a load bus. The lowest voltage is at Bus 19 because it is located away from generators; one load is connected to this bus, amounting 9.5 MW and 3.4 MVAR. Voltage is governed by reactive power, which is controlled through generator excitation system. Therefore, since the voltage at all buses are within the acceptable limits, it indicates that the reactive power supplied by the generators is sufficient to meet the reactive power consumption in the system. The results in Table 4.2 is plotted into a graph as shown in Figure 4.2.

Table 4.2: Bus voltage at base case condition

Bus No	Bus voltage (p.u)	Bus No	Bus voltage (p.u)
1	**1.0300**	16	0.9755
2	1.0250	17	0.9655
3	1.0079	18	0.9640
4	1.0018	**19**	**0.9574**
5	1.0086	20	0.9594
6	0.9914	21	0.9638
7	0.9890	22	0.9750
8	0.9786	23	0.9850
9	0.9760	24	0.9751
10	0.9692	25	0.9839
11	0.9737	26	0.9658
12	0.9935	27	0.9900
13	1.0200	28	0.9902
14	0.9814	29	0.9889
15	0.9819	30	0.9861

Note: Bolted font shows the highest and lowest bus voltage

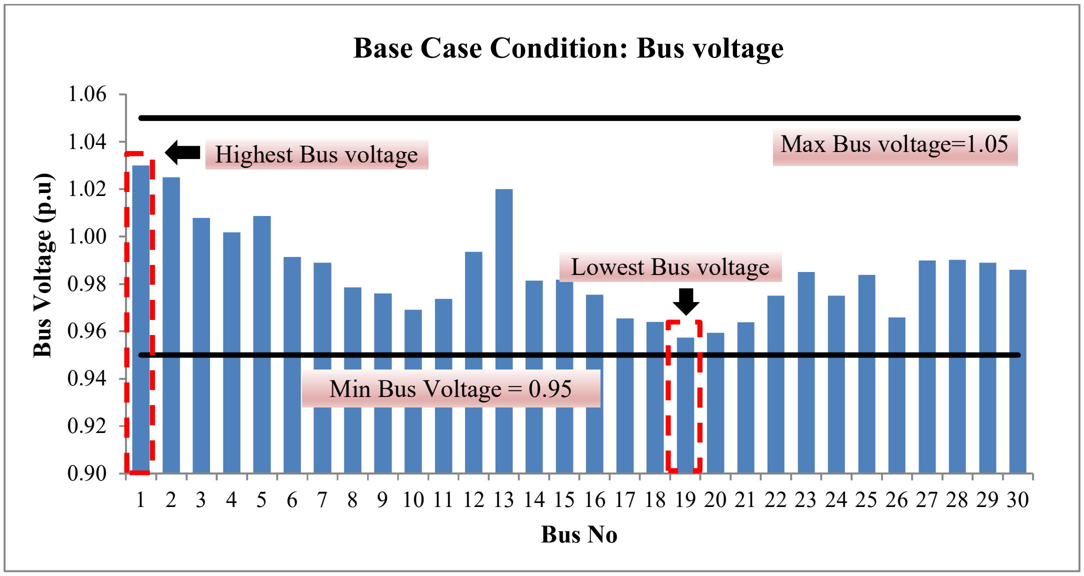


Figure 4.2: Distribution of bus voltage

Table 4.3 and Figure 4.3 show FVSI and LQP of each line. FVSI and LQP values at all lines are within the acceptable limit which are less than 1.00, thus the voltage stability is maintained. If the indices value closed to 1.00 the line is approaching towards instability conditions that may lead to voltage collapse. The values are sorted from the strongest to the weakest line. The strongest line is TX 27 to Bus 28 while the weakest line is TX 2 to Bus 6. Both strongest and weakest line is a line connected with step up transformer rated at 11/132kV. The FVSI and LQP values are complement to each other by showing the same strongest and weakest line in the system with small variance in value.

FVSI and LQP are proportional to the power transfer between the two buses. The value of FVSI are slightly lower as compared with LQP. This is because, FVSI is subject to reactive power at receiving end while LQP are subject to reactive power at receiving end and active power at sending end.

Table 4.3: Distribution of FVSI and LQP

Lines	Voltage Stability Index		Lines	Voltage Stability Index	
	LQP	FVSI		LQP	FVSI
TX 27 to 28	**0.00023**	**0.00021**	10 to 20	0.02113	0.02441
TX 22 to 24	0.00106	0.00036	12 to 14	0.02153	0.02503
6 to 7	0.00260	0.00280	9 to 10	0.02770	0.02762
TX 27 to 29	0.00453	0.00433	15 to 18	0.02740	0.03161

Lines	Voltage Stability Index	
	LQP	**FVSI**
19 to 20	0.00488	0.00575
29 to 30	0.00532	0.00652
14 to 15	0.00297	0.00656
6 to 28	0.00784	0.00871
9 to 11	0.00930	0.00882
1 to 2	0.01004	0.01072
TX 15 to 23	0.01305	0.01206
18 to 19	0.01044	0.01223
10 to 17	0.01222	0.01392
TX 27 to 30	0.01615	0.01519
10 to 21	0.01495	0.01761
3 to 4	0.01819	0.01915
24 to 25	0.01493	0.01942
16 to 17	0.01844	0.02086
TX 10 to 22	0.02450	0.02306
12 to 15	0.01883	0.02341
TX 25 to 27	0.02455	0.02408

Lines	Voltage Stability Index	
	LQP	**FVSI**
4 to 12	0.03258	0.03255
4 to 6	0.03190	0.03353
TX 23 to 24	0.04028	0.03968
12 to 16	0.03516	0.04015
6 to 8	0.04127	0.04343
8 to 28	0.04042	0.04348
TX 21 to 22	0.04625	0.04441
25 to 26	0.03689	0.05174
5 to7	0.04923	0.05618
6 to 9	0.06211	0.06065
TX 2 to 5	0.06438	0.06183
TX 1 to 3	0.08556	0.08205
6 to 10	0.08884	0.08665
TX 2 to 4	0.08994	0.08733
TX 12 to 13	0.10784	0.09400
TX 2 to 6	**0.12876**	**0.12458**

Note: Bolted font shows the highest and lowest Voltage Stability Index (VSI)

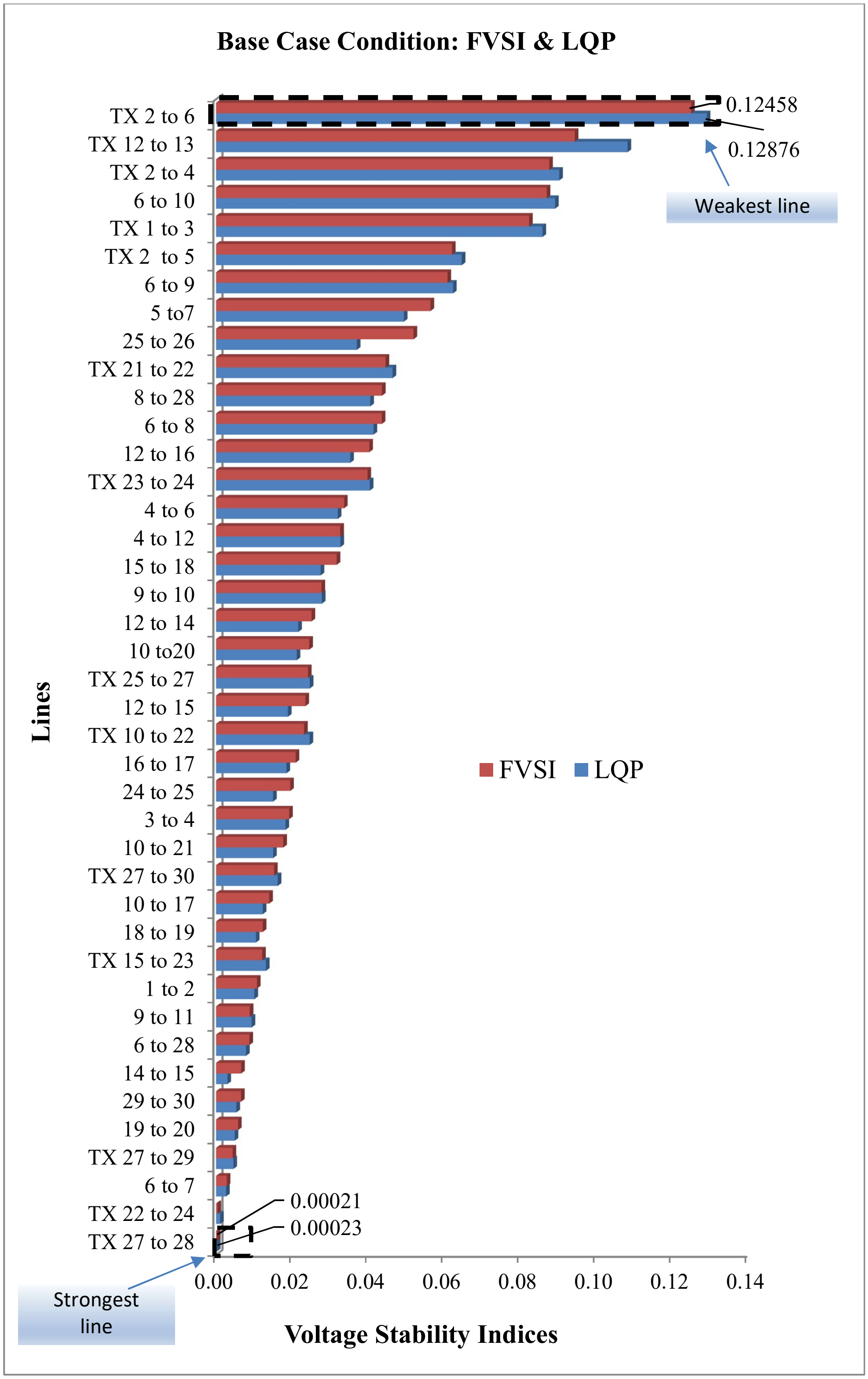


Figure 4.3: Distribution of FVSI and LQP

Figure 4.4 shows the related generators and loads that justify TX 2 to Bus 6 and TX 27 to Bus 28 present as the weakest and strongest lines in IEEE 30 Bus Test System. The higher the power transfer in the system, the higher the indices and thus it indicates that line TX 2 to Bus 6 is the weakest line in the system. The smaller the power transfer in the system, the lower the indices and this indicates that line TX 27 to Bus 28 is strongest line in the system.

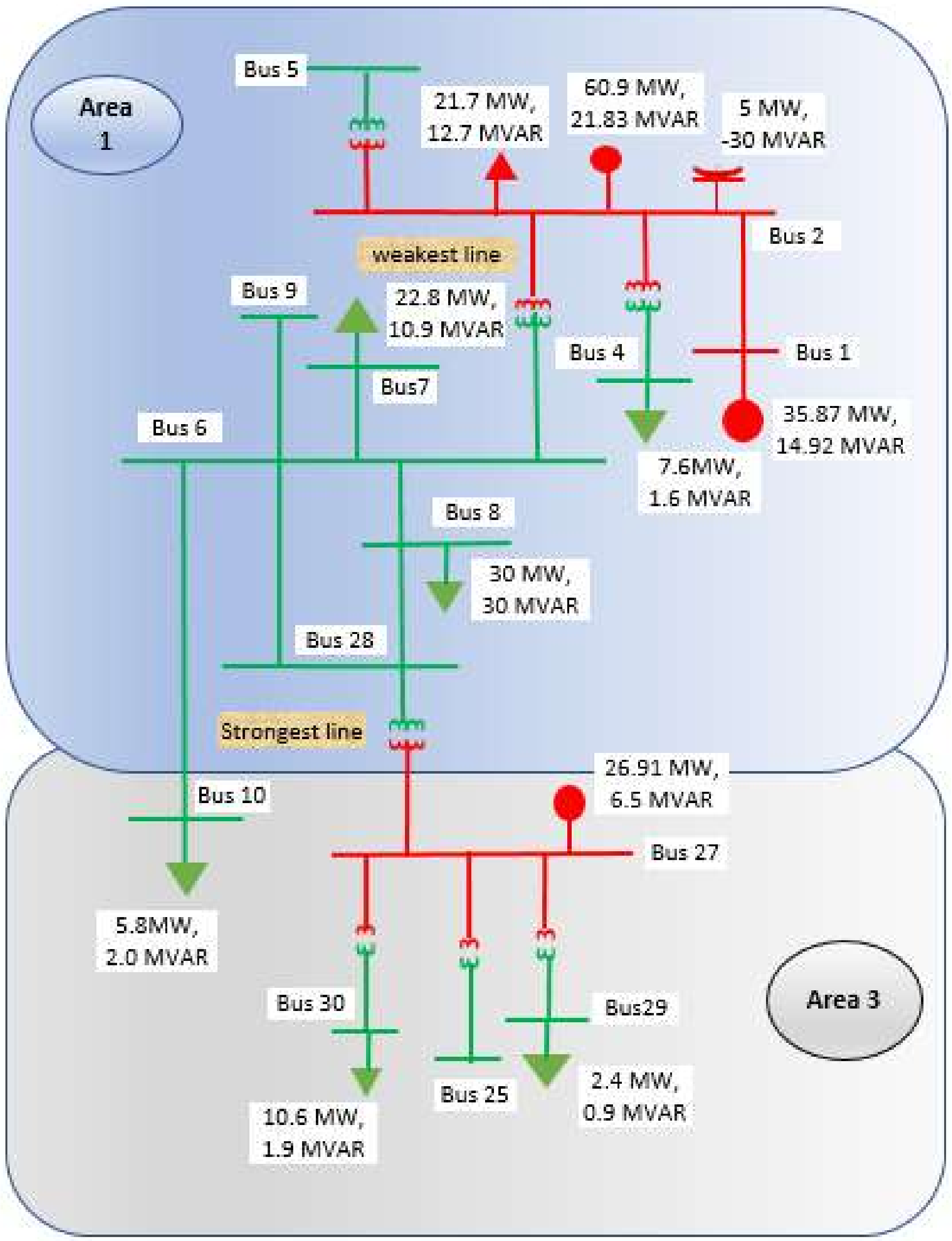


Figure 4.4: The related generators and loads within the strongest and weakest line.

TX 2 to Bus 6 is located at Area 1, which is the area that large amount of reactive power resources but also large amount of reactive power consumption. There is a large amount of power transfer between TX 2 to Bus 6 this is because large amount of loads are connected on Bus 2, Bus 8 and Bus 10. Referring to Figure 4.4, 12.7 MVAR load is connected at Bus 2 while 30 MVAR and 2 MVAR are connected to Bus 8 and Bus 10 respectively. These buses are connected directly to Bus 6.

TX 27 to Bus 28 is a tie line connecting between Area 1 and Area 3. As illustrated in Figure 3.2 of Chapter 3, Area 3 has the smallest amount of reactive power resources, which is 16.46 MVAR but with large amount of reactive power consumption, which is 25.8 MVAR. Hence, most of the reactive power is imported from other areas so as to meet the load demand.

4.3 Scenario 1: Load increment at all buses

In scenario 1, the loads are increased at all buses up to 4 stages. The loads are gradually increased at staged values as below: -

- Stage 1: 1 MW, 1 MVAR
- Stage 2: 2 MW, 2 MVAR
- Stage 3: 5 MW, 5 MVAR
- Stage 4: 10 MW, 10 MVAR

One of the essential requirements in power systems is to ensure balanced between the total generation capacity and the total load demand plus losses in normal and under disturbance conditions. Under normal condition, the system is stable or balanced if the total generation capacity fulfil the total load demand and losses as given in the following equation: -

$$\text{Total generation} = \text{Total load} + \text{Total losses} \qquad \text{(Equation 4.1)}$$

Table 4.4 shows the difference between the total active and reactive powers supply and consumption at base case condition and at all stages of load increment, neglecting losses. The difference between the total active and reactive powers supply and consumption are presented by positive (+) and negative (-) sign. The positive (+) sign indicates that the total generation active and reactive powers supply is sufficient to meet the load demand while the negative (-) sign indicates total generation active and reactive powers supply is insufficient to meet the load demand. Based on Table 4.4, the insufficient active and reactive powers supply from the generators to meet the load demand has occurred since stage 1 of the load increment.

Table 4.4: The difference between total active and reactive powers supply and consumption at all stages of load increment.

Stages	**Total active and reactive powers supply**		**Total active and reactive powers consumption**		**The different between total active and reactive powers supply & consumption**	
	P (MW)	**Q (MVAR)**	**P (MW)**	**Q (MVAR)**	**P (MW)**	**Q (MVAR)**
Base condition	195.56	109.45	194.20	108.20	+1.36	+1.25
Stage 1			215.20	129.20	-19.64	-19.75
Stage 2			236.20	150.20	- 40.64	- 40.75
Stage 3			299.20	213.20	-103.64	- 103.75
Stage 4			404.20	218.02	-208.64	-108.57

Table 4.5 shows the power factor of generators in operation at all stages of load increment. The table shows that power factor of generators in operation are reduced with load increment. The higher the load increment, the lower the power factor of the generators in operation. It is observed that the power factor of generators in operation is still within the acceptable limits at stage 1. This indicates that the total generation capacity is sufficient to meet the load demand although the total load demand exceeds the total generation supply of -19.64 MW and -19.75 MVAR. This is because, the imbalance between the total generation supply and the total loads demand is balanced by G1 which serves as a slack bus to fulfil the load demand within the generation capacity. The power factor of generators G13, G22, G23 and G27 in operation are reducing below acceptable limit since stage 2 of load increment. At stage 4 of the load increment, the power factor of all generators in operation decreases due to the load increment exceeds the maximum capability of respective generators. Generators are the source of reactive power supply in

the system. However, the generated MVAR is limited by generator capability limit. Therefore, as reactive load is increased, the generator may operate near or beyond the capability limit as presented by low operating power factor. In addition, allowable operating power factor for generator is within 0.85 - 1.00, lesser than 0.85 shows that generators are operating at over excited condition that will lead to heating of the field winding.

Table 4.5: Power factor of generators in operation at all stages of load increment

Generators No	Base Case Condition	Stage 1	Stage 2	Stage 3	Stage 4
G1	0.9233	0.9189	0.9496	0.9539	**0.7374**
G2	0.9415	0.9121	0.8778	0.8579	**0.7128**
G13	0.9045	0.8556	**0.8289**	**0.7846**	**0.6272**
G22	0.9081	0.9315	**0.8268**	**0.4016**	**0.3266**
G23	0.9004	0.9064	**0.8074**	**0.5139**	**0.4327**
G27	0.9721	0.9052	**0.8375**	**0.7128**	**0.4836**

Note: Bolted font shows power factor of generators in operation below acceptable limits

Table 4.6 shows the voltage at all buses for all stages of the load increment. The higher the load increment, the lower the voltage on each bus. It is observed that Bus 1 which serves as a slack bus remained constant at 1.05 p.u at all stages of load increment. The under voltage condition starts to occur at bus 19 since stage 1 of load increment. There are more under voltage occurrence on other buses at stage 2 and stage 3. At stage 4 of the load increment, the under voltage condition occurs at all buses.

Table 4.6: Bus voltage at all stages of load increment

Bus No	**Bus Voltage (p.u)**				
	Base condition	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
1	1.0300	1.0500	1.0500	1.0500	1.0500
2	1.0250	1.0400	1.0380	1.0250	**0.9441**
3	1.0079	1.0199	1.0169	1.0043	**0.8841**
4	1.0018	1.0117	1.0079	0.9923	**0.8450**
5	1.0086	1.0211	1.0184	1.0043	**0.8852**
6	0.9914	1.0000	0.9958	0.9788	**0.8127**
7	0.9890	0.9985	0.9941	0.9757	**0.8210**
8	0.9786	0.9869	0.9822	0.9637	**0.7898**
9	0.9760	0.9758	0.9700	0.9570	**0.7103**
10	0.9692	0.9657	0.9605	0.9545	**0.6863**
11	0.9737	0.9714	0.9633	**0.9434**	**0.6746**
12	0.9935	0.9958	0.9917	0.9796	**0.7377**
13	1.0200	1.0300	1.0300	1.0250	**0.8260**
14	0.9814	0.9787	0.9719	0.9537	**0.6712**
15	0.9819	0.9783	0.9725	0.9592	**0.6778**
16	0.9755	0.9731	0.9662	**0.9497**	**0.6726**
17	0.9655	0.9615	0.9549	**0.9433**	**0.6626**
18	0.9640	0.9555	**0.9447**	**0.9181**	**0.5851**
19	0.9574	**0.9480**	**0.9365**	**0.9086**	**0.5680**
20	0.9594	0.9507	**0.9399**	**0.9150**	**0.5837**
21	0.9638	0.9591	0.9546	0.9540	**0.6825**
22	0.9750	0.9700	0.9700	0.9900	**0.7434**
23	0.9850	0.9800	0.9800	0.9900	**0.7315**
24	0.9751	0.9709	0.9696	0.9772	**0.7193**
25	0.9839	0.9887	0.9876	0.9808	**0.7618**
26	0.9658	0.9640	0.9560	**0.9279**	**0.6376**
27	0.9900	1.0000	1.0000	0.9900	**0.8033**
28	0.9902	0.9985	0.9946	0.9774	**0.8008**
29	0.9889	0.9972	0.9955	0.9801	**0.7794**
30	0.9861	0.9944	0.9927	0.9772	**0.7756**

Note: Bolted font shows under voltage condition

Figure 4.5 shows the location of buses 16, 17, 18, and 19 are far away from generators and reactive power supply and the consumption are within Area 2 and Area 3. The voltage is governed by reactive power which control through generator excitation system. Lacking of reactive power will lead to the under voltage condition. As reactive load increases, there will be violation in voltage if the reactive power resources are insufficient to meet the load demand. Therefore, the most affected bus will be the bus that is located away from generators which is the source of reactive power injection. Thus, under voltage occurs at Bus 19 since Bus 19 is located away from the generators. The subsequent load increment will contribute under voltage condition at other buses within Bus 19 vicinity.

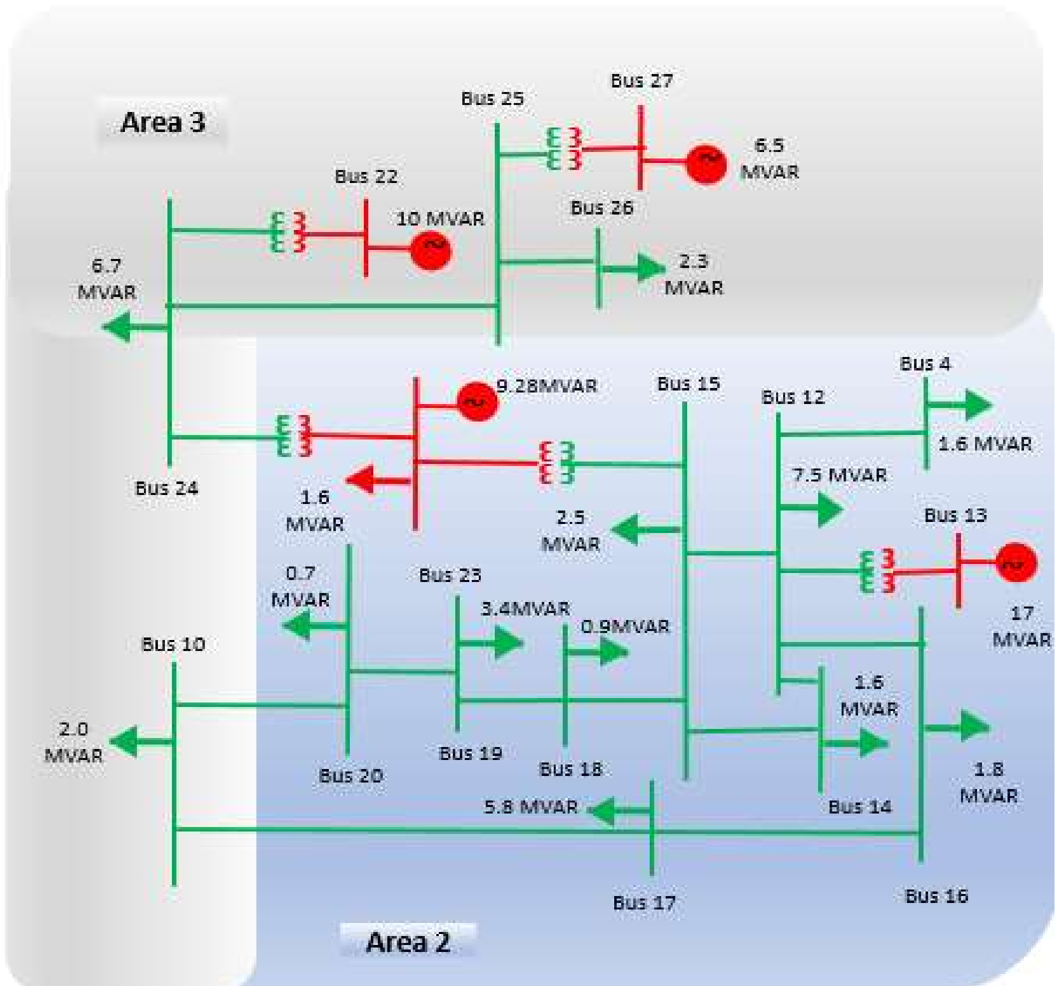


Figure 4.5: The location of Bus 16, 17, 18 and 19 and total reactive power supply and consumption within Area 2 and 3.

Table 4.7 shows the FVSI and LQP at all stages of load increment. The FVSI and LQP are slightly increased at every stages of the load increment but still remained below 1.00. The FVSI and LQP are proportional to the power transfer between the 2 buses. The higher the power transfer in the system, the higher the indices. Therefore, increased in load reflects an increase of power transfer in the system. Thus, the FVSI and LQP values will increase proportionally to the load increment.

Table 4.7: FVSI and LQP at all stages of load increment

Lines	Base Condition		Stage 1		Stage 2		Stage 3		Stage 4	
	LQP	FVSI	LQP	FVSI	LQP	FVSI	LQP	FVSI	LQP	FVSI
6 to 7	0.00260	0.00280	0.00120	0.00128	0.00150	0.00126	0.00117	0.03152	0.04486	0.05042
19 to 20	0.00488	0.00575	0.00664	0.00782	0.00663	0.00584	0.00622	0.01877	0.06440	0.07348
14 to 15	0.00297	0.00656	0.00556	0.01227	0.00558	0.00456	0.00601	0.07278	0.10120	0.22337
29 to 30	0.00532	0.00652	0.00522	0.00640	0.00530	0.00515	0.00536	0.00591	0.01101	0.01272
6 to 28	0.00784	0.00871	0.00596	0.00662	0.00610	0.00534	0.00632	0.03642	0.04966	0.04990
9 to 11	0.00930	0.00882	0.01834	0.01764	0.01854	0.01767	0.01884	0.05240	0.24125	0.20908
1 to 2	0.01004	0.01072	0.01923	0.02007	0.02052	0.01826	0.03745	0.03035	0.31386	0.24722
18 to 19	0.01044	0.01223	0.01338	0.01575	0.01384	0.01298	0.01095	0.02371	0.09147	0.10076
10 to 17	0.01222	0.01392	0.01306	0.01486	0.01352	0.01143	0.01389	0.04650	0.12427	0.13924
10 to 21	0.01495	0.01761	0.01863	0.02193	0.01664	0.01676	0.01828	0.02737	0.12120	0.14208
3 to 4	0.01819	0.01915	0.02342	0.02456	0.02526	0.02435	0.02716	0.02072	0.17492	0.16928
24 to 25	0.01493	0.01942	0.04126	0.05400	0.03256	0.03122	0.04162	0.04331	0.22844	0.25859
16 to 17	0.01844	0.02086	0.02485	0.02838	0.02584	0.02482	0.02270	0.01359	0.02932	0.02186
12 to 15	0.01883	0.02341	0.03528	0.04414	0.03662	0.03336	0.04114	0.02242	0.10131	0.06328
10 to 20	0.02113	0.02441	0.03549	0.04087	0.03645	0.03257	0.03844	0.11135	0.49728	0.52942
12 to 14	0.02153	0.02503	0.03555	0.04155	0.03622	0.03211	0.03911	0.03329	0.16483	0.14582
9 to 10	0.02770	0.02762	0.04116	0.04089	0.03556	0.03215	0.04258	0.01012	0.17771	0.14682
8 to 28	0.04042	0.04348	0.04225	0.04562	0.04228	0.04326	0.04343	0.08306	0.10526	0.11102
15 to 18	0.02740	0.03161	0.04183	0.04892	0.04201	0.04105	0.04215	0.10599	0.38205	0.37914
4 to 12	0.03258	0.03255	0.07113	0.06990	0.08225	0.07998	0.10968	0.00564	0.75016	0.48501
4 to 6	0.03190	0.03353	0.03518	0.03689	0.03622	0.03126	0.03728	0.02161	0.13714	0.13197
12 to 16	0.03516	0.04015	0.04984	0.05738	0.04567	0.03987	0.05069	0.05207	0.23143	0.21355
6 to 8	0.04127	0.04343	0.04169	0.04383	0.04180	0.04079	0.04252	0.04396	0.10347	0.10401
25 to 26	0.03689	0.05174	0.05258	0.07352	0.04768	0.04376	0.05597	0.15241	0.38162	0.45734
5 to7	0.04923	0.05618	0.05500	0.06241	0.05723	0.47650	0.05855	0.04059	0.23257	0.22796
6 to 9	0.06211	0.06065	0.09616	0.09314	0.09818	0.09678	0.11294	0.03482	0.38969	0.18364
6 to 10	0.08884	0.08665	0.13515	0.13020	0.15798	0.12564	0.17692	0.01271	0.55841	0.16925
TX 22 to 24	0.00106	0.00036	0.00353	0.00352	0.00277	0.00189	0.00357	0.04508	0.12437	0.12427
TX 27 to 28	0.00023	0.00021	0.00691	0.00578	0.00725	0.00533	0.00941	0.13141	0.16882	0.15743
TX 27 to 29	0.00453	0.00433	0.01136	0.01106	0.00876	0.00787	0.01130	0.03603	0.12786	0.11821
TX 15 to 23	0.01305	0.01206	0.00736	0.00642	0.00855	0.00654	0.00592	0.16491	0.48886	0.48396
TX 27 to 30	0.01615	0.01519	0.02281	0.02167	0.03355	0.02278	0.02263	0.04590	0.15389	0.13648
TX 10 to 22	0.02450	0.02306	0.01847	0.01709	0.01976	0.01879	0.01534	0.16493	0.51495	0.50919
TX 25 to 27	0.02455	0.02408	0.04514	0.04430	0.03265	0.03164	0.04523	0.03375	0.15024	0.11179
TX 23 to 24	0.04028	0.03968	0.03722	0.03672	0.03542	0.03341	0.03336	0.04820	0.17480	0.17256
TX 21 to 22	0.04625	0.04441	0.04650	0.04458	0.46620	0.04398	0.04578	0.15702	0.48639	0.46836
TX 2 to 5	0.06438	0.06183	0.07307	0.06967	0.07560	0.05431	0.08200	0.09786	0.46204	0.41119
TX 1 to 3	0.08556	0.08205	0.11452	0.10804	0.12522	0.11734	0.15811	0.12321	0.65126	0.53867
TX 2 to 4	0.08994	0.08733	0.10788	0.10381	0.11252	0.00232	0.11898	0.10926	0.53365	0.46306
TX 12 to 13	0.10784	0.09400	0.15294	0.13963	0.15292	0.13789	0.15284	0.11317	0.61449	0.52692
TX 2 to 6	0.12876	0.12458	0.15082	0.14448	0.13967	0.12543	0.17859	0.10926	0.57197	0.46306

4.4 Scenario 2: Load increment at the sending and receiving ends of weakest line (TX 2 to Bus 6)

The weakest line of the IEEE 30 Bus Test System is TX 2 to Bus 6 which is connected with step up transformer 11/132 kV. Bus 2 is generator bus with rated voltage at 11 kV while Bus 6 is a load bus with rated voltage at 132 kV. Since, TX 2 to Bus 6 is connected with step up transformer 11/132 kV, the source of power is flows from Bus 2 to Bus 6. This is the reason for Bus 2 is known as the sending end while Bus 6 is known as the receiving end. Bus 2 and Bus 6 are located at Area 1 with total generation of 96.85 MW, 36.76 MVAR and total load consumption of 89.5 MW and 57.4 MVAR. As shown in chapter 3, Figure 3.2, Area 1 is known as large amount of reactive power resources but large amount of reactive power consumption. The 16 identified loads are added one at a time to Bus 2 and Bus 6 respectively to investigate the impact of load increment to power system stability. The values of generators power factor, bus voltage and VSI are compared before and after loads increment to analyse generators performance with respect to generator capability limits and voltage stability with respect to VSI.

Furthermore, with load increment at the sending and receiving ends of the weakest line. The power factor of generators in operation is observed at all six generators. However, only power factor of generators G2, G22 and G27 in operation is analysed since these three generators are affected with load increment at Bus 2 or Bus 6. In addition, voltage at Bus 8 is analysed since under voltage condition occurs during load increment at Bus 6 with variable reactive power at constant active power of 54 MW and 58 MW.

Table 4.8 shows power factor of G2 generators in operation at variable reactive power at constant active power of 54 MW and 58 MW. Comparing with the base case condition, the power factor of generator G2 in operation is decreasing and below the acceptable limits with respect to load increment since 1 MVAR of load increment. It is observed that power factor of generator G2 in operation is slightly lower with load increment at Bus 2 as compared to load increment at Bus 6. The power factor of G2 generator in operation is constant at 0.7128 with a load increment at Bus 2 of more than 33 MVAR. However, the power factor of G2 generator in operation is constant at 0.7128 with load increment at Bus 6 of more than 54 MVAR. The results in Table 4.8 is plotted into a graph as shown in Figure 4.6.

Table 4.8: Power factor of generator G2 in operation with variable reactive power at constant active powers of 54 MW and 58 MW.

Total Q (MVAR)	Power factor of generator G2 in operation				
	Load increment at Bus 2		Load increment at Bus 6		At base case condition
	P=54 MW	P=58 MW	P=54 MW	P=58 MW	
1	**0.8425**	**0.8346**	**0.8491**	**0.8411**	0.9415
33	**0.7128**	**0.7128**	**0.7436**	**0.7358**	
35	**0.7128**	**0.7128**	**0.7371**	**0.7294**	
40	**0.7128**	**0.7128**	**0.7211**	**0.7135**	
41	**0.7128**	**0.7128**	**0.7179**	**0.7128**	
54	**0.7128**	**0.7128**	**0.7128**	**0.7128**	
58	**0.7128**	**0.7128**	**0.7128**	**0.7128**	

Note: The bolted font indicates the power factor of the generator below the acceptable limit

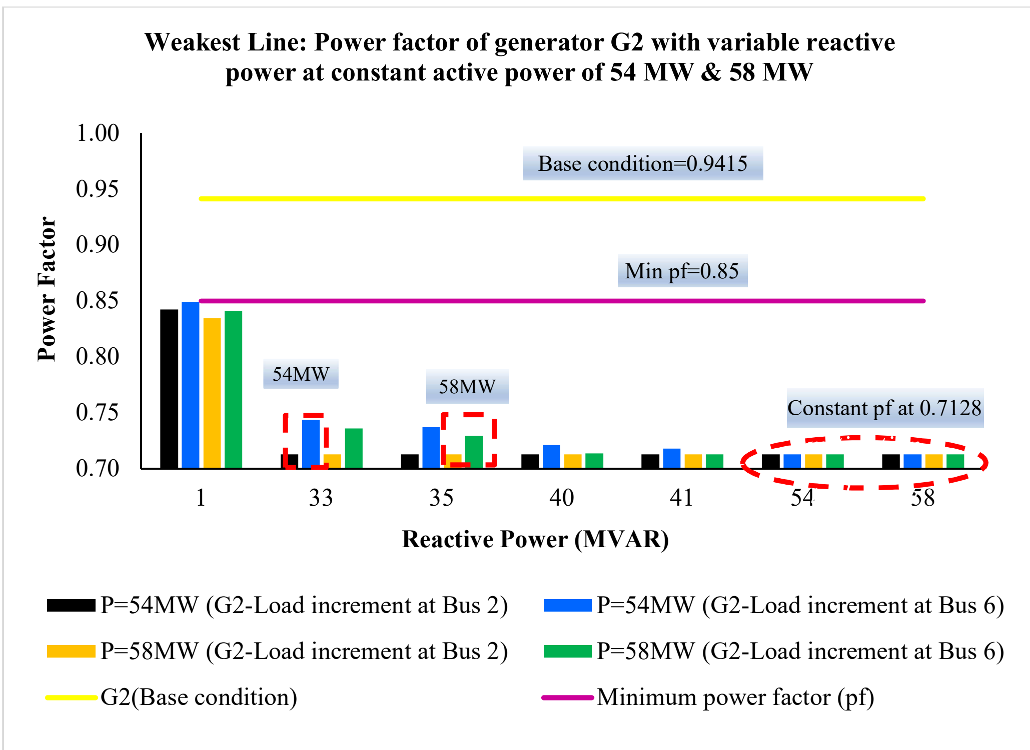


Figure 4.6: Power factor of generator G2 in operation with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.9 shows power factor of generator G22 in operation with variable reactive power at constant active power of 54 MW and 58 MW. Comparing with base case condition, the power factor of generator G22 in operation is decreasing with a load increment. The power factor of generator G22 in operation is slightly lower with load increment at Bus 6 as compared with load increment at Bus 2. The power factor of generator G22 in operation is still within the acceptable limits at all stages of load increment at Bus 2, while the power factor of generator G22 in operation is reducing below the acceptable limits with load increment more than 58 MW, 33 MVAR at Bus 6. The results in Table 4.9 is plotted into a graph as shown in Figure 4.7.

Table 4.9: Power factor of generator G22 in operation with variable reactive power at constant active powers of 54 MW and 58 MW.

Total Q (MVAR)	Power factor of generator G22 in operation				
	Load increment at Bus 2		Load increment at Bus 6		At base case condition
	P=54MW	P=58MW	P=54MW	P=58MW	
1	0.9067	0.9065	0.8882	0.8882	0.9081
33	0.8951	0.8936	**0.8200**	**0.8185**	
35	0.8930	0.8915	**0.8155**	**0.8140**	
40	0.8875	0.8860	**0.8042**	**0.8027**	
41	0.8864	0.8849	**0.8020**	**0.7999**	
54	0.8718	0.8703	**0.7653**	**0.7623**	
58	0.8673	0.8657	**0.7538**	**0.7508**	

Note: The bolted font indicates the power factor of the generator in operation below the acceptable limit

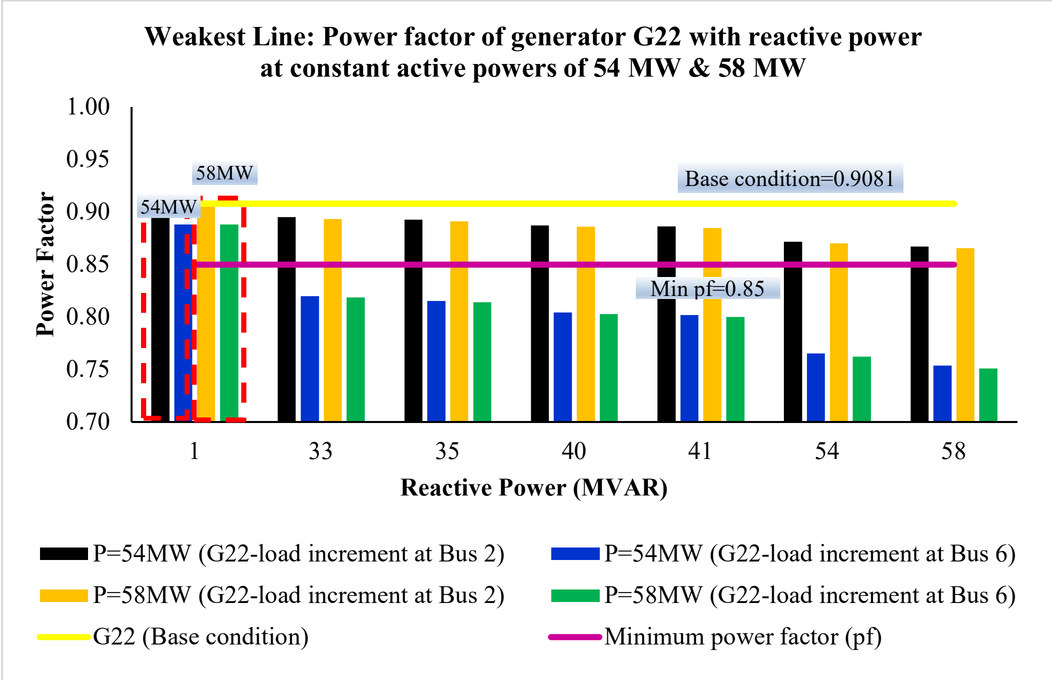


Figure 4.7: Power factor of generator G22 in operation with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.10 shows power factor of generator G27 in operation with variable reactive power at constant active power of 54 MW and 58 MW. Comparing with base case condition, the power factor of G27 generator in operation is decreasing with load increment. The power factor of G27 generator in operation is slightly lower with load increment at Bus 6 compared with load increment at Bus 2. The power factor of generators G27 in operation is still within the acceptable limit at all stages of load increment at Bus 2. The power factor of generators G27 in operation below the acceptable limits with load increment at Bus 6 more than 58 MW and 54 MVAR. The results in Table 4.10 is plotted into a graph as shown in Figure 4.8.

Table 4.10: Power factor of generator G27 in operation with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	**Power Factor generator G27 in operation**				
	Load increment at Bus 2		**Load increment at Bus 6**		**At base case condition**
	P=54 MW	**P=58 MW**	**P=54MW**	**P=58MW**	
1	0.9711	0.9710	0.9571	0.9559	0.9721
33	0.9618	0.9606	0.8843	0.8825	
35	0.9600	0.9588	0.8789	0.8722	
40	0.9553	0.9540	0.8656	0.8638	
41	0.9544	0.9531	0.8629	0.8605	
54	0.9365	0.9396	**0.8183**	**0.8147**	
58	0.9411	0.9365	**0.8040**	**0.8004**	

Note: The bolted font indicates the power factor of the generator below the acceptable limit.

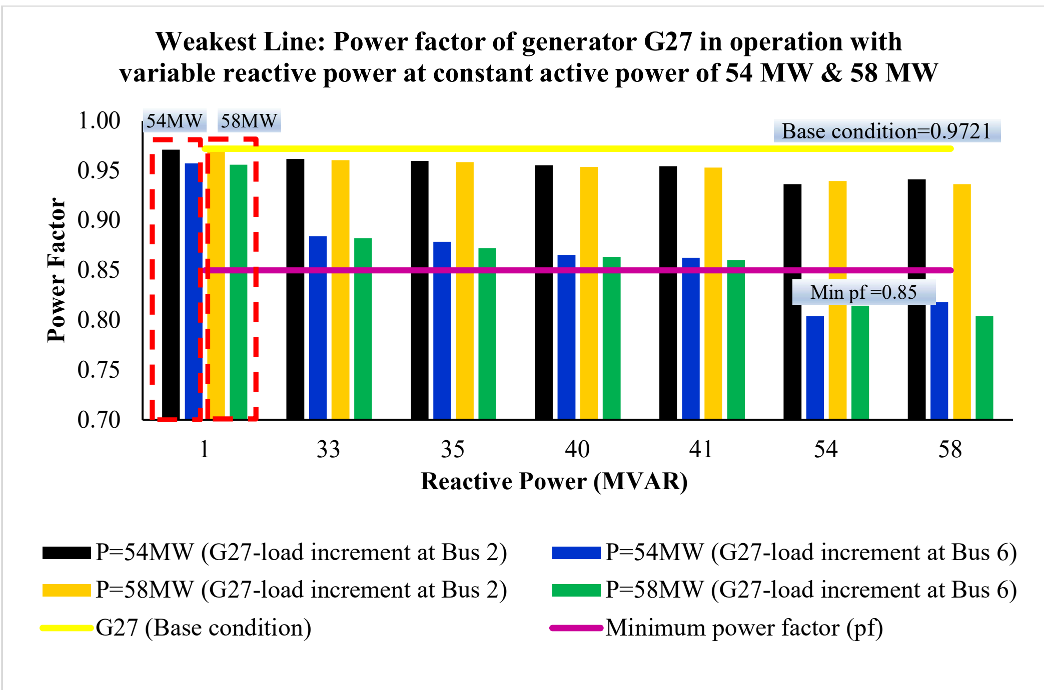


Figure 4.8: Power factor of generator G27 in operation with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.11 shows power factor of generators G2, G22 and G27 in operation with variable active power at minimal reactive power of 1 MVAR. The power factor of generator G2 in operation is decreasing and below the acceptable limits since 54 MW and 1 MVAR. The power factor of generator G2 in operation is slightly lower with load increment at Bus 2 compared with load increment at Bus 6. However, the power factor of generators G22 and G27 in operation are still within the acceptable limits since 54 MW and 1 MVAR. The power factor of G22 and G27 generators in operation is slightly lower with load increment at Bus 6 compared with Bus 2. The results in Table 4.11 is plotted into a graph as shown in Figure 4.9.

Table 4.11: Power factor of generators G2, G22 and G27 in operation at variable active power with minimal reactive power of 1 MVAR

Total P (MW)	Power Factor of generators G2, G22 and G27 in operation						
	Load increment at Bus 2			Load increment at Bus 6			At base case condition
	G2	G22	G27	G2	G22	G27	
54	**0.8425**	0.9067	0.9711	**0.8491**	0.8896	0.9571	G2=0.9415 G22=0.9081 G27=0.9721
55	**0.8406**	0.9066	0.9710	**0.8471**	0.8893	0.9568	
58	**0.8346**	0.9065	0.9710	**0.8411**	0.8882	0.9559	
66	**0.8186**	0.9063	0.9708	**0.8247**	0.8853	0.9533	

Note: Bolted font shows generator power factor below acceptable limits

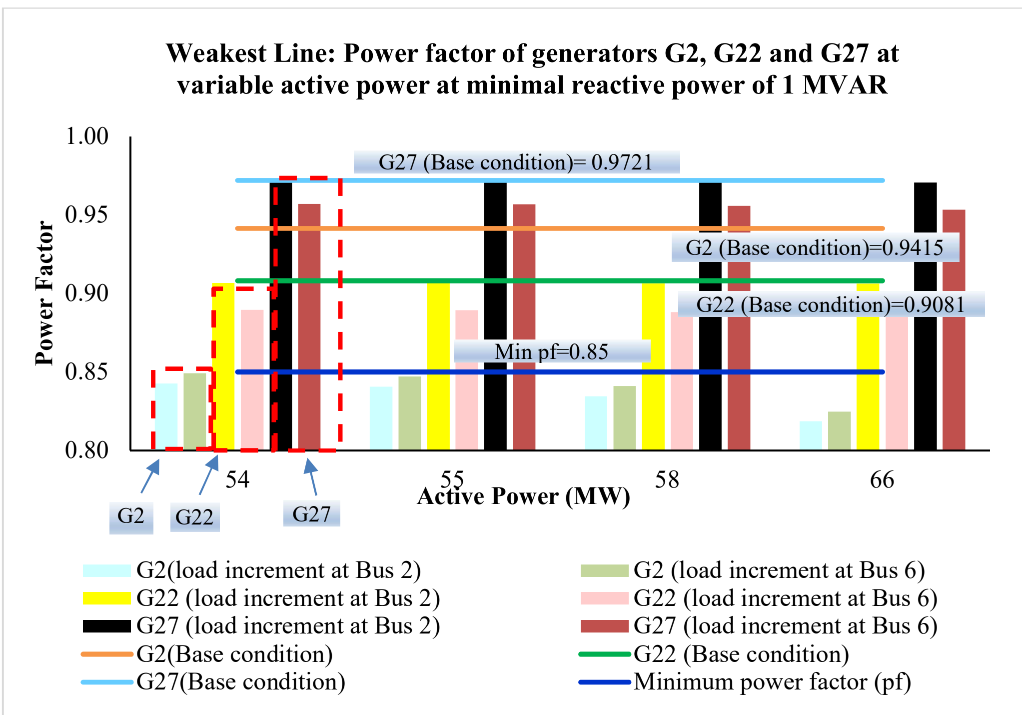


Figure 4.9: Power factor of generators G2, G22 and G27 in operation at variable active power with minimal reactive power of 1 MVAR

Table 4.12- 4.13 show voltage at Bus 8 (V8), voltage at Bus 2 (V2) and voltage at Bus 6 (V6) with variable reactive power at constant active power of 54 MW and 58 MW. Table 4.12 shows V8 with respect to load increment at Bus 2 or Bus 6 while Table 4.13 shows V2 with respect to load increment at Bus 2 and V6 with respect to load increment at Bus 6. The results at every stages of load increment are compared with base case condition for analysis purposes. Voltage at all buses are monitored but only V2, V6 and V8 are presented in table since Bus 2 and Bus 6 are the sending and receiving ends of the weakest line while Bus 8 is the affected bus due to load increments at Bus 6 or Bus 2. The under voltage occurs at V8 due to load increment at Bus 6. The under voltage occurred at load increment of more than 58 MW and 58 MVAR.

Table 4.12: V8 with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	V8 (p.u)				
	Load increment at Bus 2		Load increment at Bus 6		At base case condition
	P=54 MW	P=58 MW	P=54 MW	P=58 MW	
1	0.9784	0.9784	0.9753	0.9751	V8=0.9786
33	0.9762	0.9759	0.9623	0.9621	
35	0.9758	0.9755	0.9615	0.9612	
40	0.9748	0.9745	0.9594	0.9592	
41	0.9746	0.9743	0.9590	0.9587	
54	0.9719	0.9716	0.9523	0.9517	
58	0.9711	0.9708	0.9501	**0.9496**	

Note: The bolted font indicates the bus voltage below the acceptable limit

Table 4.13: V2 & V6 with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	V2 (p.u)		V6 (p.u)		At base case condition
	Load increment at Bus 2		Load increment at Bus 6		
	P=54 MW	P=58 MW	P=54 MW	P=58 MW	
1	1.0250	1.0250	0.9880	0.9878	V2=1.0250 V6=0.9920
33	1.0204	1.0199	0.9747	0.9744	
35	1.0196	1.0191	0.9739	0.9735	
40	1.0175	1.0170	0.9719	0.9736	
41	1.0171	1.0166	0.9713	0.9736	
54	1.0116	1.0111	0.9644	0.9639	
58	1.0099	1.0094	0.9622	0.9617	

The results from Table 4.12 and 4.13 are plotted into a chart as shown in Figure 4.10. V8 (Bus 2) presents voltage at Bus 8 with respect to load increment at Bus 2, V8 (Bus 6) presents voltage at Bus 8 with respect to load increment at Bus 6, V6 presents voltage at Bus 6 with respect to load increment at Bus 6 and V2 presents voltage at Bus 2 with respect to load increment at Bus 2. Figure 4.10 shows that there is significant reduction on V2, V6 and V8 with respect to load increment. The results show V2, V8 (Bus 2), V8 (Bus 6) and V6 are significant to each other with load increment at constant active power of 54 MW and 58 MW. The under voltage occurs at V8 with respect to load increment of more than 58 MW and 58 MVAR at Bus 6.

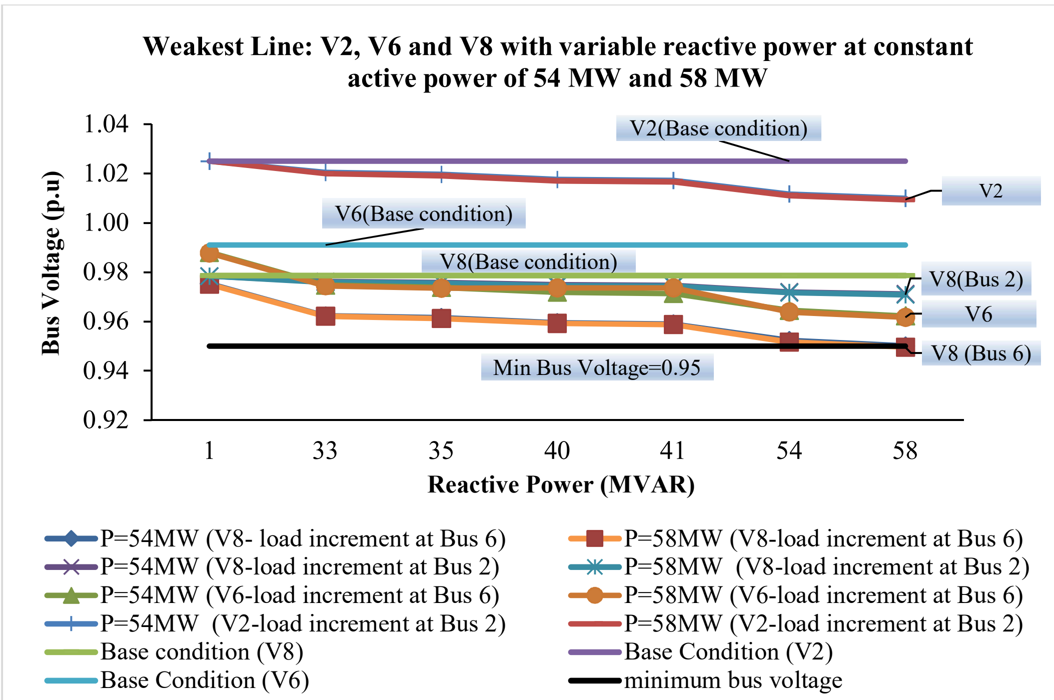


Figure 4.10: V2, V6 and V8 with variable reactive power at constant active power of 54 MW and 58 MW.

Table 4.14 shows voltage at Bus 8 (V8), voltage at Bus 2 (V2) and voltage at Bus 6 (V6) with variable active power at minimal reactive power of 1 MVAR. The table shows V8 with respect to load increment at Bus 2 or Bus 6, V2 with respect to load increment at Bus 2 and V6 with respect to load increment at Bus 6. The results at every stages of load increment are compared with base case condition for analysis purposes. There is significant reduction on V6 and V8 with respect to load increment. V2 remains at 1.025 p.u when subjected to load increment. There is no under voltage occurs at Bus 8 with variable active power increment at Bus 2 or Bus 6 with a condition that reactive power remains minimal at 1 MVAR. The result from Table 4.14 is plotted into a chart as shown in Figure 4. 11.

Table 4.14: V2, V6, and V8 with variable active power at minimal reactive power of 1 MVAR.

Total P (MW)	V8 (p.u)		V2 (p.u)	V6 (p.u)	At base case condition
	Load increment at Bus 2	Load increment at Bus 6	Load increment at Bus 2	Load increment at Bus 6	
54	0.9784	0.9753	1.0250	0.9880	V2=1.0250 V6=0.9920 V8=0.9786
55	0.9784	0.9753	1.0250	0.9880	
58	0.9784	0.9751	1.0250	0.9878	
66	0.9784	0.9746	1.0250	0.9873	

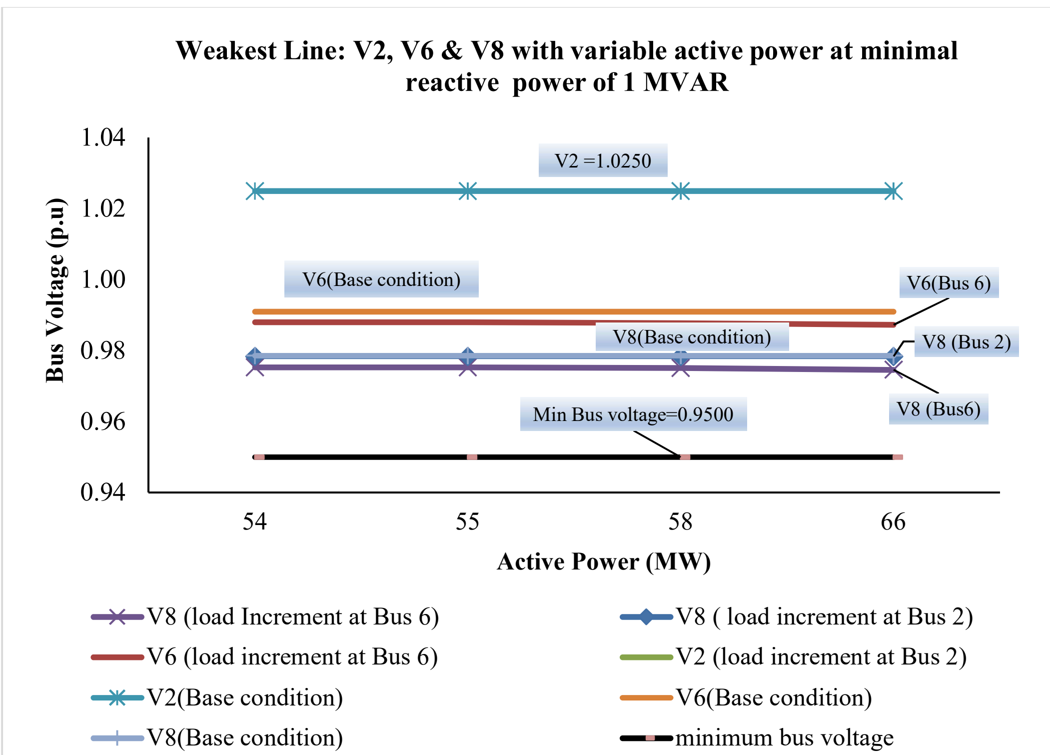


Figure 4.11: V2, V6 and V8 with variable active power at minimal reactive power of 1 MVAR

Table 4.15 shows FVSI and LQP with variable reactive power at constant active power of 54 MW and 58 MW. The results show both indices are less than 1. The value of LQP is slightly higher compared with the value of FVSI at each stages of load increment. Comparing with base case condition, FVSI and LQP are decreasing with load increment at Bus 2 while FVSI and LQP are increasing with load increment at Bus 6. The result from Table 4.15 is plotted into a chart as shown in Figure 4.12. LQP (Bus 6) and FVSI (Bus 6) present load increment at Bus 6 while LQP (Bus 2) and FVSI (Bus 2) present load increment at Bus 2.

Table 4.15: FVSI & LQP with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	FVSI & LQP								
	Load increment at Bus 2				Load increment at Bus 6				At base case condition
	P=54 MW		P=58 MW		P=54 MW		P=58 MW		
	FVSI	LQP	FVSI	LQP	FVSI	LQP	FVSI	LQP	
1	0.1262	0.1290	0.1262	0.1290	0.1320	0.1464	0.1320	0.1473	LQP =0.1288 FVSI =0.1246
33	0.1182	0.1211	0.1110	0.1136	0.1793	0.1932	0.1799	0.1947	
35	0.1171	0.1200	0.1159	0.1188	0.1825	0.1963	0.1825	0.1973	
40	0.1130	0.1160	0.1118	0.1147	0.1896	0.2034	0.1903	0.2050	
41	0.1124	0.1154	0.1119	0.1148	0.1916	0.2053	0.1917	0.2065	
54	0.1030	0.1060	0.0988	0.1019	0.2069	0.2207	0.2064	0.2212	
58	0.1000	0.1032	0.0944	0.0970	0.2111	0.2249	0.2107	0.2255	

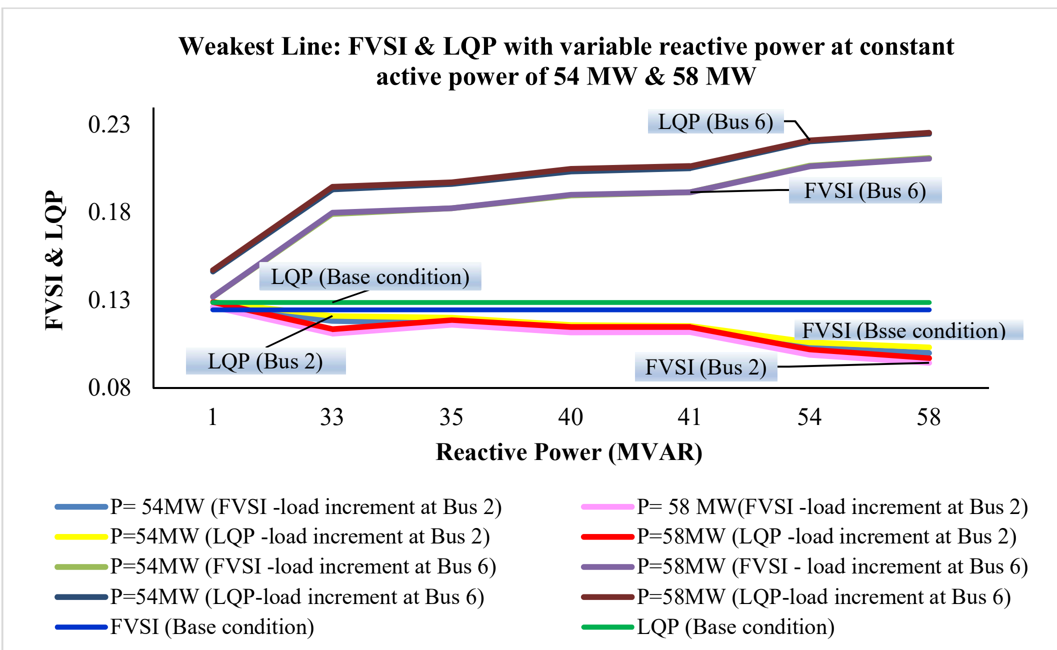


Figure 4.12: FVSI & LQP versus variable reactive power at constant active power of 54 MW and 58 MW

Table 4.16 shows FVSI and LQP with variable active power at minimal reactive power of 1 MVAR. The results show that both indices are less than 1. Load increment at Bus 2, the FVSI and LQP are almost constant with slightly reduced while load increment at Bus 6, the FVSI and LQP are slightly higher. The result from Table 4.16 is plotted into a chart as shown in Figure 4.13.

Table 4.16: FVSI & LQP at variable active power with minimal reactive power of 1 MVAR

Total P (MW)	FVSI & LQP				
	Load increment at Bus 2		Load increment at Bus 6		At base case condition
	FVSI	LQP	FVSI	LQP	
54	0.1262	0.1290	0.1320	0.1456	LQP=0.1288 FVSI=0.1246
55	0.1262	0.1290	0.1314	0.1460	
58	0.1262	0.1290	0.1320	0.1473	
66	0.1262	0.1288	0.1314	0.1457	

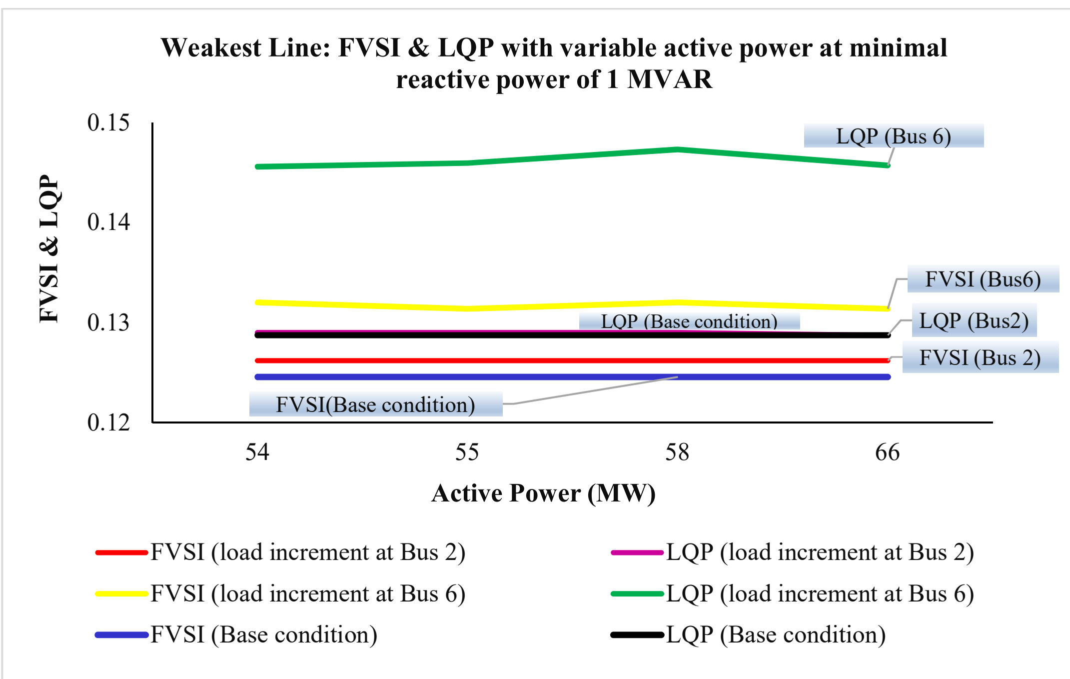


Figure 4.13: FVSI & LQP with variable active power at minimal reactive power of 1 MVAR

4.4.1 Mitigation techniques for weakest line (TX 2 to Bus 6): Injection of PV and installation of SVC

As for mitigation techniques, only one load of 58 MW, 35 MVAR is selected to be placed at only Bus 6 due to load increment at Bus 6 contributes severe impact compared to load increment at Bus 2. The 58 MW, 35 MVAR load is selected because it satisfies TNB load criteria which is load with power factor more than 0.85 and cause violation to the system.

The injection of 50 MW PV is placed at Bus 2 or Bus 6 at a time while the installation of 50 MVAR SVC is always placed at Bus 6 due to the concept that SVC is a reactive power support to improve bus voltage and at the same time to reduce the VSI value. PV is set to operate at unity power factor indicating that PV only contributes to active power while SVC is set to almost zero power factor indicating that SVC only contributes to reactive power

Table 4.17 presents power factor of generators G2, G22 and G27 in operation with and without injection of PV and installation of SVC. The power factor of generators G2, G22 and G27 in operation are significantly improved with injection of PV and installation of SVC. The results in Table 4.17 are plotted in graph as shown in Figure 4.14.

Table 4.17: Power Factor of generators G2, G22 and G27 in operation with and without injection of PV and installation of SVC

Generator No	Power factor of generators in operation			
	Base Condition	without PV and SVC (58 MW, 35 MVAR load increment at Bus 6)	With PV at Bus 2 (sending end) and SVC at Bus 6	With PV at Bus 6 (receiving end) and SVC at Bus 6
G2	0.9415	0.7294	0.9645	0.9657
G22	0.9081	0.8140	0.9199	0.9120
G27	0.9721	0.8722	0.9812	0.9893

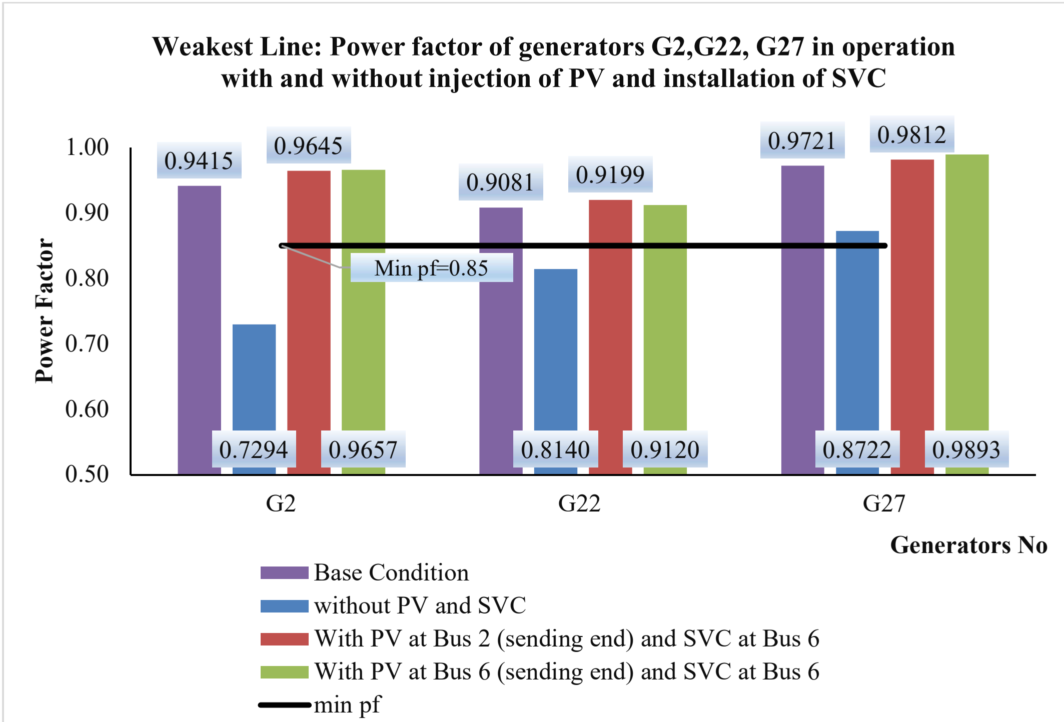


Figure 4.14: Power factor of generator G2, G22 and G27 in operation with and without injection of PV and installation of SVC.

Table 4.18 shows V2, V6 and V8 with and without installation of PV and SVC. V2 remains constant at 1.0250 p.u as per base condition with the PV injection and SVC installation. V6 and V8 are significantly improved with injection of PV and installation of SVC. The results in Table 4.18 are plotted into a graph as shown in Figure 4.15.

Table 4.18: V2, V6 and V8 with and without injection of PV and installation of SVC

Bus No	Bus voltage (p.u)			
	Base Condition	without PV and SVC (58 MW, 35 MVAR load increment at Bus 6)	With PV at Bus 2 (sending end) and SVC at Bus 6	With PV at Bus 6 (receiving end) and SVC at Bus 6
Bus 2 (V2)	1.0250	1.0191	1.0250	1.0250
Bus 6 (V6)	0.9914	0.9735	0.9736	0.9970
Bus 8 (V8)	0.9786	0.9612	0.9814	0.9841

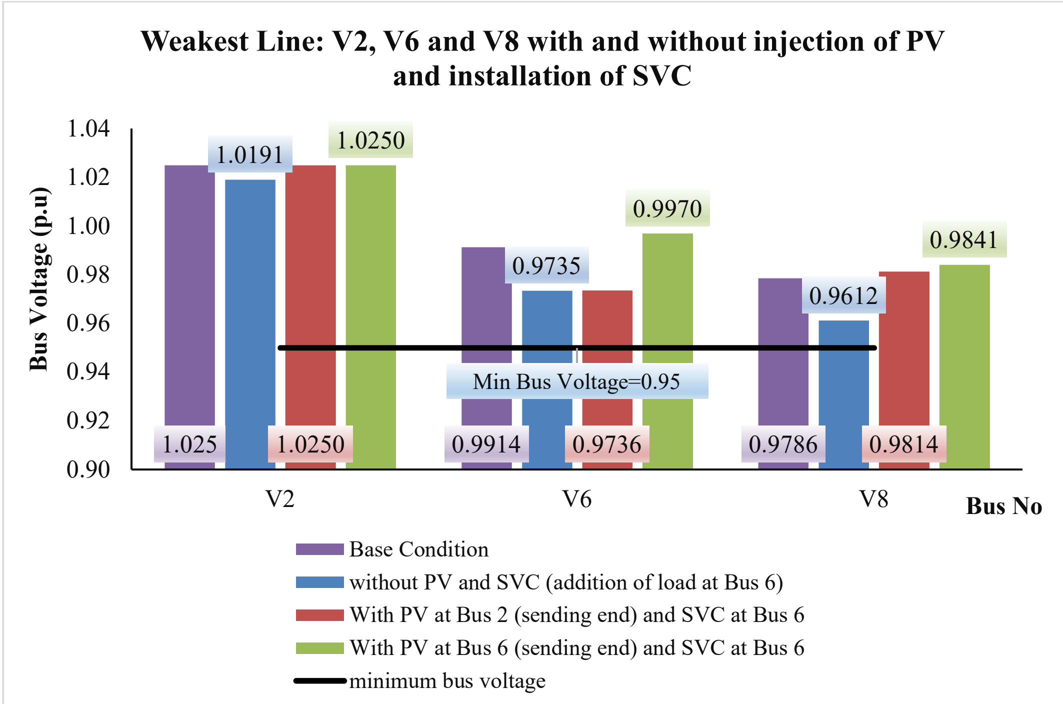


Figure 4.15: V2, V6 and V8 with and without injection of PV and installation of SVC

Table 4.19 shows FVSI and LQP with and without injection of PV and installation of SVC. The FVSI and LQP are significantly improved with injection of PV and installation of SVC. The results in Table 4.19 are plotted into a graph as shown in Figure 4.16.

Table 4.19: FVSI and LQP with and without injection of PV and installation of SVC

Voltage Stability Indices	Base Condition	without PV and SVC	With PV at Bus 2 (sending end) and SVC at Bus 6	With PV at Bus 6 (receiving end) and SVC at Bus 6
LQP	0.1288	0.1973	0.1251	0.1090
FVSI	0.1246	0.1825	0.1068	0.1036

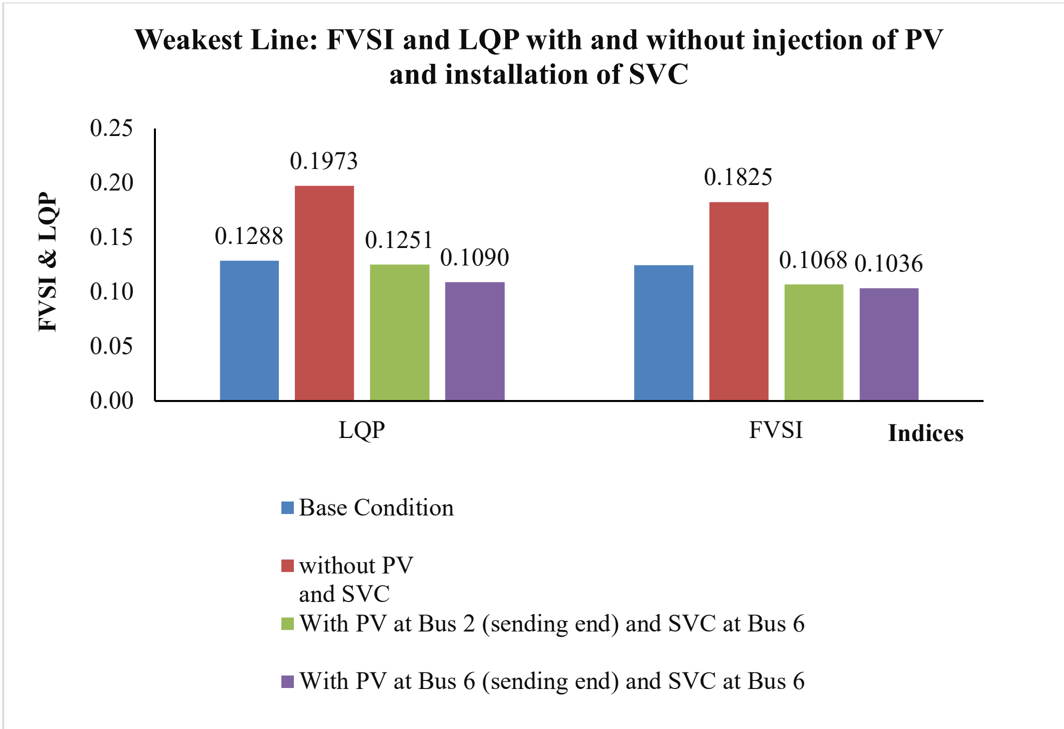


Figure 4.16: FVSI and LQP with and without injection of PV and installation of SVC

4.4.2 Conclusion for load increment at the sending and receiving ends of the weakest line (TX 2 to Bus 6) including conclusion for mitigation techniques.

Figure 4.17 presents affected buses and generators due to load increment, additional PV and SVC for mitigation techniques and actual reactive power supply and consumption within these areas. As a result of load increment, there are only 2 areas have been affected which are Area 1 and Area 3. As explained in Chapter 3, Area 1 has large amount of reactive power resources but large amount of reactive power consumption. In addition, Area 3 has smaller amount of reactive power resources but large amount of reactive power consumption. There are 3 generators affected which are G2, G22 and G27 and only 1 bus voltage is affected, which is Bus 8 as a result of load increment. G2 and Bus 8 are located in Area 1 while G22 and G27 are located in Area 3.

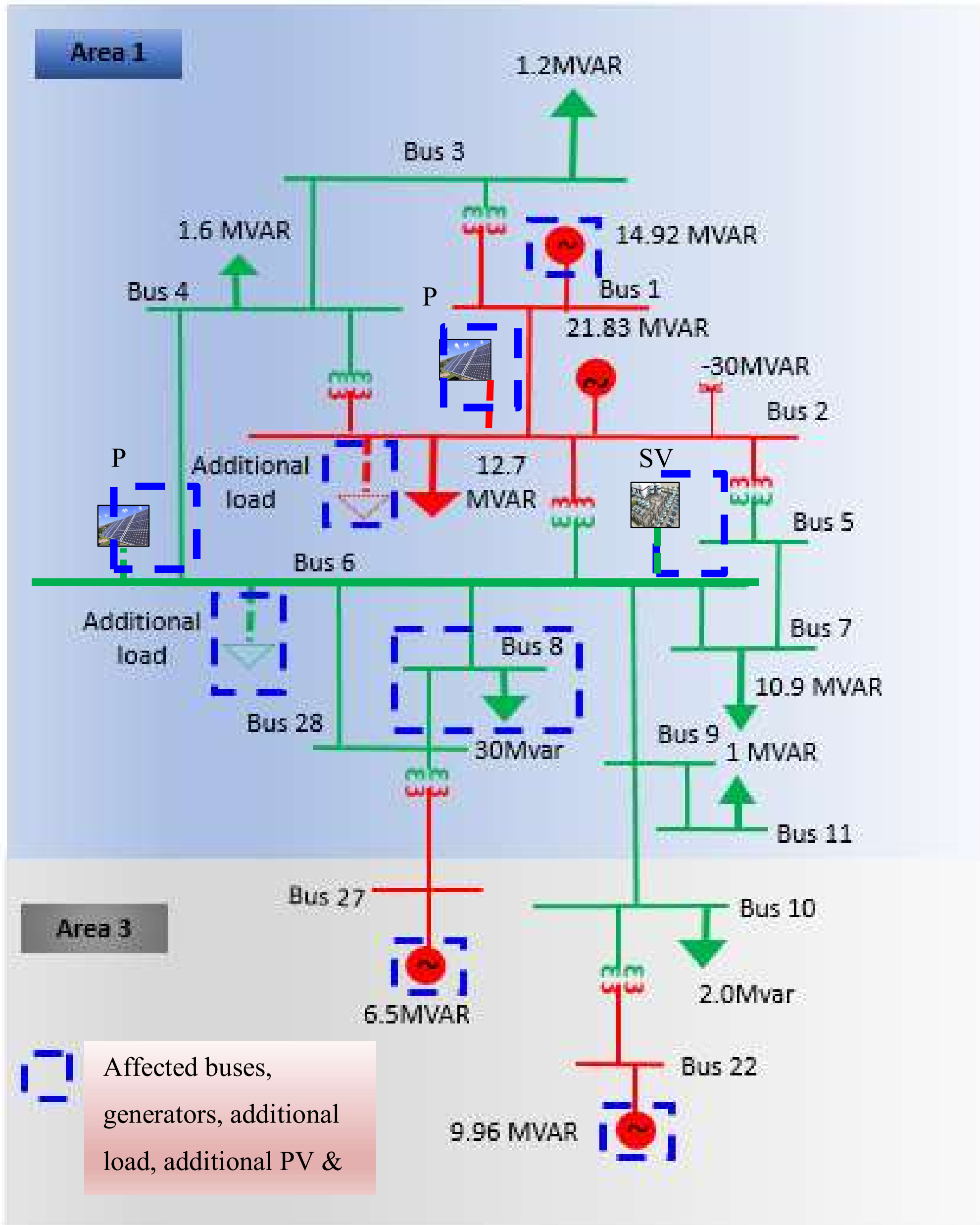


Figure 4.17: Affected buses and generators due to load increment at Bus 2 or Bus 6. Additional PV and SVC for mitigation techniques and actual reactive power supply and consumption within these areas.

The power factor of generator G2 in operation is below acceptable limits at all stages of load increment at Bus 2 or Bus 6, either with variable reactive power at constant active power of 54 MW and 58 MW or with variable active power at minimal reactive power of 1 MVAR. The low operating power factor of generator G2 is due to the load is increased at Bus 2 itself and G2 is supplying reactive power directly to the additional load beyond its capability limits. This shows that G2 is operating at overexcited condition that will lead to heating of the field winding at all stages of load increment.

In relation to load increment at Bus 2 either with variable reactive power at constant active power of 54 MW and 58 MW or with variable active power at minimal reactive power of 1 MVAR, other than power factor of generator G2 operating below acceptable limits, there is no power factor of other generators operated below acceptable limits. Furthermore, there is also no under voltage condition occurs at all buses with load increment at Bus 2. This shows that with load increment at Bus 2, the reactive power supply by others generators G22, G27, G13, G1 and G23 are not affected and operated within the generator capability limits. There is no violation in voltage since reactive power resources in Area 1 is sufficient to support the reactive load increment at Bus 2. The reduction of FVSI and LQP values is due to the reduction of power transfer between TX 2 to Bus 6. As load is increased at Bus 2, the power transferred is increased at others lines nearby Bus 2.

In relation to load increment at Bus 6 with variable reactive power at constant active power of 54 MW and 58 MW, in addition to power factor of generator G2 that is operating below the acceptable limits, the power factor of G22 and G27 are also operating below the acceptable limits. These indicate that with load increment at Bus 6, power factor of G2, G22 and G27 are affected. Generators are the main source of reactive power supply in the system. However, the generated MVAR is limited by generator capability limits. Therefore, as reactive load increased, the generator may operate near or beyond its capability limits as presented by low operating power factor. The generators G2, G22 and G27 operate at over excited condition that will lead to heating of the field winding. The most affected generators, will be the generators are located near bus that experiences load increment. Thus, the most affected generators are G2, followed by G22 and G27. The voltage is governed by reactive power, as reactive power increased, there will be voltage violation if reactive power resources are insufficient to support the reactive load demand. Thus, under voltage condition occurs at Bus 8 with load increment of more than 58 MW and 58 MVAR due to the lacking of reactive power supply to Bus 8. The most affected bus will be the bus that is located away from generators, which is the source of reactive power injection. Bus 8 is a spur bus, connected directly to Bus 6 and equipped with load amounting to 30 MW and 30 MVAR, the load increment of more than 58MW and 58

MVAR at Bus 6 causes insufficient reactive power supply to the load connected at Bus 8; thus this will lead to under voltage condition. The slightly increased of FVSI and LQP values is due to an increase of power transfer between TX 2 to Bus 6.

The load increment at Bus 6 contributes severe impact on power factor of generators in operation, bus voltage, and FVSI and LQP indices compared to the load increment at Bus 2. In addition, the load increments with more variable reactive power at constant active power 54 MW and 58 MW contribute severe impact compared to load increment with variable active power at minimal reactive power of 1 MVAR. There is a significant reduction on power factor of generators G2, G22 and G27 in operation, under voltage occurred at Bus 8 and increase in LQP and FVSI due to load increment at Bus 6 with variable reactive power at constant active power of 54 MW and 58 MW.

The generators performance and voltage stability are improved with injection of PV and installation of SVC. The generators are operating within generator capability limits which is proven by the improvement in power factor of generators in operation to be within 0.85 to 1.00, bus voltage improved within 0.95 -1.05 p.u and reduction in values of FVSI and LQP.

4.5 Scenario 3: Load increment at the sending and receiving ends of the strongest line (TX 27 to Bus 28)

The strongest line of IEEE 30 Bus Test System is TX 27 to Bus 28, which is connected to the step up transformer 11/132 kV. Bus 27 is generator bus with a rated voltage of 11 kV while Bus 28 is a load bus with a rated voltage of 132 kV. Since, TX 27 to Bus 28 is connected with step up transformer 11/132 kV, the source of powers flows from Bus 27 to Bus 28. This is the reason for Bus 27 is known as the sending end while Bus 28 is known as the receiving end. As explained in Chapter 3, Bus 27 is located in Area 3 where this area is identified to have smallest amount of reactive power resources but large amount of reactive power consumption. Hence, the reactive power is imported from other areas. Bus 28 is located at Area 1 where this area is identified to have large amount of reactive power resources and also large amount of reactive power consumption. The same amount of 16 identified loads are added to the weakest line and also to the strongest line to investigate the impact of load increment to power system stability. The load will be added at Bus 27 and Bus 28 one at a time. The power factor of generators in operation, bus voltage and VSI are compared before and after loads increment to analyse generators performance with respect to generator capability limits and voltage stability with respect to VSI.

Furthermore, with load increment at the sending and receiving ends of the strongest line. The power factor of generators in operation is observed at all six generators. However, only power factor of generators G2, G22, G23 and G27 in operation is analysed since these four generators are affected due to load increment either at Bus 27 or Bus 28. The under voltage condition occurs at buses located mostly in Area 3 which are Bus 25, Bus 26, Bus 27, Bus 29 and Bus 30. Only Bus 28 experiences under voltage condition due to load increment located in Area 1.

Table 4.20 shows power factor of generator G27 in operation with variable reactive power at constant active power of 54 MW and 58 MW. The power factor of G27 generator in operation is decreasing and below acceptable limit at all stages of load increment except for 1 MVAR load increment at Bus 28. The power factor of generator G27 in operation is slightly lower with load increment at Bus 27 compared with load increment at Bus 28. Furthermore, the power factor of G27 generator in operation constant at 0.4836 with load increment at Bus 27 more than 33 MVAR. The results in Table 4.20 are plotted into a graph as shown in Figure 4.18.

Table 4.20: Power factor of generator G27 in operation with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	**Power Factor of G27 generator in operation**				
	Load increment at Bus 27		**Load increment at Bus 28**		**At base case condition**
	P=54 MW	**P=58 MW**	**P=54 MW**	**P=58 MW**	
1	**0.8485**	**0.8351**	0.9071	0.8882	0.9721
33	**0.4836**	**0.4836**	**0.7392**	**0.7326**	
35	**0.4836**	**0.4836**	**0.7287**	**0.7222**	
40	**0.4836**	**0.4836**	**0.7030**	**0.6967**	
41	**0.4836**	**0.4836**	**0.6979**	**0.6917**	
54	**0.4836**	**0.4836**	**0.6352**	**0.6292**	
58	**0.4836**	**0.4836**	**0.6162**	**0.6094**	

Note: The bolted font indicates the power factor of the generator below the acceptable limit

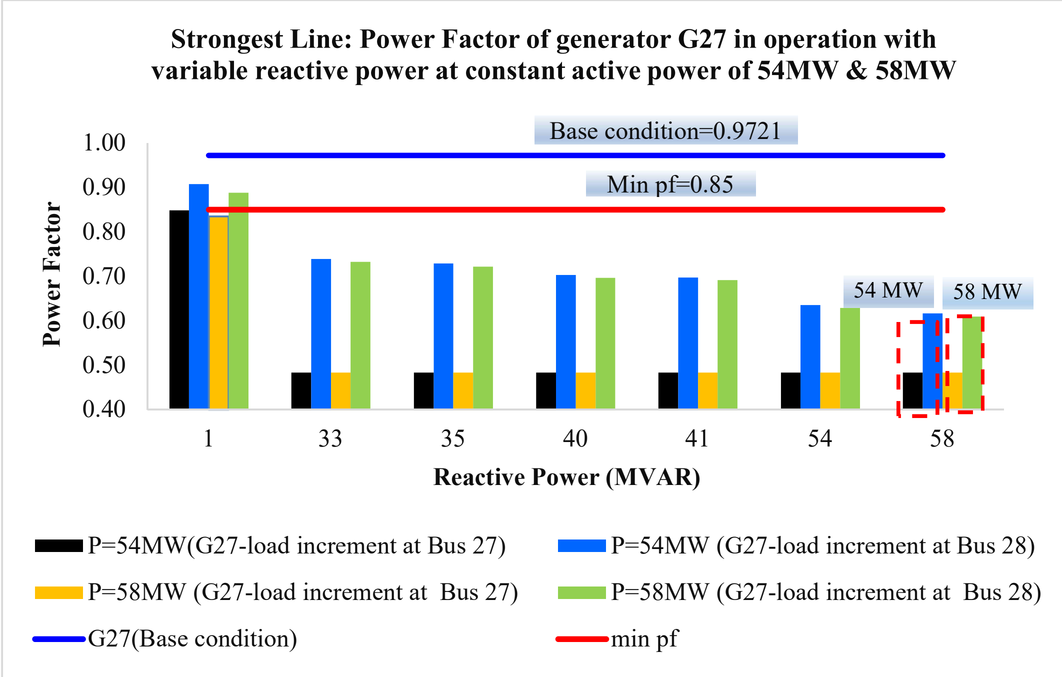


Figure 4.18: Power factor of generator G27 in operation with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.21 shows power factor of generator G2 in operation with variable reactive power at constant active power of 54 MW and 58 MW. The power factor of generator G2 in operation below the acceptable limits at all stages of 58 MW load increment. The power factor of generator G2 in operation within the acceptable limits at load increment less than 54 MW and 35 MVAR reactive power at Bus 27 and load increment less than 54 MW and 1 MVAR at Bus 28. The power factor of generator G2 in operation is slightly lower with load increment at Bus 28 compared to load increment at Bus 27. The load increment at Bus 28 causes severe impact to power factor of generator G2 in operation compared with load increment at Bus 27. The results from Table 4.21 are plotted into a chart as shown in Figure 4.19.

Table 4.21: Power Factor of generator G2 in operation with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	Power Factor of G2 generator in operation				
	Load increment at Bus 27		Load increment at Bus 28		At base case condition
	P=54 MW	P=58 MW	P=54 MW	P=58 MW	
1	0.8576	**0.8494**	0.8577	**0.8339**	
33	0.8574	**0.8466**	**0.7739**	**0.7661**	
35	0.8519	**0.8411**	**0.7685**	**0.7608**	
40	**0.8380**	**0.8271**	**0.7553**	**0.7476**	0.9415
41	**0.8352**	**0.8242**	**0.7526**	**0.7450**	
54	**0.7971**	**0.7860**	**0.7185**	**0.7128**	
58	**0.7850**	**0.7739**	**0.7128**	**0.7128**	

Note: The bolted font indicates the power factor of the generator below the acceptable limit

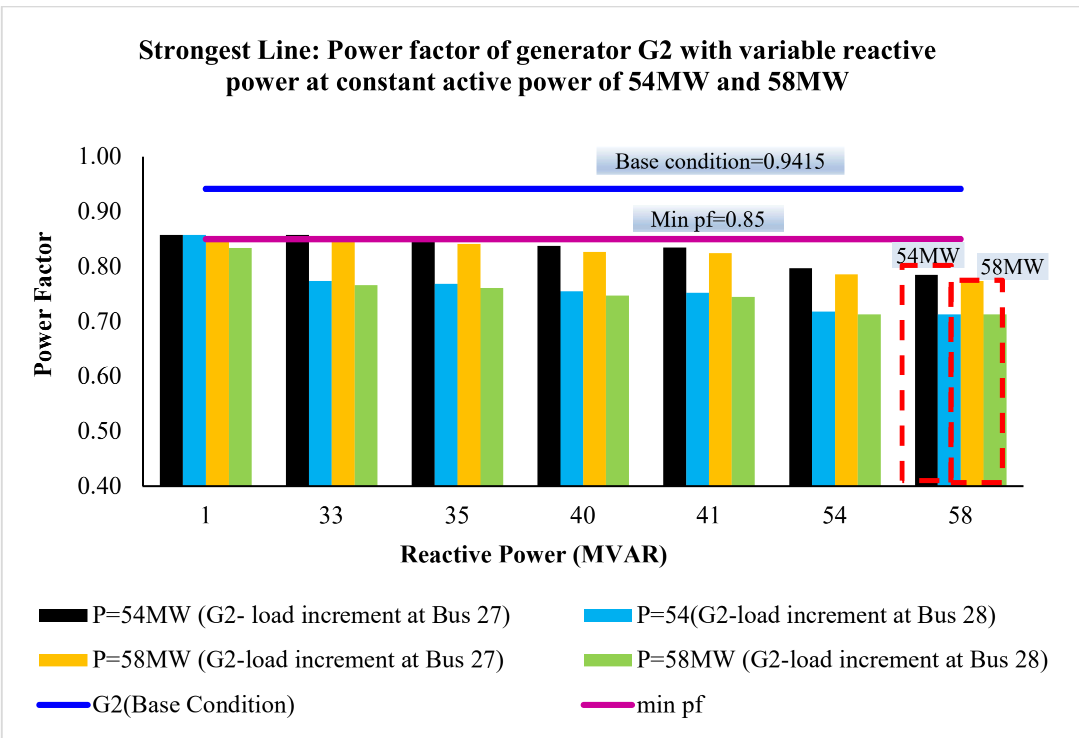


Figure 4.19: Power factor of G2 generator in operation with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.22 shows power factor of generator G22 in operation with variable reactive power at constant active power of 54 MW and 58 MW. The power factor of generator G22 in operation below the acceptable limit with load increment more than 54 MVAR at Bus 27. The power factor of generator G22 in operation below the acceptable limit with load increment of more than 33 MVAR at Bus 28. The power factor of generator G22 in operation is slightly lower with load increment at Bus 28 compared to load increment at Bus 27. The results in Table 4.22 are plotted into a graph as shown in Figure 4.20.

Table 4.22: Power factor of generator G22 in operation with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	Power Factor generator G22 in operation				
	Load increment at Bus 27		Load increment at Bus 28		At base case condition
	P=54 MW	P=58 MW	P=54 MW	P=58 MW	
1	0.9201	0.9201	0.9019	0.8995	0.9081
33	0.9197	0.9161	**0.8472**	**0.8464**	
35	0.9119	0.9081	**0.8436**	**0.8427**	
40	0.8911	0.8871	**0.8344**	**0.8336**	
41	0.8868	0.8827	**0.8326**	**0.8318**	
54	**0.8265**	**0.8220**	**0.8084**	**0.8072**	
58	**0.8069**	**0.8023**	**0.7999**	**0.7976**	

Note: The bolted font indicates the power factor of the generator below the acceptable limit

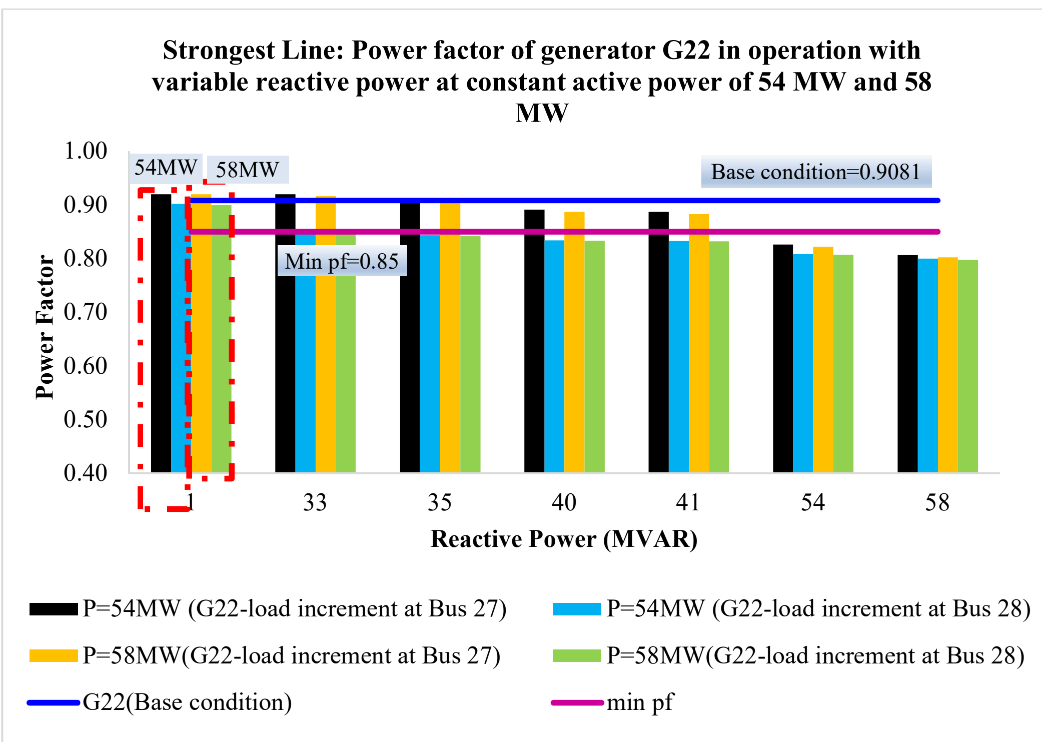


Figure 4.20: Power Factor of generator G22 in operation with variable reactive power at constant active power of 54 MW and 58 MW.

Table 4.23 shows the power factor of generator G23 in operation with variable reactive power at constant active power of 54 MW and 58 MW. The power factor of generator G23 in operation is below the acceptable limit for load increment at Bus 27 more than 54 MVAR. Moreover, the power factor of generator G23 in operation is within the acceptable limit at all stages of load increment at Bus 28. Generally, the power factor of generator G23 in operation is slightly lower with load increment at Bus 27 compared to load increment at Bus 28. The results in Table 4.23 are plotted into a graph as shown in Figure 4.21.

Table 4.23: Power Factor of generator G23 in operation with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	**Power Factor G23 generator in operation**				
	Load increment at Bus 27		**Load increment at Bus 28**		**At base case condition**
	P=54 MW	**P=58 MW**	**P=54 MW**	**P=58 MW**	
1	0.9164	0.9168	0.9038	0.9040	0.9004
33	0.9160	0.9135	0.8862	0.8863	
35	0.9095	0.9070	0.8850	0.8852	
40	0.8893	0.8900	0.8822	0.8823	
41	0.8891	0.8864	0.8816	0.8817	
54	**0.8404**	**0.8374**	0.8739	0.8739	
58	**0.8245**	**0.8214**	0.8711	0.8706	

Note: The bolted font indicates the power factor of the generator below the acceptable limit

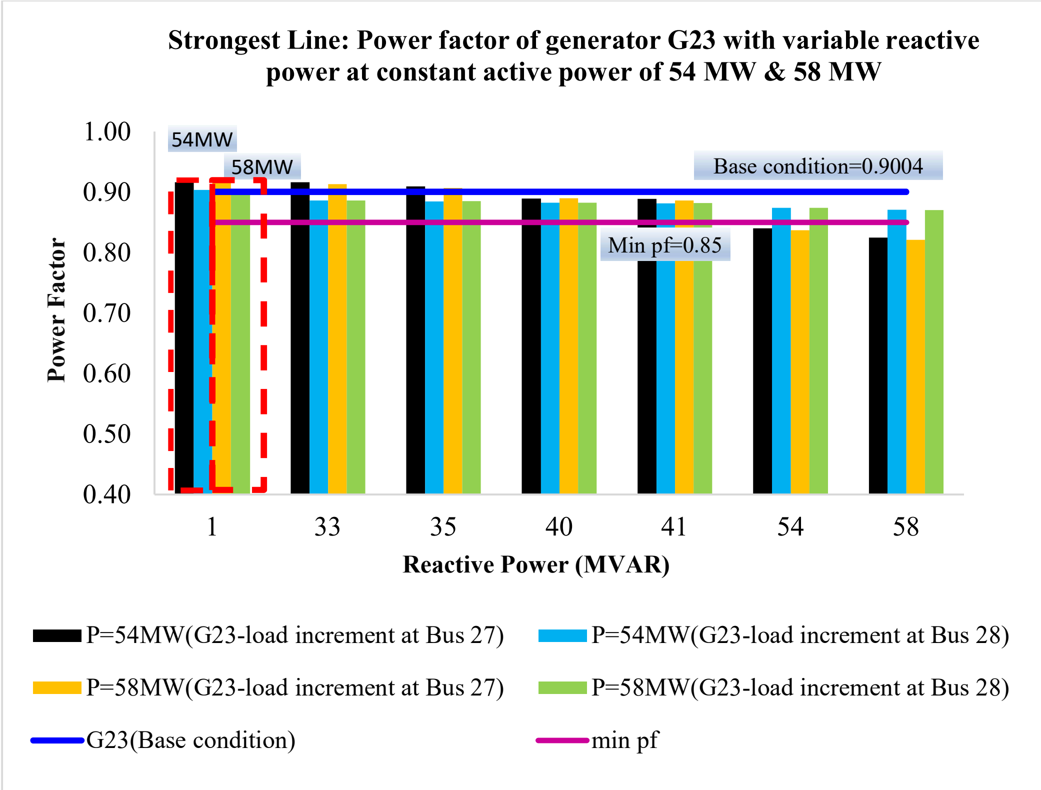


Figure 4.21: Power factor of generator G23 in operation with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.24 shows power factor of generators G2, G22, G23, and G27 in operation with variable active power at minimal reactive power 1 MVAR. The power factor of generators G22 and G23 in operation are within the acceptable limits at all stages of load increment. However, with load increment at Bus 27, the power factor of generator G2 in operation is below the acceptable limit with load increment more than 58 MW while the power factor of generators G27 in operation is below the acceptable limit at all stages of load increment. The results in Table 4.24 are plotted into a graph as shown in Figure 4.22.

Table 4.24: Power Factor of generators G2, G22, G23 and G27 in operation with variable active power at minimal reactive power of 1 MVAR.

Total P (MW)	Power Factor of generators G2, G22, G23 and G27 in operation								
	Load increment at Bus 27				Load increment at Bus 28				At base case condition
	G2	G22	G23	G27	G2	G22	G23	G27	
54	0.8576	0.9201	0.9164	**0.8485**	0.8577	0.9019	0.9038	0.9071	G2=0.9415 G22=0.9081 G23=0.9004 G27=0.9721
55	0.8556	0.9201	0.9164	**0.8452**	0.8558	0.9017	0.9038	0.9056	
58	**0.8494**	0.9201	0.9168	**0.8351**	**0.8339**	0.8995	0.9040	0.8882	
66	**0.8323**	0.9198	0.9177	**0.8067**	**0.8339**	0.8995	0.9040	0.8882	

Note: The bolted font shows power factor of generators in operation below acceptable limits

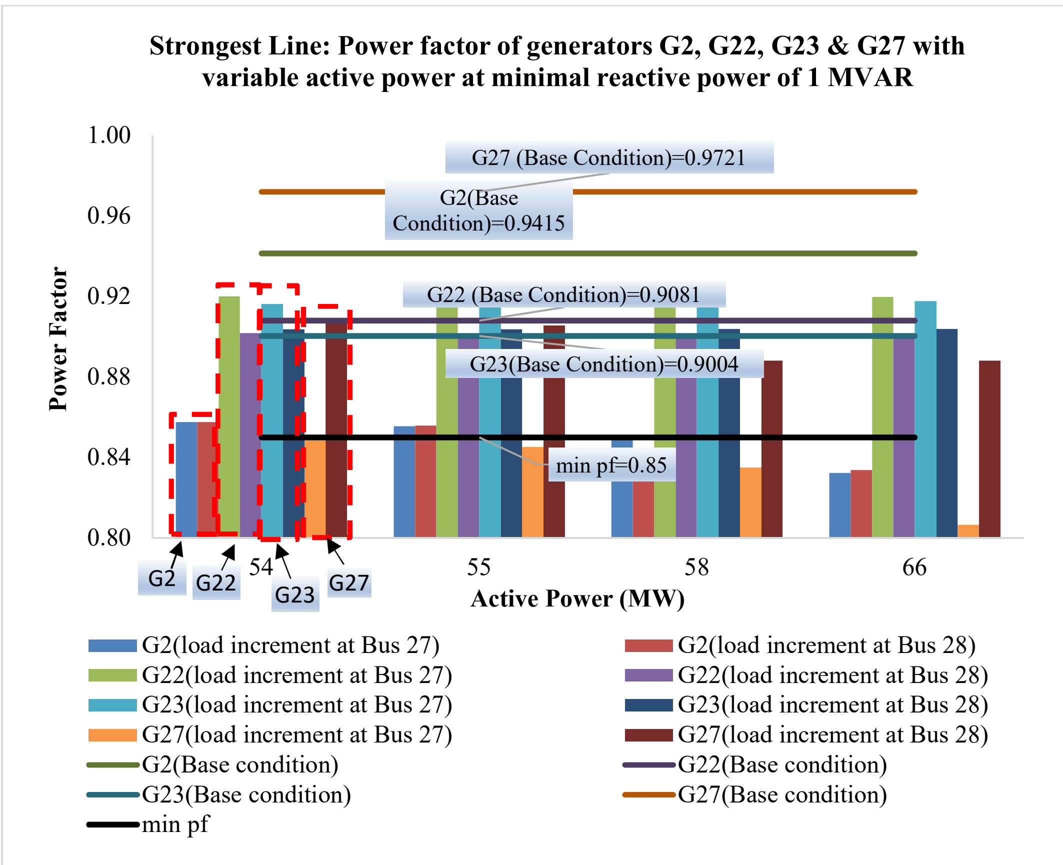


Figure 4.22: Power factor of generators G2, G22, G23 and G27 in operation with variable active power at minimal reactive power of 1 MVAR

Table 4.25 shows voltage at Bus 25 (V25) with variable reactive power at constant active power of 54 MW and 58 MW. The table shows V25 with respect to a load increment at Bus 27 or Bus 28. The V25 is decreasing with respect to a load increment at Bus 27. The under voltage condition occurs with load increment of more than 54 MVAR at Bus 27. The V25 is almost constant and within the acceptable limit with a load increment at Bus 28. The results in Table 4.25 are plotted into a graph as shown in Figure 4.23.

Table 4.25: V25 with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	V25 (p.u)				
	Load increment at Bus 27		Load increment at Bus 28		At base case condition
	P=54 MW	P=58 MW	P=54 MW	P=58 MW	
1	0.9772	0.9767	0.9824	0.9820	0.9839
33	0.9771	0.9753	0.9825	0.9824	
35	0.9744	0.9726	0.9828	0.9824	
40	0.9675	0.9650	0.9828	0.9825	
41	0.9661	0.9643	0.9828	0.9825	
54	**0.9475**	**0.9456**	0.9827	0.9825	
58	**0.9415**	**0.9396**	0.9827	0.9828	

Note: The bolted font indicates the bus voltage below the acceptable limit

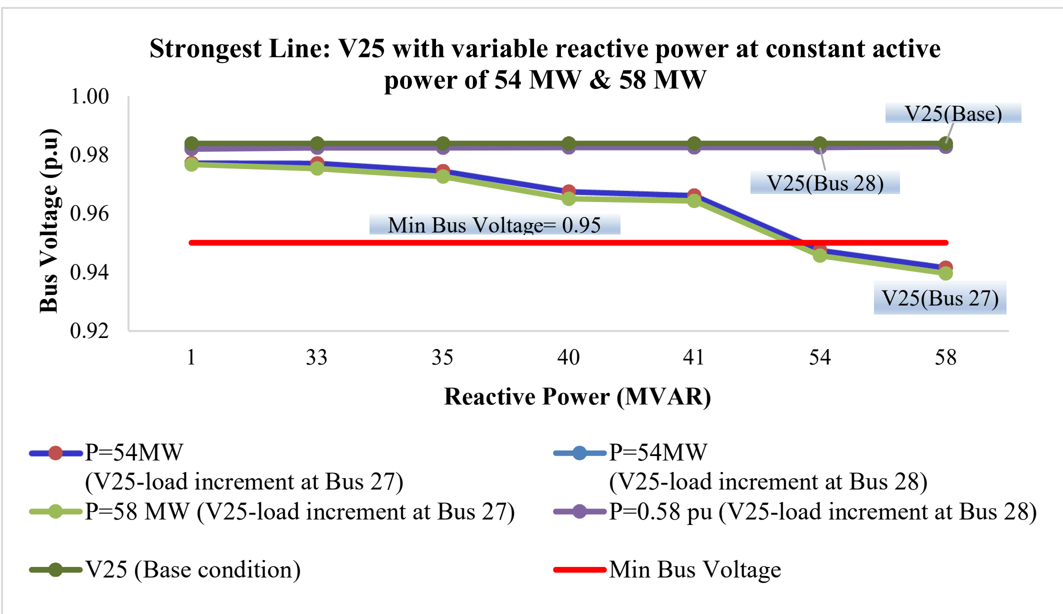


Figure 4.23: V25 with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.26 shows voltage at Bus 26 (V26) with variable reactive power at constant active power of 54 MW and 58 MW. The table shows V26 with respect to load increment at Bus 27 and Bus 28. The V26 is decreasing with a load increment at Bus 27. The under voltage condition occurs with load increment at Bus 27 of more than 40 MVAR. The V26 almost constant and within the acceptable limit with a load increment at Bus 28. The results in Table 4.26 are plotted into a graph as shown in Figure 4.24.

Table 4.26: V26 with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	**V26 (p.u)**				
	Load increment at Bus 27		**Load increment at Bus 28**		**At base case condition**
	P=54 MW	**P=58 MW**	**P=54 MW**	**P=58 MW**	
1	0.9590	0.9584	0.9642	0.9638	V26=0.9658
33	0.9589	0.9570	0.9644	0.9643	
35	0.9561	0.9542	0.9644	0.9643	
40	**0.9491**	**0.9472**	0.9644	0.9643	
41	**0.9477**	**0.9457**	0.9644	0.9643	
54	**0.9286**	**0.9266**	0.9645	0.9644	
58	**0.9226**	**0.9205**	0.9645	0.9644	

Note: The bolted font indicates the bus voltage below the acceptable limit

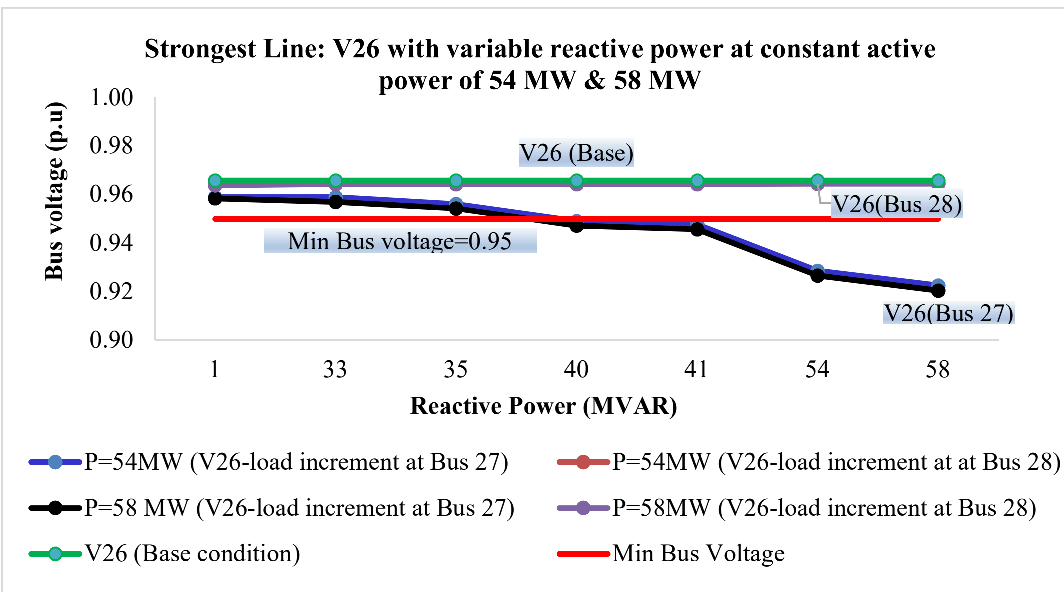


Figure 4.24: V26 with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.27 shows voltage at Bus 27 (V27) with variable reactive power at constant active power of 54 MW and 58 MW. The table shows V27 with respect to a load increment at Bus 27 and Bus 28. The V27 is decreasing with a load increment at Bus 27. The under voltage occurs with a load increment at Bus 27 more than 54 MVAR. The V27 remains constant at 0.9900 p.u with a load increment at Bus 28. The results in Table 4.27 are plotted into a graph as shown in Figure 4.25.

Table 4.27: V27 with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	V27(p.u)				
	Load increment at Bus 27		Load increment at Bus 28		Base Condition
	P=54 MW	P=58 MW	P=54 MW	P=58 MW	
1	0.9900	0.9900	0.9900	0.9900	0.9900
33	0.9898	0.9881	0.9900	0.9900	
35	0.9861	0.9844	0.9900	0.9900	
40	0.9767	0.9749	0.9900	0.9900	
41	0.9748	0.9730	0.9900	0.9900	
54	**0.9492**	**0.9474**	0.9900	0.9900	
58	**0.9411**	**0.9392**	0.9900	0.9900	

Note: The bolted font indicates the bus voltage below the acceptable limit

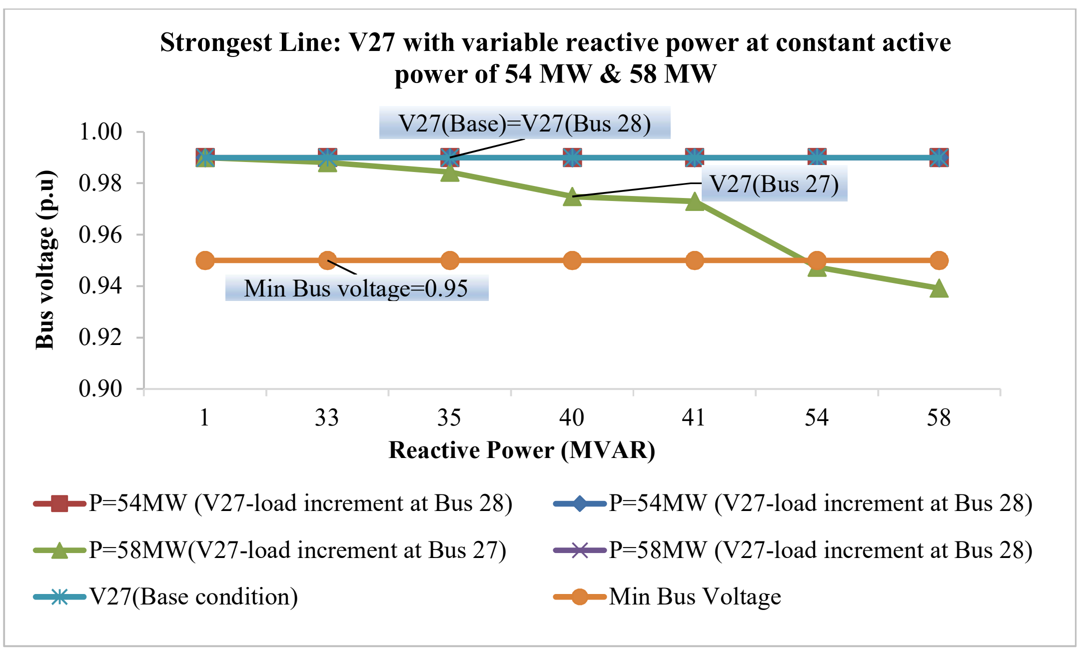


Figure 4.25: V27 with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.28 shows voltage at Bus 28 (V28) with variable reactive power at constant active power of 54 MW and 58 MW. The table shows V28 with respect to a load increment at Bus 27 or Bus 28. The under voltage occurs with a load increment at Bus 28 of more than 54 MVA. The V28 remains to be within the acceptable limit with a load increment at Bus 27. The results in Table 4.28 are plotted into a graph as shown in Figure 4.26.

Table 4.28: V28 with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	**V28 (p.u)**				
	Load increment at Bus 27		**Load increment at Bus 28**		**At base case condition**
	P=54 MW	**P=58 MW**	**P=54 MW**	**P=58 MW**	
1	0.9827	0.9820	0.9815	0.9808	0.9902
33	0.9826	0.9813	0.9607	0.9600	
35	0.9813	0.9799	0.9593	0.9586	
40	0.9778	0.9765	0.9560	0.9553	
41	0.9771	0.9758	0.9553	0.9546	
54	0.9678	0.9665	**0.9465**	**0.9457**	
58	0.9649	0.9635	**0.9436**	**0.9426**	

Note: The bolted font indicates the bus voltage below the acceptable limit

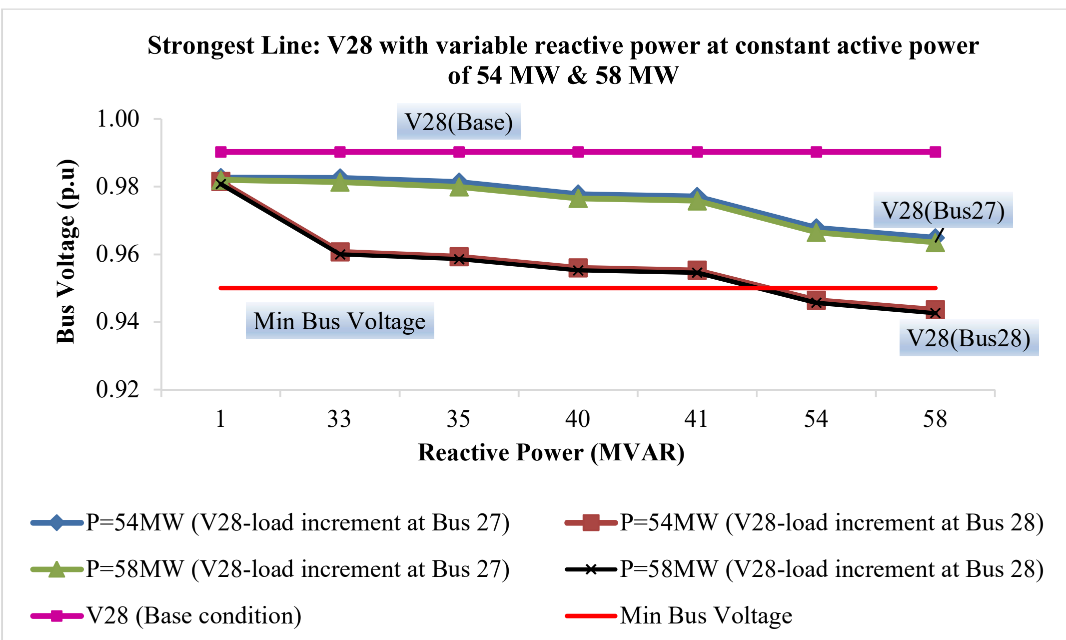


Figure 4.26: V28 with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.29 shows voltage at Bus 29 (V29) with variable reactive power at constant active power of 54 MW and 58 MW. The V29 is decreasing with a load increment at Bus 27. The under voltage condition occurs with a load increment at Bus 27 more than 54 MVA. The V29 remains constant at 0.9889 p.u with a load increment at Bus 28. The results in Table 4.29 are plotted into a graph as shown in Figure 4.27.

Table 4.29: V29 with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	**V29(p.u)**				
	Load increment at Bus 27		**Load increment at Bus 28**		**Base Condition**
	P=54 MW	**P=58 MW**	**P=54 MW**	**P=58 MW**	
1	0.9889	0.9889	0.9889	0.9889	0.9861
33	0.9887	0.9870	0.9889	0.9889	
35	0.9850	0.9833	0.9889	0.9889	
40	0.9756	0.9738	0.9889	0.9889	
41	0.9737	0.9719	0.9889	0.9889	
54	**0.9481**	**0.9462**	0.9889	0.9889	
58	**0.9399**	**0.9380**	0.9889	0.9889	

Note: The bolted font indicates the bus voltage below the acceptable limit

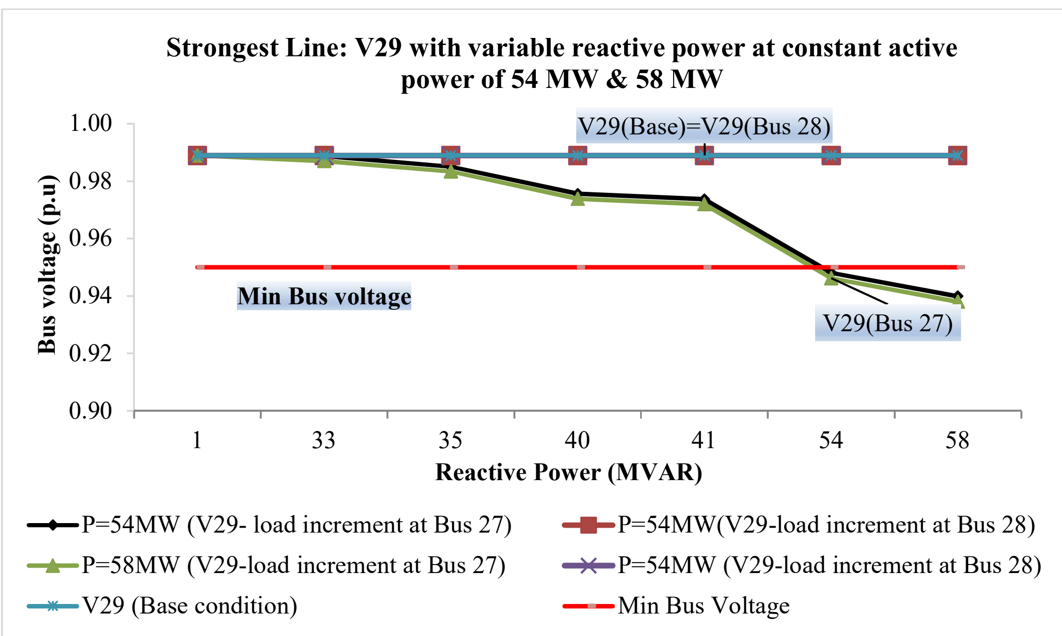


Figure 4.27: V29 with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.30 shows voltage at Bus 30 (V30) with variable reactive power at constant active power of 54 MW and 58 MW. The V30 is decreasing with a load increment at Bus 27. The under voltage condition occurs with a load increment at Bus 27 more than 54 MVA. The V30 remains constant at 0.9861 p.u with a load increment at Bus 28. The results in Table 4.30 are plotted into a graph as shown in Figure 4.28.

Table 4.30: V30 with variable reactive power at constant active power of 54 MW and 58 MW

Total Q (MVAR)	V30 (p.u)				
	Load increment at Bus 27		Load increment at Bus 28		Base Condition
	P=54 MW	P=58 MW	P=54 MW	P=58 MW	
1	0.9861	0.9861	0.9861	0.9861	0.9861
33	0.9859	0.9842	0.9861	0.9861	
35	0.9822	0.9804	0.9861	0.9861	
40	0.9727	0.9709	0.9861	0.9861	
41	0.9708	0.9690	0.9861	0.9861	
54	**0.9452**	**0.9433**	0.9861	0.9861	
58	**0.9370**	**0.9351**	0.9861	0.9861	

Note: The bolted font indicates the bus voltage below the acceptable limit

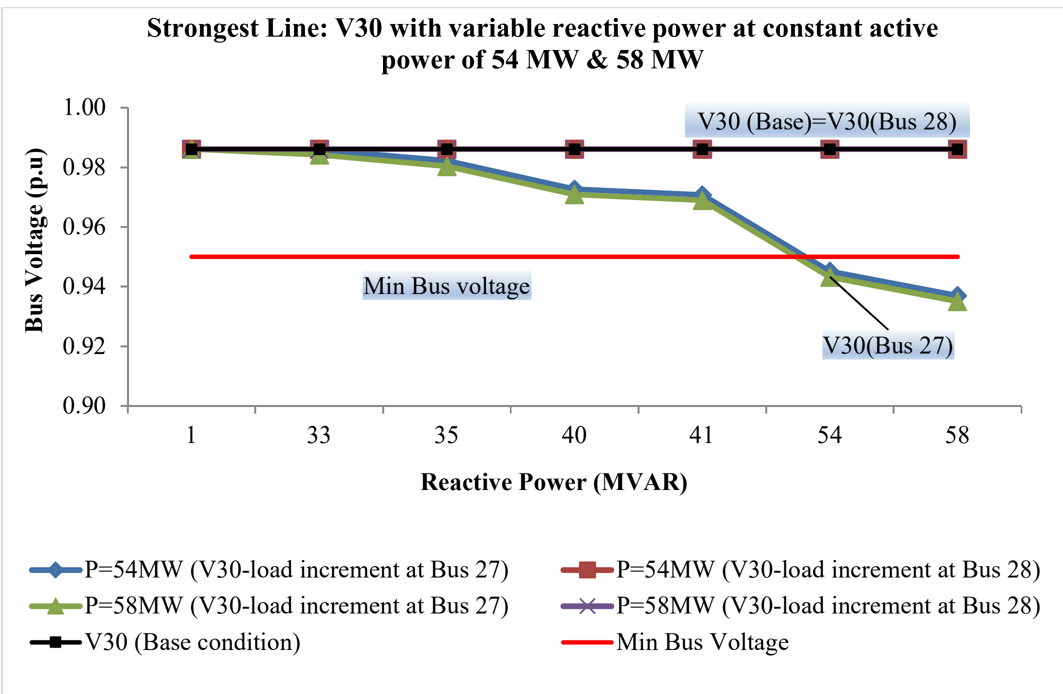


Figure 4.28: V30 with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.31 shows V25, V26, and V27 while Table 4.32 shows V28, V29 and V30 with respect to load increment with variable active power at minimal reactive power of 1 MVAR. The results show that there is no under voltage condition occurs at V25, V26, V27, V28, V29 and V30 due to load increment with variable active power at minimal reactive power of 1 MVAR either at Bus 27 or Bus 28. Voltage at Bus V25 and V26 are slightly reduced while the voltage at Bus V27, V28, V29, and V30 remain constant with the load increment at either at Bus 27 or Bus 28. The results in Table 4.31 and 4.32 are plotted into a graph as shown in Figure 4.29.

Table 4.31: V25, V26 & V27 with variable active power at minimal reactive power of 1 MVAR

Total P (MW)	**V25, V26, V27**						
	Load increment at Bus 27			**Load increment at Bus 28**			**Base condition**
	V25	**V26**	**V27**	**V25**	**V26**	**V27**	
54	0.9772	0.9590	0.9900	0.9824	0.9642	0.9900	V25=0.9839 V26=0.9658 V27=0.9900
55	0.9771	0.9588	0.9900	0.9823	0.9642	0.9900	
58	0.9767	0.9584	0.9900	0.9820	0.9638	0.9900	
66	0.9756	0.9573	0.9900	0.9820	0.9638	0.9900	

Table 4.32: V28, V29 & V30 with variable active power at minimal reactive power of 1 MVAR

Total P(MW)	**V28, V29, V30**						
	Load increment at Bus 27			**Load increment at Bus 28**			**Base condition**
	V28	**V29**	**V30**	**V28**	**V29**	**V30**	
54	0.9827	0.9889	0.9861	0.9815	0.9889	0.9861	V28=0.9902 V29=0.9889 V30=0.9861
55	0.9825	0.9889	0.9861	0.9813	0.9889	0.9861	
58	0.9820	0.9889	0.9861	0.9808	0.9889	0.9861	
66	0.9805	0.9889	0.9861	0.9794	0.9889	0.9861	

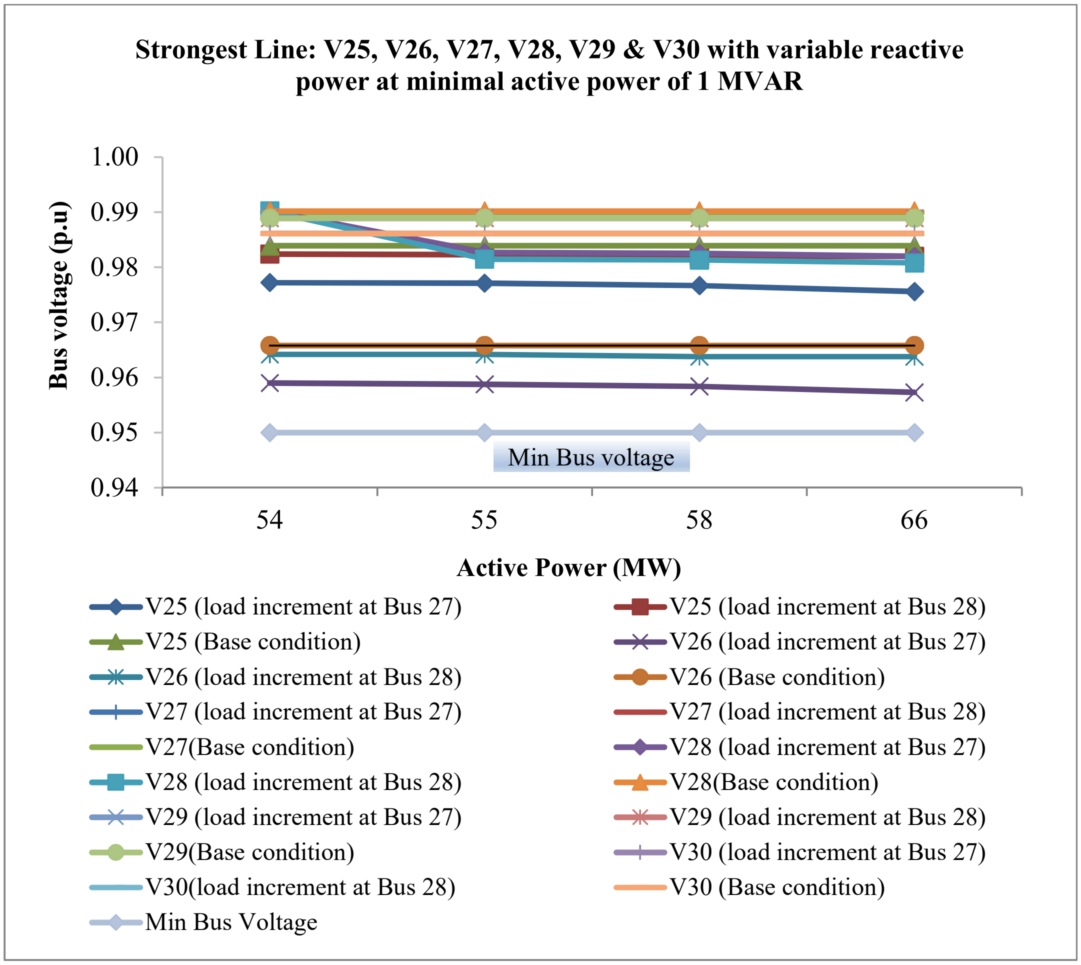


Figure 4.29: V25, V26, V27, V28, V29 & V30 with variable active power at minimal reactive power of 1 MVAR.

Table 4.33 and 4.34 shows FVSI and LQP when subject to load increment with variable reactive power at constant active power of 54 MW and 58 MW. Comparing to base case condition, the graph shows that FVSI and LQP are increased with respect to load increment either at Bus 27 or Bus 28. The FVSI and LQP are higher with load increment at Bus 28 compared to load increment at Bus 27. The FVSI and LQP are consistently increased with load increment at Bus 28. However, the FVSI and LQP are shown fluctuation with a load increment at Bus 27. The result in Table 4.33-4.34 are plotted into a graph as shown in Figure 4.30.

Table 4.33: Load increment at Bus 27- FVSI and LQP with variable reactive power at constant active power of 54 MW and 58 MW

<table>
<tr><th rowspan="3">Total Q (MVAR)</th><th colspan="5">Load increment at Bus 27</th></tr>
<tr><th colspan="2">FVSI</th><th colspan="2">LQP</th><th rowspan="2">At base case condition</th></tr>
<tr><th>P=54 MW</th><th>P=58 MW</th><th>P= 54 MW</th><th>P= 58 MW</th></tr>
<tr><td>1</td><td>0.02220</td><td>0.0236</td><td>0.03651</td><td>0.04056</td><td rowspan="7">LQP =0.00023

FVSI =0.00021</td></tr>
<tr><td>33</td><td>0.02152</td><td>0.0362</td><td>0.03583</td><td>0.05306</td></tr>
<tr><td>35</td><td>0.02716</td><td>0.0091</td><td>0.04126</td><td>0.02630</td></tr>
<tr><td>40</td><td>0.00285</td><td>0.0029</td><td>0.01738</td><td>0.02017</td></tr>
<tr><td>41</td><td>0.00215</td><td>0.0022</td><td>0.01666</td><td>0.01954</td></tr>
<tr><td>54</td><td>0.07019</td><td>0.0712</td><td>0.08146</td><td>0.08520</td></tr>
<tr><td>58</td><td>0.09290</td><td>0.0933</td><td>0.09421</td><td>0.10545</td></tr>
</table>

Table 4.34: Load increment at Bus 28- FVSI and LQP with variable reactive power at constant active power of 54 MW and 58 MW

<table>
<tr><th rowspan="3">Total Q (MVAR)</th><th colspan="5">Load increment at Bus 28</th></tr>
<tr><th colspan="2">FVSI</th><th colspan="2">LQP</th><th rowspan="2">At base case condition</th></tr>
<tr><th>P=54 MW</th><th>P=58 MW</th><th>P= 54 MW</th><th>P= 58 MW</th></tr>
<tr><td>1</td><td>0.0333</td><td>0.0361</td><td>0.03463</td><td>0.03746</td><td rowspan="7">LQP =0.00023

FVSI =0.00021</td></tr>
<tr><td>33</td><td>0.1145</td><td>0.1173</td><td>0.11573</td><td>0.11855</td></tr>
<tr><td>35</td><td>0.1193</td><td>0.1221</td><td>0.12059</td><td>0.12341</td></tr>
<tr><td>40</td><td>0.1318</td><td>0.1346</td><td>0.13305</td><td>0.13588</td></tr>
<tr><td>41</td><td>0.1346</td><td>0.1374</td><td>0.13583</td><td>0.13865</td></tr>
<tr><td>54</td><td>0.1679</td><td>0.1707</td><td>0.16910</td><td>0.17193</td></tr>
<tr><td>58</td><td>0.1783</td><td>0.1818</td><td>0.17928</td><td>0.18303</td></tr>
</table>

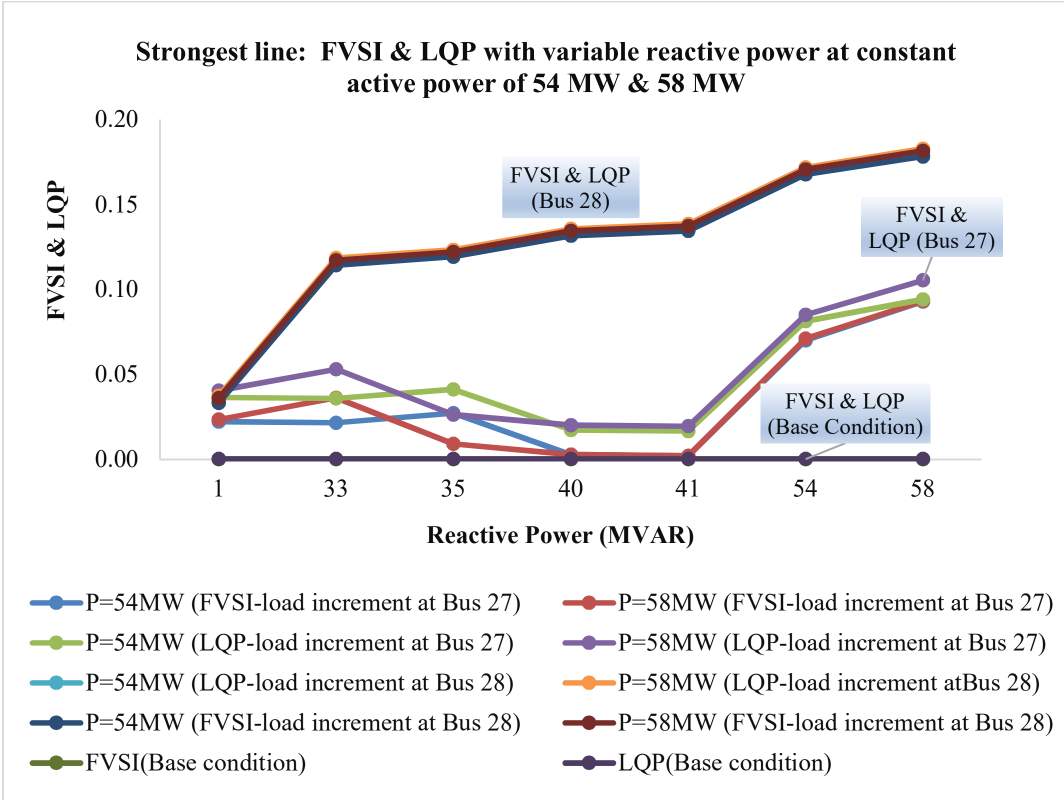


Figure 4.30: FVSI and LQP with variable reactive power at constant active power of 54 MW and 58 MW

Table 4.35 shows FVSI and LQP with variable active power at minimal reactive power of 1 MVAR. As compared with base case condition, the graph shows FVSI and LQP are increased with load increment at Bus 27 or Bus 28. The FVSI and LQP are compliment to each other with load increment at Bus 28. However, there is significantly increased inconsistence with load increment at Bus 27. The results in Table 4.35 are plotted into a graph as shown in Figure 4.31.

Table 4.35: FVSI & LQP at variable active power with minimal reactive power of 1 MVAR

Total P (MW)	Load increment at Bus 27		Load increment at Bus 28		Base condition
	FVSI	LQP	FVSI	LQP	
54	0.02220	0.03651	0.03330	0.03463	LQP =0.00023 FVSI =0.00021
55	0.02220	0.03710	0.03400	0.03535	
58	0.02359	0.04056	0.03608	0.03746	
66	0.02567	0.04888	0.04163	0.04314	

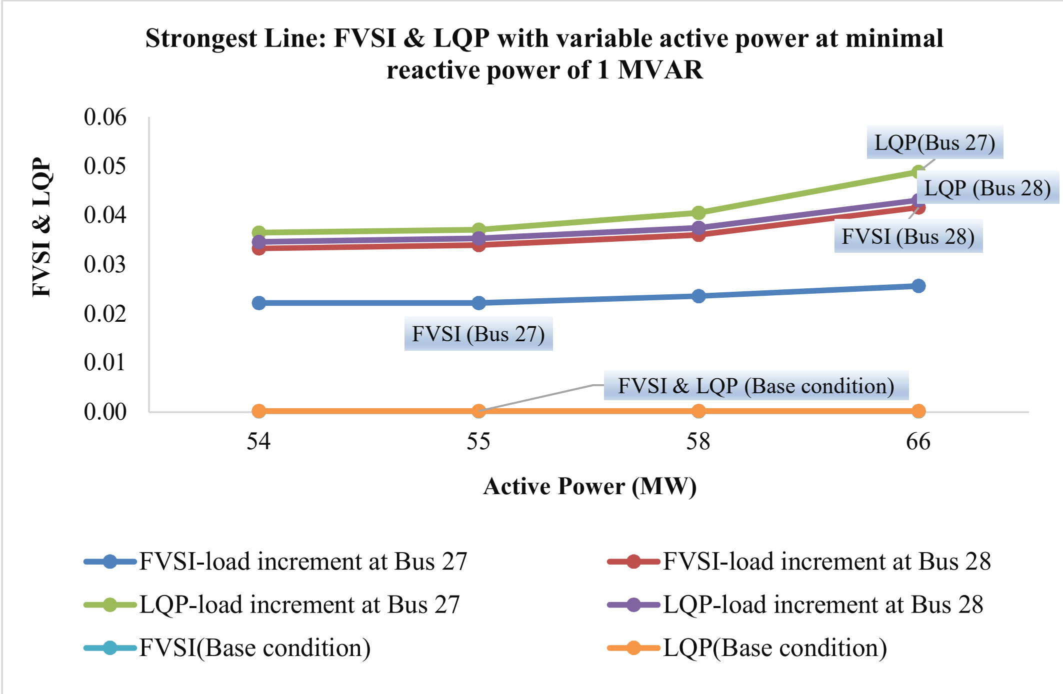


Figure 4.31: FVSI & LQP at variable active power with minimal reactive power of 1 MVAR

4.5.1 Mitigation techniques for strongest line (TX 27 to Bus 28): Injection of PV and installation of SVC.

As for mitigation techniques, only one load of 58 MW, 35 MVAR is selected to be placed at Bus 27 due to load increment at Bus 27, which contributes to severe impact compared to load increment at Bus 28. The 58 MW, 35 MVAR load is selected because it satisfies TNB load criteria, which is load with power factor more than 0.85 and cause violation to the system.

The injection of 50 MW PV is placed at Bus 27 or Bus 28 one at a time while the installation of 50 MVAR SVC is always placed at Bus 28 due to the concept that SVC is a reactive power support to improve bus voltage and at the same time to reduce the VSI value. PV is set to operate at unity power factor indicating that PV only contributes the active power while SVC is set to almost zero power factor indicating that SVC only contributes the reactive power.

Table 4.36 presents power factor of generators G2, G22, G23 & G27 in operation with and without injection of PV and installation of SVC. The power factor of generators G2, G22, G23 & G27 are significantly improved with injection of PV and installation of SVC. Although the power factor of G27 is improved with the injection of PV and installation of SVC, the values are still below the acceptable limits. This indicates that the G27 still is operating beyond its capability limits with the injection of PV and installation of SVC. The results in Table 4.36 are plotted into a graph as shown in Figure 4.32.

Table 4.36: Power Factor of generators G2, G22, G23 and G27 in operation with and without injection of PV and installation of SVC.

Generator No	Base Condition	without PV and SVC	With PV at Bus 27 (sending end) and SVC at Bus 28	With PV at Bus 28 (receiving end) and SVC at Bus 28
G2	0.9415	0.8411	0.9999	0.9997
G22	0.9081	0.9081	0.9873	0.9930
G23	0.9004	0.9070	0.9450	0.9541
G27	0.9721	**0.4836**	**0.6767**	**0.6289**

Note: The bolted font indicates the bus voltage below the acceptable limit

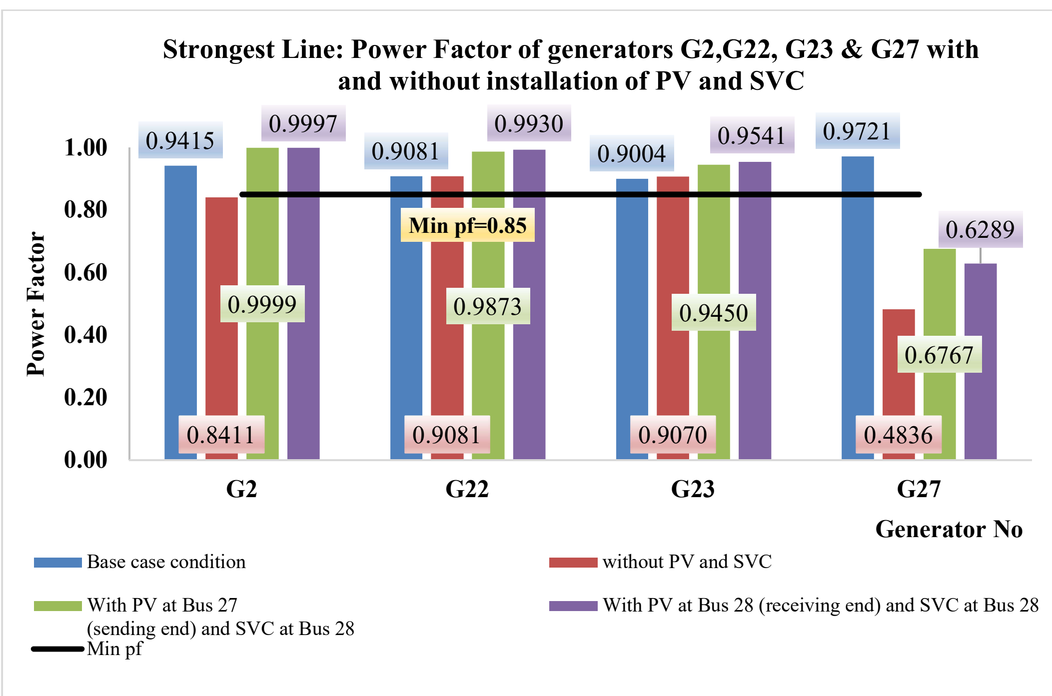


Figure 4.32: Power Factor of generators G2, G22, G23 and G27 in operation with and without injection of PV and installation of SVC.

Table 4.37 shows V25, V26, V27, V28, V29 and V30 with and without injection of PV and installation of SVC. Voltage at all the 6 buses are significantly improved and there is not much difference either injection of PV at Bus 27 or Bus 28, and installation of SVC at Bus 28. The results in Table 4.27 are plotted into a graph as shown in Figure 4.33.

Table 4.37: V25, V26, V27, V28, V29 and V30 with and without injection of PV and installation of SVC

Bus No	**Bus voltage (p.u)**			
	Base case condition	**without PV and SVC**	**With PV at Bus 27 (sending end) and SVC at Bus 28**	**With PV at Bus 28 (receiving end) and SVC at Bus 28**
Bus 25 (V25)	0.9839	0.9726	0.9900	0.9855
Bus 26 (V26)	0.9658	0.9542	0.9719	0.9674
Bus 27 (V27)	0.9900	0.9844	1.0000	1.0000
Bus 28 (V28)	0.9902	0.9799	1.0249	1.0249
Bus 29 (V29)	0.9889	0.9833	0.9989	0.9989
Bus 30 (V30)	0.9861	0.9804	0.9961	0.9961

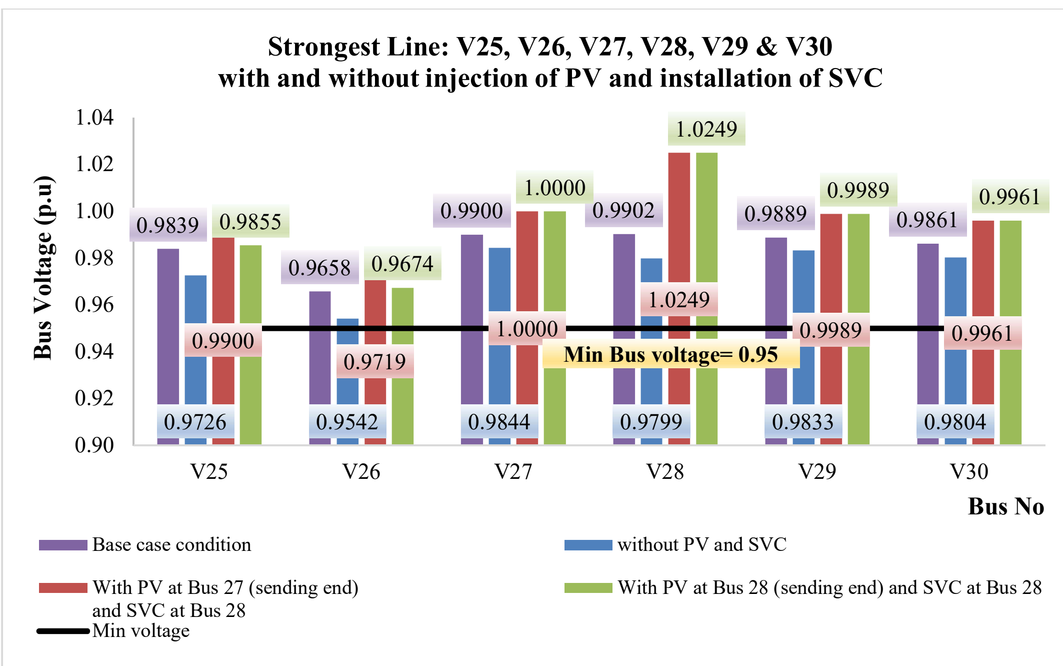


Figure 4.33: V25, V26, V27, V28, V29 and V30 with and without injection of PV and installation of SVC

Table 4.38 shows FVSI and LQP with and without injection of PV and installation of SVC. The FVSI and LQP are significantly improved with injection of PV and installation of SVC. The results in Table 4.38 are plotted into a graph as shown in Figure 4.34.

Table 4.38: FVSI and LQP with and without injection of PV and installation of SVC.

Voltage Stability Indices	Base Case Condition	without PV and SVC	With PV at Bus 27 (sending end) and SVC at Bus 28	With PV at Bus 28 (receiving end) and SVC at Bus 28
LQP	0.00106	0.12341	0.00996	0.00993
FVSI	0.00036	0.12211	0.10900	0.08976

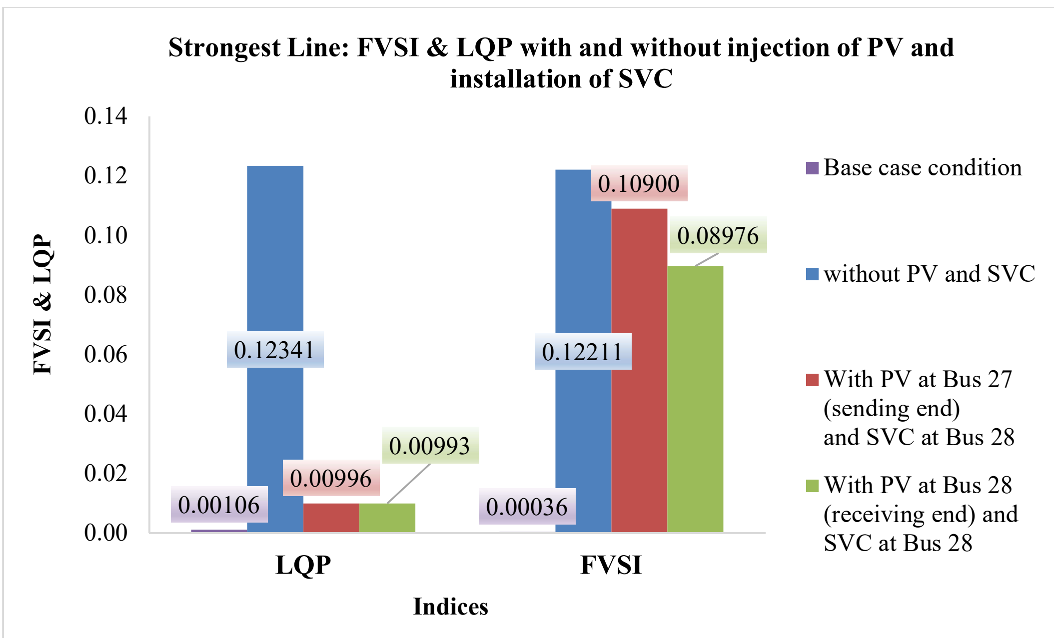


Figure 4.34: FVSI and LQP with and without injection of PV and installation of SVC.

4.5.2 Conclusion for load increment at the sending and receiving ends of the strongest line (Bus 27 to Bus 28) including conclusion for mitigation techniques.

Figure 4.35 presents the affected generators and buses due to load increment, additional PV and SVC for mitigation techniques, and actual reactive power supply and consumption within these areas. As a result of load increment, all the 3 areas are affected. As explained in Chapter 3, Area 1 has the large amount of reactive power resources but large amount of reactive power consumption, Area 2 is an area where reactive power supplied is sufficient to provide the reactive power consumption. Area 3 has the smaller amount of reactive power resources compared large amount of reactive power consumption. There are four generators affected which are G27, G2, G22 and G23. Furthermore, there are 6 bus voltage affected which is V25, V26, V27, V28, V29 and V30 as a result of load increment. The G2 and Bus 28 are located in Area 1, while G22, G27, Bus 25, Bus 26, Bus 27, Bus 29 and Bus 30 are located in Area 3, and G23 is located in Area 2.

As load increases at Bus 27 with variable reactive power at constant active power of 54 MW and 58 MW, the power factor of generators G27, G2, G22, G23 in operation are affected. In addition, under voltage condition occurs at V25, V26, V27, V29 and V30. Bus 27 located in Area 3 is known to have the smallest amount of reactive power resources but large amount of reactive power consumption. At base case condition, reactive power is imported from others areas to ensure generators are operating within the generator capabilities limits and bus voltage are within the acceptable limits. As reactive power increases, there will be an increased in reactive power that needs to be supplied by the generators. However, the reactive power supplied by the generators is limited by the generators capability limits. Therefore, the generators may operate near or beyond its capability limits as presented by low operating power factor to fulfil the increased in reactive load demand. Thus, the lacking of reactive power will lead to under voltage condition within these areas. Even though, under voltage conditions have occurred at V25, V26, V27, V29 and V30 due to the load increment at Bus 27, the most affected bus is V26 since V26 is located further away from the generator. Furthermore, it is a spur bus and connected with load demand of 3.5 MW and 2.3 MVAR. The most affected generators, will be the generators that are located near the bus that experienced load increment. Thus, the most affected generators are G27, G2, G22 and lastly G23 which is located in Area 2.

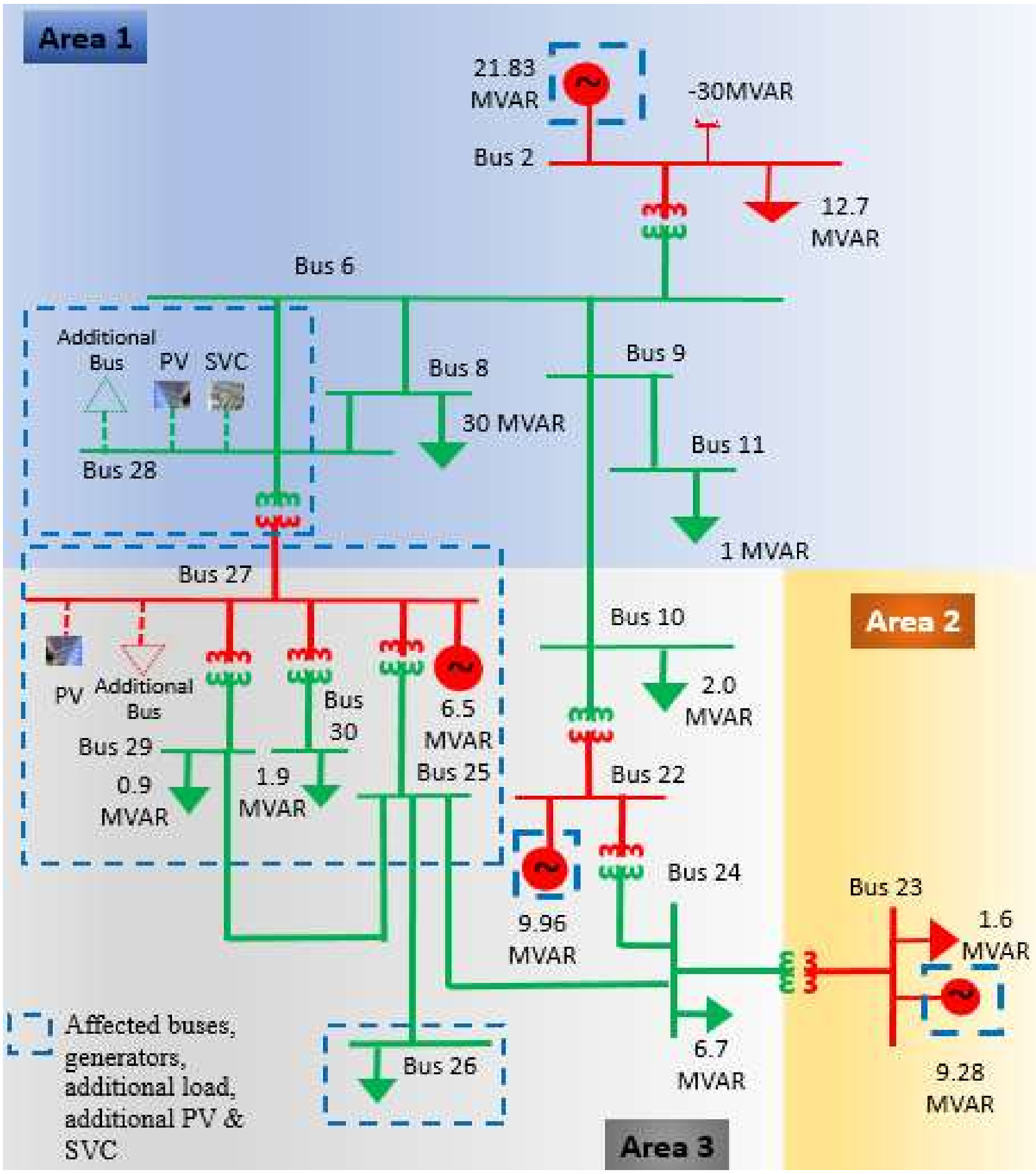


Figure 4.35: Affected buses and generators due to load increment at Bus 27 or Bus 28. Additional PV and SVC for mitigation techniques and actual reactive power supply and consumption within these areas.

In relation to load increment at Bus 28 with variable reactive power at constant active power of 54 MW and 58 MW, the power factor of generators G27, G2, G22, G23 in operation are affected. In addition, under voltage condition only occurs at V28. Bus 28 located in Area 1, which is known to have large amount of reactive power resources but large amount of reactive power consumption. Hence, with load increment at Bus 28, there is no significant impact to generator power factor and bus voltage compared to load increment at Bus 27. This is because, the increased in reactive power is supplied by generators within its vicinity. However, the low operating power factor presented by G27, G2, G22 and G23 is because the generators are operating near or beyond generator capability limits. The affected generators are operating at over excited condition that will lead to the heating of field winding. The most affected generators are G2, followed by G27, G22 and lastly G23 which is located in Area 2. The voltage is governed by the reactive power. As reactive power increased, there will be violation in voltage if reactive power resources are insufficient to support the reactive load demand. Thus, there is under voltage condition occurring at Bus 28 due to the lacking of reactive power supply.

The load increment at Bus 27 contributes to severe impact on power factor of generators in operation, bus voltage, FVSI and LQP compared to the load increment at Bus 28. In addition, the load increments with more variable reactive power at constant active power 54 MW and 58 MW contribute to severe impact compared to load increment with variable active power at minimal reactive power of 1 MVAR. There is a significant reduction on power factor to generators G2, G27, G22 and G27 in operation, under voltage occurs at V25, V26, V27, V28, V29 and V30. In addition, there is an increased in LQP and FVSI due to load increment.

The generators performance and voltage stability are improved with the injection of PV and installation of SVC. The generators are operating within generator capability limits except for G27 which is still below the acceptable limits. This indicates that even G27 is improved but it is still operating beyond the generator capability limits despite of PV injection of and SVC installation. In addition, bus voltage has improved to be within 0.95-1.05 p.u and reduction in values of FVSI and LQP.

4.6 Summary of Chapter 4

This chapter presents the results and discussions on the impact of load increment to power system stability by analysing voltage stability with respect to Voltage Stability Indices (VSI) and generator performance with respect to generator capability limits. The voltage is governed by reactive power; thus, lacking of reactive power will lead to under voltage condition. Furthermore, generators are the main source of reactive power supply to power system; however, the generated reactive power is limited by generator capability limits. Therefore, as reactive load is increased, the generator may operate near or beyond its capability limit as presented by low operating power factor. The allowable operating power factor for a generator is between 0.85 - 1.0, lesser than 0.85 will cause the generator to operate at over excitation condition that will lead to heating of the field winding. As reactive load increases, there will be violation in voltage if reactive power resources are insufficient to support the reactive load demand. The most affected bus will be the bus that is located further away from generator, which is the main source of reactive power generation. Injection of PV and installation of SVC have improved generator performance and voltage stability in the system. The generator is operating within the generator capability limits and the bus voltage is within the acceptable limits, which is proven by the reduction of voltage stability indices.

CHAPTER 5

CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

5.1 Introduction

This chapter concludes this research work and propose recommendation for future researcher. This chapter summarises all findings based on the results obtained from simulations and ends with the recommendation for future works.

5.2 Conclusion

This research work analyses on the impact of load increment to power system stability by analysing generator performance with respect to generator capability limits, and voltage stability with respect to Voltage Stability Indices (VSI). The research work uses IEEE 30 Bus Test System modelled in PSS®E 34 environment. Power flow simulation is performed during load increment while dynamic simulation is performed during PV injection and SVC installation. Furthermore, injection of PV and installation of SVC are introduced in the system as mitigation techniques in maintaining power system stability due to load increment.

The base case condition is stimulated without any additional load and without any PV and SVC integration. The VSI are calculated for each of the transmission lines as indication of voltage stability and to identify the strongest and weakest lines in the system. The strongest and weakest lines in the system are determined using selected VSI which are Fast Voltage Stability Index (FVSI) and Line Stability Factor (LQP). There are three scenarios being simulated to achieve the research objectives. The various amount of loads are introduced at all buses, sending and receiving ends of the weakest and strongest lines to achieve the objectives of the research work. The result at each scenario is investigated and compared with base case condition. The results before and after injection of PV and installation of SVC were compared and analysed to evaluate its contribution and effectiveness in the system.

Based on simulation results, the increased in reactive power in the system contributes severe impact to generator performance and voltage stability. This is the reason for load increment with variable reactive power at constant active power of 54 MW and 58 MW gives more significant impact to generator performance and voltage stability compared with load increment with variable active power at minimal reactive power of 1 MVAR. In addition, load increment at the sending end of the strongest line contributes severe impact to generator performance and voltage stability compared to load increment at the receiving end of the strongest line. Moreover, load increment at the receiving end of the weakest line contributes severe impact to generator performance and voltage stability compared to load increment at the sending end of the weakest line.

For load increment at the sending end of the strongest line with variable reactive power at constant active power of 54 MW and 58 MW, there are four generators and 5 bus voltage affected due to load increment. The power factor of generators G27, G2, G22 and G23 operate below the acceptable limits and V25, V26, V27, V29 and V30 experience under voltage condition. For load increment at the receiving end of the weakest line with variable reactive power at constant active power, three generators and one bus voltage are affected due to the load increment. The power factor of generators G2, G22 and G27 are operating below the acceptable limits and V8 has experienced under voltage condition.

As reactive load increases, there will be an increase in reactive power supply by the generators which is limited by the generators capability limits. Therefore, as reactive load is increased, the generator may operate near or beyond its capability limit as presented by low operating power factor. The most affected generators will be the generator that is located near the additional load. Lacking of reactive power will lead to under voltage condition since voltage is governed by the reactive power. The violation in bus voltage occurs once reactive power resources are insufficient to support the reactive load demand. The most affected buses will be the bus that is located far away from the generators.

The voltage stability and generator performance are improved with the injection of PV and installation of SVC. It can be observed that the generator is operating within the generator capability limits and the bus voltage within the acceptable limits which are proven by the reduction of voltage stability indices.

5.3 Recommendation for Future Work

The uncontrolled load increment in the system will lead to the power system instability. This research work only focuses on the impact of static load increment at lagging power factor to power system stability. The analysis is done by monitoring generator performance with respect to generator capability limits and voltage stability with respect to voltage stability indices (VSI). The injection of PV and installation of SVC are introduced as mitigation techniques to improve generator performance and voltage stability. Thus, the following are recommended as key areas for future research work: -

- To study the impact of other types of load increment such as static load at leading power factor, dynamic load and composite load to power system stability focusing on frequency and rotor angle stability.
- To study the impact of other renewable energy resources such as biomass and distributed energy as mitigation techniques to improve power system stability.

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APPENDIX

Dynamic Data for generators and PV

Hydro Generator Data

1	'GENSAL' 1	9.5000	0.11600	0.10000	2.5000	
	0.0000	1.0560	0.89000	0.20130	0.15000	
	0.12000	0.13700	0.33200	/		
1	'SCRX' 1	0.10000	10.000	100.00	0.50000E-01	
	0.0	5.0000	0.0000	0.0000	/	
1	'HYGOV' 1	0.50000E-01	1.0000	16.500	0.50000E-01	
	0.50000	0.16700	1.0000	0.0000	2.0000	
	1.2000	0.20000	0.80000E-01/			
2	'GENSAL' 1	9.5000	0.11600	0.10000	2.5000	
	0.0000	1.0560	0.89000	0.20130	0.15000	
	0.12000	0.13700	0.33200	/		
2	'SCRX' 1	0.10000	10.000	100.00	0.50000E-01	
	0.0	5.0000	0.0000	0.0000	/	
2	'HYGOV' 1	0.50000E-01	1.0000	16.500	0.50000E-01	
	0.50000	0.16700	1.0000	0.0000	2.0000	
	1.2000	0.20000	0.80000E-01/			

Steam Generator Data

13	'GENROE' 1	6.5000	0.10000	0.34000	0.19000	
	2.8000	0.0000	1.4500	1.1590	0.23800	
	0.36200	0.15000	0.14000	0.16000	0.46000	/
13	'SEXS' 1	0.10000	10.000	100.00	0.50000E-01	
	0.0	3.0000	/			
13	'TGOV1' 1	0.50000E-01	0.49000	0.85000	0.0000	
	1.5000	5.0000	0.0000	/		
22	'GENROE' 1	6.5000	0.10000	0.34000	0.19000	
	2.8000	0.0000	1.4500	1.1590	0.23800	
	0.36200	0.15000	0.14000	0.16000	0.46000	/

22 'SEXS' 1 0.10000 10.000 100.00 0.50000E-01
0.0 3.0000 /

22 'TGOV1' 1 0.50000E-01 0.49000 0.85000 0.0000
1.5000 5.0000 0.0000 /

Gas Generator Data

23 'GENROE' 1 3.7970 0.10000 0.42400 0.72000E-01
5.4000 0.0000 1.9600 1.8820 0.29300
0.45400 0.20600 0.17000 0.10000 0.47000 /

23 'SEXS' 1 0.10000 10.000 100.00 0.50000E-01
0.0 3.0000 /

23 'TGOV1' 1 0.50000E-01 0.49000 0.85000 0.0000
1.5000 5.0000 0.0000 /

27 'GENROE' 1 3.7970 0.10000 0.42400 0.72000E-01
5.4000 0.0000 1.9600 1.8820 0.29300
0.45400 0.20600 0.17000 0.10000 0.47000 /

27 'SEXS' 1 0.10000 10.000 100.00 0.50000E-01
0.0 3.0000 /

27 'TGOV1' 1 0.50000E-01 0.49000 0.85000 0.0000
1.5000 5.0000 0.0000 /