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VOLTAGE STABILITY PROBLEM IN A DISTRIBUTION SYSTEM WITH DISTRIBUTED GENERATOR

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ในขณะที่ความต้องการใช้ไฟฟ้าได้เพิ่มขึ้นอย่างต่อเนื่อง แต่การก่อสร้างสายส่งและโรงไฟฟ้าทำได้ยากเนื่องจากปัญหาด้านสิ่งแวดล้อมและด้านการเมือง ในอนาคตอันใกล้นี้เป็นที่คาดหมายว่าการผลิตไฟฟ้าโดยใช้เครื่องกำเนิดไฟฟ้าขนาดเล็กจะเพิ่มขึ้น โดยเฉพาะอย่างยิ่งในระบบจำหน่าย ผู้ผลิตไฟฟ้ารายเล็กมากมักจะเชื่อมต่อเครื่องกำเนิดไฟฟ้าเหนี่ยวนำเข้ากับระบบจำหน่าย เพราะเครื่องกำเนิดไฟฟ้าเหนี่ยวนำมีข้อดีเมื่อเทียบกับเครื่องกำเนิดไฟฟ้าซิงโครนัสในแง่ของความทนทานและการลงทุน อย่างไรก็ตามเป็นที่ทราบกันว่าเครื่องกำเนิดไฟฟ้าเหนี่ยวนำมีความต้องการกำลังไฟฟ้ารีแอคทีฟ ดังนั้นวิทยานิพนธ์ฉบับนี้จึงได้ศึกษาผลกระทบของเครื่องกำเนิดไฟฟ้าเหนี่ยวนำที่มีต่อปัญหาเสถียรภาพแรงดัน

วิทยานิพนธ์ฉบับนี้อาศัยการวิเคราะห์ทั้งแบบสถิตและพลวัต สำหรับการวิเคราะห์แบบสถิตได้ใช้ดัชนีชี้วัดเสถียรภาพแรงดัน PQVSI เป็นเครื่องมือหลักเพื่อตรวจสอบว่า จุดทำงานของระบบอยู่ใกล้กับจุดที่จะเกิดการสูญเสียเสถียรภาพแรงดันมากน้อยเพียงใด นอกจากนั้นวิทยานิพนธ์นี้ยังได้ทำการจำลองแบบพลวัต เพื่อตรวจสอบความถูกต้องของผลการวิเคราะห์แบบสถิตอีกด้วย จากการศึกษาพบว่า เครื่องกำเนิดไฟฟ้าเหนี่ยวนำมีผลทำให้เสถียรภาพแรงดันของระบบแย่ลงโดยเฉพาะเมื่อระบบจ่ายโหลดแบบอินดัคทีฟขนาดใหญ่ ซึ่งสาเหตุนี้จะนำไปสู่ปัญหาการสูญเสียทั้งในเครื่องกำเนิดไฟฟ้าเหนี่ยวนำเองและเสถียรภาพแรงดันของระบบจำหน่ายทั้งระบบ ดังนั้นการใช้เครื่องกำเนิดไฟฟ้าเหนี่ยวนำในระบบจำหน่ายจะต้องได้รับการพิจารณาเป็นพิเศษ ในวิทยานิพนธ์ฉบับนี้ ได้ทำการแสดงให้เห็นถึงผลดีของการติดตั้งตัวเก็บประจุที่ขั้วของเครื่องกำเนิดไฟฟ้าแบบเหนี่ยวนำซึ่งจะช่วยเพิ่มสมรรถนะการทำงานของเครื่องกำเนิดไฟฟ้าแบบเหนี่ยวนำให้ดียิ่งขึ้น

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With difficulties in building new transmission lines and power plants, due to environmental and political issues, while electricity demand is continuously increasing, it is expected that, in the near future, more distributed generations will penetrate into power systems, especially into the distribution system. As several competitive advantages of an induction generator compared to a synchronous generator such as durability, low investment cost and etc., it is possible that many of very small power producers may connect this type of generators into the distribution system. However, as we know, rather than generate reactive power, the induction generator consumes it. Thus, impact of the induction generator on voltage stability should be carefully investigated. We focus on this aspect in this thesis.

Both static and dynamic analyses were performed in this thesis. In static analysis, the degree of voltage instability based on PQVSI index is used as the main tool to assess how close the present operating condition to the voltage instability point. In addition to the static analysis, the dynamic voltage stability was conducted as well. The dynamic voltage characteristics were observed, which is eventually used to verify the results obtained from the static analysis. It provides clearer and more accurate figure of the actual dynamics of voltage instability process following a disturbance in the system, which in this case is a load change. The studies indicating an unhealthy impact of induction generators on the system's voltage stability are shown in this thesis, especially when the system is intended to serve large inductive loads. These phenomena lead to both unstable of the induction generator itself, and unstable of the entire distribution system through voltage instability. As a consequence, special treatment should be implemented in the case of utilizing induction generators in the distribution system. An example treatment in this study, which is disclosing the advantage of installing capacitor at the induction generator terminal in enhancing the utilization of the induction generator, had been presented.

Department	: Electrical Engineering	Student's Signature	
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CHAPTER I

INTRODUCTION

1.1 Motivation

With increasing of electricity demand, also the difficulties in building new transmission lines and new power plants, problems of releasing land in appropriate areas to build the power equipment, political issues, and etc, the need of power system stability mainly on voltage stability is becoming important. At present, most power systems are loaded near their steady-state stability limits for all the time, which may result in voltage instability at any time possible. When the power system is operated close to its stability limit, it is required to study the system in the pressurized environment without neglecting the network's reliability and security. If such a system facing voltage instability, it can make greater possibility to the system having several blackouts. It means also, voltage stability becomes a major concern and a big issue for power system engineer. Investigation of voltage instability is an important aspect in power system reliability, security and power system quality studies.

Typically, real power has high correlation with rotor angle stability, reactive power has high correlation with voltage stability study. Lack or surplus of reactive power could lead to voltage instability in the local or global power system network when in such a system exists an increasing or decreasing electricity demand. In other words, voltage stability mainly involves reactive loads and the means of voltage control. A power system is considered as voltage stable at a given operating state if when subjected to a certain disturbance, the voltage close by the loads reaches the post-disturbance stability values. A power system experiences voltage collapse when the post-disturbance balance voltage close by the loads is below the tolerable limits. Voltage collapse can be formed as a partial or total loss of voltage. Voltage security is a system potentiality to remain stable after having significant contingencies or increasing of load, not only able to operate stable [1].

Today's distribution power system only consist of consumers connected to the network, but in the future, it has been predicted that distributed generators in the small size capacity will also contribute in the distribution network. As illustration, a consumer that has small capacity of generator is not only consuming power from the power grid, but it can also be a small power producer participating in carrying out the power system load. When many consumers also contribute as small power producers, these can meet the demand of the local consumer, so local consumers are not depending anymore with transmitting power from high voltage transmission network. When this happens, electrical distribution network is becoming micro power network. In practice, distributed Generator's size is varying from 15 kilowatts to approximately 10 MW, included also here power storage equipments, so their size is much smaller than traditional central power station generators [2].

In the view of environment reservation and energy conservation, distributed generator with small size of generating capacity mostly shall use the primary source from the renewable energy, such as low-head hydro, solar power, fuel cell, wind power, waste burning, photovoltaic power generation, and etc. As running out of fossil fuel source like oil and coal in the past decade, also arduousness of discovering new source of fossil fuel, many researcher start to think in exploiting the renewable energy sources as an alternative way to solve threatening primary energy crisis because excessive dependency on fossil fuel. Only in 11 years, the percent growth of global cumulative installed wind power capacity in the world is exceeding 1500 % or equal to 20,076 MW started from year 1996, and the increment growth per year between 20.77 % and 37.36 %. This remarkable development is a proven result that renewable energy might replace the fossil fuel in the foreseen future [3]. Wind power generation units often use induction generator because of its merit, which is able to operate in variable speeds according to the wind speed [4, 5].

With many advantages of induction generator, it is possible that many of very small power producers may connect this type of generator into the distributed system instead of an expensive synchronous generator. Utilization of induction generator was starting in the early of twentieth century, but in 60's and 70's they had extensively disappeared. Increasing of oil price made induction generator showed up once more in the industry as its advantages, such as low price, lightweight, very rugged, durable, and little need of control system compared with synchronous generator. So it can minimize the overall system maintenance requirements. When induction machine is rotated exceeding its synchronous speed by external prime mover, its induced torque will have reverse direction, so it will act like power generating. But, when utilized as a generator, an asynchronous machine has limited practical applications. Such kinds of limitations are the difficulty to control the terminal voltage and frequency at the allowable range under varying load patterns. Asynchronous machine doesn't have its own field exciter, so it can not produce reactive power, Instead it consumes reactive power, so external reactive power sources should be connected continuously to maintain its stator magnetic field and generate reactive power in its terminal [6]. Nevertheless, the residual flux from the rotor machines can provide the initial self excitation of those machines actually, but only in a few levels of self excitation. However, sometimes, this residual flux can be not enough to produce the rated voltage. A shunt capacitor, as a reactive power source, installed in its machine terminal to initially excite the induction generator voltage is popularly used. This type of machine is called Self Excited Induction Generator (SEIG) [7].

In [8], the authors investigated the application of SVC (Static Var Compensator) and the tap changing transformer to improve the static voltage stability margin in the power system using synchronous generators. The improved stability margin also enhances the overall voltage profile in the power system. Dealing with dynamic voltage stability, the SVC also increased the steady state voltage magnitude, but we must consider carefully with the product of excessive voltage transient oscillation due to excessive value of utilized capacitor. This oscillation might be reduced with application of optimum value of capacitor.

For practical purpose, engineers can use 2/3 rule of thumb to locate the DG to its best contribution to the network. This rule also works well in locating the capacitor even though this is just an approximation to reduce network losses and sometimes produces error. Reducing the distribution network loading might be done by putting the DG at the end of feeder having the most load in the network. When DG is put near the substation, DG placement will not make any effect in the change of network loading pattern [9]. This means also that DG might not improve much the voltage profile network. But for more exact result in getting voltage support from the DG placement, [10] offered a technique to make the most effective use of DG in voltage improvement by inserting active and reactive power of DG at the appropriate site. This technique was based on voltage sensitivity of lines to get the near optimal placing in the network. But in reference [11], it was revealed and must be noted carefully that DG has function only to support the network weakness, consequently can not control the network. While the system network is in detrimental condition, it was proven that the DG could not drastically enhance the system's voltage stability limit; even the DG had been operated in various modes and placed at distinct site. Once more, the synchronous generators were utilized in this investigation. In another research, the authors in [12] used 4 operation types in driving synchronous generator, which are Distributed Generation injecting real power (DG-P), DG injecting reactive power (DG-Q), real-reactive power generation mode (DG-PQ), and DG-QPQ. The last operating mode was a DG-PQ but having Q priority and generating reactive power only for small adjustment. When the load was increasing, the DG would set the DG-Q reactive injection at the limit, and then the DG control system would be energized so that the DG could be operated in the real-reactive (PQ) generation mode. They disclosed the fact that the injections of real and reactive power were the essential factors for enhancing the feeder voltage profile in the power network.

In this thesis, Induction Generator, as one of Distributed Generator types, is investigated. We study the consequence of utilizing Grid Connected Induction Generator in the voltage stability and examine the P-V curve of the several bus in the network. The Induction Generator's site is determined by the most loaded bus in the network. The effect of reactive power sources installed close to the Induction Generator bus and the effect of power factor of demand were also investigated. This research study both static and dynamic analysis. For static analysis, steady state model utilizing conventional power flow to acquire the P-V curve and to obtain voltage stability index is employed. In this research, the voltage stability index based on transmission line is used as the main tool to assess how close the present operating condition to the voltage instability point. In addition to the static analysis, the time domain simulation has been carried out in order to investigate the dynamic voltage behavior of the induction machine installed in the network.

1.2 Objective of Research

The particular objectives of this thesis are as follows :

1. Modelling the steady state induction generator model to include in the power network and voltage stability index which are suitable for static voltage stability analysis
2. Investigating the static voltage stability of the power network which is utilizing induction generator
3. Modelling the dynamic induction generator model in order to be able to investigate the dynamic voltage stability phenomenon in the induction generator installed distribution system.
4. Investigating the dynamic voltage behavior of induction generator, especially when having load changes.

1.3 Scope of Work

This research is limited by following scopes :

1. The static modeling in this research includes :
   - Static Induction Generator model used in this thesis is using steady state model based on grid connected squirrel cage induction generator installed in distribution system.
   - The Induction Generator's (IG) site is determined by the most loaded bus in the network. The P-V curve of the selected bus in the network also will be presented in analyzing static voltage stability with increasing load at particular bus, assumed there is a bilateral contract between IG owner and consumer at that load bus.
   - The effects of reactive power source installed close to the Induction Generator bus and the effect of load's power factor are investigated.
   - The effects of IG location in the network are also studied : at the bus electrically near the main grid, at the centre of the network which is the most loaded bus in the network, and at the end of the network, which is electrically far from the main grid.
   - The induction generator model will be included in the conventional Newton Raphson power flow to acquire the P-V curve and to obtain the voltage stability indices; the PQVSI index is used.
   - Network thermal limitation and probabilities on self excitation of Induction Machine upon loss of power from the main grid are not considered.
2. The dynamic modeling in this research includes :
   - The dynamic induction generator model used in this thesis is the reduced third order DQ model based on grid connected squirrel cage induction generator installed in distribution system.
   - The dynamic voltage condition of the induction machine is investigated when load increment occurred.
   - Loads are modeled with dynamic constant real and reactive power.

1.4 Research Methodology

1. Literature reviews on background knowledge, modeling, and application of induction generator and voltage stability index related to distributed generation.
2. Study and develop model for the induction generator installed in distribution system and also voltage stability index which are suitable for static voltage stability analysis. In addition to the static analysis, to investigate dynamic condition in time domain simulation, model for the dynamic induction generator installed in distribution system is also developed.
3. Study how to incorporate induction generator model into the power network.
4. Test the proposed model on the test system.
5. Analyze the result.
6. Make conclusions and documents for publication and thesis report.

1.5 Expected Contribution

It is expected that the result will be useful for analysis of the voltage stability in the power system utilizing induction generator especially for power system operation and planning. It will be crucial to power system engineer to be able to schedule and prepare a proper power system operation and planning to help mitigate voltage instability within the actual power systems. The contributions of this research would be :

1. Able to understand the static and dynamic behaviors of induction generator,
2. Able to understand mechanisms of several static voltage stability indices.
3. Able to acquire tools for investigating the static and dynamic voltage stability phenomena in distribution system installed with induction generator.

For the following sections,

Chapter II introduces briefly to the general concept of the distributed generation (DG) including definition, considerations to the renewed attention in DG, and its influences to the network.
Chapter III provides description about Induction Generator in static and dynamic model.
Chapter IV describes about static voltage stability, dynamic voltage stability, and static voltage stability indices.
Chapter V gives description the network and load representation in dynamic analysis. In chapter VI, the numerical example of various case studies are presented followed by the discussion.
The last is the conclusion of this thesis illustrated in chapter VII.

CHAPTER II

DISTRIBUTED GENERATION

The concept behind distributed generation (DG) is not new at all. Initially, electric utilities have been established this kind of machine in isolated territories, without connection to other grids. However, technological evolutions, such as transformers, protection and control equipment, and etc., lead to the development of AC networks, allowing for electric energy to be transferred over longer distances. This make possible of connecting utility grids one another into large scale interconnected electricity systems, and interconnection bring obvious advantages (e.g., sharing peak load coverage, and backup power). Technological advances are not limited, however, to large-scale operations. DG technologies include small combustion turbine generators (including micro turbines), internal combustion reciprocating engines and generators, photovoltaic panels, and fuel cells are introduced in the market with small capacities. But, because the DG products tend to be simpler and smaller than their older generations, they are expected to appear in the distribution network even in the near-term.

Electric restructuring has spurred the consideration of DG power because all participants in the energy industry, which are buyers and sellers, must be more responsive to market forces. DG is a priority in parts of the country where the spinning reserve margins are shrinking, because industrial and commercial users are having increasing electricity demands year by year and transmission-distribution network constraints are limiting power flows. These reasons, technological innovations and a changing economic and regulatory environment, result in a renewed attention for DG.

The authors in [13] described five leading considerations to the renewed attention in DG :

- DG has a flexible operation technology, so can be used as peak shaving, continuous operation, or standby capacity.
- DG could improve system's reliability and quality of power supply. Competition at power system interconnections make each power producer tries to have competitive price compared with others. This reduced cost might affect reliability levels and quality of supply from power producer.
- DG can be an alternative of investment caused by expanding transmission and distribution capacity, or can be a bypass for transmission and distribution costs.
- DG can support the performance of the existing grid, because of its ability to provide ancillary services.
- Environmental regulations make players in the electricity business to search for environmental friendly energy solutions. DG using renewable energy and DG's potentiality to optimize energy consumption of an industry having large and constant demand of heat, can be a choice for electricity business players.

2.1 Definition of Distributed Generation

The study in [13] discussed about definition of DG. The best definition of DG that is generally accepted in practice appears to be 'an electric power generation source that is connected directly to the distribution network or on the customer side of the meter'. Even it seems a quite wide definition, but it sets no limit on generation technology, using renewable as a primary source or not, or on capacity of potential DG application. The latter's reason is because the maximum DG capacity that can be connected to the distribution network is a function of the capacity of the distribution network itself.

The technical subjects concerned with distributed generation, however, can be diversified significantly with the rating. Therefore, it is relevant to introduce classifications of distributed generation. In [14], the authors suggested the following separation for these classifications:

- Micro distributed generation : ~ 1 Watt < 5 kW
- Small distributed generation : 5 kW < 5 MW
- Medium distributed generation : 5 MW < 50 MW
- Large distributed generation : 50 MW < ~ 300 MW

2.2 Distributed Generation on Distribution Systems

Distribution systems at present are designed and planned to operate passively in unidirectional power flows, without any generation on the distribution system or at customer loads, which is different from transmission systems whose designs and plans are intended to operate as active systems with both generation and consumption. With the recent development of Distributed Generation, the distribution systems should deal with bidirectional power flows, and must be ready to include this type of power flows in their network designs and operation principles.

Hence, the connection of generation sources on the distribution system might significantly affect the power flows, voltage conditions, reliability, security, stability, power system protection, and safety for both customers and electricity producers. These influences may present either in positive or negative impacts, depending on the properties of the interconnection location, distributed generator characteristics, and customer's load characteristics. Positive influences are generally called "system support benefits", and include:

- loss reduction,
- improved utility system reliability, stability, and security,
- voltage support and improved power quality,
- transmission and distribution capacity release,
- rescheduling of upgraded or even new transmission and distribution infrastructures.

In practice, to attain above support benefits is much more complex than is sometimes considered. The Distributed Generation sources must be reliable, dispatchable, of the proper size and at the proper locations. In addition, they must also meet several other operating criteria as well. Unfortunately, many Distributed Generations will not be utility owned or will be variable energy sources such as solar and wind; there is no guarantee that these conditions will be satisfied and that the full system support benefits will be made in reality. In fact, power system operations may be adversely affected by the introduction of Distributed Generation if certain minimum standards of control, installation and placement can not be maintained. Thus, the Distributed Generation must, at least, be acceptably coordinated with the following two factors; power system operating philosophy and feeder design, to have positive benefits mentioned before. The larger the cumulative Distributed Generation capacity on a circuit relative to the feeder capacity and demand, the more critical is this coordination with these factors [15].

CHAPTER III

INDUCTION GENERATOR

The induction machine is used in a wide variety of applications as a means of converting between electrical and mechanical power. It is without doubt that this type of machine is the workhorse of the industry. Accordingly, the induction machine technology is in a well established existence. The main benefit of the induction machine is the rugged simple brushless construction and no need of control DC excitation system compared with synchronous machine. The disadvantages of both the DC machine and the synchronous machine are wiped out in the induction machine, resulting in low initial capital cost, minimizing the overall system maintenance requirements, and having higher quality of transient performance. With aforementioned facts, Induction Generators are extensively used for constant or variable speed and constant or variable voltage/frequency, in small hydro power plants, wind energy systems, emergency power supplies, etc. The machine's capacity is obtainable on the market in diverse power ratings, from several kilowatts up to several megawatts capacity, and even bigger.

In grouping the induction generator, there are two kinds of induction generator based on operating method [16]:

1. Grid connected induction generator: This kind of installation draws reactive power from utility grid to provide its excitation to set up the rotating magnetic field and build up the induction machine terminal voltage, also known as line excitation. In this manner, induction machine will always draw reactive power, on that account, shunt capacitor or other reactive power source might be used to compensate this requirement.
2. Self excited induction generator: This kind of installation is having almost similar mechanism with self excitation DC generator. A shunt capacitor with suitable size connected across the induction machine terminal voltage can supply the reactive power to set up the rotating magnetic field and build up the induction machine terminal voltage. It is important to keep in mind that such building up the terminal voltage is also determined by the machine rating, machine speed, capacitor size, and load characteristics.

3.1 Induction Generator Equivalent Circuit in Static Model

The general form of equivalent circuit of an induction machine is suggested by the similarity to a transformer. Assume that the rotor is rotating at the steady speed n round/minute where the stator magnetic field is rotating at the synchronous speed of n_1 round/minute, related to the number of poles of the machine and the power supply frequency, f_s. The rotor is then traveling at a speed n_1-n round/min backward with respect to the stator field, or the slip of the rotor is n1-n round/minute. Slip, s, is more usually expressed as a function of the synchronous speed. This relative motion of the stator flux and the rotor conductors induces voltage of frequency sf_s. Thus, the electrical behavior of an induction machine is similar to that of a transformer but with the additional feature of frequency transformation. In fact, a wound rotor induction machine can be used as a frequency converter.

Let consider conditions in the stator. The synchronously rotating air gap flux wave generates balanced polyphase counter emfs in the phases of the stator. The stator terminal voltage differs from the counter emf by the voltage drop in the stator leakage impedance, the phasor relation for the phase under consideration being

$$\tilde{V} = \tilde{E}_s - \tilde{I}_s (R_s + jX_s) \tag{3.1}$$

where

$\tilde{V}$ = stator terminal voltage

$\tilde{E}_s$ = counter emf generated by resultant air gap flux

$\tilde{I}_s$ = stator current

R_s = stator effective resistance

X_s = stator leakage reactance

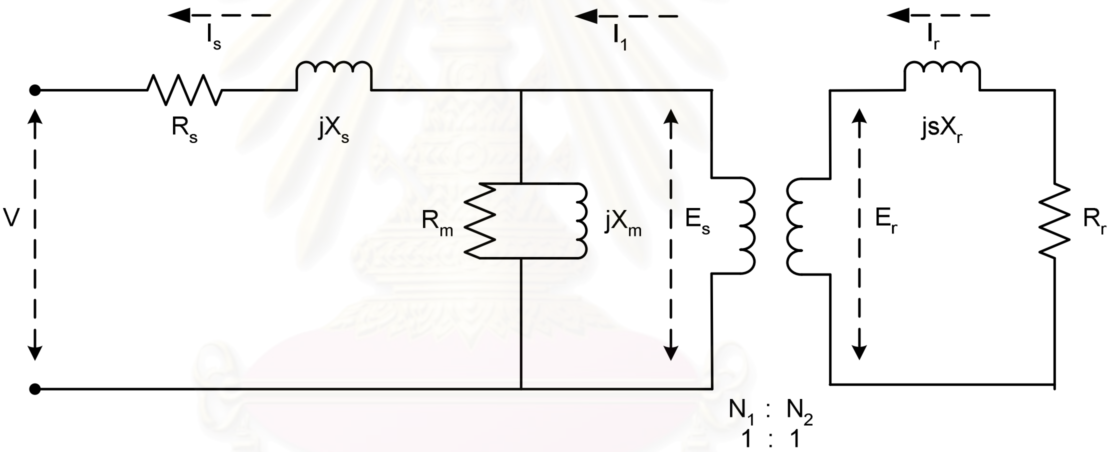

Figure 3.1 Stator and rotor equivalent circuit for an induction generator in steady state

The equivalent circuit shown above, which represents stator phenomena, is exactly like that for the primary of a transformer. To complete the circuit, the effects of the rotor must be incorporated. This is done by considering stator and rotor voltages and currents in terms of rotor quantities as referred to the stator. The number of effective turns per phase in the stator winding is assumed the same with the number in the rotor winding. In the case of the induction machine, we will see that in addition to referring the rotor impedance by the square of the stator/rotor turns ratio like in transformer case, we must take into account the fact that the rotor's induced emf has lower frequency compared to the frequency of voltage on stator's side, and thus that the rotor inductive reactance is proportionally lowered.

Since the rotor is short circuited, the phasor relation between the slip frequency emf $\tilde{E}_r$ generated in the reference phase of the referred rotor and the current $\tilde{I}_r$ in this phase is

$$\frac{\tilde{E}_r}{\tilde{I}_r} = Z_{2s} = R_r + jsX_r \tag{3.2}$$

where

Z_{2s} = slip frequency rotor leakage impedance per phase referred to stator

R_r = referred effective resistance

X_r = referred rotor's leakage reactance at synchronous frequency

The stator sees a flux wave and an mmf wave rotating at synchronous speed. This flux wave induces both the slip frequency rotor voltage $\tilde{E}_r$ and the stator counter emf $\tilde{E}_s$. If it were not for the effect of speed, the referred rotor voltage would equal the stator voltage, since the referred rotor winding is identical with the stator winding. Nevertheless, because the relative speed of the flux wave with respect to the rotor is *s* times its speed with respect to the stator, the relation between the effective values of stator and rotor emf's is

$$E_r = sE_s \tag{3.3}$$

The rotor mmf wave must counteract the mmf of the load component $\tilde{I}_1$ of the stator current, and therefore, since the stator and referred rotor windings have the same number in turns,

$$N_1 I_r = N_2 I_1 \quad \Rightarrow \quad I_r = I_1 \tag{3.4}$$

Division of equation (3.3) by (3.4) then gives

$$\frac{E_r}{I_r} = \frac{sE_s}{I_1} \tag{3.5}$$

Through substitution of equation (3.2) in the phasor equivalent of equation (3.5) we have

$$\frac{s\,\tilde{E}_s}{\tilde{I}_1} = \frac{\tilde{E}_r}{\tilde{I}_r} = R_r + jsX_r \tag{3.6}$$

Division by *s* then gives

$$\frac{\tilde{E}_s}{\tilde{I}_1} = \frac{R_r}{s} + jX_r \tag{3.7}$$

Previous equations show how the stator sees magnetic conditions in the air gap which result in induced stator voltage $\tilde{E}_s$ and stator load current $\tilde{I}_1$. Consequently, the effect of the rotor can be simplified into the equivalent circuit shown in Fig. 3.2.

We will model the induction machine with considering [17] and modifying the model regarding its function as generator based on grid connected induction generator. The customary load flow was adjusted with incorporating the nonlinear features of induction machine. In this study, the machine will be modeled in the steady state equation and Newton Raphson power flow algorithm will be utilized. The slip and reactive power of the machine would be recalculated during the load flow iterations. The reactive power in induction machine depends on characteristic of the terminal voltage [5, 18], and the slip is also influenced by the real power and the terminal voltage as well[5].

The induction machine is modeled by standard equivalent circuit of a three-phase squirrel cage induction machine as shown in Fig. 3.2. In this model, core magnetizing resistance is also included, and all machine parameters are referred to stator side.

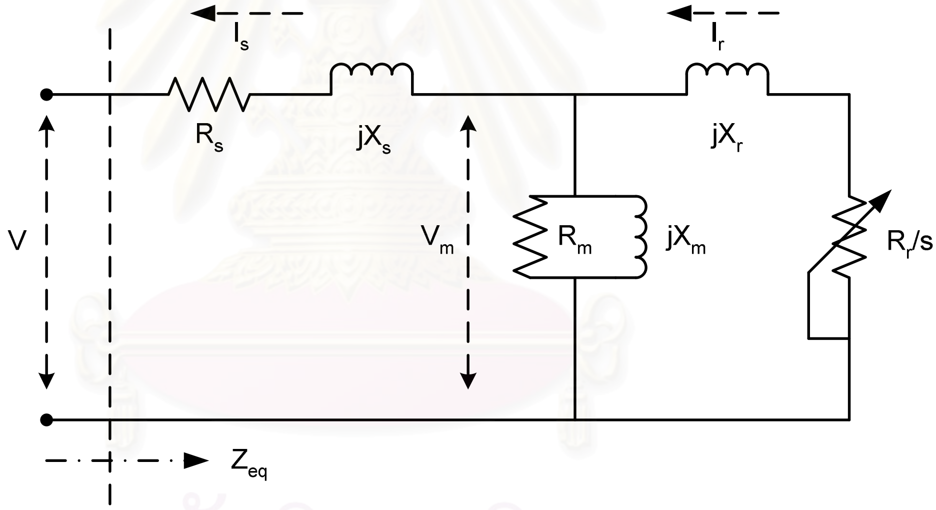

Figure 3.2 Standard equivalent circuit of a three-phase squirrel cage induction machine in steady state

where :

R_s	=	stator resistance
X_s	=	stator leakage reactance
R_m	=	magnetizing core resistance
X_m	=	magnetizing core reactance
R_r	=	rotor resistance
X_r	=	rotor leakage reactance
s	=	slip of the induction machine, having minus sign when operated as generator

The slip equation can be written as :

$$s = \frac{\omega_s - \omega_r}{\omega_s} \tag{3.8}$$

where ω_s = stator winding field synchronous speed and ω_r = rotor speed.

The slip will have positive sign when the machine acts as a motor and have negative sign when the machine acts as a generator. Based on Fig. 2 shown above, the output power generating by induction generator can be expressed by :

$$\mathrm{P_g} = -\left|\mathrm{I_s}\right|^2 \mathrm{R_s} - \left|\mathrm{I_r}\right|^2 \frac{\mathrm{R_r}}{\mathrm{s}} - \frac{\left|\mathrm{V_m}\right|^2}{\mathrm{R_m}} \tag{3.9}$$

where,

$$\left|I_s\right| = \frac{\left|V\right|}{\left|Z_{eq}\right|} \tag{3.10}$$

$$\left|V_m\right| = \left|-I_r\left[\frac{R_r}{s} + jX_r\right]\right| \tag{3.11}$$

$$I_r = I_s + \left[\frac{V_m}{R_p + jX_p}\right] \tag{3.12}$$

$$\left|I_r\right| = \frac{\left|V\right|}{\left|Z_{eq}\right|}\sqrt{\frac{R_p^{\,2} + X_p^{\,2}}{\left(R_p + \frac{R_r}{s}\right)^2 + \left(X_p + X_r\right)^2}} \tag{3.13}$$

The parallel components of magnetizing elements R_m and jX_m can be equivalently written in the series form of :

$$Z_p = R_p + jX_p \tag{3.14}$$

where :

$$R_p = \frac{X_m^{\,2} R_m}{R_m^{\,2} + X_m^{\,2}} \tag{3.15}$$

$$X_p = \frac{R_m^{\,2} X_m}{R_m^{\,2} + X_m^{\,2}} \tag{3.16}$$

All of the machine elements can also be written as :

$$Z_{eq} = R_{eq} + jX_{eq} \tag{3.17}$$

where :

$$R_{eq} = \frac{\left[\frac{R_r}{s}(R_s + R_p) + A\right]\left[\frac{R_r}{s} + R_p\right] + \left[(X_s + X_p)\frac{R_r}{s} + B\right]\left[X_r + X_p\right]}{\left(\frac{R_r}{s} + R_p\right)^2 + (X_r + X_p)^2} \tag{3.18}$$

$$X_{eq} = \frac{\left[(X_s + X_p)\frac{R_r}{s} + B\right]\left[\frac{R_r}{s} + R_p\right] - \left[\frac{R_r}{s}(R_s + R_p) + A\right]\left[X_r + X_p\right]}{\left(\frac{R_r}{s} + R_p\right)^2 + (X_r + X_p)^2} \tag{3.19}$$

$$\left|Z_{eq}\right|^2 = \frac{\left(\frac{R_r}{s}\right)^2\left[(R_p + R_s)^2 + (X_p + X_s)^2\right] + \frac{R_r}{s}\left[2A(R_p + R_s) + 2B(X_p + X_s)\right] + A^2 + B^2}{\left(\frac{R_r}{s} + R_p\right)^2 + (X_r + X_p)^2} \tag{3.20}$$

Noted that :

$$A = R_s R_p - X_s X_r - X_s X_p - X_p X_r \tag{3.21}$$

$$B = R_s X_r + R_s X_p + X_s R_p + R_p X_r \tag{3.22}$$

After substituting (3.10), (3.11), (3.13) into (3.9), the machine slip can be written as a quadratic equation below :

$$as^2 + bs + c = 0 \tag{3.23}$$

where :

$$a = P_g R_m (A^2 + B^2) + |V|^2 \left(R_s R_m \left[R_p{}^2 + (X_r + X_p)^2\right] + X_r{}^2\left[R_p{}^2 + X_p{}^2\right]\right) \tag{3.24}$$

$$b = P_g R_r R_m \left(2A\left[R_p + R_s\right] + 2B\left[X_p + X_s\right]\right) + |V|^2 \left(R_r R_m \left[R_p{}^2 + X_p{}^2\right] + 2R_s R_r R_p R_m\right) \tag{3.25}$$

$$c = P_g R_r{}^2 R_m \left[(R_p + R_s)^2 + (X_p + X_s)^2\right] + |V|^2 R_r{}^2 \left[R_s R_m + \left(R_p{}^2 + X_p{}^2\right)\right] \tag{3.26}$$

The smallest magnitude of the negative real slip obtained from (3.23) is chosen as a stable operation condition and used when calculating the reactive power needed by the induction generator. Then, the equation of reactive power needed by the machine is described by :

$$Q_g = -\frac{|V|^2 X_{eq}}{|Z_{eq}|^2} \tag{3.27}$$

The procedures for load flow calculation including induction generator in the network can be summarized as follows:

1. Read network data
2. Define the initial induction generator terminal voltage and all PQ buses
3. Build the Y bus
4. Set iteration k = 1
5. Solve the slip polynomial equation (3.23) and choose the value which is having the smallest magnitude of negative slip
6. Define the reactive power needed by the induction generator with respect to (3.27)
7. Calculate the network's load flow with considering the generated real power from induction generator and needed reactive power of the induction generator
8. Repeat step number 5 to 7, until the induction generator terminal voltage and slip of the machine convergent.

3.2 Dynamic Model of Induction Generator in DQ Reference Frame

The idealized three phase Induction Machine is assumed in this research. It possess symmetrical air gap, and identically displaced 120 degree both in stator-rotor windings. The machine inductances are functions of the rotor speed, which the voltage expressions in differential equations are time varying except when the rotor is blocked. Then, the DQ transformation is used to convert the variables, in order to lessen the complexity of these differential equations. In the stationary or synchronously rotating reference frame, the DQ variables of the machine are in the same frame as those usually used for the supply network. It is a favorable reference frame choice, when the supply network is large or complex.

In analyzing power system, especially dynamic stability, it is commonly to neglect the stator and grid transients, therefore, a third order model of Induction Machine is enough to be utilized. This third order model can be obtained by omitting the stator flux transients. The derivatives of the stator flux linkages are set to be zero, and the stator flux linkages are then solved as functions of the rotor flux linkages and the rotor speed. The equivalent circuit representation of an induction machine in the DQ arbitrary reference frame can be shown in the following figure.

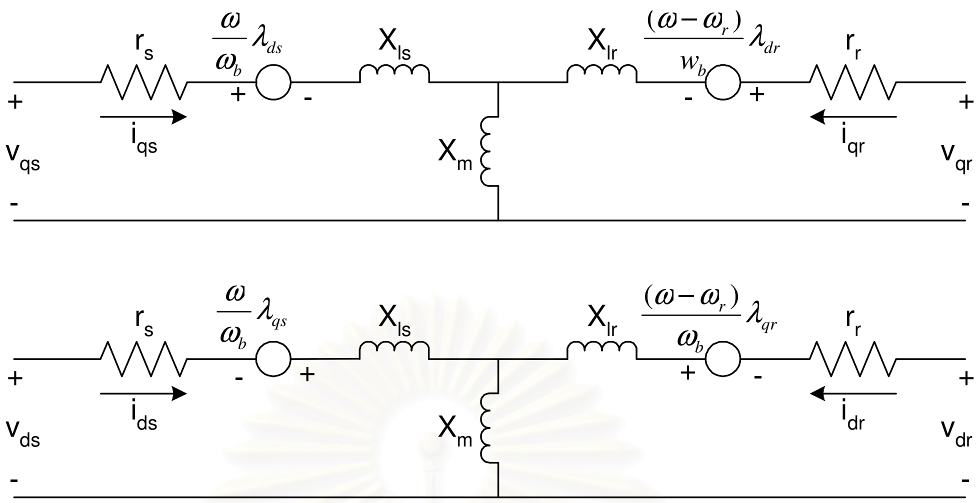

Figure 3.3 Equivalent circuit representation of an induction machine in DQ reference frame

Researches conducted by [19, 20] revealed that the third order model works well in representing the dynamic operation. Several benefits of utilizing this models can be summarized as follows:

1. This model is the best compromise between accuracy and simplicity for dynamic stability studies.
2. This third order model is consistent with the AC network model where electromagnetic transients of the power lines are neglected as well as the fact that stator transient has much faster time constant compared to the rotor acceleration/deceleration.
3. In the event of voltage disturbance caused by any possible reason, [19] stated that the third order model is superior than the first and second order models to forecast Induction Machine reactive power and stator current.
4. The basic third-order model can well predict all the responses to torque and frequency perturbations up to at least 10 Hz [19].

The voltage equations of a three-phase symmetrical induction generator in terms of equivalent DQ-base system neglecting the stator flux transients and all electrical variables and parameters are viewed from the stator side, with respect to the arbitrary rotating reference frame *w*, can be written as follows [21]:

$$V_{ds} = -\frac{w}{w_b}\psi_{qs} + r_s i_{ds} \tag{3.28}$$

$$V_{qs} = \frac{w}{w_b}\psi_{ds} + r_s i_{qs} \tag{3.29}$$

$$V_{dr} = 0 = \frac{p}{w_b}\psi_{dr} - \frac{(w - w_r)}{w_b}\psi_{qr} + r_r i_{dr} \tag{3.30}$$

$$V_{qr} = 0 = \frac{p}{w_b}\psi_{qr} + \frac{(w - w_r)}{w_b}\psi_{dr} + r_r i_{qr} \tag{3.31}$$

where V_{ds}, V_{qs}, V_{dr}, V_{qr} are the stator and rotor voltages in the DQ axes, respectively, r_s, r_r are the stator and rotor resistance, and i_s, i_r are the stator and rotor current. Rotor voltages are equal to zero because in induction machine, the rotor windings are short circuited.

The stator and rotor flux linkages relation in voltage equations above can be expressed together by using the following equation :

$$\begin{bmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} = \begin{bmatrix} X_{ls} + X_m & 0 & X_m & 0 \\ 0 & X_{ls} + X_m & 0 & X_m \\ X_m & 0 & X_{lr} + X_m & 0 \\ 0 & X_m & 0 & X_{lr} + X_m \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{3.32}$$

where X_{ls}, X_{lr}, X_m, are the stator reactance, the rotor reactance, and the magnetizing reactance, respectively.

If flux linkages are chosen as independent variables, then above compact equation may be solved for currents, and written as :

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} = \frac{1}{(X_{ls} + X_m)(X_{lr} + X_m) - X_m^{\ 2}} \begin{bmatrix} X_{lr} + X_m & 0 & -X_m & 0 \\ 0 & X_{lr} + X_m & 0 & -X_m \\ -X_m & 0 & X_{ls} + X_m & 0 \\ 0 & -X_m & 0 & X_{ls} + X_m \end{bmatrix} \begin{bmatrix} \psi_{ds} \\ \psi_{qs} \\ \psi_{dr} \\ \psi_{qr} \end{bmatrix} \tag{3.33}$$

The electromagnetic torque is defined as:

$$T_e = (\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \tag{3.34}$$

where T_e is negative for generator action.

The active power is given by:

$$P_{machine} = V_{ds} i_{ds} + V_{qs} i_{qs} \tag{3.35}$$

The reactive power is defined as:

$$Q_{machine} = V_{qs} i_{ds} - V_{ds} i_{qs} \tag{3.36}$$

The mechanical system of the induction machine is given by :

$$T_e - T_{mech} = 2H \frac{d}{dt}\left(\frac{w_r}{w_b}\right) \tag{3.37}$$

All variables in all equations above are in per unit, except w, w_r, and w_b are in radian/second, which are arbitrary reference frame speed, rotor speed, and synchronous speed base respectively. Also H is an inertia constant in second, which is defined as the ratio of the kinetic energy of the rotating mass at base speed to the rated power. In per unit, P_e is equal to T_e, also in steady state condition T_e is equal to the applied shaft torque T_{mech}. When we have real power at the output machine as a set point, then

$$\begin{aligned} T_{mech} &= \begin{bmatrix} -\psi_{qs} & \psi_{ds} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \\ &= \begin{bmatrix} -\psi_{qs} & \psi_{ds} \end{bmatrix} \begin{bmatrix} V_{ds} & V_{qs} \\ 1 & j \end{bmatrix}^{-1} \begin{bmatrix} P_{outmachine} \\ i_{ds} + ji_{qs} \end{bmatrix} \end{aligned} \tag{3.38}$$

CHAPTER IV

VOLTAGE STABILITY

With the economics reason and the tight competition in power deregulation at present, to obtain maximum profits, the power systems are operated near their maximum load ability limits. This situation brings the system close to the voltage instability point. Voltage instability puts in jeopardy the power system reliability and power system security. In the simple words, operating power system close to its maximum capability causes high possibility of voltage instability to occur.

Voltage stability is the ability of the system to keep the voltages of all buses in the network within acceptable limit under normal condition or after being experienced with a disturbance [22]. There are two ways to evaluate voltage stability, which are static voltage stability analysis and dynamic voltage stability analysis [22]. Both are described separately in the following section.

4.1 Static Voltage Stability Analysis

Static analysis involves only the algebraic equations and therefore static analysis technique can be used. It is computationally less comprehensive than dynamic analysis, thus in this analysis we will mainly use the steady state model or linearized dynamic model around the steady state operation. In the past, the static analysis used conventional power-flow technique to generate the P-V or Q-V curve at particular buses. This technique requires extra computational time, and doesn't easily provide datum of the main cause of the instability. At some point this technique may not give the Q-V curve completely due to the power flow divergence which is caused by particular problems in the another part of the system. Therefore, special techniques such as V-Q sensitivity and the modal analysis are recently used. They have been extensively studied over the past two decades.

The maximum real power of load that can be held by the power system before network collapse is called a nose-point or static voltage stability. At this point the voltage is extremely decreased and impossible to go back to the acceptable range. This event can be seen from the P-V curve, the relation between voltages magnitude and power transferred by the network.

The advantages of static analysis can be mentioned as follows :

1. It provides the information about stability margin using static voltage stability indices,
2. It can be used in on-line implementation.

In the contrary, this analysis has some drawbacks, which are :

1. It has less accuracy (because not considering the dynamic aspects of the problem),
2. The results are too optimistic compared to dynamic analysis [23, 24].
3. This analysis can not represent the events behind the voltage instability phenomena.

4.2 Dynamic Voltage Stability Analysis

At present, voltage stability is considered as a dynamic phenomena [25], and on that account, voltage stability analysis needs dynamic techniques in modeling the power system. With proper modeling, by dynamic voltage stability simulation, one can :

1. give the accurate figure and illustrate the event of the actual dynamics of voltage instability process following a disturbance, so
2. can explain the mechanism of voltage instability in the system and also
3. can provide corrective suggestions to improve voltage stability as one will have more opportunity to examine voltage instability mechanisms deeply and thoroughly.

The dynamic analysis of voltage stability may be studied using :

1. eigenvalues analysis,
2. energy function methods,
3. time domain simulation methods.

In many researches, the dynamic analysis is usually based on time domain simulation to produce time responses of related events. It models power system components by appropriate nonlinear ordinary differential and algebraic equations, The time frame of simulation ranges from the order of a few seconds to several minutes.

As the increasing dispersion of Induction Generator in distributed generation power network, this kind of machine might have chances to affect power system performance and operation. This becomes a reason how important to investigate the Induction Generator especially in the dynamic voltage stability.

4.3 Static Voltage Stability Indices

When operating the electrical power network, it is crucial to know the distance of the present operating point to the voltage stability limit. This distance can be evaluated with voltage stability indices. These indices depict the system strength to meet load demand and to face the sudden disturbance from a part or more of the system. It is also important to note that these indices should be easy to comprehend by the network operators and should have systematic calculation [25]. The results from the voltage stability analysis should give a system operator abilities to [26] :

1. diagnose how close the present system operating point from its instability point.
2. recognize which parts of the network that has the greatest contribution to the voltage instability
3. identify the severity of loading location; which bus is operated closest to its stability limit. Sometimes, this bus is called the weakest bus.

Many researchers had studied the assessment tools for calculating Voltage Stability Indices. Several indices of voltage security to examine the system's strength are described separately in the following sections.

4.3.1 P-V and Q-V curve

In P-V curve method, real power demand at either a particular bus or a group of buses will be successively increased until system's voltage collapses; we will refer this operating condition as a nose-point [25]. The margin between present operating condition and the curve's nose point can be used to assess the system security level. This margin is then used as voltage stability indices. For Q-V curve method, the curve is obtained by successively increasing the reactive power injected in either a certain bus or a group of buses. Then examine the system's voltage. Using the Q-V curve, network operators can determine how much the reactive power must be injected to the weak bus before the system's voltage bus end up to the allowable minimum level. The voltage stability limit is reached when the curve point has dQ/dV = 0. Distance between current operating condition and the point having dQ/dV = 0, which is in the bottom of the curve, is defined as a reactive power margin.

4.3.2 Modal Analysis

This approach provides the degree of the voltage stability, which indicates the sensitivity factor of the network condition [27]. It does not use conventional power flow program to obtain voltage's critical nose point, which does not exactly provide indication of how much stable the corresponding system and requiring tedious computing time especially when evaluating large complex system. The conventional power flow represents the system's steady state, but sometimes this approach is not enough to illustrate the critical condition because there is a necessity to incorporate the more detail steady state model in the critical condition simulation.

Modal analysis can predict voltage instability in a large power system, precisely quantifying stability margin, recognizing voltage-weak area in the system which is vulnerable to voltage collapse, and being able to answer the responsible key factors in voltage instability. Thus, it helps the network operator in determining the preventive action in the daily basis operation planning. In this method, the smallest eigenvalue and eigenvector is calculated from the reduced Jacobian matrix of the power network. This eigenvalues are relating to system voltage and reactive power characteristics. The possibility of voltage collapse situation can be estimated using the evaluation of the smallest positive eigenvalue, where it gives the indication on how close the system to the voltage instability condition. Then, bus participation factor will be calculated and then used to determine the weakest bus of the system. The weakest bus in this sense means that this bus has large impact on the power system to end up with the voltage collapse. However, this method is not used in this research.

4.3.3 Fast Voltage Stability Index (FVSI)

This method uses voltage and reactive flow datum from power flow studies. The line which possesses value of FVSI close to 1.00, indicates that this line is close to its instability point [26]. When FVSI is larger than 1.00, one of the bus connected to the line is having large voltage drop, that can lead to voltage collapse. Below is the derivation of the index.

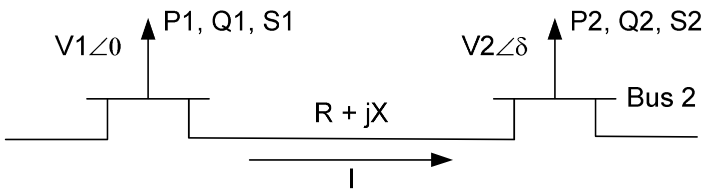

Figure 4.1 Two-bus power system

Fig. 4.1 is a Two-bus power system model, where the idea of the index is originating. The current *I* flowing in the line with impedance Z=*R*+*jX* is given by:

$$I = \frac{V_1\angle 0 - V_2\angle\delta}{R + jX} \tag{4.1}$$

The apparent power at bus 2 is :

$$S_2 = V_2 I^* \tag{4.2}$$

Rearranging above equation results in :

$$\begin{aligned} I &= \left(\frac{S_2}{V_2}\right)^* \\ &= \frac{P_2 - jQ_2}{V_2\angle -\delta} \end{aligned} \tag{4.3}$$

Combine (4.1) and (4.3); then, we will have :

$$\begin{aligned} &\frac{V_1\angle 0 - V_2\angle\delta}{R + jX} = \frac{P_2 - jQ_2}{V_2\angle -\delta} \\ &V_1V_2\angle -\delta - V_2^{\,2}\angle 0 = RP_2 + XQ_2 - j\left(RQ_2 - XP_2\right) \end{aligned} \tag{4.4}$$

Segregating the real part yields :

$$V_1V_2\cos\delta - V_2^{\,2} = RP_2 + XQ_2 \tag{4.5}$$

; and the imaginary part is :

$$-V_1V_2\sin\delta = -RQ_2 + XP_2 \tag{4.6}$$

Rearrange (4.6) for P_2 and substitute into (4.5), then make it into polynomial equation of V_2 :

$$V_2^{\,2} - \left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1V_2 + \left(X + \frac{R^2}{X}\right)Q_2 = 0 \tag{4.7}$$

The roots for V_2 are then :

$$V_2 = \frac{\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1 \pm \sqrt{\left[\left(\frac{R}{X}\sin\delta + \cos\delta\right)V_1\right]^2 - 4\left(X + \frac{R^2}{X}\right)Q_2}}{2} \tag{4.8}$$

To provide real roots of V_2, the discriminator will be set to be greater than or equal to '0', which is :

$$\left[\left(\frac{R}{X}\sin\delta+\cos\delta\right)V_1\right]^2-4\left(X+\frac{R^2}{X}\right)Q_2\geq 0$$

$$\frac{4Z^2Q_2X}{(R\sin\delta+X\cos\delta)^2V_1^{\,2}}\leq 1 \tag{4.9}$$

Because δ is normally very small, then $\mathrm{R}\sin\delta\approx 0$, and $\mathrm{X}\cos\delta\approx \mathrm{X}$.

Therefore, the proposed voltage stability index is as follows :

$$FVSI_{ij}=\frac{4Z^2Q_j}{V_i^2X} \tag{4.10}$$

where :

Z = line impedance
X = line reactance
Q_j = reactive power flow into receiving end
V_i = sending end voltage

It should be noted that to maintain the stability, the value of FVSI should be kept less than 1.00.

4.3.4 Voltage Collapse Proximity Indicator (VCPI)

This method studies the index of each line in the network using maximum power transfer concept [28]. The upcoming equations are the proposed Voltage Collapse Proximity Indicator :

$$VCPI(1)=\frac{P_r}{P_{r(\max)}} \tag{4.11}$$

$$VCPI(2)=\frac{Q_r}{Q_{r(\max)}} \tag{4.12}$$

where P_r and Q_r are real and reactive power transferred to the receiving end bus of a particular transmission line, which is acquired from power flow calculations, and $P_{r(max)}$ and $Q_{r(max)}$ are the maximum real and reactive power that can be transferred along the line. From the experimental results, it was shown that VCPI(1) and VCPI(2) were approximately equal in any state of loading. Alternatively, it is enough for using one indicator only from both indicators. The VCPI indices range from 0 on no load condition to 1 on the voltage collapse condition.

4.3.5 PQ Voltage Stability Index (PQVSI)

This index is extracted from Two-bus power system transmission line model as well. The PQVSI is defined from the receiving end apparent power at present condition divided by its apparent power at nose point of the PV curve. Let we consider the Two-bus power system transmission line model as follows :

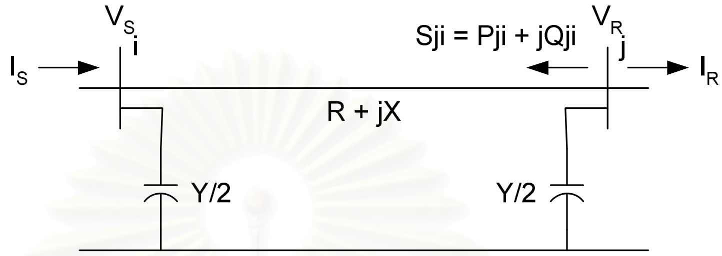

Figure 4.2 2-bus power system transmission line model

From the transmission line model in 2-port network form:

$$V_S = AV_R + BI_R$$
$$V_S - AV_R = BI_R \tag{4.13}$$

where

$$A = 1 + \frac{YZ}{2} \tag{4.14}$$

$$B = Z = R + jX \tag{4.15}$$

and

$$I_R = (-\frac{S_{ji}}{V_R})^* \tag{4.16}$$

Then

$$V_S - AV_R = -B\frac{S_{ji}^*}{V_R^*} \tag{4.17}$$

$$V_S V_R^* - A|V_R|^2 = -BS_{ji}^* = -B(P_{ji} - jQ_{ji}) \tag{4.18}$$

$$V_S V_R^* = A|V_R|^2 - B(P_{ji} - Q_{ji}) \tag{4.19}$$

$$
\begin{aligned}
B^{*}V_{S}V_{R}^{*} &= AB^{*}\left|V_{R}\right|^{2}-\left|B\right|^{2}(P_{ji}-jQ_{ji}) \\
&= \left|V_{R}\right|^{2}\left(\mathrm{Real}\{AB^{*}\}+j\mathrm{Imag}\{AB^{*}\}\right)-\left|B\right|^{2}(P_{ji}-jQ_{ji}) \\
&= \left(\left|V_{R}\right|^{2}\mathrm{Real}\{AB^{*}\}-\left|B\right|^{2}P_{ji}\right)+j(\left|V_{R}\right|^{2}\mathrm{Imag}\{AB^{*}\}+\left|B\right|^{2}Q_{ji})
\end{aligned}
\tag{4.20}
$$

Square of the magnitude of above equation :

$$
\left|B\right|^{2}\left|V_{S}\right|^{2}\left|V_{R}\right|^{2}=\left(\left|V_{R}\right|^{2}\mathrm{Real}\{AB^{*}\}-\left|B\right|^{2}P_{ji}\right)^{2}+(\left|V_{R}\right|^{2}\mathrm{Imag}\{AB^{*}\}+\left|B\right|^{2}Q_{ji})^{2} \tag{4.21}
$$

$$
\begin{aligned}
&\left|V_{R}\right|^{4}\left(\mathrm{Real}\{AB^{*}\}^{2}+\mathrm{Imag}\{AB^{*}\}^{2}\right)+ \\
&\left|V_{R}\right|^{2}\left(2\mathrm{Imag}\{AB^{*}\}\left|B\right|^{2}Q_{ji}-2\mathrm{Real}\{AB^{*}\}\left|B\right|^{2}P_{ji}-\left|B\right|^{2}\left|V_{S}\right|^{2}\right)+ \\
&\left(\left|B\right|^{4}P_{ji}^{2}+\left|B\right|^{4}Q_{ji}^{2}\right)=0
\end{aligned}
\tag{4.22}
$$

At PV curve's nose point, the discriminator of above quadratic equation must be 0 :

$$
\begin{aligned}
&\left(2\mathrm{Imag}\{AB^{*}\}\left|B\right|^{2}Q_{ji}-2\mathrm{Real}\{AB^{*}\}\left|B\right|^{2}P_{ji}-\left|B\right|^{2}\left|V_{S}\right|^{2}\right)^{2}- \\
&4\left(\mathrm{Real}\{AB^{*}\}^{2}+\mathrm{Imag}\{AB^{*}\}^{2}\right)\left(\left|B\right|^{4}P_{ji}^{2}+\left|B\right|^{4}Q_{ji}^{2}\right)=0
\end{aligned}
\tag{4.23}
$$

$$
\begin{aligned}
&\left(2\mathrm{Imag}\{AB^{*}\}\left|B\right|^{2}Q_{ji}-2\mathrm{Real}\{AB^{*}\}\left|B\right|^{2}P_{ji}-\left|B\right|^{2}\left|V_{S}\right|^{2}\right)^{2}= \\
&4\left(\mathrm{Real}\{AB^{*}\}^{2}+\mathrm{Imag}\{AB^{*}\}^{2}\right)\left(\left|B\right|^{4}P_{ji}^{2}+\left|B\right|^{4}Q_{ji}^{2}\right)
\end{aligned}
\tag{4.24}
$$

$$
\begin{aligned}
&\left(2\mathrm{Imag}\{AB^{*}\}Q_{ji}-2\mathrm{Real}\{AB^{*}\}P_{ji}-\left|V_{S}\right|^{2}\right)^{2}= \\
&4\left(\left|AB^{*}\right|^{2}\right)\left(P_{ji}^{2}+Q_{ji}^{2}\right)
\end{aligned}
\tag{4.25}
$$

$$
\begin{aligned}
&\left(2\mathrm{Imag}\{AB^{*}\}Q_{ji}-2\mathrm{Real}\{AB^{*}\}P_{ji}-\left|V_{S}\right|^{2}\right)^{2}= \\
&4\left(\left|A\right|^{2}\left|B\right|^{2}\right)\left(P_{ji}^{2}+Q_{ji}^{2}\right)
\end{aligned}
\tag{4.26}
$$

Let assume increasing of power flow in transmission line with constant power factor; thus

$$
\tan\theta=\frac{Q_{ji}^{0}}{P_{ji}^{0}}=\frac{Q_{ji}^{NP}}{P_{ji}^{NP}} \tag{4.27}
$$

$$\left(2\text{Imag}\{AB^*\}Q_{ji}^{NP} - 2\text{Real}\{AB^*\}P_{ji}^{NP} - |V_S|^2\right)^2 = 4\left(|A|^2|B|^2\right)\left(P_{ji}^{NP\,2} + Q_{ji}^{NP\,2}\right) \tag{4.28}$$

$$\left(2\text{Imag}\{AB^*\}P_{ji}^{NP}\tan\theta - 2\text{Real}\{AB^*\}P_{ji}^{NP} - |V_S|^2\right)^2 = 4\left(|A|^2|B|^2\right)P_{ji}^{NP\,2}\sec^2\theta \tag{4.29}$$

$$\left(2\text{Imag}\{AB^*\}\tan\theta - 2\text{Real}\{AB^*\}\right)P_{ji}^{NP} - |V_S|^2 = \pm 2|A||B|P_{ji}^{NP}\sec\theta \tag{4.30}$$

$$P_{ji}^{NP} = \frac{|V_S|^2}{2\text{Imag}\{AB^*\}\tan\theta - 2\text{Real}\{AB^*\} \pm 2|A||B|\sec\theta} \tag{4.31}$$

Because we concern the power flow at receiving end bus only, thus $P_{ji}<0$, then

$$P_{ji}^{NP} = \frac{|V_S|^2}{2\text{Imag}\{AB^*\}\tan\theta - 2\text{Real}\{AB^*\} - 2|A||B|\sec\theta} \tag{4.32}$$

The index PQVSI will be

$$PQVSI = \sqrt{\frac{P_{ji}^{0\,2} + Q_{ji}^{0\,2}}{P_{ji}^{NP\,2} + Q_{ji}^{NP\,2}}} = \frac{P_{ji}^{0}}{P_{ji}^{NP}}\sqrt{\frac{1+\tan^2\theta}{1+\tan^2\theta}} = \frac{P_{ji}^{0}}{P_{ji}^{NP}} \tag{4.33}$$

To ascertain voltage stability of the considered system, the PQVSI value must be kept below 1.00. When the PQVSI value reaches 1.00, any subsequent load increase in the system will make one line or more overload, and cause voltage instability in the entire system. ***In this research, we will focus on this index.***

CHAPTER V

NETWORK AND LOAD REPRESENTATION IN DYNAMIC ANALYSIS

5.1 Network Representation

Typically, the power network is represented by steady state network performance equations, which neglect fast electromagnetic transients in the network [29]. The AC network model can be illustrated either in power-balance form or current-balance form. The latter form will be used in this research because it is more widely used in industry software environment, which is principally the nodal set of equations shown as follows.

$$I_{bus} = Y_{bus} V_{bus} \tag{5.1}$$

or

$$\begin{bmatrix} I_1 \\ \vdots \\ I_i \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & \cdots & Y_{1i} & \cdots & Y_{1n} \\ \vdots & & & & \vdots \\ Y_{i1} & \cdots & Y_{ii} & \cdots & Y_{in} \\ \vdots & & & & \vdots \\ Y_{n1} & \cdots & Y_{ni} & \cdots & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_i \\ \vdots \\ V_n \end{bmatrix} \tag{5.2}$$

In this manner, during execution of dynamic simulations, the network solution at any time, t, is found by computation of the load-flow network solution at any time-step. When explained in simplified terms, it is achieved using the algorithm producing the vector of the currents going into the network at the power system nodes, using the node admittance matrix, multiplied by the vector of the node voltages. With consideration of the previous equation (5.2), Y_{bus} is n×n bus admittance matrix, consists of n network buses with ground as the reference, I_{bus} is the net injected current vector and V_{bus} is bus voltage vector. By this way, the fundamental-frequency transients in the network solution are omitted.

From the network equation above, they have to be gyrated between inputs and outputs, since there are different dynamic models of machine regarding with their kind of inputs and outputs. For example, some dynamic model of machines can be modeled to have voltage as an input and current as an output to network, while load buses are modeled to have the current as the input to the network. If we want to gyrate the i^{th} bus because in this bus will have current as an input and voltage as an output, then Y_{bus} in equation above should be modified as hybrid matrix. In that case, input for each bus can be either voltage or current, related with the connected machine properties, like shown subsequently [29].

$$\begin{bmatrix} I_1 \\ \vdots \\ V_i \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} - \dfrac{Y_{1i}Y_{i1}}{Y_{ii}} & \cdots & \dfrac{Y_{1i}}{Y_{ii}} & \cdots & Y_{1n} - \dfrac{Y_{1i}Y_{in}}{Y_{ii}} \\ \vdots & & & & \vdots \\ -\dfrac{Y_{i1}}{Y_{ii}} & \cdots & \dfrac{Y_{i1}}{Y_{ii}} & \cdots & -\dfrac{Y_{in}}{Y_{ii}} \\ \vdots & & & & \vdots \\ Y_{n1} - \dfrac{Y_{ni}Y_{i1}}{Y_{ii}} & \cdots & \dfrac{Y_{ni}}{Y_{ii}} & \cdots & Y_{nn} - \dfrac{Y_{ni}Y_{in}}{Y_{ii}} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ I_i \\ \vdots \\ V_n \end{bmatrix} \tag{5.3}$$

5.2 Load Representation For Dynamic Analysis

Many studies have emphasized that load representation can have a significant influence on analysis results. This section is dedicated to summarize basic dynamic load modeling concepts in dynamic performance analysis. The accurate modeling of loads remains a difficult task due to several aspects, including :

- Large number of diverse load components.
- Ownership and location of load devices in customer facilities not directly accessible to the electric utility.
- Changing load composition with time of day and week, seasons, weather, and through time.
- Lack of precise information on the composition of the load.
- Uncertainties regarding the characteristics of many load components, particularly for large voltage or frequency variations.

Load is a portion of the system that is not explicitly expressed in a system model, but rather is handled as if it were a single power-consuming device connected to a bus in the system model. Load in this context includes, not only the connected load devices, but some or all of the following [30]:

- Substation step-down transformers
- Subtransmission feeders
- Primary distribution feeders
- Distribution transformers
- Secondary distribution feeders
- Shunt capacitor
- Voltage regulators
- Customer wiring, transformers, and capacitors

Load characteristics can diversify considerably with time of day, day of week, season, and weather. It may be wise and careful in some studies to assume the worst-case load model for the problem under study.

Power system load model can be considered as a set of mathematical equations that describe the correlation between the real and reactive power at a given bus in the system, also the voltage and/or frequency at the same bus. There are two kinds of load models in representing above relationship [22]:

1. Static load model; this model describes the load relationship at any instant of time using algebraic equations with the bus voltage and/or frequency at that instant.

2. Dynamic load model; this model uses differential equations to describe the relationship among system parameters that change through time. A generic dynamic model of the aggregate load is sufficient to provide insights into the various phenomena of the voltage stability problem.

5.3 Constant MVA load model

The constant MVA-type load representation is the most conservative model from the system stability point of view because of its effect in amplifying voltage oscillations: a drop in voltage will cause an increase in load current resulting in a further voltage drop. Thus we can say that in the majority of cases constant MVA loads lower the stability limit. Conversely, constant impedance loads have a decided damping effect on voltage oscillations. For true voltage instability, at least a part of the total load must be of self-restoring (constant MVA) type. Constant MVA load may also be called constant power load model. The newer electronic ballasts, high efficiency lamps, light-controlled dimming fixtures, and electronic devices, are closer to a constant MVA load.

It also has been recognized that the most constricted load from the viewpoint of voltage stability is the load that maintains a constant MVA characteristic, either due to the nature of the load itself or due to the action of control mechanisms that are intended to maintain constant voltage at the load supply point, such as LTC's, distribution voltage regulators, and etc., thereby rendering any load constant MVA. It should be noted that even without voltage control action, certain apparently static loads, such as thermostatically controlled heating loads tend to behave as constant MVA loads in the longer term because of their constant energy consumptions, We will, therefore, concentrate primarily on constant MVA loads.

In a dynamic voltage stability analysis, it is important to model the relevant dynamics of the load. Employing only a static model for constant MVA loads can lead to erroneous and, often, misleading results. A constant MVA load model considered here must not be only a static load because, practically, it cannot jump immediately from one demand level to another as the demand changes. The dynamic behavior of constant MVA load used in this research is represented by a simple first order delay model.

The dynamic constant MVA load model used in this research is shown in Fig. 5.1. For any sudden voltage change, load's $G(t)+jB(t)$ parameters are maintained at its pre-disturbance value modeled by the integrator which opposes change of the output instantaneously. The dynamics characteristic is then modeled by the relation $G(t)V(t)^2$. The mismatch between the model output and the steady-state load demand is the error signal. This signal is fed back to the integration block that gradually changes the state variable $G(t)$ and $B(t)$. This process continues until a new steady-state (error = 0) is reached. Analytical expressions of the constant power load model including real (P) and reactive (Q) power dynamics are [31]:

$$T_L \frac{d}{dt} G(t) = P_0 - V_L(t)^2 G(t) \tag{5.4}$$

$$T_L \frac{d}{dt} B(t) = Q_0 - V_L(t)^2 B(t) \tag{5.5}$$

where V_L, P_0, G, Q_0, B, T_L are load voltage, real power set point, load conductance which is adjusted to maintain constant power, reactive power set point, load susceptance which is adjusted to maintain constant power, and load time constant respectively. It is noted here that the specific time delay varies due to the dynamic response of a particular load.

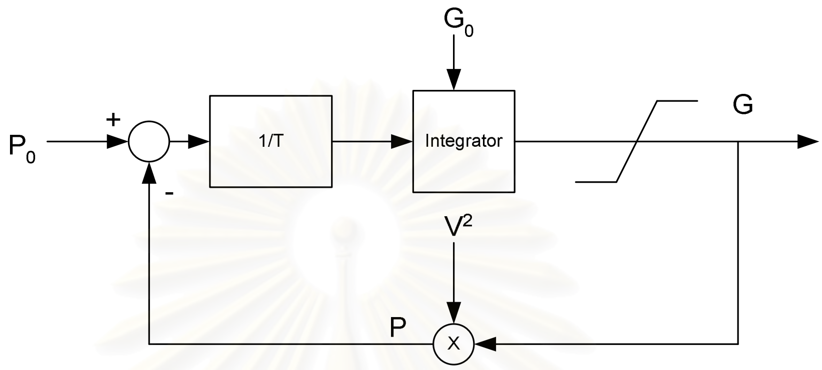

Figure 5.1 Constant energy load block diagram

CHAPTER VI

NUMERICAL EXAMPLE AND DISCUSSION

Several case studies were conducted to investigate the impact of induction generator operation in the power system network. Firstly, the static analyses are conducted. Then in the latter part, the dynamic analyses are performed to examine the dynamic characteristics of the system having the induction generator. In the static analysis, we used PEA 35-bus system as a test system. We chose to locate the induction generator at the most loaded bus, which was bus 12, because that bus was connected with total load of 6.767 MW, 4.189 MVAR. It was also assumed that there is a bilateral contract or a power purchase agreement between bus 12 and bus 27. Thus, we have to increase the load at bus 27 for this purpose. That was why we would specifically investigate the voltage stability at bus no 12 and bus no 27. In getting the PV curve, the load at bus 27 and the induction generator capacity at bus 12 were increased at the same time, where unity power factor was assumed. The identical generators would be connected in parallel at the same bus to obtain larger generating capacity of induction generator, in the multiple of 1 MW. Then, simulation results would be examined. The PQVSI index was calculated for each line in the system as the load increased. Then, it is used to measure degree of voltage instability of the system. Subsequently, to compare with the case having synchronous generators, the induction generator position would be replaced with synchronous generator. In addition, impact of the induction generator equipped with capacitor bank was also investigated. The network would be remodeled to include a capacitor bank at the same bus with the induction generator. Capacitor bank having size of 1/3 of induction generator capacity as used in the Rejsby Hede windfarm, Denmark [32] was installed. Thereafter, impact of lagging and leading load power factor were investigated in this research. For the last case of static analysis, the consequence of induction generator location considering voltage stability was inspected. Three possible locations are examined: near from the main grid, at the middle of the network, and at the end point of the network.

The high cost of simulating large power systems in real time forced most of the voltage stability studies to be limited to the static techniques. However, this comes on the expense of the inability to capture the accurate voltage dynamic behavior in the system. In dynamic analysis, we will demonstrate the dynamic model of induction generator to estimate the voltage dynamic behavior of induction machines after a load change in the system. For this purpose, two systems are studied. First, the 6-bus system, a small system used in [33], is analyzed here and then the results are compared. Next, the PEA 35-bus system, exactly the same system as that in static analysis, is then analyzed. However, we decided to locate the induction generator at the most loaded bus, which was bus 12. Accordingly, we increased the load at bus 27 and then examined the dynamic characteristics of the system. The studies are divided into 6 cases, which comprise (i) increasing generator output in stable operating condition, (ii) increasing generator output in unstable operating condition, (iii) increasing load at unity power factor, (iv) increasing load at 0.9 lagging power factor, (v) increasing load at 0.7 lagging power factor, and (vi) installing capacitor at the induction generator terminal and increasing load at 0.7 lagging power factor.

6.1 Static Analysis

Test system used in this section is the Tahsai system, a PEA distribution system consisting of 35 buses, 34 lines, 18 load points, and a 1 single infeed modeled as a synchronous generator at bus 1. Total demand is 8.879 MW and 5.496 MVAR, are connected at bus 6, 8, 9, 10, 11, 14, 15, 16, 17, 18, 20, 22, 24, 26, 28, 30, 32, and 34, respectively. The network is shown in Fig. 6.1.

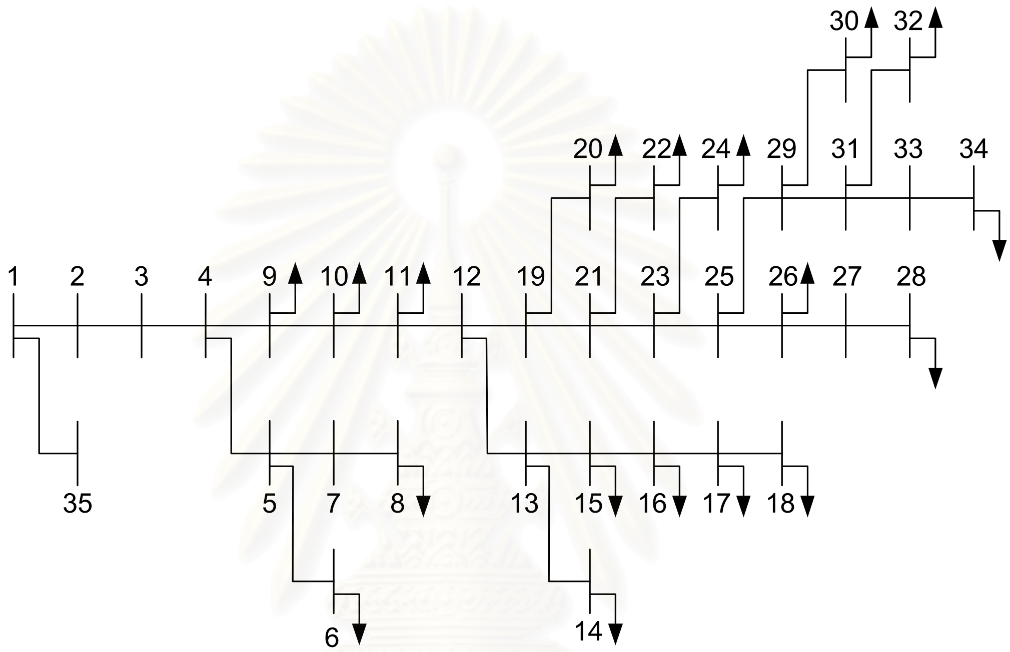

Figure 6.1 Single line diagram of the 35 bus studied system

6.1.1 The case with induction generator

In order to show the impact of induction generator on the voltage stability, the PV curve was obtained as shown in Fig. 6.2. The simulations were terminated at induction generator capacity reaching 10 MW and the voltage magnitude at bus 12, induction generators installed bus, equals 0.91629 p.u. Any succeeding increment would result in an unstable operation of induction generator. However, at this condition, the network system was not collapsed yet.

In all load steps, the line connecting between bus 11 and 12 was having the maximum value of PQVSI as shown in Fig. 6.3. At 10 MW load condition, the PQVSI index was 0.20362, and the voltage magnitude at bus 27, the bus receiving power from the induction generators, equals 0.89351 p.u., which was the second lowest of voltage magnitude. It means that as the load increases the voltage stability level is more degraded. This condition could happen as the reactive power needed by the induction generator flows through this line, so the line was quite loaded with reactive power flow as the induction generator capacity increases. Any further power flow increased in this line will cause this line having PQVSI index proceed towards 1.00, resulting in the instability in the entire system.

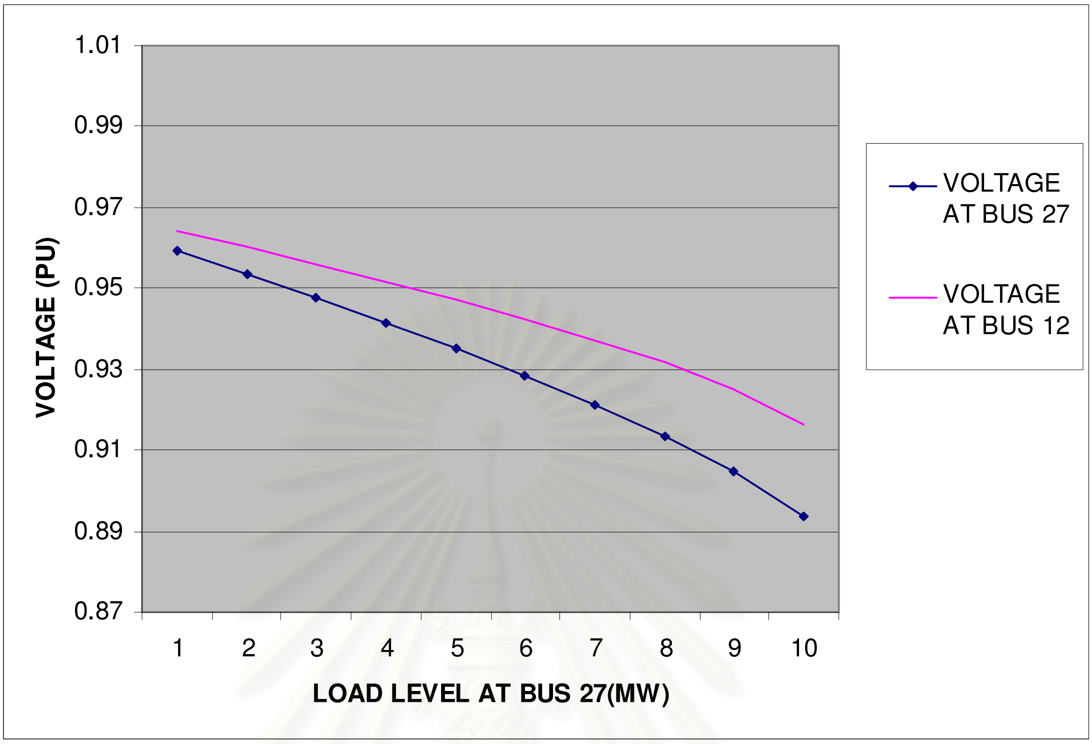

Figure 6.2 PV curve with unity power factor load, system having induction generator

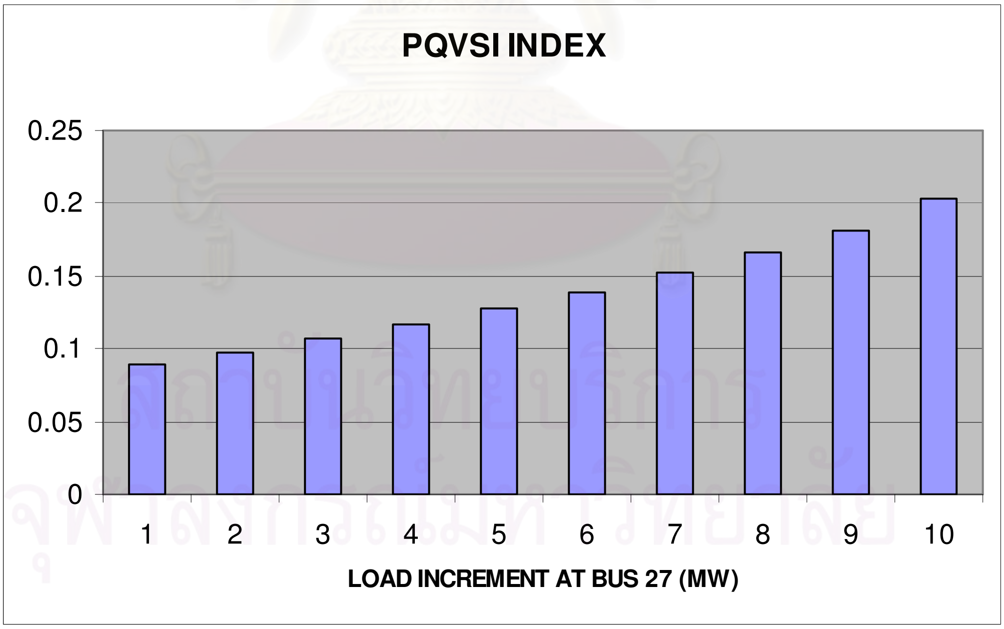

Figure 6.3 PQVSI index for system with induction generator

6.1.2 The case with synchronous generator

For the sake of comparison, we replaced the induction generator at bus 12 with a synchronous generator. The synchronous generator at bus 12 still could serve the load with more than 10 MW, whereas the induction generator was unable to serve it as shown in Fig. 6.4.

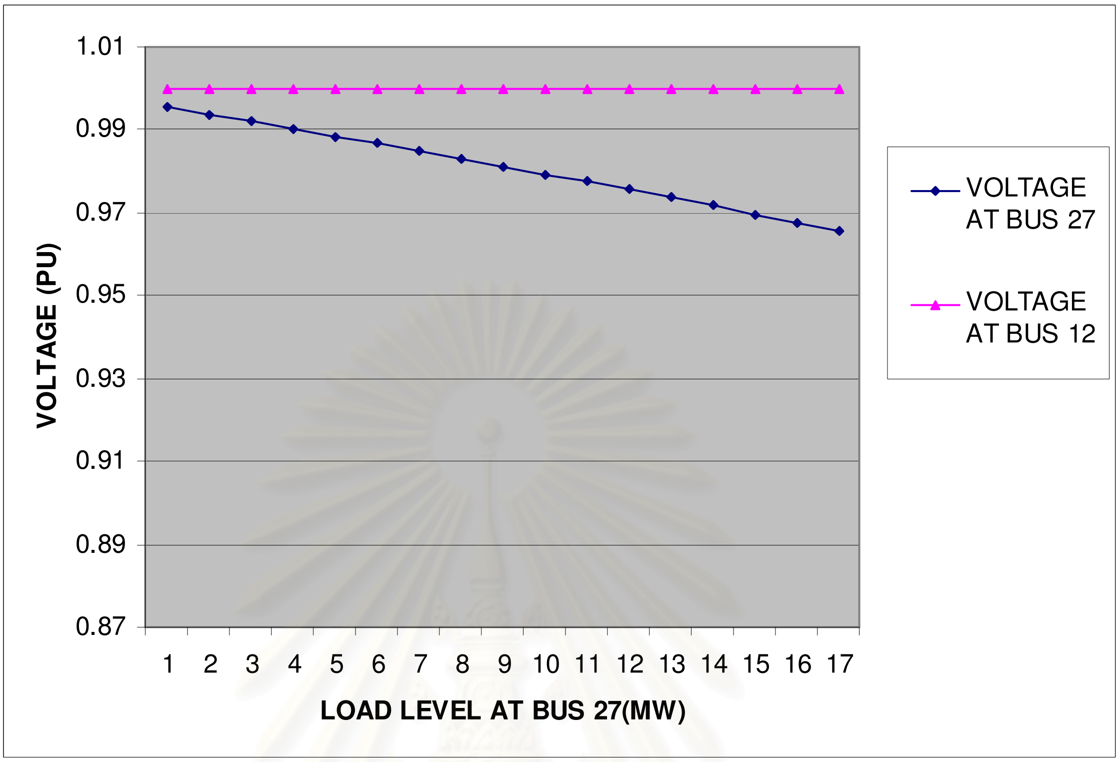

Figure 6.4 PV curve with unity power factor, system having synchronous generator

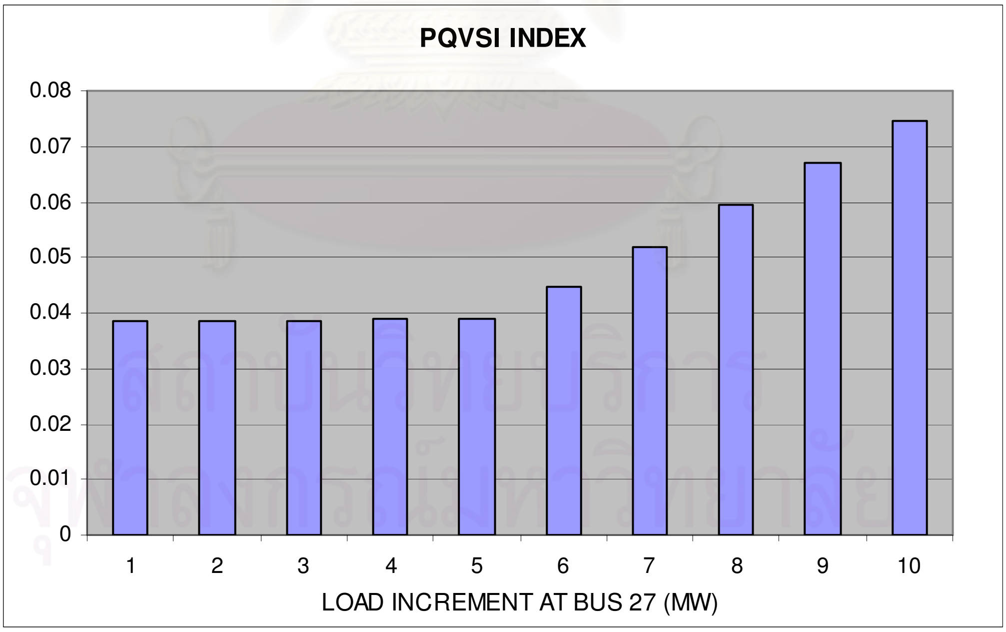

Figure 6.5 PQVSI index for system with synchronous generator

At 10 MW load, as illustrated in Fig. 6.5, the PQVSI index was only 0.07446 for line connecting between bus 26 and 27, and voltage magnitude at bus 27 equals 0.9793 p.u., which was the second from the lowest voltage. When compared to the case with induction generator, the system in this case was more immune and robust to the load increasing.

6.1.3 The case of induction generator utilizing capacitor banks

Here, capacitor banks were installed at the same bus with the induction generator. It has size of 1/3 of induction generator capacity. Clearly seen in this case as presented in Fig. 6.6, capacitor banks could improve the induction generator capability to stably serve the load until 12 MW, more than 10 MW compared to the first case. The possible reason why the induction generator with a capacitor bank can supply more power to the main grid is due to the fact that some of the reactive power from capacitor banks can also enhance the voltage level at generator bus. Because the induction generator has some voltage dependent characteristics, such as the increasing of slip when the voltage connected to it is decreasing [5]; when the voltage at the induction generator terminal is somewhat enhanced, its slip will be smaller so that the induction generator can be stably operated with higher power generation.

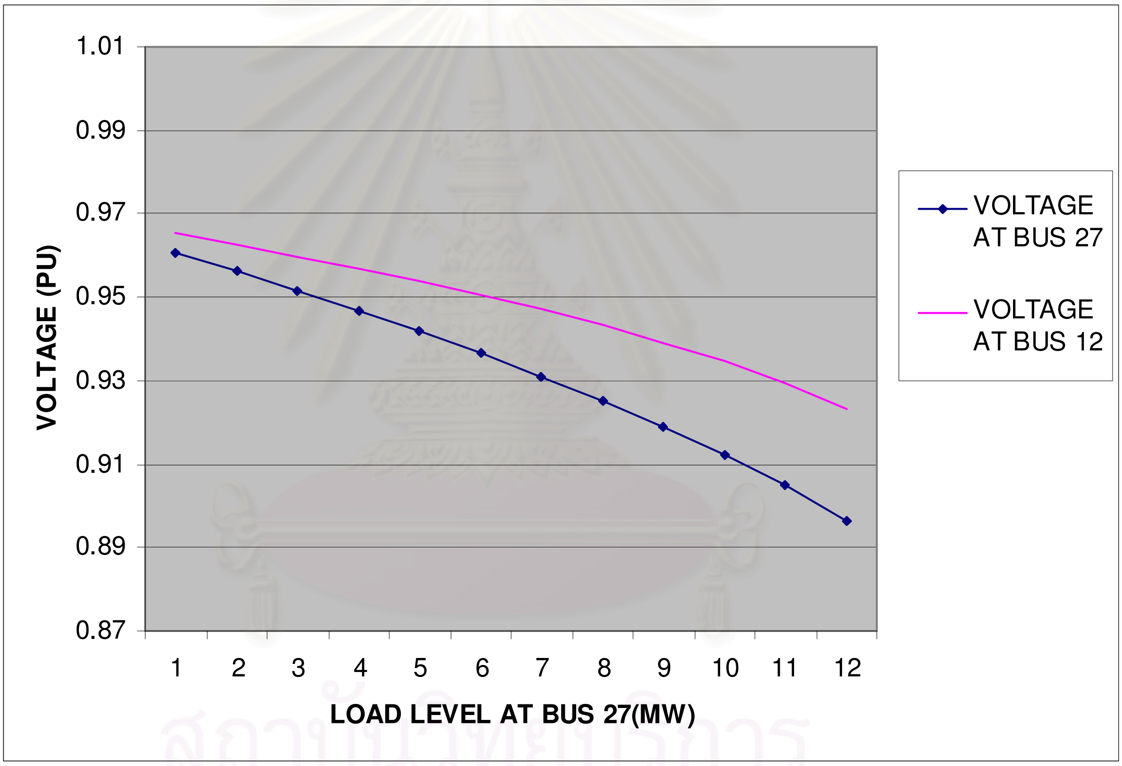

Figure 6.6 PV curve with unity power factor, system having induction generator utilizing capacitor banks

In all load steps, the line connecting between bus 11 and 12 was having the maximum value of PQVSI as shown in Fig. 6.7. The PQVSI index at load 12 MW was 0.18610, and V_{27} = 0.89657 p.u. as indicated in Fig. 6.7 and 6.6 respectively. The index was still lower compared to the index of the first case, as the reactive power needed by the induction generator was compensated by the capacitor banks. Thus, reactive power required from the main grid, flowing through the line connecting between bus 11 and 12, was not so high. This makes the system healthier.

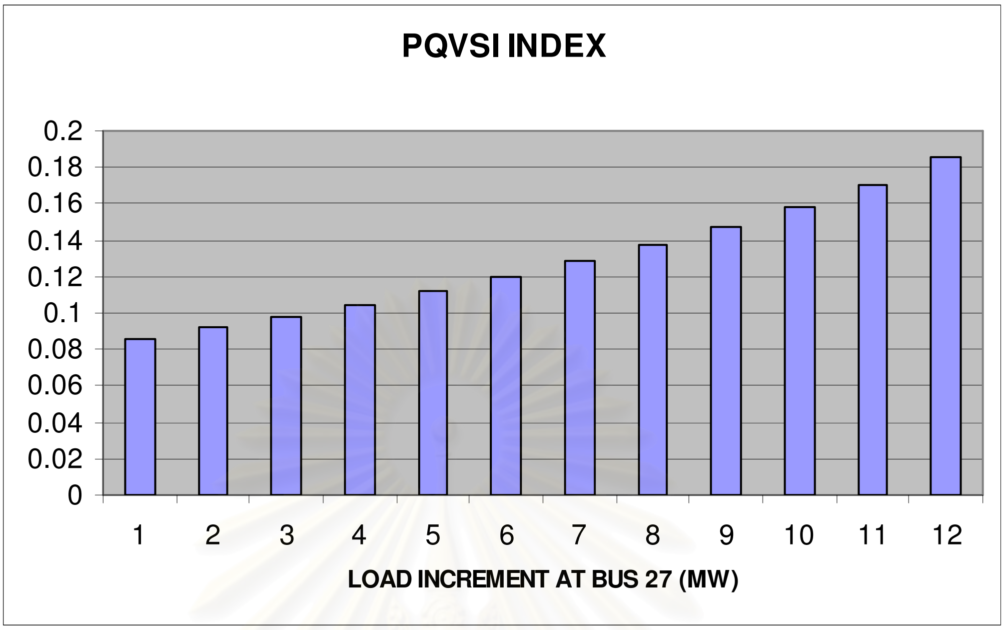

Figure 6.7 PQVSI index for system with induction generator utilizing capacitor banks

6.1.4 The case of lagging power factor load with induction generator

Objective of this study is to show that the lagging power factor load deteriorates the induction generator performance. The results are indicated in Fig. 6.8. For example, in the case of lagging 0.9 power factor, the induction generator can only served load up to 7 MW with slip of -0.07908. When the load has more decreasing lagging power factor, the system voltage stability would be more susceptible to the load increasing as illustrated in Fig. 6.9. This was due to the fact that the reactive power was not only consumed by the induction generator, but also was consumed by the inductive load. As in the case of lagging 0.9 power factor load, the excessive reactive power flow through the line made the voltage at the induction generator terminal drop to only 0.9190 p.u., hence the machine must operate in the higher slip. If an induction generator were having a wind turbine prime mover, practically this situation would cause the protection system trip the induction generator out. Typically the protection relay is set to protect the induction generator when its speed reaches 10% above its synchronous speed, to prevent damaging its prime mover [32].

Still, in the case of lagging 0.9 power factor load, in all load increments, the line between bus 11 and 12 has the maximum value of PQVSI index. When the system connected with 7 MW load, the PQVIS index was 0.19705, and V_{27} = 0.88962 p.u.. This was due to the fact that more reactive power was flowing from the main grid to serve the lagging load and the induction generators at bus 27 and bus 12, respectively. This makes the system weaker.

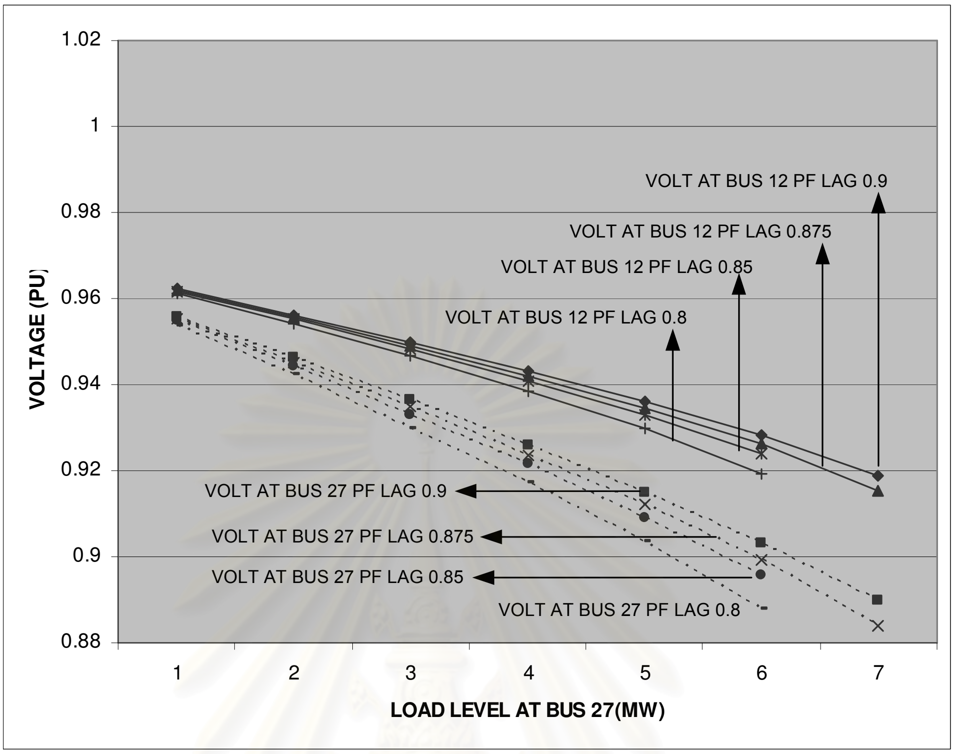

Figure 6.8 PV curve with different lagging power factor load, system having induction generator

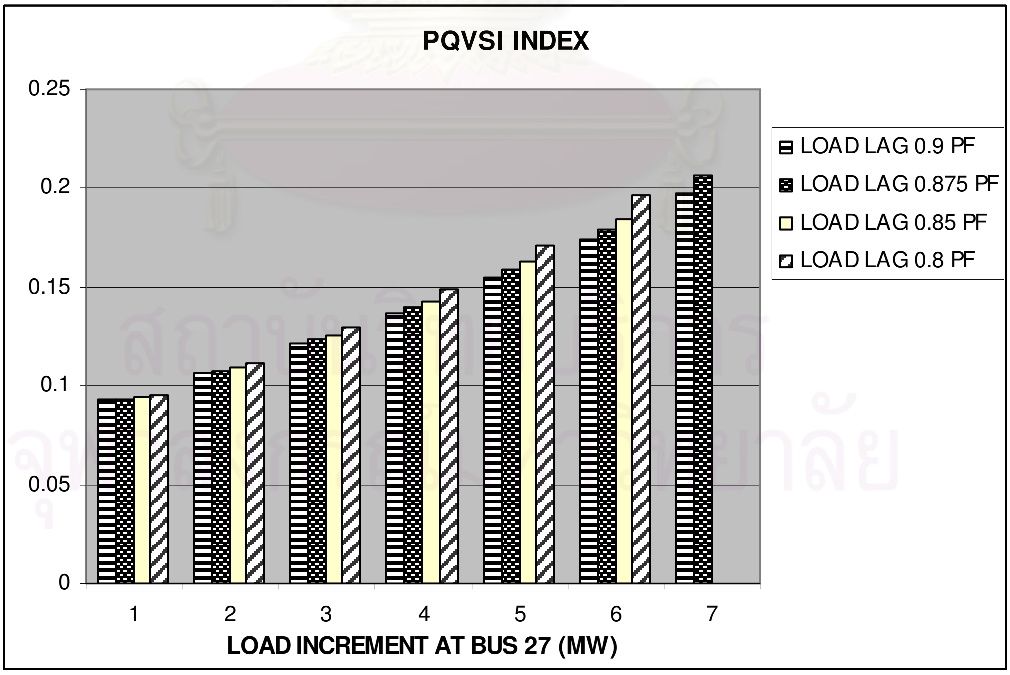

Figure 6.9 PQVSI index with different lagging power factor load, for system with induction generator

6.1.5 The case of leading power factor load with induction generator

In this section, the impact of the leading power factor load on enhancing the induction generator performance will be pointed up. The simulation results are illustrated in Fig. 6.10. It can be seen in the case of leading 0.9 power factor load that the voltage at induction generator terminal, bus 12, was still high enough compared to the 1st case, which was V_{12} = 0.92219 p.u. Consequently, this type of load could enhance performance of the induction generator to serve the load up to 15 MW. When the load has more decreasing leading power factor, the system voltage stability would be more immune to the load increasing as illustrated in Fig. 6.11. As the system was connected with 15 MW load, the PQVIS index was 0.18897, and V_{27} = 0.91541 p.u. This could happen because the leading load could be considered as a part of reactive power sources compensated that needed by the induction generators.

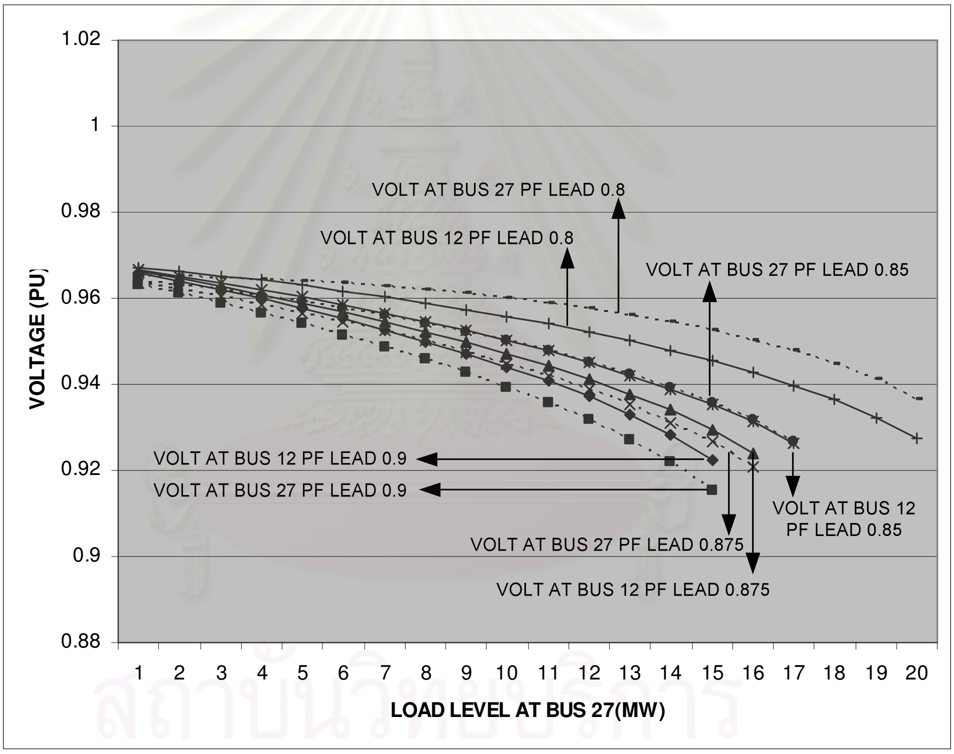

Figure 6.10 PV curve with different leading power factor load, system having induction generator

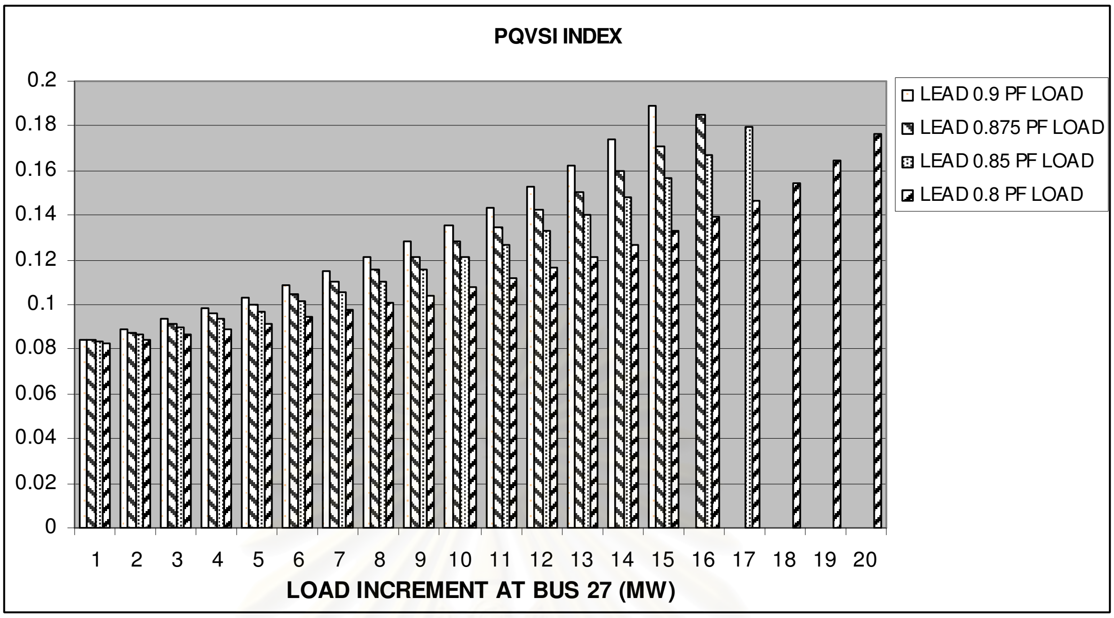

Figure 6.11 PQVSI index with different leading power factor load, for system with induction generator

6.1.6 The case where induction generator installed at different locations

The objective of this analysis is to study impact of induction generator when installing at different locations. Three possible locations are examined; bus 3 – representing bus electrically near from the main grid,, bus 12 -bus at the centre of the network which is the most loaded bus in the system,, and bus 33 –bus at the end of the network, electrically far from main grid. To be able to make comparison, we still assume that load at bus 27 will increase as the induction generator capacity increases. In addition, we assume unity power factor load.

Figure 6.12 shows that when the induction generator was located at bus 3, the induction generator still could serve the load more than 10 MW. When located at bus 12, the induction generator only could supply the load up to 10 MW with voltage at machine terminal was 0.91629 pu. Unfortunately, when connected at bus 33, the operating condition became more severe; as the induction generator could only supply power up to 6 MW with voltage of 0.92413 pu. at machine terminal. This is due to the voltage characteristic of the radial network. The voltage at the receiving-end location of the network will be the lowest, compared to that of the buses near the main grid. As a further matter, the reactive power absorbed by the induction generator could reduce the voltage level at the machine terminal. This made the induction generator unable to be operated in higher capacity.

The degree of voltage instability revealed by the PQVSI index was more vulnerable to the load increment when the induction generator connected at bus 33. As the reactive power delivers from the main grid to the receiving-end bus, it makes additional losses in the whole system, and eventually brings about the voltage instability in the system. Hence, considering the aforementioned description, from the voltage stability point of view, it would be better if the induction generator is connected close to the main grid.

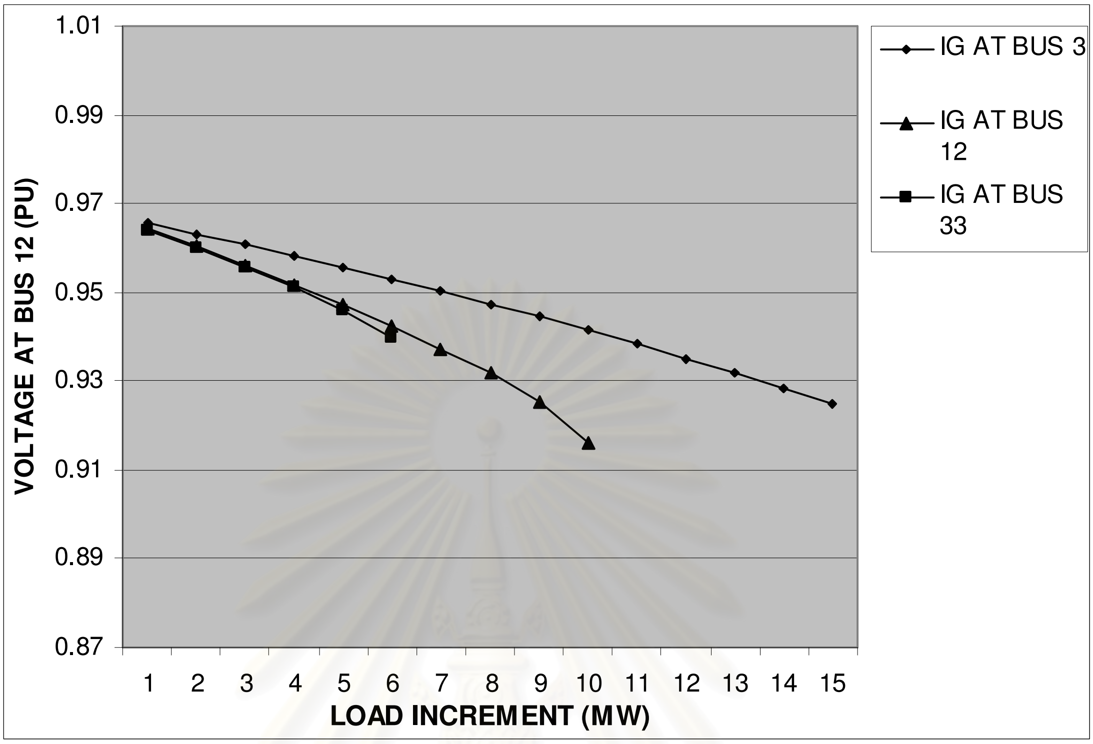

Figure 6.12 PV curve of the induction generator sited at different location

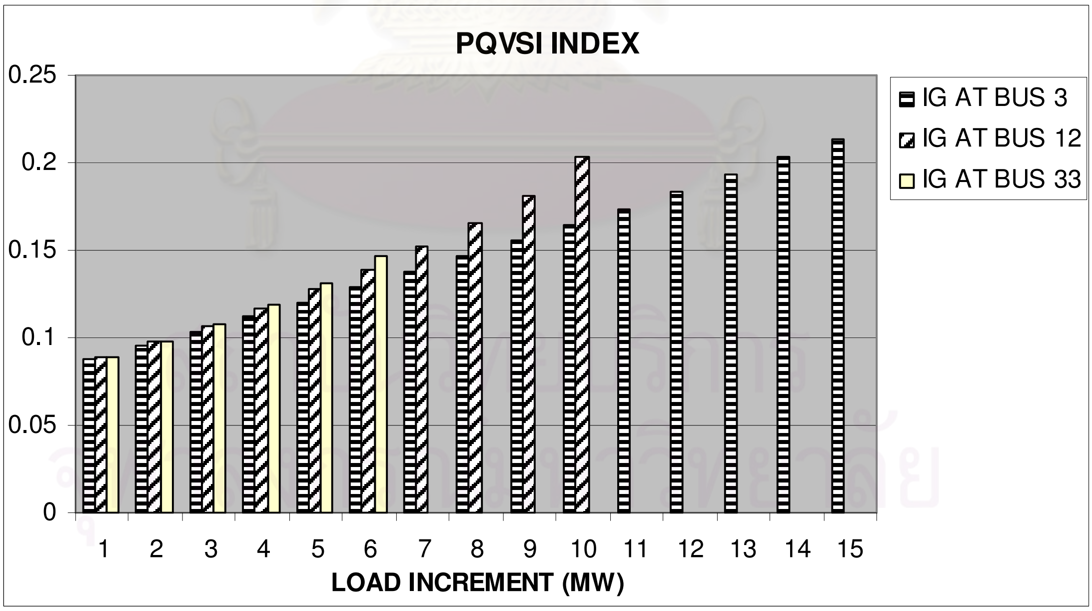

Figure 6.13 PQVSI index of the system having induction generator located in different site

6.2 Dynamic Analysis

In this section, 6-bus system as well as PEA 35-bus system will be used as test systems for model verification. The 6-bus system is firstly analyzed. Then, the results are compared with what had been done in [33]. Next, the dynamics analysis of PEA 35-bus system will be demonstrated. Six case studies will be shown in this sections.

6.2.1 Dynamic simulation of 6-bus system

The 6-bus system is shown in Figure 6.14. It consists of 6 buses, 7 lines, and 3 load points, where bus 1 was considered as the reference bus. Loads, with total load of 100 MW and 22 MVar, are connected at bus 2, 3, 4, and 5, respectively. The Induction Generator is installed at bus 6. The current operating condition is shown in Table 6.1. In this mode of operation, as the main grid operates at constant voltage and constant frequency, the Induction Generator is assumed to be running at steady state under a certain real and reactive power flow condition, which is exporting 25 MW and absorbing 27.4611 MVar from the network.

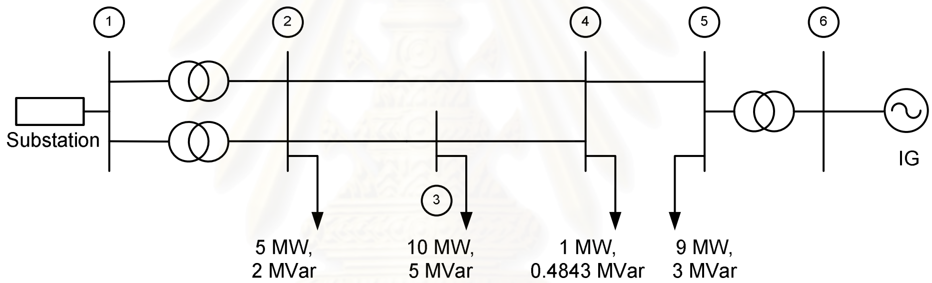

Figure 6.14 Single line diagram of 6-bus studied system

Table 6.1 6-bus test system operating condition

Bus	Voltage		Generation		Load	
	Mag(pu)	Ang(deg)	P (MW)	Q (MVar)	P (MW)	Q (MVar)
1	1	0	0.7478	39. 9347	0	0
2	0.9960	0.0508	0	0	5	2
3	0.9816	-0.4670	0	0	10	5
4	0.9874	0.6533	0	0	1	0.4843
5	0.9826	1.0681	0	0	9	3
6	0.9680	2.3268	25	-27.4611	0	0
Total			25.7478	12.4736	25	10.4843

From the time domain simulation, using 6 bus test system, It can be seen that the results are exactly the same as the steady state results provided in Table 6.1. From time domain simulation, voltage magnitude at bus 1, 2, 3, 4, 5, and 6 are 1.0, 0.9960, 0.9816, 0.9874, 0.9826, and 0.9680 per unit, respectively. For the voltage angles, they are 0, 0.0509, -0.4670, 0.6533, 1.0681, and 2.3269 degree, respectively. These results are exactly the same as those obtained from the static load flow calculation. Hence, it can be served as evidence that the dynamics models used in this research are correct.

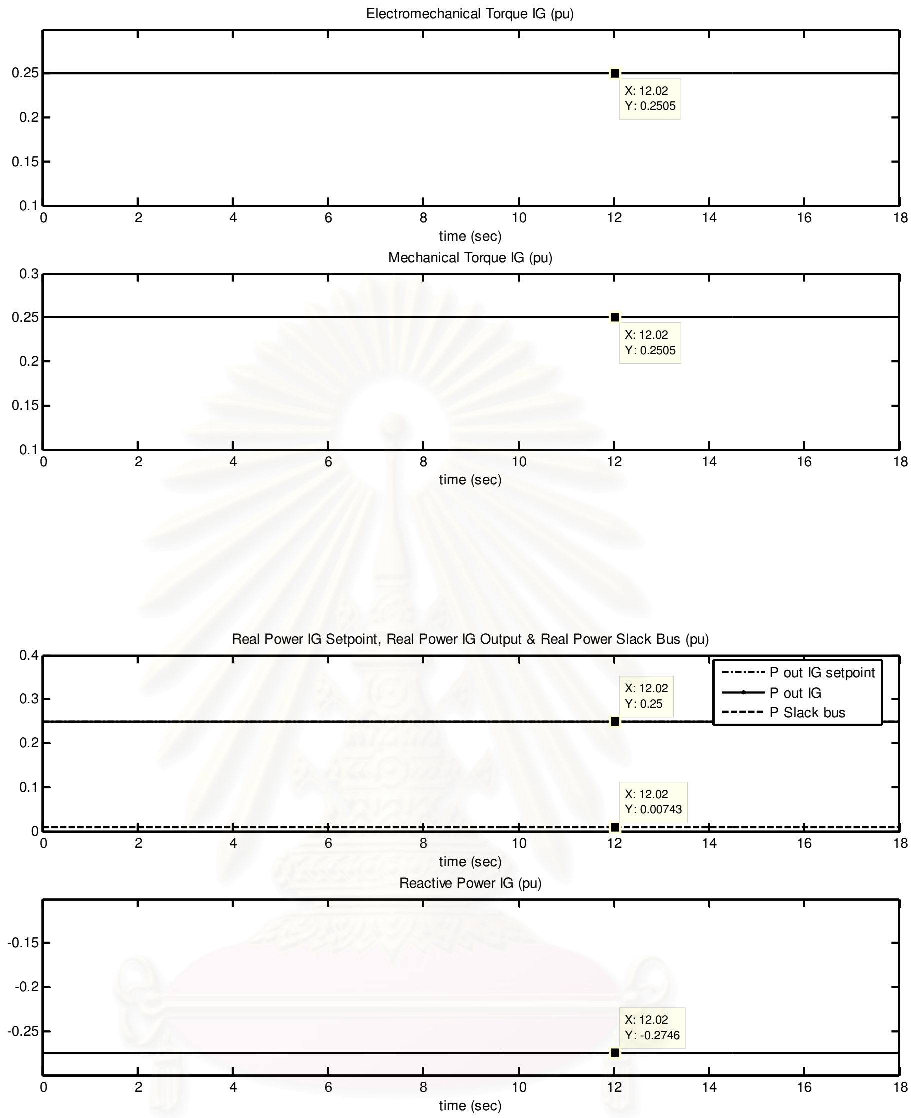

Figure 6.15 Time domain simulation result in 6-bus system

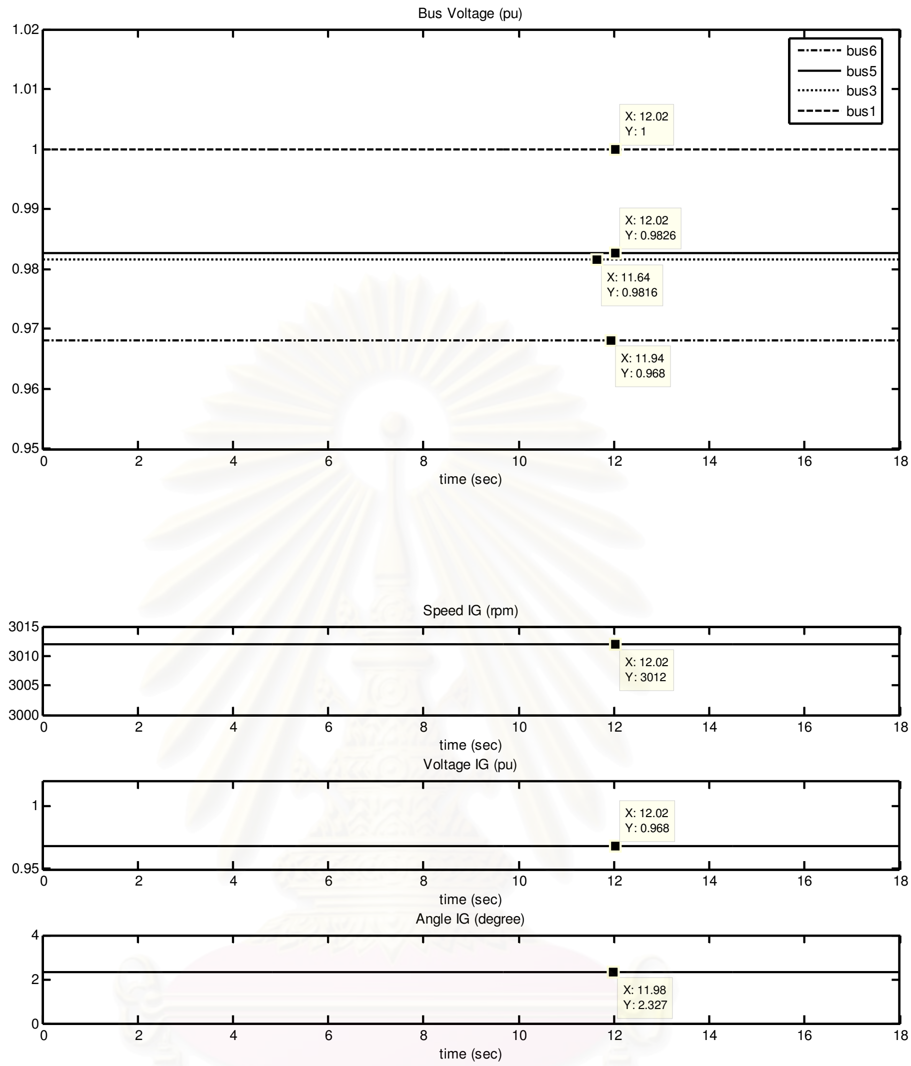

Figure 6.15 Time domain simulation result in 6-bus system (cont.)

6.2.1.1 Using 6-bus system with increasing generator output and increasing load at 0.9 lagging power factor at the nose point and at its unstable vicinity.

From static analysis, shown in Fig. 6.16, the nose-point of network's voltage stability is taken place when the Induction Generator, installed at bus 6, is operated at 139 MW and the real power load demanded at bus 4 is 115 MW. Afterwards, considering this data, this stable operating condition of the induction generator was verified by the dynamic analysis presented in Fig.6.18. In this sense, the real power output generator was set to 1.39 p.u. at t = 9 second and at the same time the load at bus 4 was increased from 0.01 + j0.004843 p.u. to 1.15 +j0.557 pu (at 0.9 p.f. lagging). Dynamics of the system voltage can be also observed from Fig.6.18.

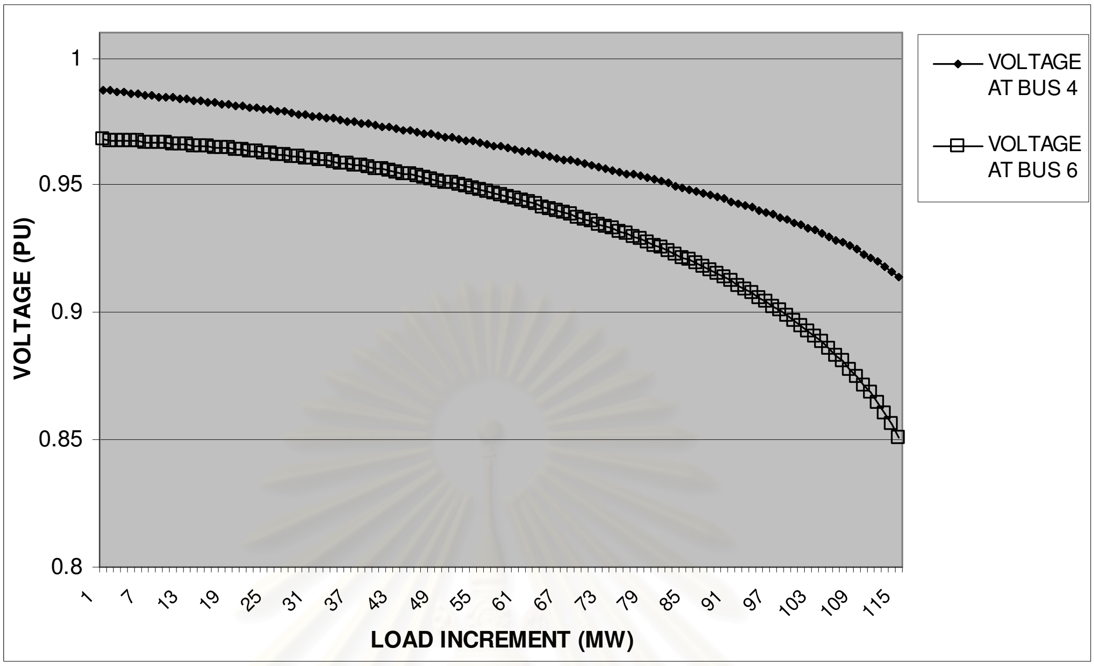

Figure 6.16 PV curve with 6-bus system having induction generator

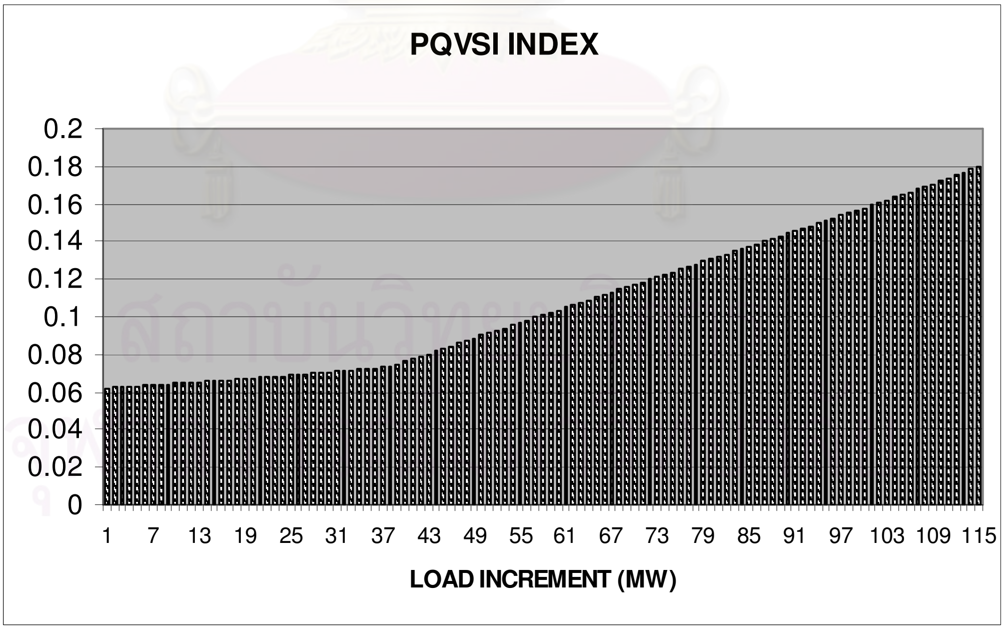

Figure 6.17 PQVSI index for 6-bus system having induction generator

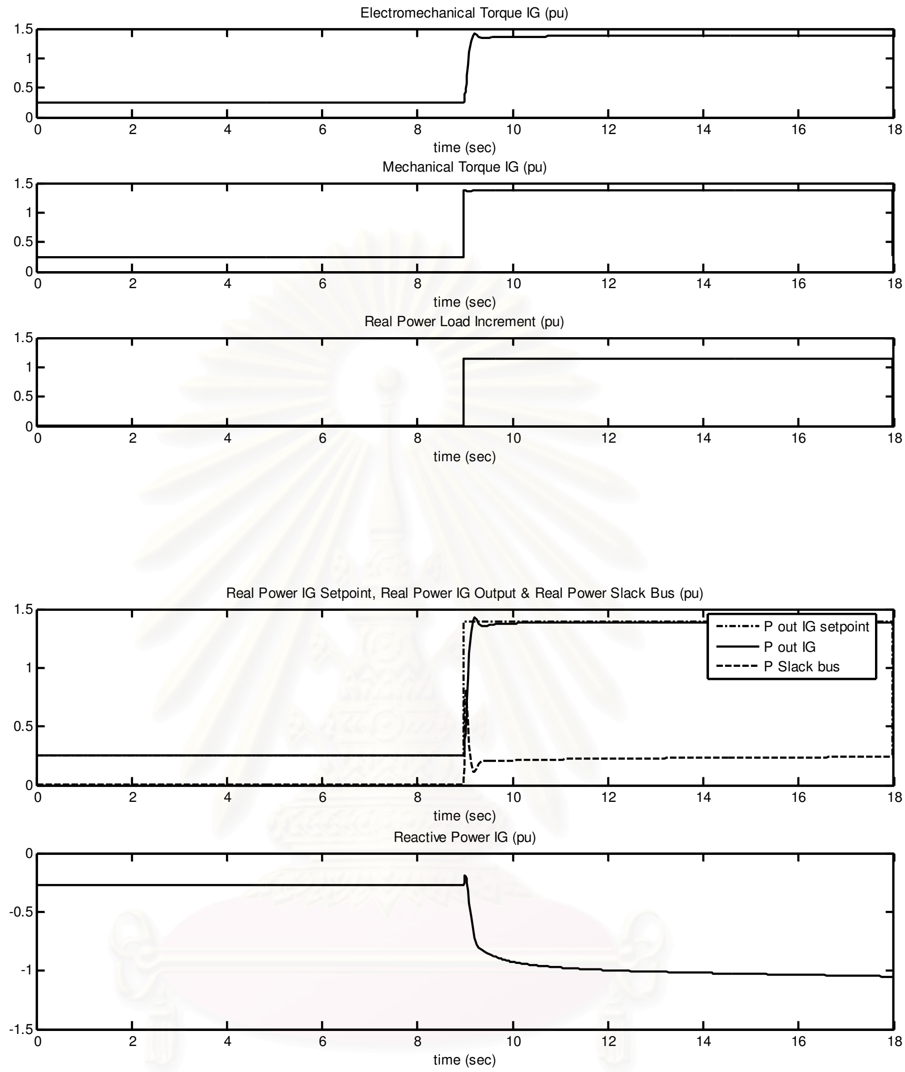

Figure 6.18 Dynamic responses of IG 6-bus system in stable operating condition

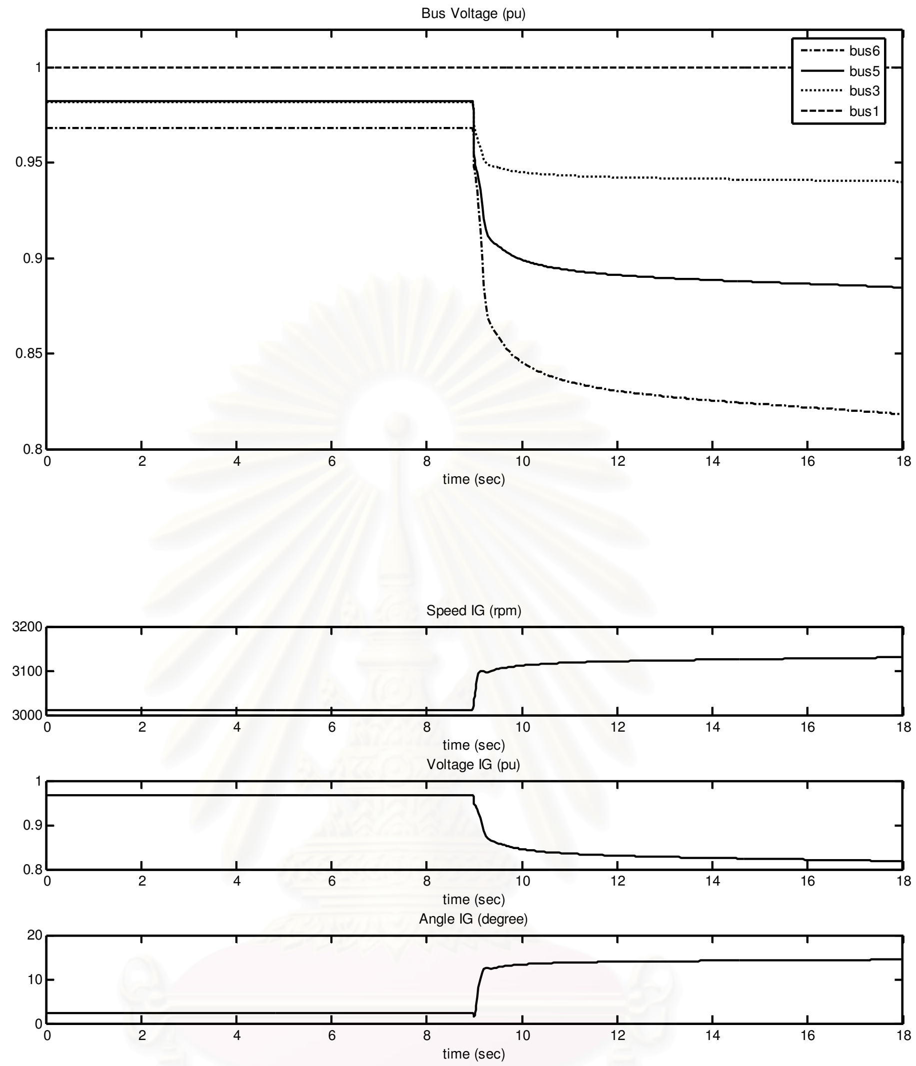

Figure 6.18 Dynamic responses of IG 6-bus system in stable operating condition (cont.)

Fig.6.18. shows that the voltage profile at terminal machine and at several buses settled down to the new value without any oscillations. The observed dynamic voltage responses are only the simple first order delay.

In static analysis, we cannot observe what actually happens if load increases beyond the nose-pose. We just know only that the system loses its stability and cannot be steadily operated. However, with dynamics analysis we can see the mechanisms of each parameter and could observe the reason why the power system becomes unstable. To represent the unstable region at the nose point's vicinity and to show the unstable operating condition of the Induction Generator, we simply increase both the power output of generator and the load at bus 4 in the level of only 0.01 p.u beyond nose point. Dynamics simulation results of this condition can be seen in Fig. 6.19. It can be seen that the Induction Generator can not be stably operated. In addition, this situation leads to the voltage collapse. Fig.6.19 also shows the system voltage characteristics and it illustrates the event of the actual dynamics of voltage instability process following a load change in the network that cannot be illustrated using only static analysis.

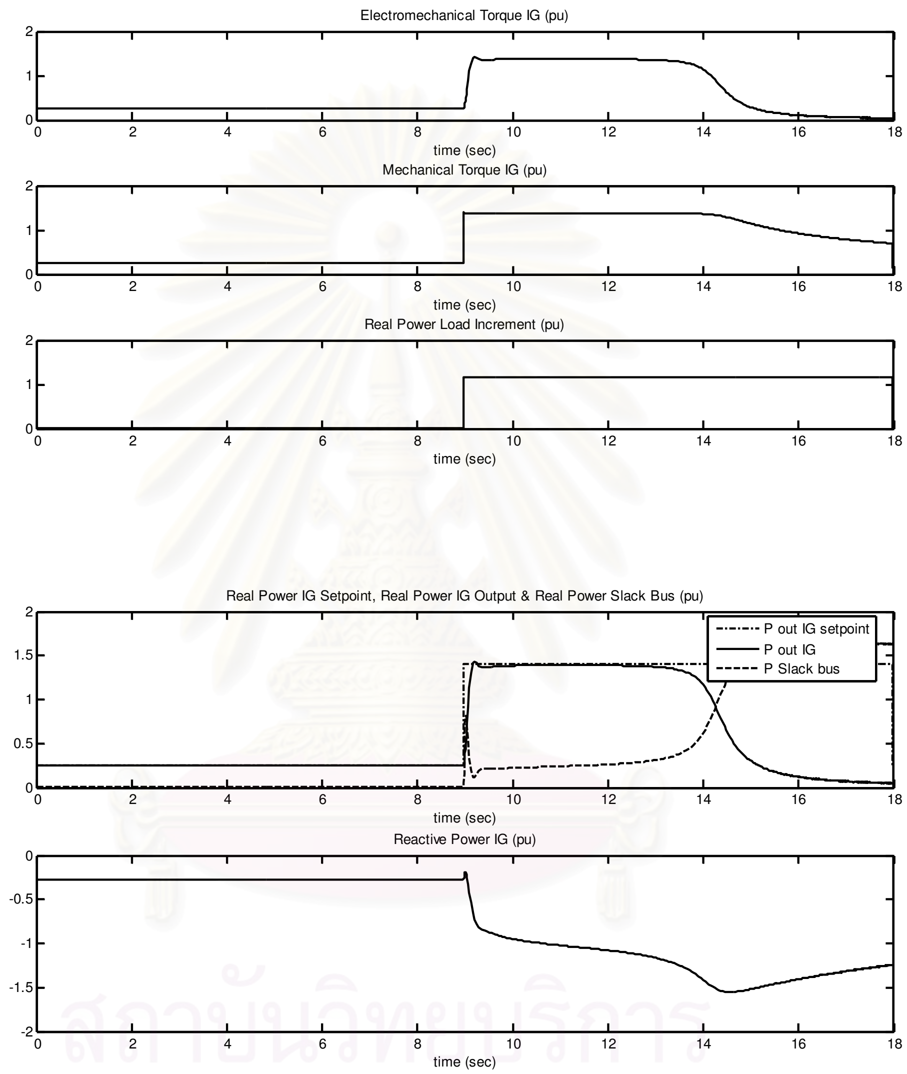

Figure 6.19 Dynamic responses of IG 6-bus system in unstable operating condition

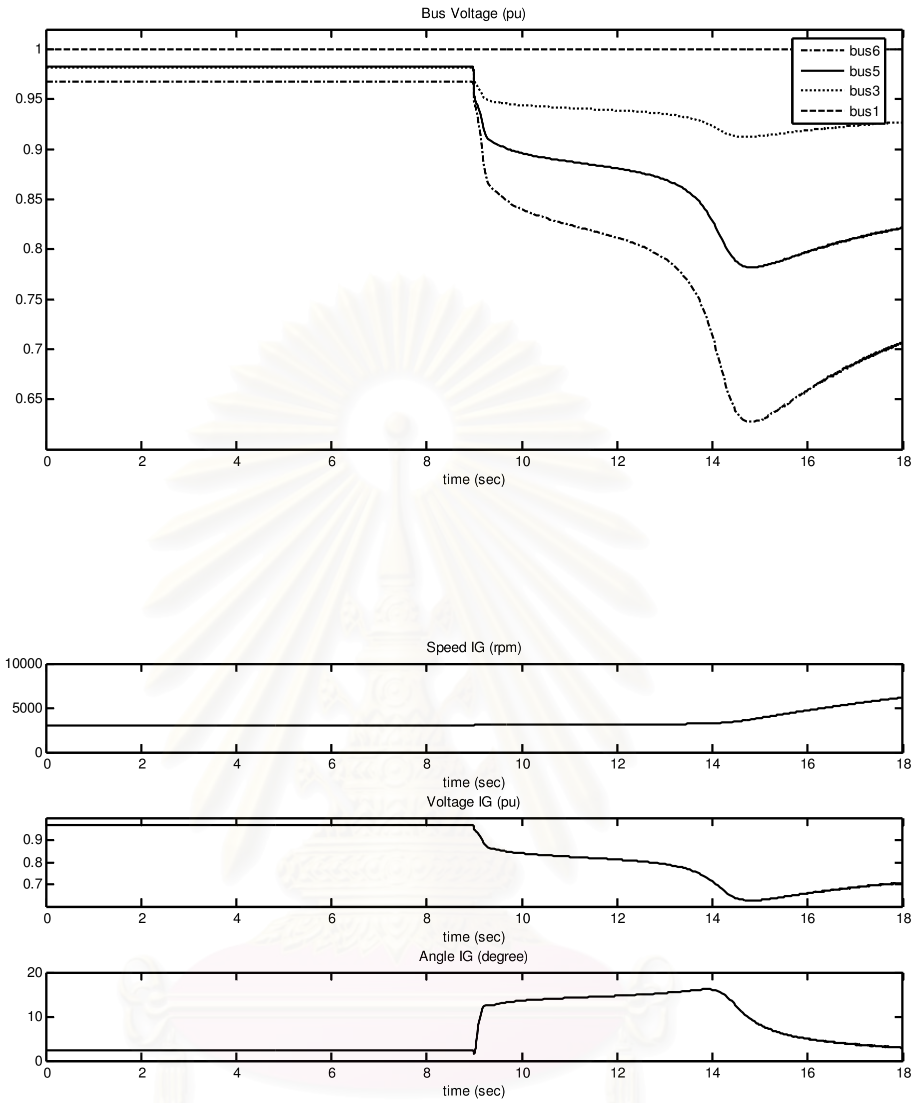

Figure 6.19 Dynamic responses of IG 6-bus system in unstable operating condition (cont.)

As seen in Fig 6.19, the rotor speed was gradually increasing and not settling down to any steady state condition. At this stage, the induction generator operates in a run away situation or in unstable operating condition, as the machine tries to accelerate continuously because of the unbalance of the applied shaft torque with the electromagnetic torque developed by the machine. The voltage at machine's terminal is not stable and continues decreasing. Then voltage collapse process starts. It should be noted that this process of the voltage collapse starts from this location and then spreads to the nearby buses.

6.2.2 Dynamic simulation of PEA 35-bus system

6.2.2.1 First case: Increasing generator output in stable operating condition

In this case, the Induction Generator was installed at bus 12 and the real power output was changed from 0.25 p.u. to 0.7 p.u. at t = 9 second. We can see from Fig.6.20 that after the first swing the electrical torque, real power output, and the rotor speed gradually settled down to the new value with less oscillation. The voltage magnitude at the machine's terminal also settled down to the new value. Here, the Induction Generator can be operated in a new stable condition which it is exporting real power to the main grid.

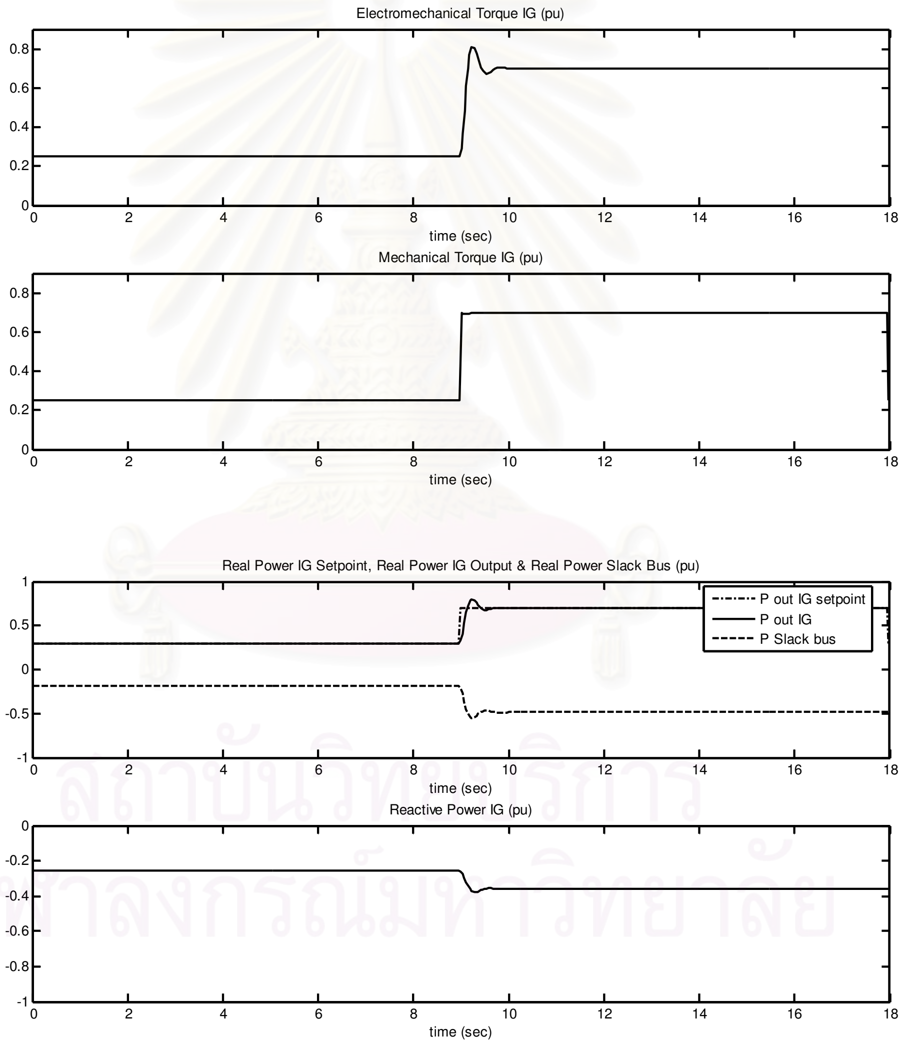

Figure 6.20 Dynamic responses of IG in the first case

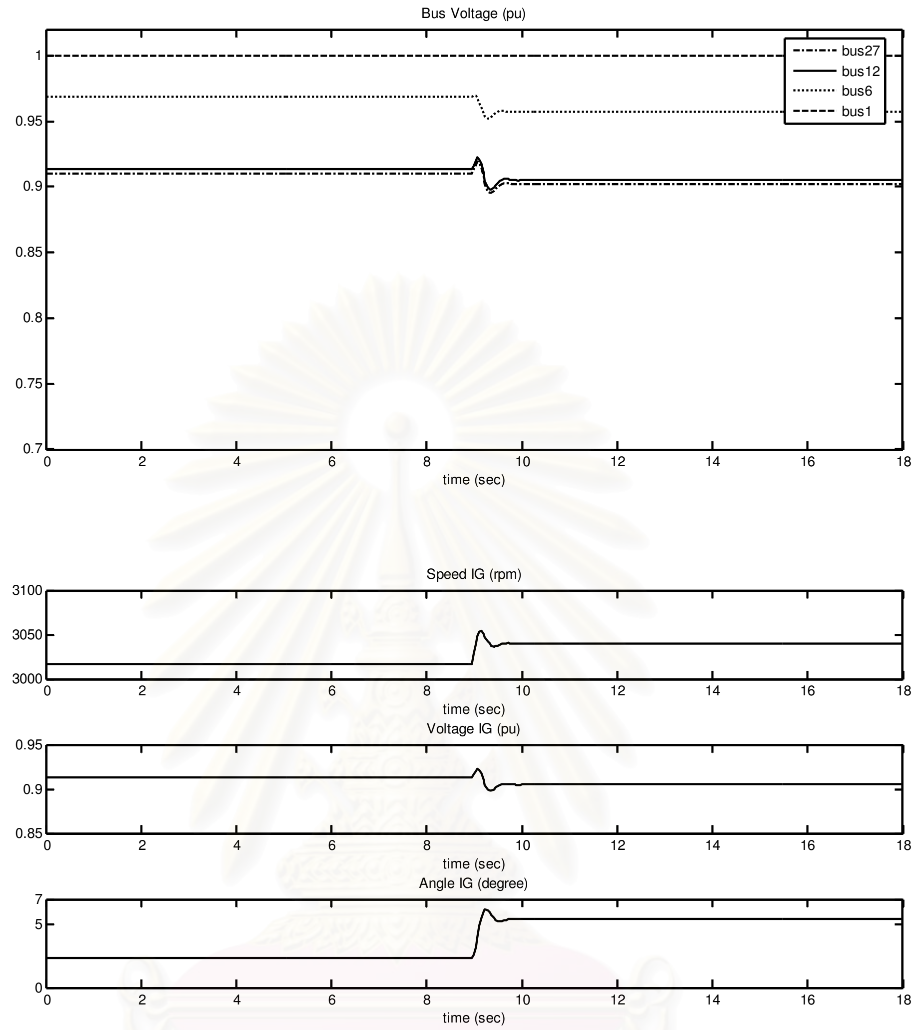

Figure 6.20 Dynamic responses of IG in the first case (cont.)

The machine stability can also be observed from its speed and angle which increase as a result of the increment of its output power. Under this condition, the generator draws more reactive power from the main grid, leading to declining of the system voltage.. It should be noted that the oscillations exist after a little overshoot in the voltage characteristics. The magnitude of these overshoots depends on the machine's parameter (inertia constant, damping constant, and rotor impedance).

6.2.2.2 Second case: Increasing generator output in unstable operating condition

In this case, the Induction Generator was installed at bus 12 and the real power output was changed from 0.25 p.u. to 1.0 p.u. at t = 9 second. It can be seen from Fig.6.21 that the rotor speed was gradually increasing and can not settling down to any steady-state value. It means that this machine can not be stably operated. The voltage at machine's terminal was also not stable and continued decreasing. Reason behind this phenomenon is that when the machine is forced to generate a large amount of real power, the reactive power needed by the Induction generator is also increasing to maintain the rotating magnetic field in the stator machine. This causes voltages of many buses in the system drop to very low level. This situation makes the Induction Generator can not be operated in stable condition as the machine tries to accelerate continuously due to an unbalance of the applied shaft torque with the electromagnetic torque developed by the machine. Such excessive over-speeding is initiated by a lack of the electric torque of induction generators, which the electric torque is proportional to the terminal voltage and stator rotating magnetic flux.

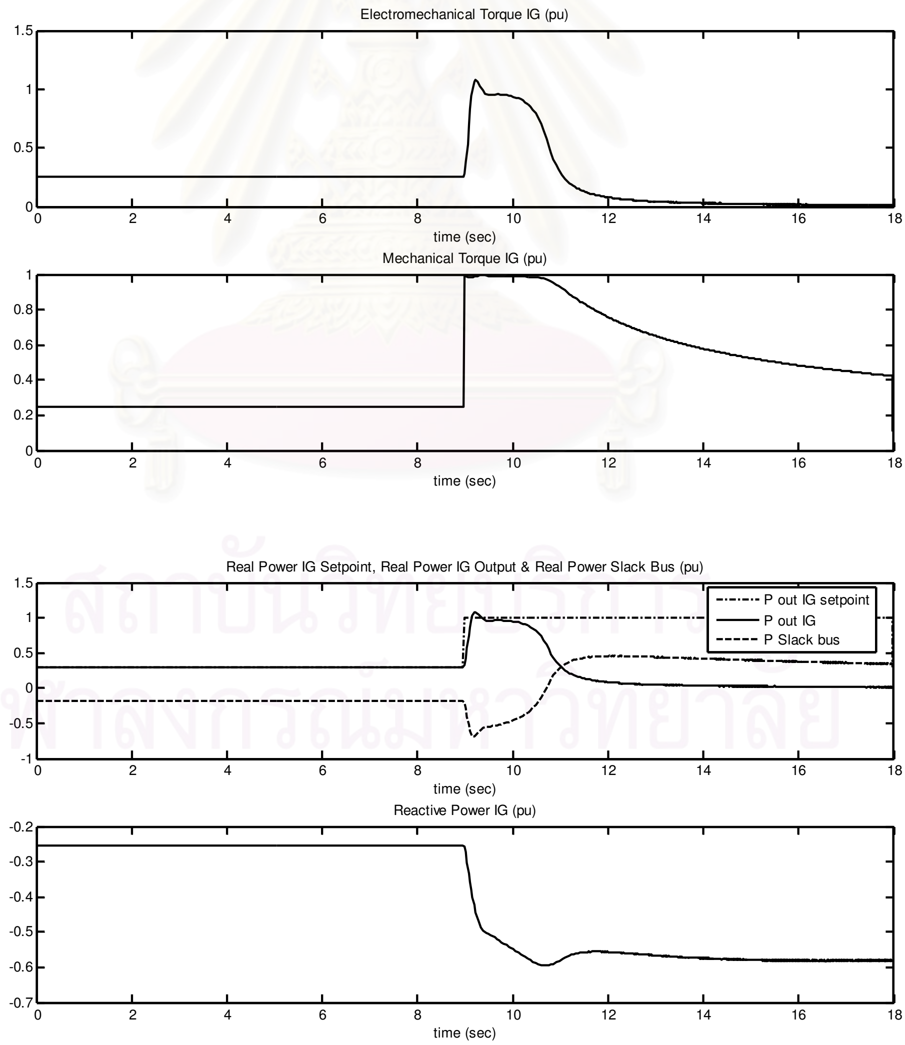

Figure 6.21 Dynamic responses of IG in the second case

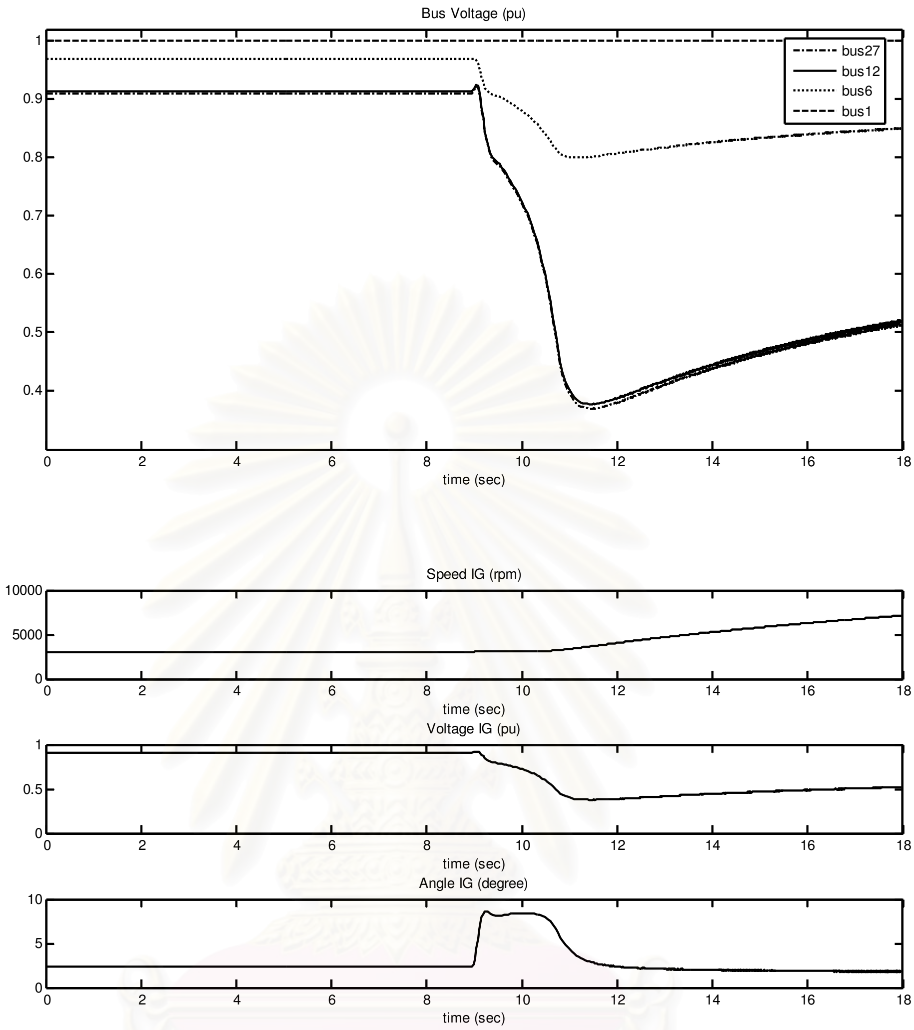

Figure 6.21 Dynamic responses of IG in the second case (cont.)

Theoretically, the reactive power absorption depends on the generator rotor slip, which also influences on the voltage behavior. In this simulation, larger acceleration of the generator rotor during the dynamic event was simulated, hence, the large reactive absorption of the generator can be graphically revealed.

6.2.2.3 Third case: Increasing load at unity power factor

In this section, the Induction Generator was installed at bus 12 and the real power output was kept constant at 0.25 p.u., and the real power load at bus 27 was changed from 0 p.u. to 0.2 p.u. at t = 9 second.

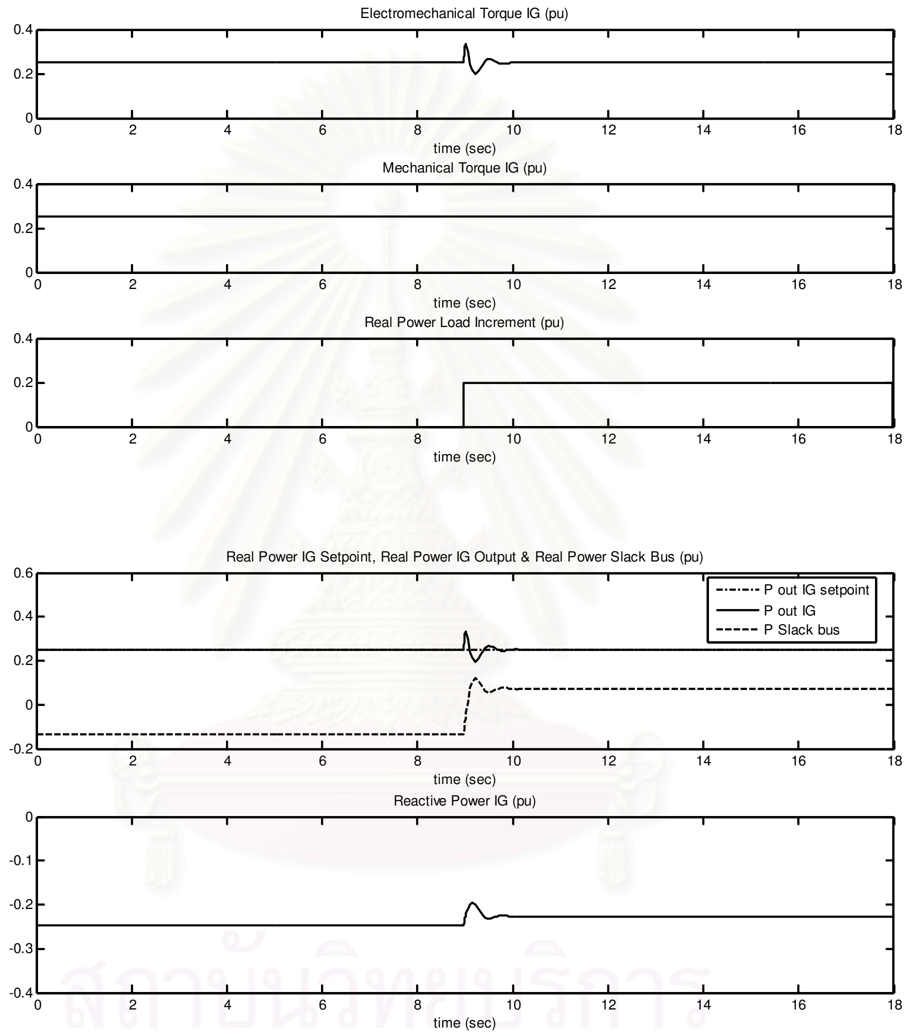

Figure 6.22 Dynamic responses of IG in the third case

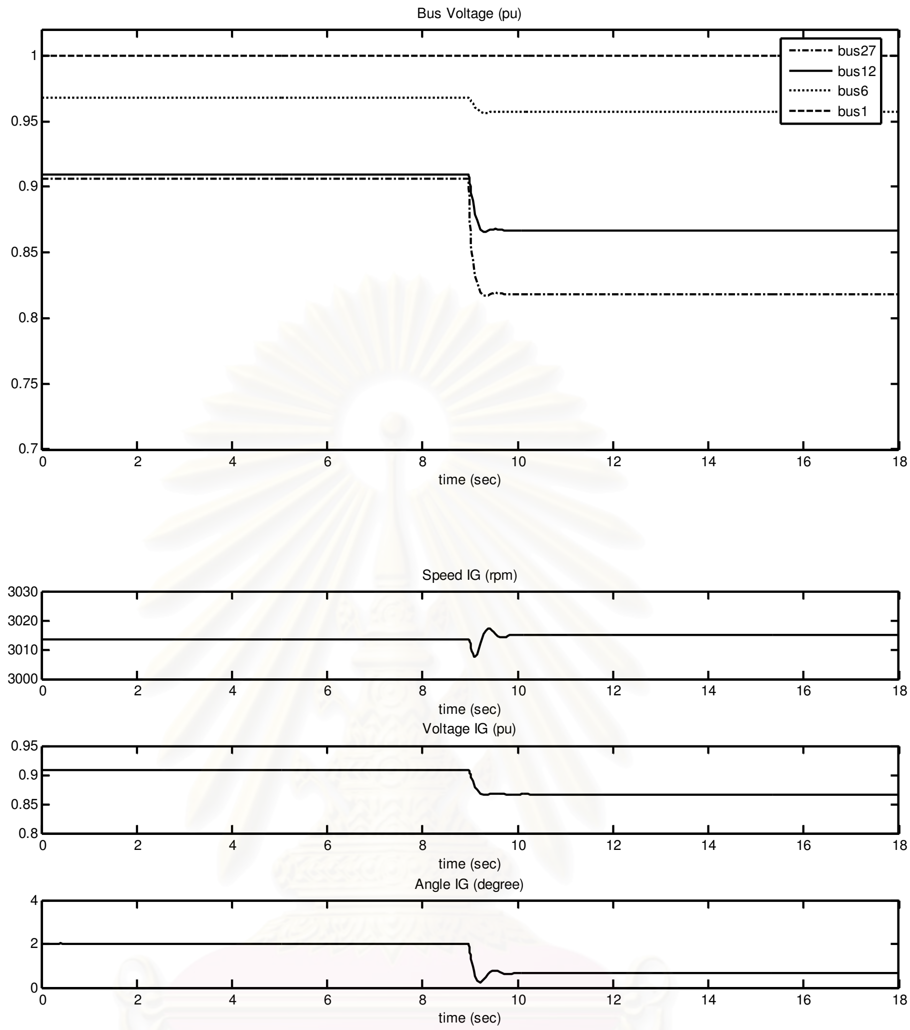

Figure 6.22 Dynamic responses of IG in the third case (cont.)

In this case, after the increase of load, the voltage at terminal machine can settle down to the new value without any oscillations. Here, we can see that as the voltage at terminal machine was decreasing, the machine speed increased a little bit. It should be noticed also that the machine tried to compensate the load increment through a sudden initial increase of its active power. However, it swings back to the setting point due to the generator control loop.

6.2.2.4 Fourth case: Increasing load at 0.9 lagging power factor.

In this situation, the Induction Generator was installed at bus 12 and the real power output was kept constant at 0.25 p.u., and the load at bus 27 was changed from 0 p.u. to 0.2+j 0.0969 p.u. at t = 9 second (0.9 lagging power factor).

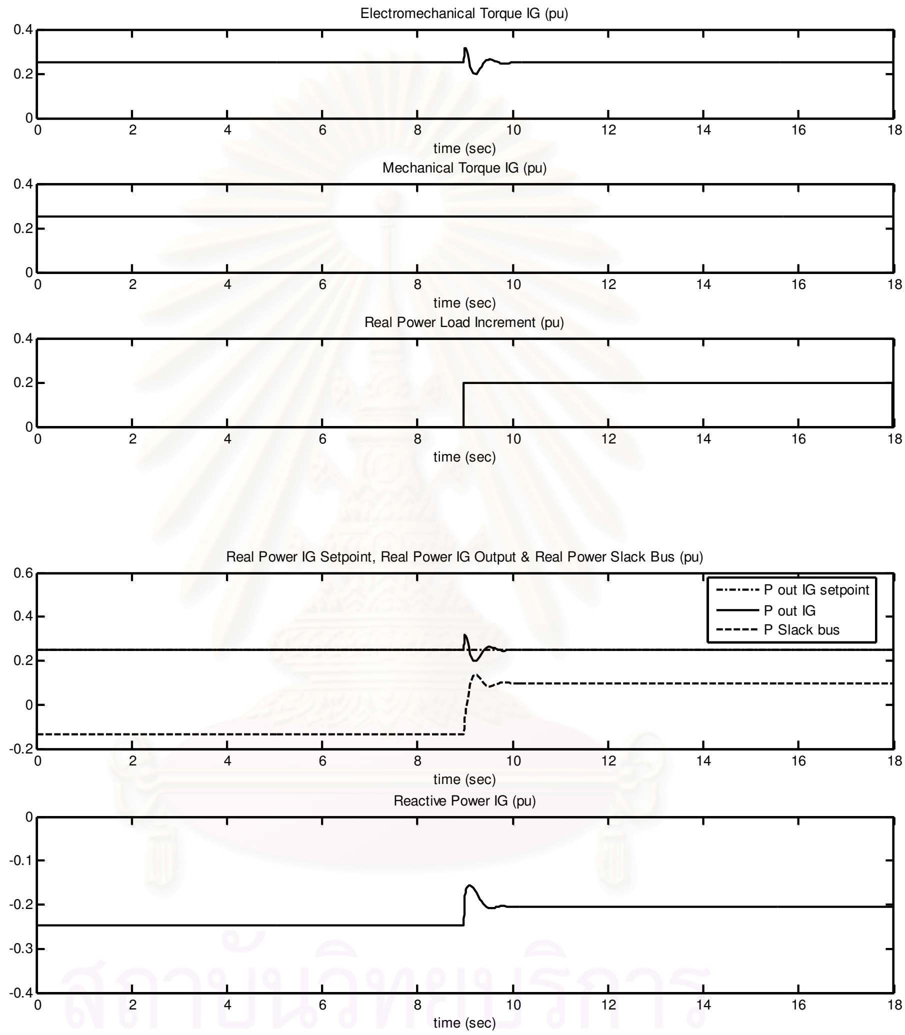

Figure 6.23 Dynamic responses of IG in the fourth case

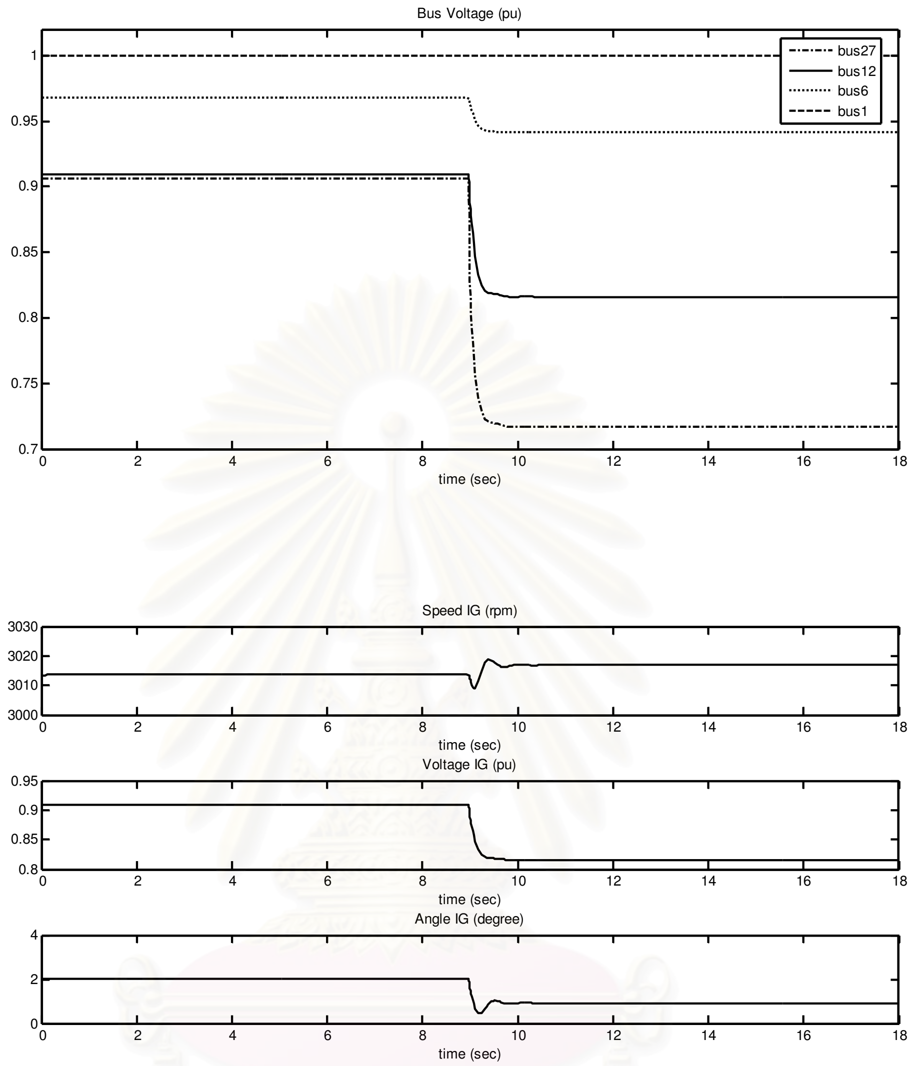

Figure 6.23 Dynamic responses of IG in the fourth case (cont.)

The voltage at terminal machine settled down to the new value without any oscillations. However, it can be seen that the voltage at terminal machine was far decreasing compared to at the case of unity power factor. This makes the machine speed more increase. We notice also that the machine tried to compensate the load increment through a sudden initial increase of its active power. However, it swings back to the setting point due to the generator control loop.

6.2.2.5 Fifth case: Increasing load at 0.7 lagging power factor

In this case, the Induction Generator was installed at bus 12 and the real power output was kept constant at 0.25 p.u., and the load at bus 27 was changed from 0 p.u. to 0.2+j 0.204 p.u. at t = 9 second (0.7 lagging power factor).

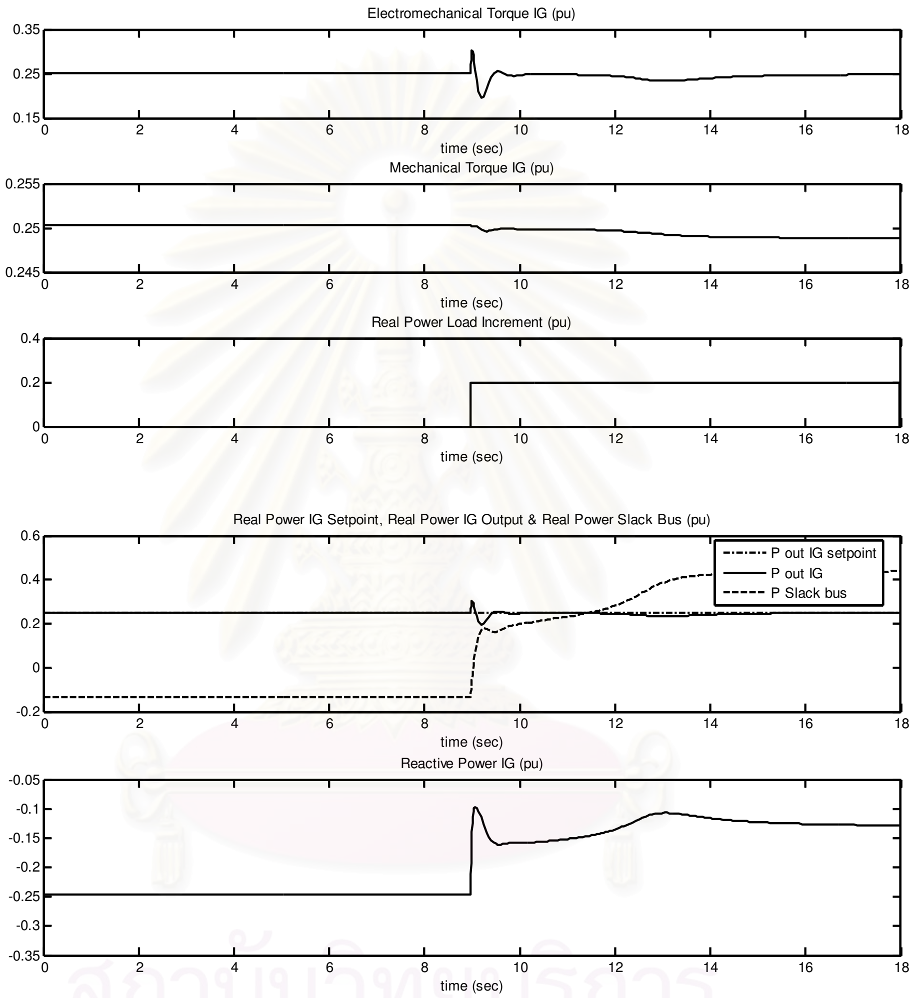

Figure 6.24 Dynamic responses of IG in the fifth case

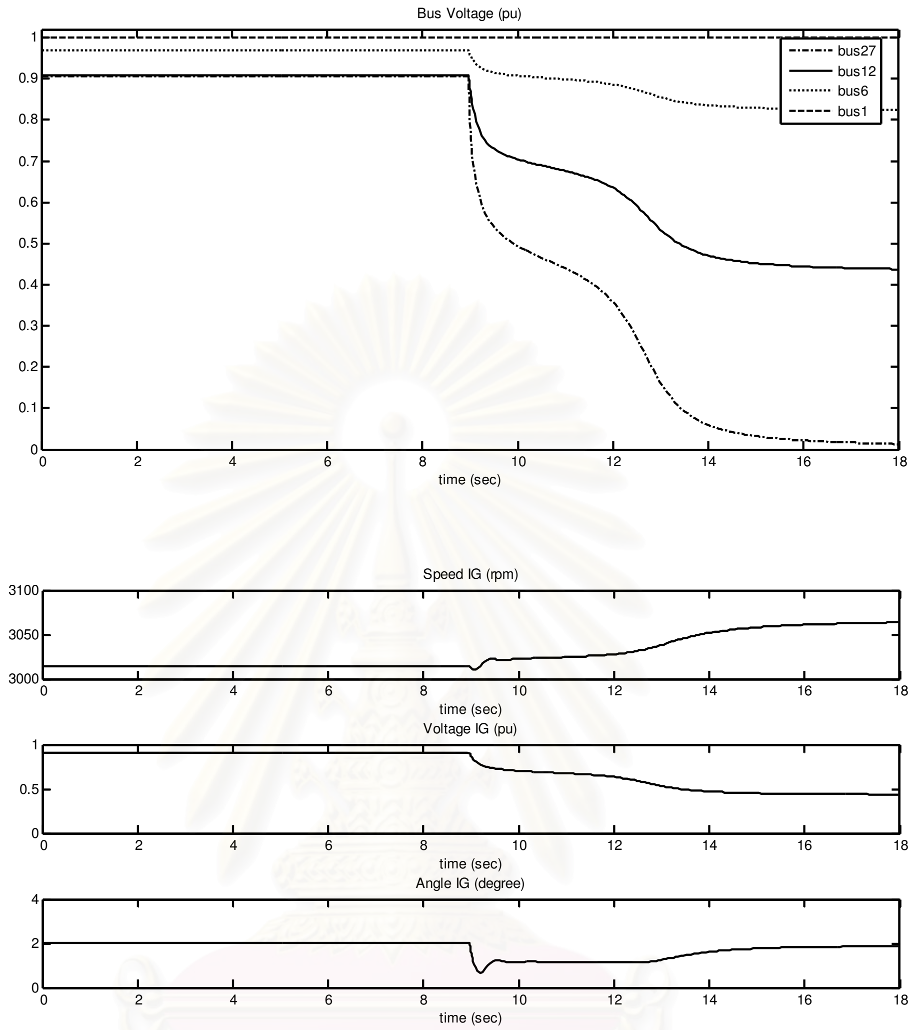

Figure 6.24 Dynamic responses of IG in the fifth case (cont.)

In this simulation, the voltage at terminal machine was not stable as it continued to decrease. This leads to the voltage collapse. It is clearly seen that the voltage at terminal machine was gradually decreasing. This makes the machine speed increase to such an extent that the generator can not return to any steady-state operating point. In another word, the machine speed was increasing beyond its breakdown torque's speed limit. This phenomenon explained why induction machine could not be operated at certain low terminal machine voltage as load increase. Here, we had an induction generator operating in a run away situation or in unstable operating condition.

6.2.2.6 Sixth case: The Induction Generator with capacitor bank

In this case, the Induction Generator was installed at bus 12 with a reactive power source at the machine terminal. The capacitor bank of the amount of 1/3 of Induction Generator real power output, like used in the Rejsby Hede windfarm, Denmark [32], was installed. The real power output of the induction generator was kept constant at 0.25 p.u., and the load at bus 27 was changed from 0 p.u. to 0.2+j 0.204 p.u. at t = 9 second (0.7 lagging power factor).

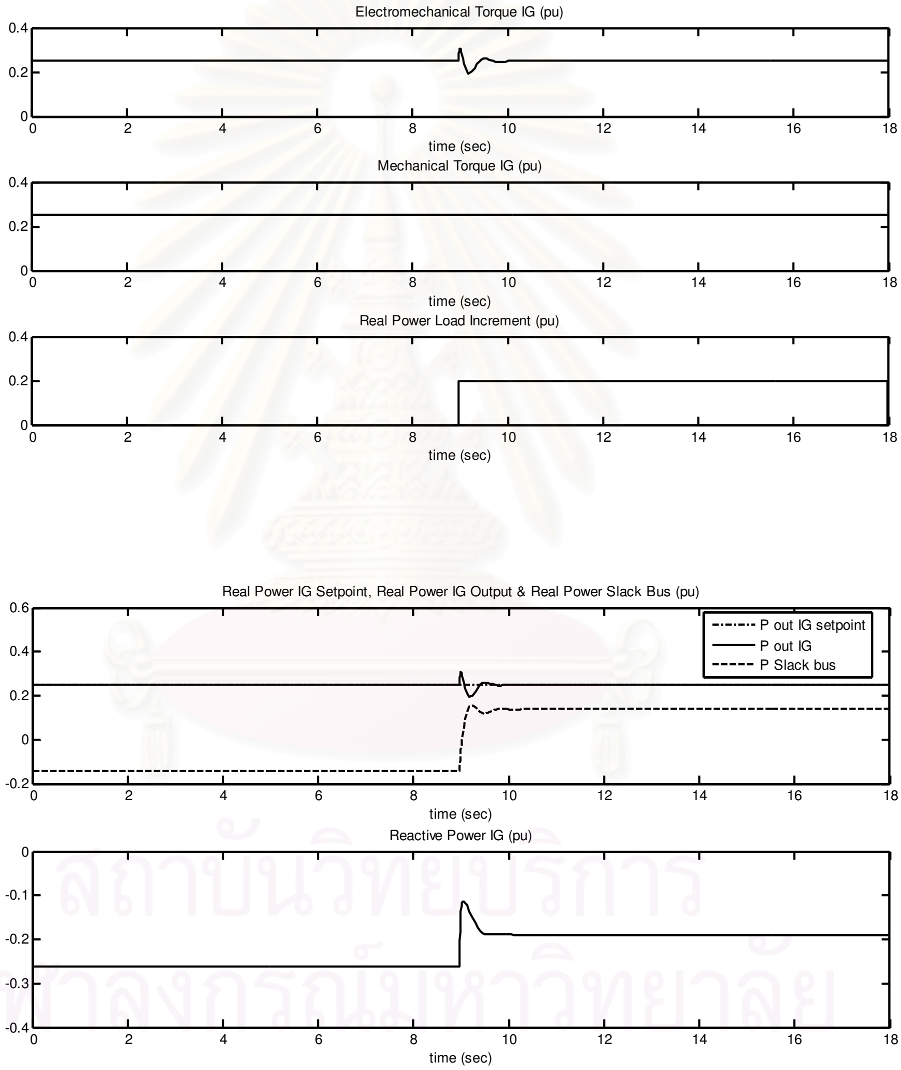

Figure 6.25 Dynamic responses of IG in the sixth case

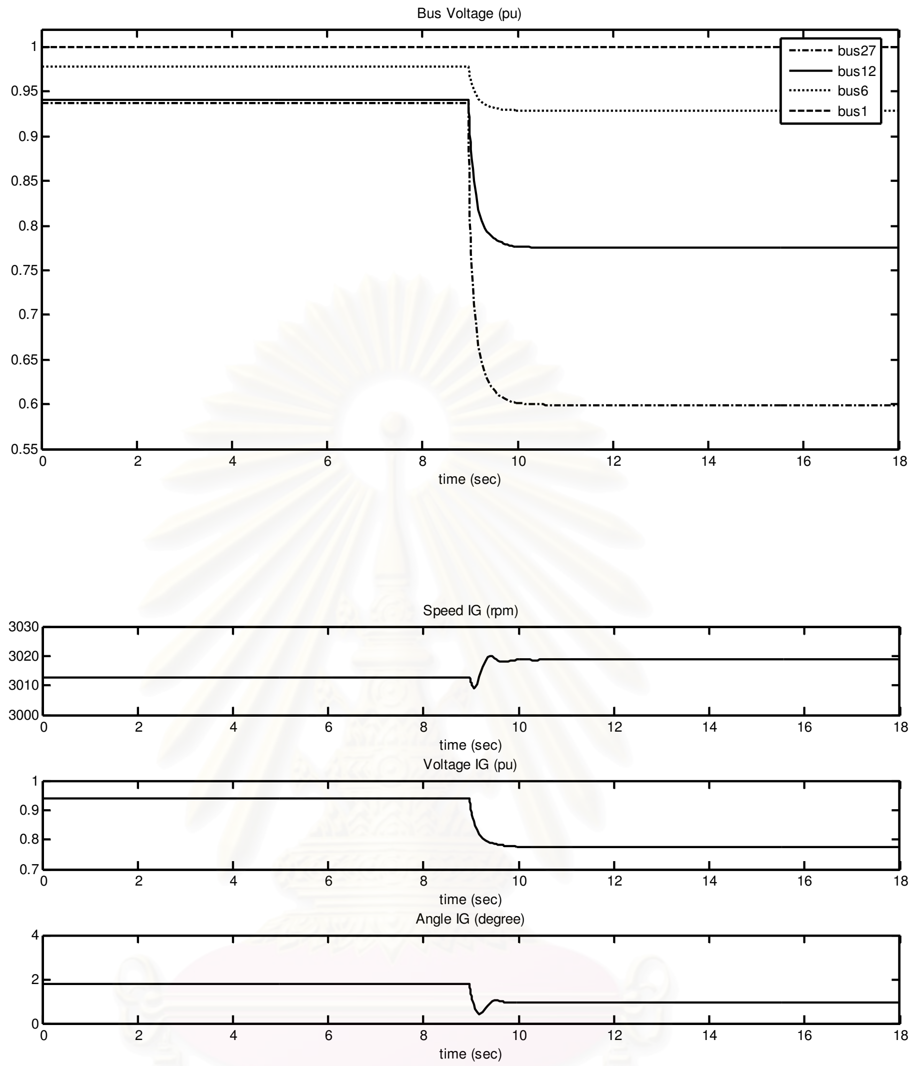

Figure 6.25 Dynamic responses of IG in the sixth case (cont.)

Compare to the previous case that the induction generator was unstably in the run away situation, in this case the Induction Generator with capacitor bank can be operated in stable condition even experiencing 0.7 lagging power factor load increment. It is due to the fact that some of the reactive power needed by the machine was supplied from the nearest capacitor banks. It made the machine terminal voltage was not too low. Hence, the Induction Generator can be stably operated. Furthermore, when the voltage at the induction generator terminal is somewhat raised up, its slip will be smaller such that the Induction Generator can be stably operated with higher loading level. In addition, the observed dynamic voltage responses correspond to lagging load increment is simply the first order delay.

CHAPTER VII

CONCLUSION

The studies on the voltage stability in the distribution system utilizing induction generators have been conducted in this thesis. This research revealed some important findings. The simulations demonstrated that induction generator could give significant impact on the voltage instability mainly in the distribution network. It can be concluded that utilization of the induction generator can deteriorate degree of voltage stability especially when the system is intended to serve inductive load. This condition is a result from the excessive reactive power required by the induction generator from the external source to build up its stator magnetic field. These phenomena drive the system to be in unstable conditions, both unstable of the induction generator itself, and unstable of the entire distribution system through the voltage instability.

Two kinds of analysis had been used in this thesis. They are static analysis and dynamic analysis. In static analysis, the degree of voltage instability based on PQVSI index is used as the main tool to assess how close the present operating condition to the voltage instability point. In this study, induction generator is modeled in the steady state equation and Newton Raphson power flow algorithm is utilized. In addition to the static analysis, the dynamic voltage stability was conducted as well to give the detailed profile of voltage characteristics and demonstrate the final stage at the point of voltage instability following a disturbance, which in this case is a load change. Using the reduced third order DQ model based on grid connected squirrel cage induction generator installed in distribution system and loads are modeled with dynamic constant real and reactive power, the dynamic characteristics of system voltage were investigated to verify the result from static analysis. It provides clearer and more accurate figure of the actual dynamics of voltage instability process following a disturbance in the system.

In this study, the advantages of installing the capacitor bank at the induction generator terminal had also been presented. The possible reason why the induction generator with a capacitor bank can supply more power to the main grid is due to the fact that some of the reactive power from capacitor banks can also enhance the voltage level at generator bus. Besides, that capacitor may result in a healthier power system network on the voltage stability point of view, reflected by the voltage stability indices used in this thesis. Another finding is also revealed. From the voltage stability point of view, installing Induction Generator at different locations might give significant impact. The system voltage stability would be more immune to the load increment when the Induction Generator is connected close to the main grid.

It is supposed several benefits come up from this thesis. A few might be put forward here, which is providing a tool in :

1. investigating the static voltage stability and its indices of the power network which is utilizing induction generator and,
2. investigating the detailed dynamic of voltage behavior and voltage figure of a network incorporating induction generator, especially when the network having a load change.

Several important aspects that might be considered as a new investigation can be deducted from this thesis. To the best author's knowledge, as mentioned in motivation section, there is no previous research covering both static and dynamic analysis in investigating voltage stability characteristic considering induction generator. Then hopefully, these studies fill the untouched areas in analyzing voltage stability, particularly on distributed generation.

It is expected that this studies will be useful for analysis of the voltage stability in the power system utilizing induction generator especially for power system operation and planning. It will be crucial to power system engineer to be able to schedule and prepare a proper power system operation and planning, to help mitigate voltage instability within the actual power systems. The contributions of this research would be a media that can help power system engineer or/and operator to be:

1. able to understand the static and dynamic behaviors of induction generator,
2. able to understand mechanisms of several static voltage stability indices.
3. able to investigate the static and dynamic voltage stability phenomena in distribution system installed with induction generator.

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APPENDIX

Table A.1 The induction machine's parameters used in static analysis

Real power generating capacity	1 MW	Xm (pu)	287
Rs (pu)	3.38	Rr (pu)	4
Xs (pu)	5	Xr (pu)	34
Rm (pu)	18100		

Table A.2 The Tahsai system, 35 bus system datum

Bus i	Bus j	R(pu)	X(pu)	B(pu)
1	2	0.0054	0.0104	0
1	35	0.0000001	0.0000001	0
2	3	0.0218	0.043	0
3	4	0.029	0.0574	0
4	5	0.0327	0.0646	0
5	6	0.0055	0.0031	0
5	7	0.0341	0.0674	0
7	8	0.011	0.0063	0
4	9	0.0015	0.0029	0
9	10	0.0029	0.0057	0
10	11	0.0058	0.0115	0
11	12	0.1198	0.2367	0
12	13	0.016	0.0316	0
13	14	0.0015	0.0028	0
13	15	0.0218	0.043	0
15	16	0.0225	0.0445	0
16	17	0.024	0.0473	0
17	18	0.0254	0.0502	0
12	19	0.0015	0.0029	0
19	20	0.0028	0.0016	0
19	21	0.0123	0.0244	0
21	22	0.0055	0.0032	0
21	23	0.0123	0.0244	0
23	24	0.0058	0.0111	0
23	25	0.0182	0.0359	0
25	26	0.0116	0.023	0
26	27	0.1133	0.2238	0
27	28	0.0441	0.0257	0
25	29	0.0196	0.0387	0
29	30	0.0015	0.0028	0
29	31	0.0211	0.0416	0
31	32	0.011	0.0064	0
31	33	0.0225	0.0445	0
33	34	0.0055	0.0032	0

Table A.3 The Tahsai system, 35 bus system loading datum

Bus	Type	Load P(MW)	Load Q(MVar)
1	PV bus	0	0
2	PQ bus	0	0
3	PQ bus	0	0
4	PQ bus	0	0
5	PQ bus	0	0
6	PQ bus	0.528	0.327
7	PQ bus	0	0
8	PQ bus	0.66	0.409
9	PQ bus	0.066	0.04
10	PQ bus	0.33	0.204
11	PQ bus	0.528	0.327
12	PQ bus	0	0
13	PQ bus	0	0
14	PQ bus	0.66	0.409
15	PQ bus	0.165	0.102
16	PQ bus	0.623	0.386
17	PQ bus	0.99	0.613
18	PQ bus	0.66	0.409
19	PQ bus	0	0
20	PQ bus	0.066	0.04
21	PQ bus	0	0
22	PQ bus	0.33	0.204
23	PQ bus	0	0
24	PQ bus	1.65	1.022
25	PQ bus	0	0
26	PQ bus	0.105	0.065
27	PQ bus	0	0
28	PQ bus	0.033	0.02
29	PQ bus	0	0
30	PQ bus	0.99	0.613
31	PQ bus	0	0
32	PQ bus	0.33	0.204
33	PQ bus	0	0
34	PQ bus	0.165	0.102
35	Slack bus	0	0

Table A.4 The induction machine's parameters used in dynamic analysis [33]

Rr (pu)	Xr (pu)	Rs (pu)	Xs (pu)	Xm (pu)	H (second)
0.014	0.098	0.01	0.1	3.5	1.5

Table A.5 The 6 bus system's parameters used in dynamic analysis [32, 33]

Bus i	Bus j	R(pu)	X(pu)	B(pu)
1	2	0.005	0.02	0
1	2	0.0046	0.02	0
2	3	0.044627	0.19178	0
3	4	0.23874	0.41541	0
2	4	0.021487	0.034271	0
4	5	0.011937	0.02077	0
5	6	0.005	0.02	0

Table A.6 The 6 bus system loading used in dynamic analysis [32, 33]

Bus	Type	Load P (MW)	Load Q (MVar)
1	PV bus	0	0
2	PQ bus	5	2
3	PQ bus	10	5
4	PQ bus	1	0.4843
5	PQ bus	9	3
6	PQ bus	-25	27.4611

BIOGRAPHY

Wisasongko Dwi Martianto was born in Yogyakarta, Indonesia, in 1979. He received B.Eng in Electrical Engineering from Gadjah Mada University, Indonesia in 2002. He was awarded JICA Project for AUN/SEED-Net scholarship to continue his Graduate study at Department of Electrical Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand on May 2007. His research interests are in power system modelling.