INTELLIGENT CONTROL FOR ENERGY MANAGEMENT SYSTEM FOR REDUCING ANCILLARY SERVICES

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A project report submitted in partial fulfilment
of the requirements for the award of
Master of Engineering in Electrical Engineering

Faculty of Engineering and Science
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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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Date : ____________________

DEDICATION

Specially dedicated to

my beloved wife and two lovely daughter.

ACKNOWLEDGEMENTS

I would like to thank everyone who had contributed to the successful completion of this project. I would like to express my gratitude to my research supervisor, **Dr. Lim Yun Seng** for his invaluable advice, guidance and his enormous patience throughout the development of the research.

In addition, I would also like to express my gratitude to my loving wife and daughters who had supported and given me encouragement to pursue this Master degree. Without theirs engorgement, I would not have finished this course work.

I am most grateful to my fellow course mate, **Mr. Kok Chin Chai** and **Mr. Roger Lee Khen Shen** for supporting and guidance to complete this course work.

ABSTRACT

In any electric force frameworks, there are two primary elements to be consistently taken after and precisely fulfilled keeping in mind to satisfy overall system stability and reliability. Mainly, (i) to keep a consistent balancing between generation and load demand, and (ii) to regular power generation (or load) and to handle power flows within the limitation of individual transmission facilities (there is no flow control). Ancillary services are not new in the market and power systems require this service to maintain reliability and stability to delivery enginery to consumers. Several ancillary services are available in the market.

This project is about to simulate the stabilization of the generation and load in balance of the power system network, also maintaining the operational reliability of the transmission network. In general, generators can only operate within a narrow range of frequencies. When the frequency is too high or too low, the protection system will disconnect the generator automatically. This causes further imbalance between load and generation. Hence the frequency shall be maintained within the limits. This project uses energy storage system to maintain the stability of the network when the generation is not matching the load profile is required. This project use MATLAB software as simulation tool to simulate the generation model and. analyse the load profile when exceeding the capacity of generation. From the result, it shows the model developed is function correctly and the objective is achieved.

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LIST OF SYMBOLS / ABBREVIATIONS

BESS	Battery Energy Storage System
DC	Direct Current
EMF	Electromagnetic Field
p.f	Power Factor
VAR	Variable Amplitude Regulator.

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CHAPTER 1

INTRODUCTION

1.1 Background of the study

In electricity markets, it relies on its power system infrastructure. Especially consumers have high expectations regarding the reliability of service from the generation. The power system must be able to operate continuously if situation changing immediately due to unexpected load demand and must remain stable for common contingencies. This paper describes ancillary service models that use the synchronous generator with excitation system as the operation of the power system to perform the reliable and stability analysis and minimize the impact on the voltage and frequency during normal operation or under unexpected disturbance. The methods discussed in this paper are on synchronous generator and battery energy storage system. Design tool MATLAB/Simulink is used to perform and analysis this study.

1.1.1 Synchronous Generator

Synchronous generators are widely used to generate the electrical energy. They change from the mechanical energy output in the another state of energy form of steam turbines, gas turbines, reciprocating engines and hydro turbines into electrical power of the grid. The term synchronous means the rotor and excited magnetic field are both turning in same speed. The magnetic field is generated mainly through the rotating shaft mounted together at the generator with permanent magnet mechanism and hence current is induced inside of the stationary armature.

The synchronous generators with embedded permanent magnet in the steel rotor do not supply any DC supply for the neither excitation circuit, nor it has slip rings and contact brushes. The permanent magnet in the generator produces the magnetic field of the rotor. There are some of generators use electromagnets to generate magnetic field in a rotor winding. This will induced the direct current in the rotor field winding and is fed through a slip-ring mechanism or provided through by a brushless exciter on the same shaft.

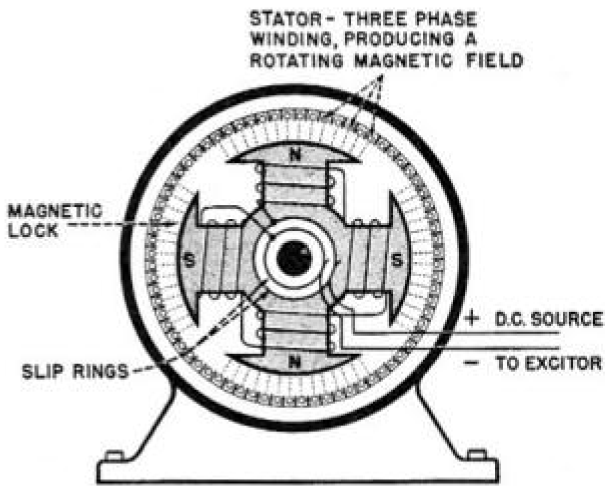

Figure 1.1: Induction Generator Cross- sectional view with DC exciter

Synchronous generators produce electricity whose frequency f (measured in hertz) is synchronized with the mechanical rotational speed in revolutions per minute (or angular speed).

$$f\ (Hz) = \omega \frac{P}{120}.[1] \qquad [1.1]$$

Where :

f = electrical frequency(Hz);

ω = rotor speed of the machine (rpm)

p = number of poles

Synchronous generator is always designed with a fixed number of poles. To maintain the frequency from the induced emf contact at the value of 50Hz or 60Hz, the generator shall be driven at a fixed synchronous speed. The table below shows to maintain the frequency at 50Hz, the numbers of individual poles should rotates in the required rotational speed.

Number of Individual Poles	2	4	8	12	24	36	48
Rotational Speed (rpm)	3,000	1,500	750	500	250	167	125

Table 1.1: Rotational speed with the individual poles at 50 Hz

Number of Individual Poles	2	4	8	12	24	36	48
Rotational Speed (rpm)	3,600	1,800	900	600	300	200	150

Table 1.2: Rotational speed with the individual poles at 60 Hz

1.2 Battery Energy Storage System (BESS) Technology

Power system reliability depends upon the ancillary services to maintain the balance between generation and consumption. The battery energy storage system (BESS) is commonly use devices as contingency grid support comprises of batteries and control mechanism. The battery is the major components in BESS and each of these technologies is rapidly developing. The battery can be categories in the following type with their advantages and disadvantages:

- Lead-acid
- Lithium ion (Li-ion)
- Nickel cadmium (NiCd)
- Nickel metal hydride (NiMH)

The existence of the lead-acid battery has been quiet sometime and considered the most mature technology that has been implemented in the electrical energy storage industrial. They are perfectly suited in the small-cycle renewable energy integration applications. The advantage of the lead-acid battery is it can be discharged repeatedly up to 80% of its capacity and suitable for integration into the grid connected systems where most of the users sell the energy back to the grid through net metering.

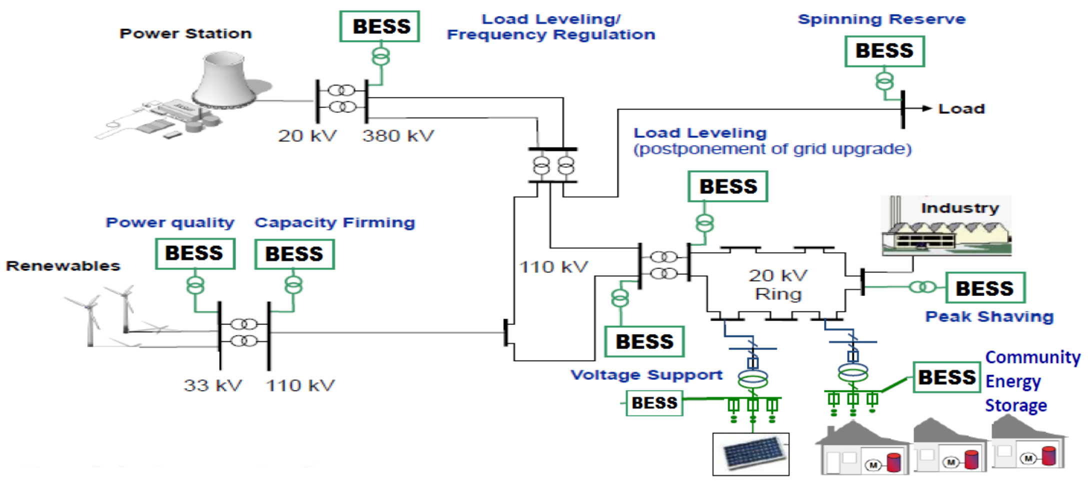

Figure 1.2: An Overview of BESS Application in Power System

1.3 Problem Statement

This project is focused on the design and simulation of simple power system network comprise of synchronous generator with excitation system and BESS to stabilize the generator's frequency and speed when the load profile of the network is existing the generation by using MATLAB/SIMULINK.

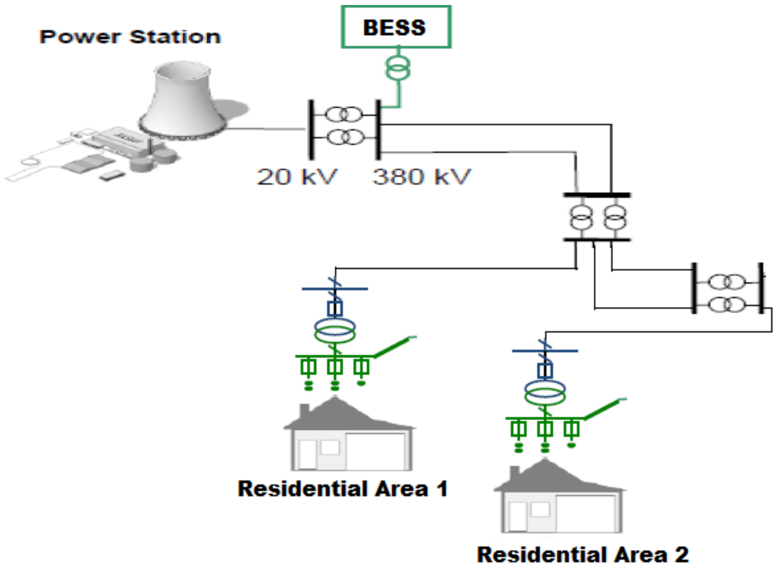

Figure 1.3 : Simple Power System Network with BESS

Battery energy storage system (BESS) is to provide the active power which connects to grid network when the demand is suddenly beyond the capacity of the generation. This will cause the entire network collapse when the power generator could not meet the load profile required. MATLAB/SIMULINK software is used to simulate the result of this simple network with or without battery storage energy system.

1.4 Objective of Project

The objectives of this project are to:

1. Simulate the current and frequency of synchronous generator to maintain the stability of the network with various load profile using MATLAB

2. Design the Energy Storage System (ESS) model to supply requires active power when load profile is exceeding capacity of synchronous generator to avoid collapsing of entire network system.

1.5 Scope of the Project

In this project, there are two main scopes to be completed for the success of this project:

1. Construct three phase network system including excitation system of synchronous generator in MATLAB together with the various load profile to view changes of current and frequency of synchronous generator.

2. Design simple Energy Storage System (ESS) with the PWM generator solution with stores energy for usage when at the time load profile beyond the capacity of generation profile.

CHAPTER 2

LITERATURE REVIEW

2.1 Synchronous Generator Operation Mode

The operation of a synchronous motor is the interaction between the magnetic fields of the stator and the rotor. Normally, the stator with 3 phase winding will be supplied with 3 phase supply. With no permanent magnet inside the steel rotor, it is provided with DC supply. Hence, with 3 phase stator winding in the generator carries 3 phase currents which produce 3 phase rotating magnetic flux and hence rotate magnetic field.

When the rotor rotates along with it and locks in with the rotating magnetic field, the generator is said to be in synchronous. Once the generator is running in at the full speed, the speed of the generator is dependent only on the supply frequency. Based on the equation from [1.1]

$$f\ (Hz) = \omega \frac{P}{120}$$

Where :

f = electrical frequency (Hz);

ω = rotor speed of the machine (rpm)

p = number of poles

Since, P / 120 is constant; hence, the equation can be further derived as following

$$f\ (Hz) \propto\ \omega\ (rpm) \qquad [1.2]$$

When the generator load is increased and beyond the breakdown load, the generator will start to falls out of synchronization zone. When this happens the field winding no longer follows the magnetic field rotation. The generator starts not to produce (synchronous) torque when falling out from synchronization zone.

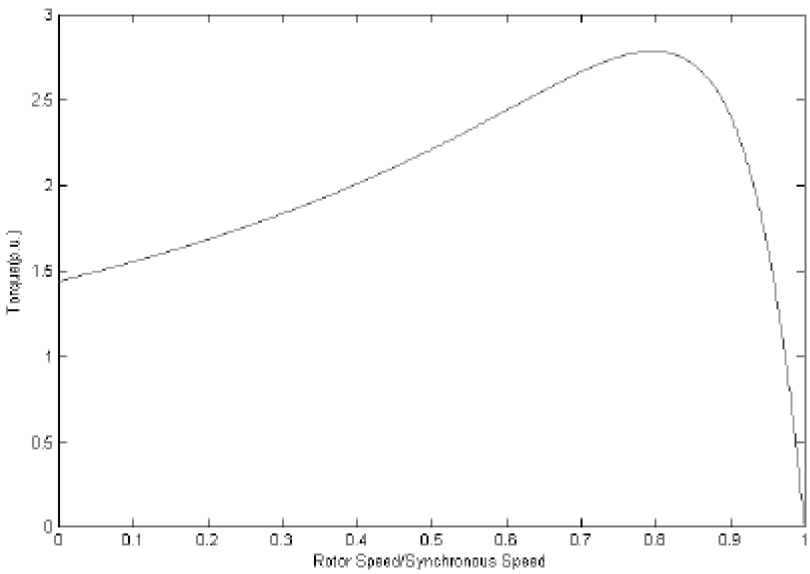

Figure 2.1: Torque Speed Characteristic of an Induction Machine

In practical, most of the synchronous generators have a partial or complete squirrel-cage damper winding to maintain the operational stability and facilitate of the starting. Since this winding is small and can be overheated on the long operation. However, due to large amount of slip-frequency voltages are produced in the rotor excitation winding, the generators protection devices start to interrupt the power supply when it senses this condition starting to happen (out of step protection).[2]

2.1.1 Field Excitation System

The filed exciter system is the "backbone" of the generator control system. It is the main power source supplies the dc magnetizing current to the field windings of a synchronous generator. Hence, ultimately this induces AC voltage and current in the generator armature.

There are two basic kinds of exciters; rotating & static exciters.

Rotating exciters can be categorized in two types.

- Rotating (brushless type) does not require slip-rings, commutators, brushes and are practically maintenance free.
- Rotating (brush type) require slip-rings, commutators and brushes and require periodic maintenance.

Static excitation means no moving parts. It provides faster transient response than rotary exciters.

- Static shunt exciters operates field power from generator output voltage
- Static series exciters operates field power from generator output voltage & current

The excitation activities which required maintaining the output voltage constant is a function of the generator load. As the generator load increases, the amount of excitation increases.

- Reactive lagging pf loads require more excitation than unity pf loads
- Leading pf loads require less excitation than unity pf loads

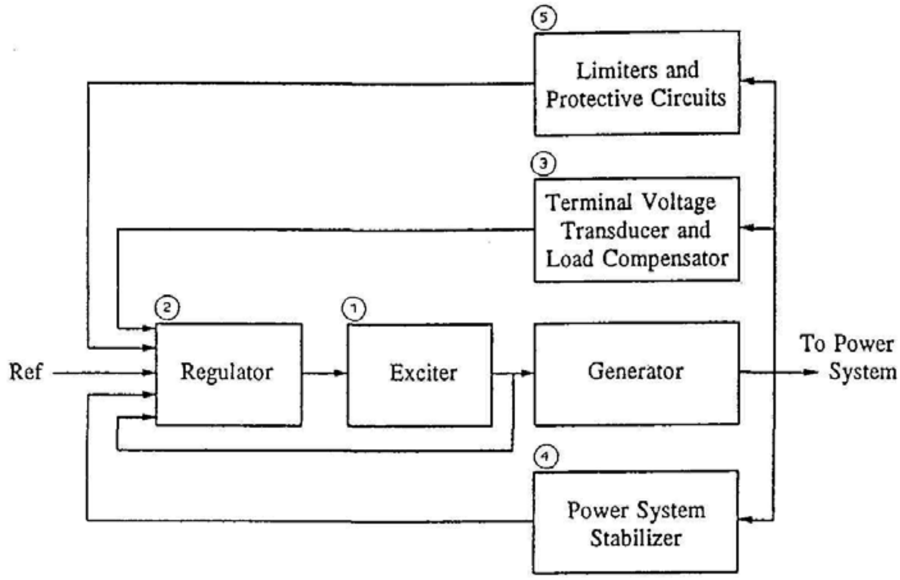

Figure 2.2: Common Elements of an Excitation System

The voltage transformers provide signals which are proportional to line voltage to the AVR and compare to a stable per unit reference voltage. The difference (error) signal is computed and used to control the output of the exciter field. For example, if load on the generator increases, the reduction in output voltage produces an error signal which increases the exciter field current resulting in a corresponding increase in rotor current and thus generator output voltage.

Since the generator field windings have high inductance, it is difficult to make fast response change in field current. Hence, this makes the control system “lag’ in the control response and it is necessary to include stabilizer mechanism to avoid instability and control the generator voltage response to the load changes. Without having stabilizer mechanism, the voltage regulator keeps increasing and reducing the excitation and makes the line voltage continually vary above and below the nominal value. Advanced voltage regulators are designed to maintain the generator line voltage within better than +/- 1% of the nominal value for wide variations of machine load.

2.1.2 Voltage-Regulation

The voltage-regulation of a generator is the voltage increase at the terminals when the load is increasing and the excitation and generator’s speed remaining constant. The voltage increase is basically the numerical difference between $Va_{(NL)}$ and $Va_{(rated)}$, expressed as

$$V = \frac{\mathrm{Va(NL)} - \mathrm{Va(rated)}}{\mathrm{Va(rated)}}\ per\ unit \qquad [2.1]$$

where

$Va_{(rated)}$ = terminal voltage of a given load

$Va_{(NL)}$ = open-circuit voltage with same field excitation.

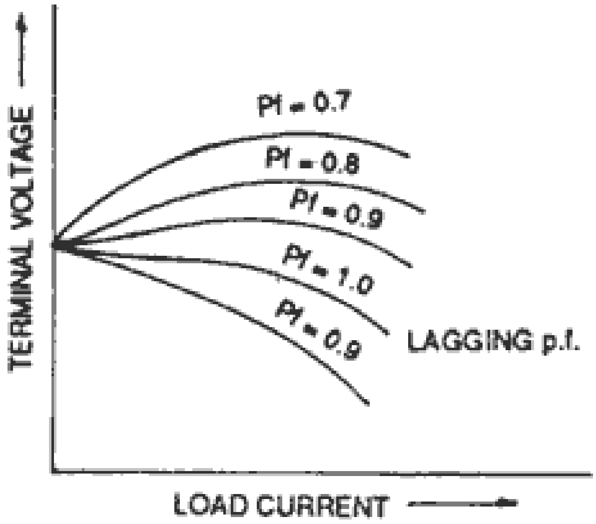

Figure 2.3: Synchronous Generators Load Characteristics

When comparing the voltages at full load (considering 1 per unit normal current), Fig. 2.3 shows that it is much dependent on the power factor (p.f) of the given loads. For unity and lagging power factors there is always a voltage drop when the load is increasing. When full-load regulation is zero, means the terminal voltage is the same either at full and no-load conditions with leading power factors. When regulation is negative, the voltage rises with load increases at lower leading power factors.

2.2 Battery energy storage technology

The goal of this project report is to design a simplified version of the battery energy storage system, in such this is not to go in more detail of the type of core attributes, and to model these attributes to observe the performance of the battery. The fundamental attributes of the battery type were determined to be

- peak charge/discharge rate
- energy capacity
- maximum depth of discharge
- capacity factor
- charge/discharge efficiency

2.2.1 Battery Type

The battery type is of the utmost importance factor of the BESS. Sometime, it is difficult to get a complete the technical specifications of the battery types which were not used explicitly in the model, but rather implicitly. In this section to outline some battery types are commonly used with choosing a battery configuration for a power system.

Lead-Acid (Pb-Acid) battery is the oldest rechargeable battery and having low energy-to-weight ratio and low energy-to-volume ratio. Its capability to supply high surge currents means the battery cells have a quite large power-to-weight ratio. It is hardly found the application in the electronics or electrical vehicle applications due to its low energy to weight ratio. With its size and weight reason, their primary application as a method to supply power to the lighting and ignition systems in the vehicle application. [3]. They are more common in the grid-level energy storage where weight and size are not a major factor. Battery types such as NiCd and NiMH are often used in the grid-level offer substantially greater storage capacity and longer life cycle than Lead-Acid battery.

Lithium-ion (Li-ion) batteries have great energy efficiency rates of 85-95%. In term of energy density and power density, these enable them to be the dominant form of energy storage with small size and weight. Relatively low self-discharge rate between 5% and 10% per month and life cycle of the batteries are about 3000 charge cycles. Their cost is prohibitively high for most applications in grid-level energy storage, where larger, cheaper alternatives abound. The cost of lithium based batteries is expected to continue to rise as they are used more frequently in consumer electronics and electric vehicle applications, while the world's known supply of lithium is being depleted faster than new stores are discovered [6].

Nickel-cadmium (NiCd) batteries are one of the popular used battery types in grid-scale energy storage. They have a substantial better charge cycle energy efficiency which positions them ahead of almost every other battery type [3] With the low self-discharge rate, this would not be relevant to the grid level connected to the BESS system.[4] One relevant aspect that NiCd would be a major component in BESS is their life cycle has an average approximately 3000 charge cycles

Nickel-metal hydride (NiMH) batteries are commonly used in many applications for their high power-to-weight ratio. Overall efficiency of charging cycle with documented rates of 50 – 80% and it not a strong is not a speciality of a typical NiMH battery. The life cycle of the NiMH battery is typically 500 and 2000 cycles depending on its application.[5].

Type	Min. Charge (%)	Efficiency (%)	Cycles	Cost ($/kWh)
Pb-Acid	30	75	1500	135
Li-Ion	20	93	3000	1145
Ni-Cd	0	75	3000	540
Na-S	0/15	89	2500/4500	500

Table 2.1: Battery types and their characterises and attributes

CHAPTER 3

METHODOLOGY

3.1 Research Methods

The simple method of research for this thesis was to build a simple model of synchronous generators coupling with field exciter system in the power plant with an integrated of BESS and observe the reaction of the synchronous generators how its react when the demand load is exceeding the load profile of the generator.

This system was modelled in MATLAB Simulink, and then its simulated field exciter (small synchronous machine) proving the field current to synchronous generators. Each of the different loads on the models tested to measure the generator speed. In second part, the BESS model is integrated into the model to overcome the shortage of the power demand from synchronous generator. Finally, the experiment was performed with different combination of loads profile with/without of BESS. The results were analysed based on of these common scenarios.

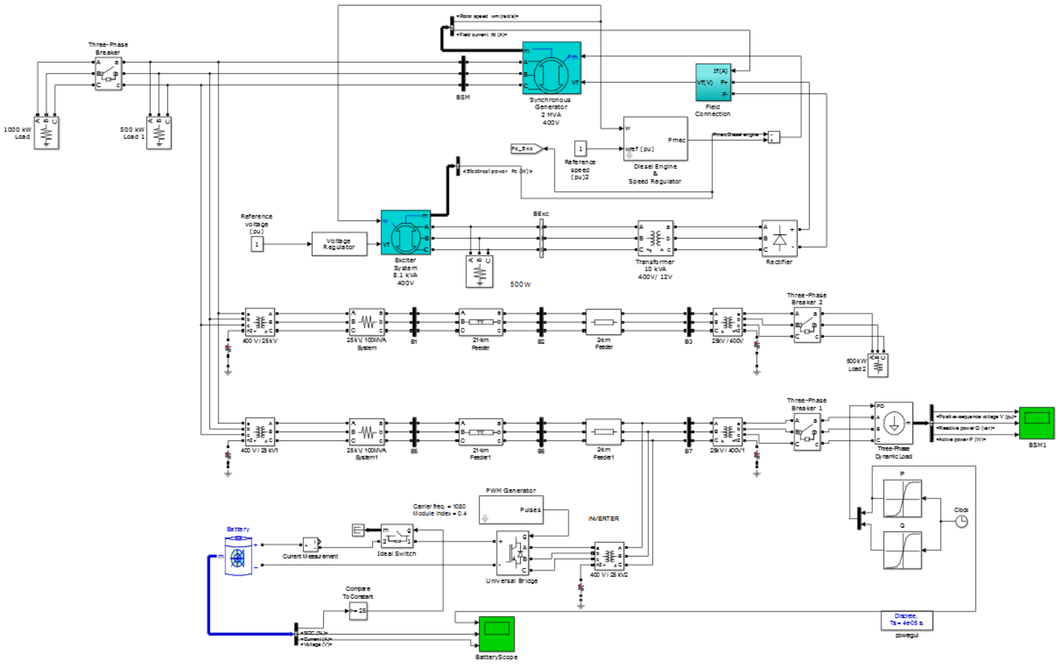

Figure 3.1: The overall model of synchronous generators coupling with field exciter system and integration of BESS.

3.2 Synchronous Machine Model

The synchronous generators are commonly used in many of the power applications because they can offer accurate control of voltage, frequency, VARs and WATTs. The control methods can be achieved by using voltage regulators and governors.

A synchronous generator consists of a rotating DC field - the rotor. An EMF is produced when the interaction between the rotor and stator with the magnetic flux developed across the air gap. When the magnetic flux is generated by the DC field poles crossing the air gap of the stator windings, hence, an alternating voltage a sinusoidal voltage is produced at the output terminals of the generator. This process calls electromagnetic induction

In most of the large generators, there is a small synchronous machine provides the excitation system which attached on the same shaft of the main synchronous generator. In this model, the Exciter is a small synchronous machine rated 8.1 kVA, 400 V, 50Hz, 1500 RPM. A step down 400V / 12 V transformers is used to adapt the 400 V output voltage of the exciter to the rectifier. In real life this transformer would not be implemented. Instead, the Exciter output voltage would rather be 12 V.

The current rectification process is handled by a rotating diode bridge circuit normally mounted on the synchronous machine shaft, thus avoiding slip rings to supply DC power to the synchronous generator field. Mechanical coupling of the Synchronous generator and the Exciter is done by using speed as mechanical input for the Exciter machine. The output of the rectifier bridge is connected directly to the synchronous generator field terminals. Filtering is not required because of the large field inductance.

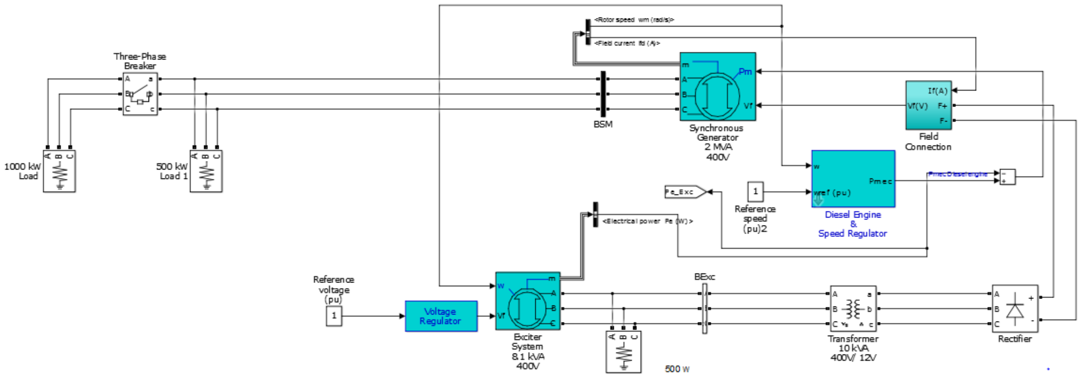

Figure 3.2: The exciter system with synchronous generator with loads

The synchronous generator is a 2 MVA, 400V, 50 Hz, 1500 rpm machine a diesel driven motor. A nominal field current (Ifn) of 100A specified in the mask parameters allows using the real voltage applied to the rotor (not the field voltage seen from stator). It results in a nominal field voltage of 9.2837 V. The field terminal voltage of the synchronous generator is measured inside the "Field Connections" subsystem.

This subsystem is required to interface the input field voltage (Vf) of the synchronous machine and the real field terminals. It uses a current source driven by the DC current output of the bridge which also corresponds to the DC field current. The voltage appearing across this current source corresponds to the field voltage which must be applied to the Vf Synchronous Machine input.

Voltage regulation of the generator is performed by controlling the field voltage of the exciter. The Diesel engine provides the total mechanical power required by the main synchronous machine and the exciter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Experiment 1

When running the following model in the MATLAB simulation, from the Synchronous Generator (2 MVA, 400V, 50 Hz, 1500 rpm) scope block with the load of 1.5 MW, the result can be observed as following:

At Trace 1, from t = 0 to t = 3 sec the synchronous machine delivers 500 kW (25 % of its rating). The excitation current starts from 112 A, At t=3 sec, an additional 1000 kW is switched on by closing the circuit breaker. In order to keep voltage at 1 pu, the excitation current increases from 112 A to 185 A.

The field voltage in Trace 2 (Figure 4.2) contains a 300 Hz ripple, but this ripple does not appear in the field current because of the large field inductance.

Trace 3 (Figure 4.2) shows that after load switching the synchronous machine terminal voltage resumes to its nominal value after a 3 second transient.

Traces 4 and 5 (Figure 4.2) show the mechanical output power of the diesel engine and the speed of the engine-generator set. Speed regulation maintains 1 pu speed and nominal frequency (50 Hz output voltage).

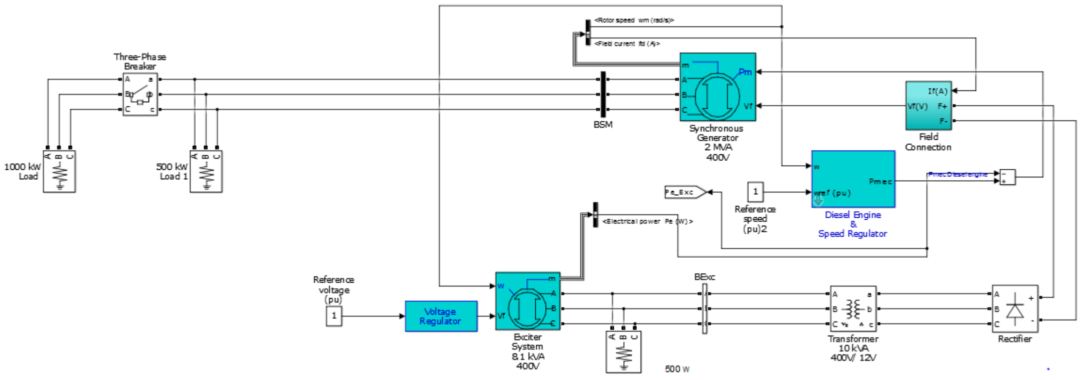

Figure 4.1: Experiment 1 model

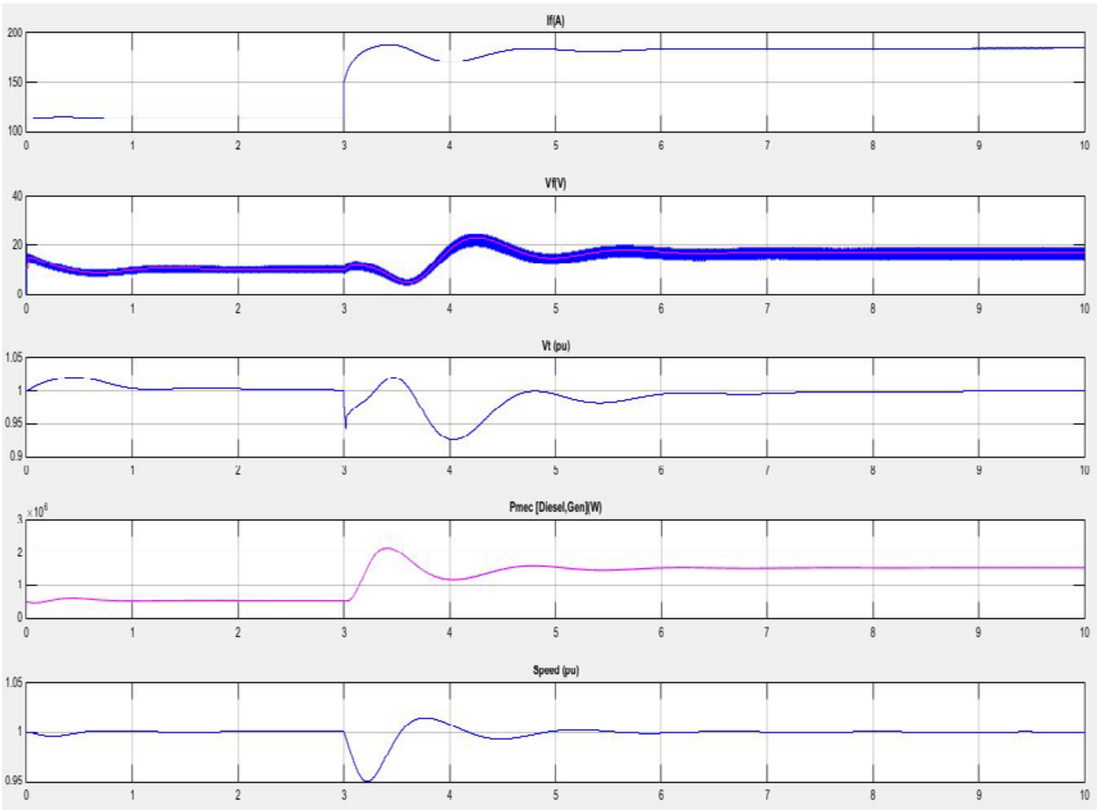

Figure 4.2: Experiment 1 result.

4.2 Experiment 2

In this experiment additional load 0.5kW is added through the long distance transmission line. From t = 0 to t = 6 sec, the synchronous machine delivers 15500 kW at 75 % of its rating after the circuit breaker closed at t=3 sec.

The circuit breaker 2 will be closed right after t=6 sec. Hence, additional 0.5 kW load demand from the synchronous generators running at 100% of it rating.

At Trace 1 (Figure 4.4), it shows right after t=6 sec the synchronous machine delivers 2MW (at 100 % of its rating). In order to keep voltage at 1 pu, the excitation current increases from 185 A to 226 A.

Trace 3 (Figure 4.4) shows that after load switching the synchronous machine terminal voltage resumes to its nominal value after a 3 second transient.

Trace 4 (Figure 4.4) show the mechanical output power of the diesel engine is increased from 1.5 MW to 2 MW after the circuit breaker 2 is closed t=6 sec.

Trace 5 (Figure 4.4) show the speed regulations of the engine-generator set is always maintains at 1 pu speed and nominal frequency (50 Hz output voltage).

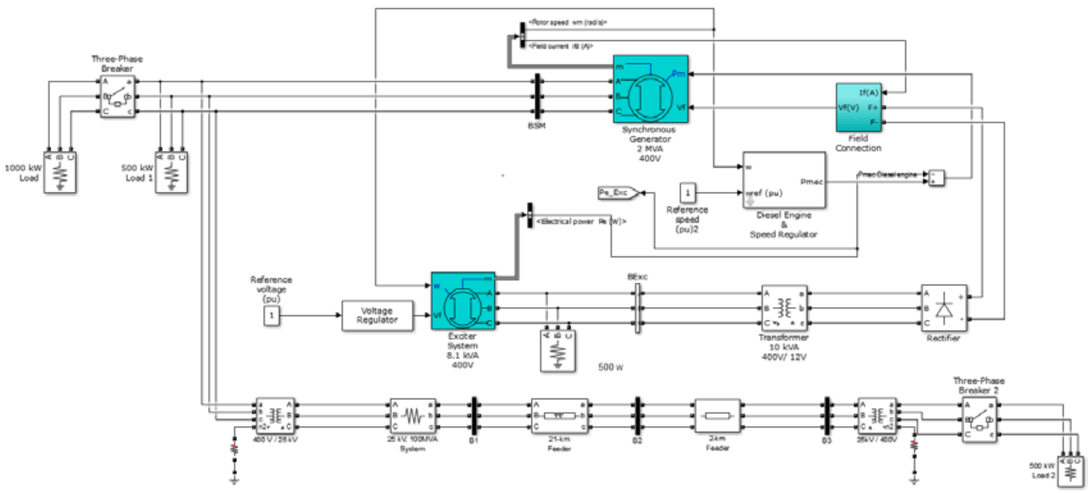

Figure 4.3: Experiment 2 model with addition 0.5kW

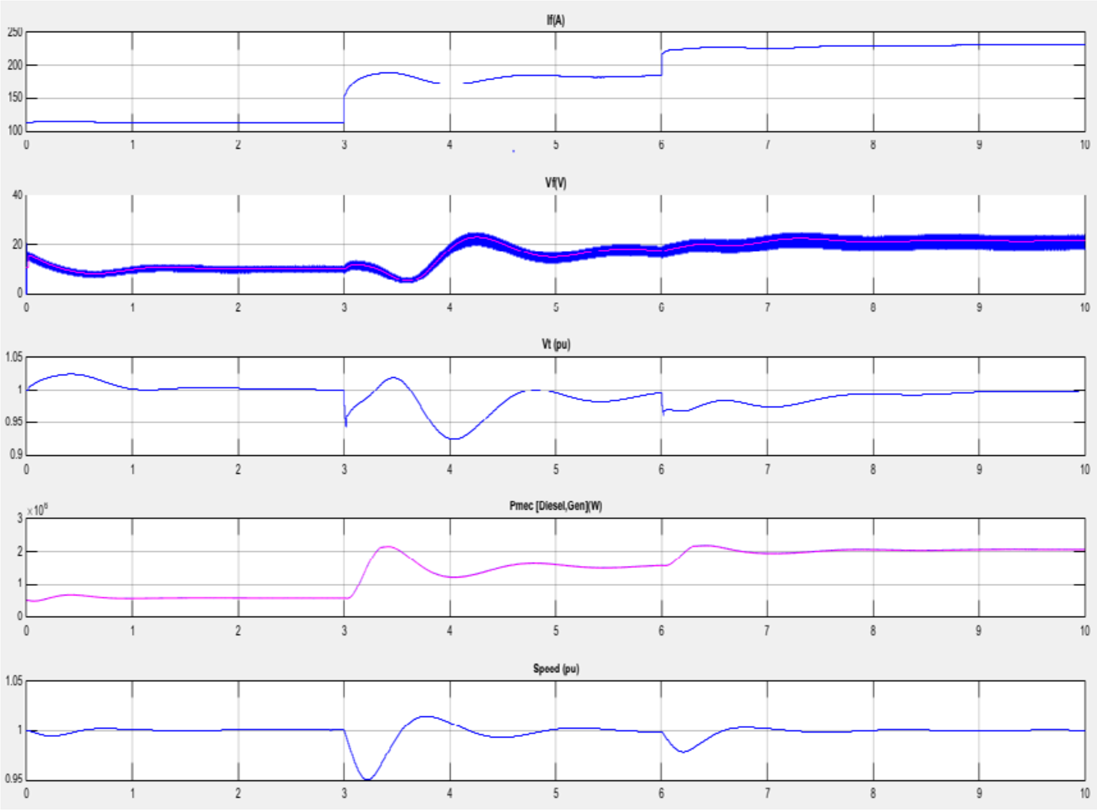

Figure 4.4: Experiment 2 result with additional 0.5 kW load.

4.3 Experiment 3

In this experiment, the load demand at 2MW is still maintain. Adding additional long distance transmission line with the variable load instead of static load demand from generator shown in Figure 4.5 (load profile generated in the table array format in MATLAB). In this model, only active power P is being formulated in the table array while the table array for the reactive power Q will not be simulated in this project thesis.

From t = 0 to t = 7 sec, the synchronous machine delivers 2 MW at 100 % of its rating after the circuit breaker 1 & 2 closed at t=2 and t=5 sec.

After t=7 sec, circuit breaker 3 is closed, the variable load will start demanding more load from the synchronous generator. The load profile is exceeding the overall capacity of the synchronous generators. In order to maintains at 1 pu speed and nominal frequency, nominal filed current increases up to 280 A before it start to collapse at t=9 sec. The generator stop to generate power after t=9 sec as the speed is decreasing gradually.

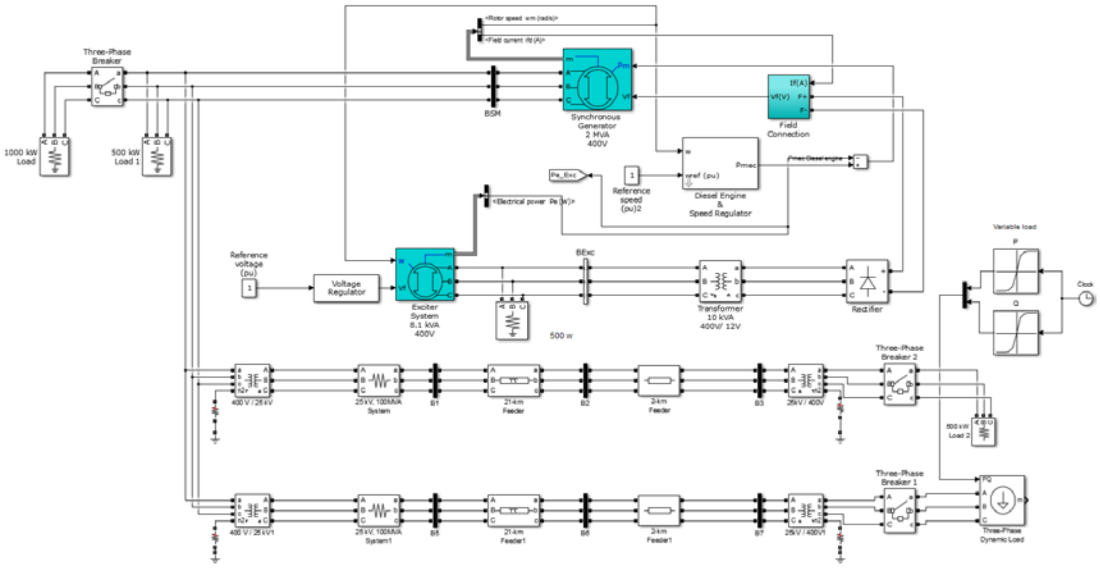

Figure 4.5: Experiment 3 model with variable load demand at instantaneously

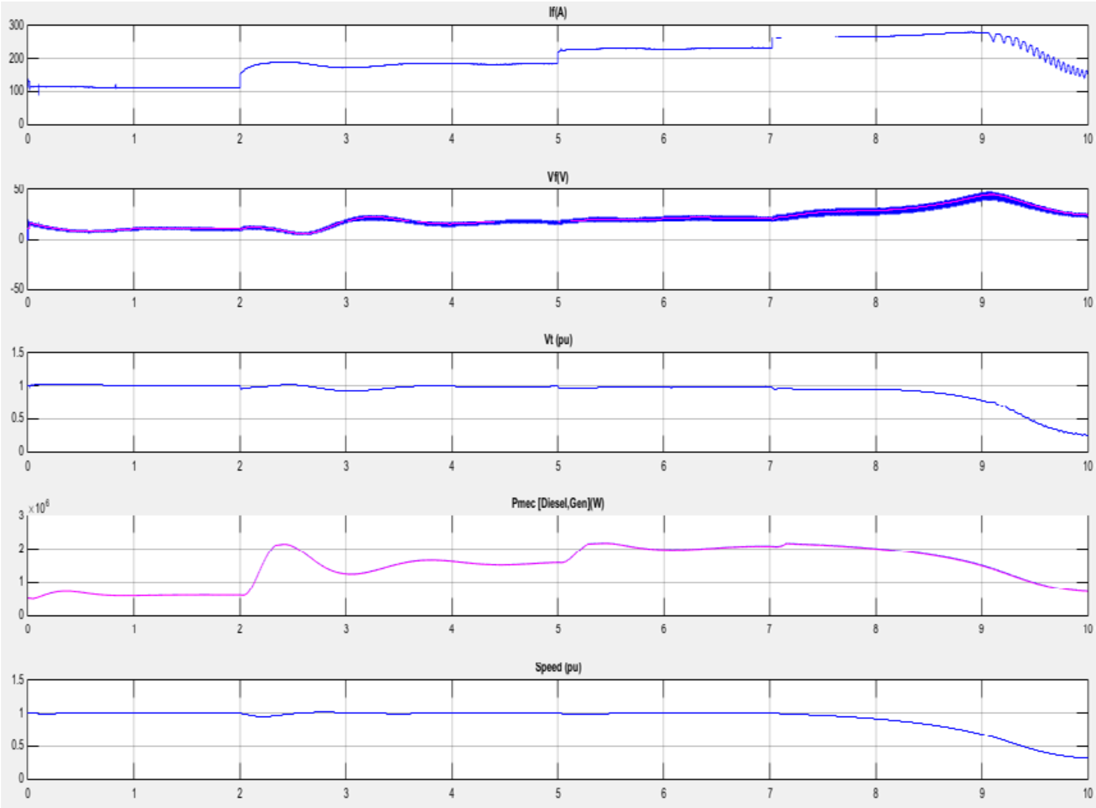

Figure 4.6: Experiment 3 result with variable load.

4.4 Experiment 4

In this experiment, the BESS model with the capacity of 40 kW is connected to the 25 kV transmission line. The entire power system is quite stable after connected with the BESS. There is significant improve in the stability of the network.

At t=7 sec, when the circuit breaker 3 is closed, the BESS start to supply the active power to the variable load following the demand in the load profile.

Although maintain the speed at 1 p.u, at the Trace 5 (Figure 4.8) show the speed of the synchronous generator is maintaining within 5% range.

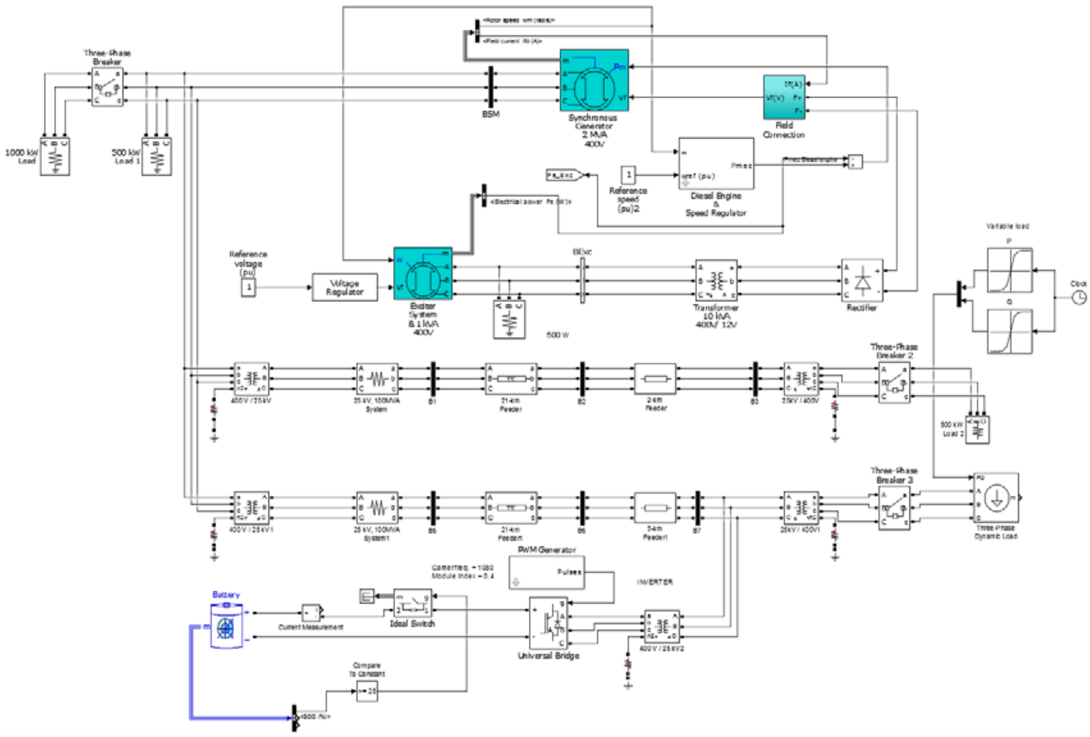

Figure 4.7: Experiment 4 model with BESS to supply the load profile from variable load.

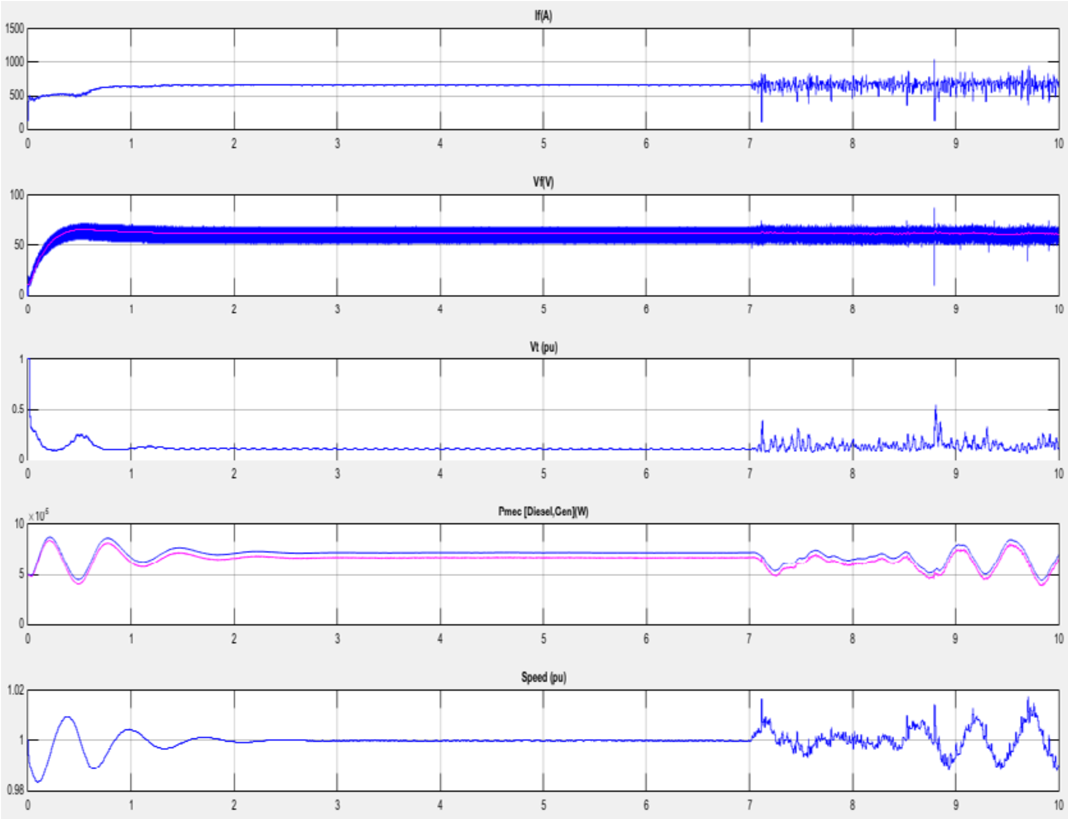

Figure 4.8: Experiment 4 model with BESS to supply the load profile from variable load

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In general, these results of each experiment reveal some important relationships between the parameters of the system. Experiment 4 has successfully shows with the BESS installed, the overall model significantly shows that the network can sustain further at any instant load demand which is greater than the generation without causing the generators to stop operation. Although cost of the installation of BESS may be expensive at the initial stage, but with the new technology, this may bring the battery cost to lower further.

The ancillary services become more important to the current power system when the consumer has a high expectation on the power quality and stability of the network. Although it is not a common in our country, but, the near future, this will become a common service in every of the power industry.

5.2 Recommendations

This is to recommend that the upcoming if anyone to take over this project, the BESS model should be included with the control mechanism. This is to control and detects the required amount of the active power required for the entire power network. BESS should also to provide the right amount of the active power according to the load profile demanded.

Secondly, to construct a similar network and connect them together commonly use same BESS with the same amount of the capacity within the same network. Mainly not all the power network needs the ancillary services at all time. With the right mechanism, this would bring more benefits to the power system operators and as well as the consumers.

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APPENDICES