ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Alireza DELJAVAN ANVARI

DEVELOPMENT OF A NEW AUTOMATIC VOLTAGE REGULATOR FOR DIESEL GENERATOR SETS USING TWO SWITCH THREE STATE BUCK-BOOST CONVERTOR

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

ADANA, 2015

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We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on 10/07/2015.

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ABSTRACT

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DEVOLOPMEN OF A NEW AUTOMATIC VOLTAGE REGULATOR FOR DIESEL GENERATOR SETS USING TWO SWITCH TREE STATE BUCK-BOOST CONVERTOR

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Diesel generator sets are used worldwide as backup systems or prime systems to provide quality energy when there is no mains power handling loads. As diesel powered generators imitate main power while working the system, should produce constant, clean voltage as much as possible. For every site, loads may vary so it is a technical challenge to provide constant voltage every time the machine works. If the system produces unstable voltage, thus may harm electrical devices.

Recent years, the use of an automatic voltage regulator for a constant voltage is promoted to the market. There are different methods to provide constant voltage output as told in previous researches. These methods are discussed along with their advantages and disadvantages. These researches used complex control methods in many mathematical calculations to achieve an acceptable dynamic and transient response that causes the design cost to rise significantly.

In this study, a new automatic voltage regulator using two switch tri-state buck-boost convertor is considered. The advantage of this method is that it keeps a constant voltage with international standards; in addition, it shows reasonable dynamic and transient response.

Key Words: Two Switch Three State Buck-Boost Converter, Controller, Synchronous generator, PWM, Switching

ÖZ

YÜKSEK LİSANS TEZİ

İKİ ANAHTAR ÜÇ DURUM BUCK-BOOST ÇEVİRİCİ KULLANILARAK DİZEL JENERATÖR SETLRİ İÇİN YENİ BİR OTOMATİK GERİLİM REGÜLATÖRÜNÜN GELİŞTİRİLMESİ

Alireza DELJAVAN ANVARI

ÇUKUROVA ÜNİVERSİTESİ
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Dizel jeneratör setleri, yükleri besleyen ana şebeke gücü olmadığında kaliteli enerji sağlamak üzere yedek ya da ana sistemler olarak tüm dünyada kullanılmaktadır. Dizel jeneratörlerin ana şebeke de olduğu gibi mümkün olduğunca sabit ve temiz voltaj üretmesi gerekmektedir. Yükler her farklı yer için değişebileceğinden, makine çalışırken sürekli sabit voltajın sağlanması teknik bir zorluktur. Eğer sistem kararsız gerilim üretir ise, bu durum yüklere zarar verebilir.

Son yıllarda, sabit bir voltaj sağlamak için otomatik gerilim regülatörü kullanımı pazarda yükselmiştir. Önceki araştırmalarda söylediği gibi sabit gerilim çıkışı sağlamak için farklı yöntemler vardır. Bu yöntemler kendi avantaj ve dezavantajları ile birlikte tartışılmıştır. Kabul edilebilir bir dinamik ve geçici hal tepkisini elde etmek için bu çalışmalarda birçok matematiksel hesaplama içeren karmaşık kontrol metotları kullanılmış olup bu durum maliyetlerin önemli ölçüde artmasına neden olmuştur.

Bu çalışmada, iki anahtar üç durum alçaltıcı-yükseltici dönüştürücü kullanarak yeni bir otomatik voltaj regülatörü ele alınmıştır. Metodun avantajı uluslar arası standartlarda sabit gerilim sağlaması ve ek olarak kabul edilebilir dinamik ve geçici hal tepkisi göstermesidir.

Anahtar Kelimeler: Iki Anahtar üç Durum Buck-Boost Çevirirci, Kontrolör, Senkron jeneratör, PWM, Anahtarlama

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Finally, I dedicate this thesis to my parents who gave me life and unconditional support throughout my life.

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LIST OF SYMBOLS

n_s	: Constant speed of Synchronous Generator
I_f	: Field Current
ϕ_f	: Field Flux
P	: Number of Pole
E_{ac}	: Line to Line Voltage A-C
E_{ab}	: Line to Line Voltage A-B
E_{bc}	: Line to Line Voltage B-C
E_{an}	: Line to Neutral Voltage Phase A
E_{bn}	: Line to Neutral Voltage Phase B
E_{cn}	: Line to Neutral Voltage Phase C
K_w	: Winding Factor
I_A	: Armature Current
E_{AR}	: Armature Reaction
ϕ_{AR}	: Armature Flux
V_a	: Terminal Voltage
X_m	: Magnetization Reactance
X_s	: Synchronous Rectance
X_l	: Leakage Reactance
R_a	: Stator Resistor
V_{nl}	: No Load Voltage
V_{fl}	: Full Load Voltage
E_{ad}	: Direct Axis of Armature Reaction
E_{aq}	: Quadrature Axis of Armature Reaction
E_f	: Excitation Voltage
I_q	: Quadratire Axis Current of I_A
I_d	: Direct Axis Current of I_A
X_d	: Direct Axis synchronous reactance
X_q	: Quadrature Axis synchronous Reactance
i_L	: Inductor Current

i_C	:	Capacitor Current
i_D	:	Diode Current
V_C	:	Capacitor Voltage
V_O	:	Output Voltage
R_L	:	Load Resistor
D	:	Duty cycle
L_f	:	Filter Inductor
C_f	:	Filter Capacitor
S	:	Switch
D_1	:	Freewheeling Diode
i_a	:	Phase A Current
i_b	:	Phase B Current
i_c	:	Phase C Current
I_{load}	:	Load Current
I_{ref}	:	References Current
U	:	Voltage
V_{ref}	:	References Voltage
T	:	Time
V_M	:	Sinusoidal Voltage Peak Value
V_o	:	Output Voltage of Converter
V_{cf}	:	Voltage Across the Filter Capacitor
R_e	:	Emulate Resistance
I_{ref}	:	Reference Current
I_{in}	:	Input Current
I_M	:	Peak Input Current
ΔI_L	:	Inductor Current Ripple
K	:	Transfer Function Constant
C_{ss}	:	Corresponding Steady State
K_P	:	Proportional Constant
K_i	:	Integral Constant
K_d	:	Derivative Constant

s : Laplace Domain Frequency

LIST OF ABBREVIATIONS

AVR	: Automatic Voltage Regulator
PID	: Proportional Integral Derivation
DAVR	: Digital Automatic Voltage Regulator
DSP	: Digital Signal Processor
ANN	: Artificial neural network
MLP	: Multilayer Perceptron
DSEG	: Doubly Salient Electro-magnetic Generator
PIDSM	: PID Sliding Mode
D/A	: Digital to Analogue
PWM	: Pulse-Width Modulation
IBM	: International Business Machines
SCR	: Silicon Controlled Rectifier
DSP	: Digital Signal Processor
CCM	: Continuous Current Mode
DCM	: Discontinuous Current Mode
PCCM	: Pseudo Continuous Current Mode
PFC	: Power Factor Correction
RMS	: Root Mean Square

1. INTRODUCTION

Delivery constant voltage at the terminals of diesel generator sets is a crucial for satisfactory main power supply system. Some disturbances such as load variations, variations in speed, power factor of load and temperature rise are factors that affect the terminal voltage. In most of the cases, changing nature of loads forces the terminal voltage to increase or decrease at some percent. The overvoltage at the terminals usually causes several problems and can also affect the performance of some electrical equipment which is fed by the terminal. To regulate the terminal voltage of the generator sets, special regulating equipment is required to keep the voltage constant. This equipment is named as automatic voltage regulator (AVR).

As regards, active power and reactive power demands are not constant and they are frequently changing. Because of the changes the power system operation is not also under steady state condition. Thus, to adjust the active power demands and power system stability, the input of generators for instance (steam input to turbo generator), must be regulated and for adjusting the reactive power the excitation of the generators must be regulated. AVR are used to regulate the output voltage of the generator thus controlling the reactive power. The automatic voltage can either be a discontinuous or continuous control type, but discontinuous one is much easier than continuous ones.

A modern static continuous type of AVR can be much better, by providing very fast response and, than discontinuous type. Then, by controlling and regulating of the output voltage through a power electronic system, which is the crucial duty of AVRs, satisfying the main power supply and keeping constant voltage at generator terminals is feasible. Furthermore, the AVRs plays a significant role to force the terminal voltage being constant and to maintain stability during and after the fault status.

In addition, AVRs are appropriate choice to control the output voltage through field excitation in variable speed application. An AVR has to provide an acceptable response for rising time and settling time. Since the 1960's, static excitation system based on thyristor rectifiers have been widely used, which can produce almost instantaneous response and high ceiling voltage. The high speed and large gain in these excitation systems improve the system transient stability considerably (C. K. Kim, 1998). At the present time, most excitation control systems have been designed as a complete specification for large turbine generators (H. Lee. et al, 2012).

By controlling the excitation system of the synchronous generator, the variation of the voltage, distributing of inactive power can be reduced and also the stability of the synchronous generator can be increased. Direct current is provided for a synchronous generator’s field winding that is the main operation and function of an excitation system, furthermore, by controlling the direct current along with field voltage, the performance of the excitation system which is the essential function to satisfy the performance of the power system is increased.

In this study to achieve a good dynamic performance and terminal voltage regulation, an automatic voltage regulator using two switch three state buck-boost converter will be designed and applied to a small generator set. An automatic voltage regulator with this converter topology has not used before.

1.1. Outline of Dissertation

In Chapter 2, previous studies are mentioned about automatic voltage regulator which are studied by different researchers. Furthermore, similar models are searched for comparison with available studies in the literature.

In Chapter 3, material and method are described in detail. Components such as synchronous generator, P-I controller and buck-boost that are used in this study are explained.

In Chapter 4, two switch three state buck-boost configuration, controller and synchronous generator configuration and parameters are given and evaluated.

In Chapter 5, simulation results for different case studies are given and evaluated. In these cases, the performance of changing the load for different cases are analyzed.

In Chapter 6, the important conclusions of the study and author’s recommendations for future work are explained.

Finally, related references used in the thesis and biographical information of the author are presented.

2. LITERATURE SURVEY

2.1. Introduction

A lot of studies have been made and are available in the literature about AVR related to control the terminal voltage of synchronous generator. In this section, some approaches are discussed figuring out what is done on this subject. Accordingly, the control system should be based on linearized method due to the fact the synchronous generator is considered non-linear. The AVR is unable to react over the entire system correspondingly causes an instability within the system and thus degrade the performance. Ibrahim et al. (1989) presented a practical implementation for a self-tuning AVR based on pole-placement, minimum-variance and detuned minimum-variance algorithm for synchronous generator which is illustrated in Figure 2.1. Also the conventional AVR is replaced with the proposed method in this paper. This implementation improved the performance of the automatic voltage regulator of the system and its stability under adverse conditions. For getting the reliable operation under unstable condition, Jacketting has been consolidated as a software program.

Self-tuned AVRs showed good results in terms of performance, however, in order to obtain an optimal solution, the performance achievement should be carefully tested, and that depends on sophisticated software being used, and the necessity of complicated calculation that AVR requires. In order to overcome such issues, the interest of personal computers handling such studies and researches started to get prevalent. A digital implementation of AVR for a synchronous generator was presented in (A.H.M.S. Ula, et, al, 1992). In the stated research a digital voltage regulator was designed using a common design method, namely the straightforward method, this was done in the z domain using the method of root locus. This implementation was done on an online IBM computer, and this method showed good results compared to other experiments performed on digital circuits.

Htay (2008) discussed about an excitation control system in generator system. The issue of this paper is focused on the construction and design of automatic voltage regulator or the excitation control of the generator. This research developed and announced the necessity of electronic control technology by modifying the AVR with SCR device's technology. The main goal of this study is increasing the reliability of the system as illustrated in Figure 2.2. In this system, the output voltage of the generator is sampled through the transformer and is rectified using a simple circuit and a bridge rectifier.

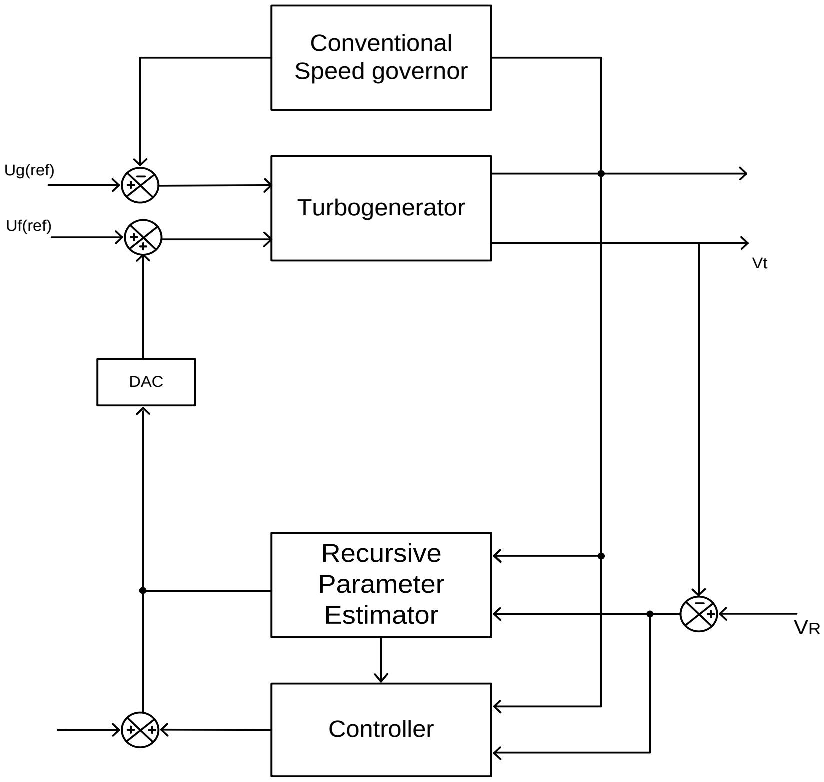

Figure 2.1. Block Diagram of Self-tuning Regulator (A.s Ibrahim, et al, 1989)

In a paper presented by (S. Funabiki, 1991), the AVR of synchronous generator based on pole assignment self-tuning regulator is proposed. The poles of the controller in addition to the pole of the close-loop transfer function of the system were experimentally discussed, furthermore, the response of the AVR system with the saturation characteristic was simulated to confirm the availability of the control method for AVR of synchronous generator. The proposed control method of this paper was experimentally clarified by using the microprocessor-based control system. Because of the variation regarding the gain of the PID controller in the field, the authors used the self-tuning PID controller for getting the best performance, moreover, stable response regarding the step up/down command of the output voltage. To show the implementation of the proposed controller, Figure 2.3 as a block diagram is considered.

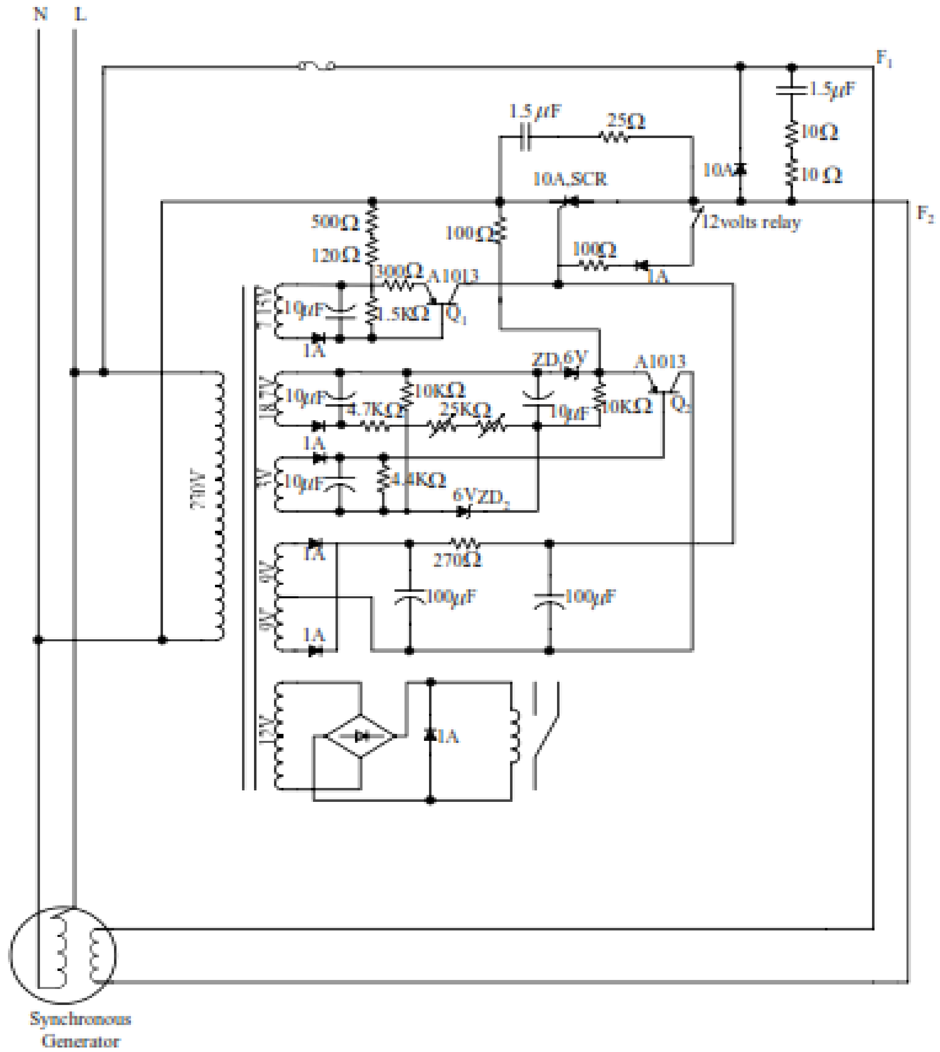

Figure 2.2. Over all Circuits of AVR for the Diesel Engine Type Synchronous Generator (M. Htay, 2008).

(R. Hasan & S. Martis, 1994) presented and examined a method of realizing a fuzzy logic for an AVR system using a personal computer. The method explored deals with the use of binary input-output Fuzzy Associative Memories for control. Error and rate of change of voltage are used to maintain a constant output voltage. The mentioned controller algorithm is based on linguistic rules and was applied using a personal computer. Fuzzy control systems are model-free estimators. In other hands, one need not state how the outputs depend mathematically on the inputs and mathematical model of the system is not required for the fuzzy control design. The computer is connected to the field winding of the alternator via a digital to analog convertor (D/A). The proposed controller can be established for solving several control problems which its flexibility is the main benefit of the AVR.

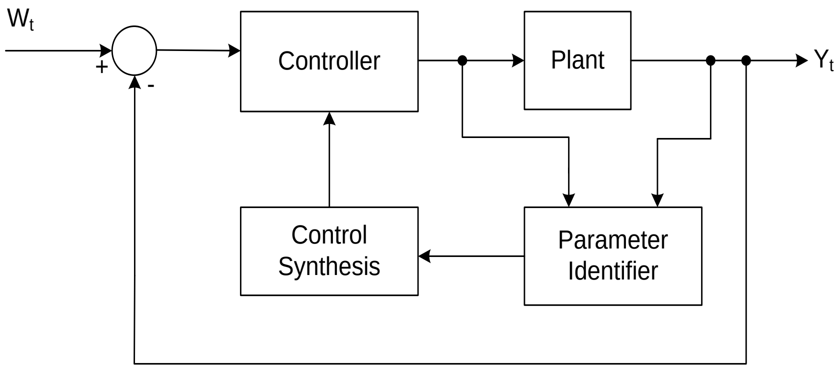

Figure 2.3. Fundamental Construction of Self-tuning Regulator (S. Funabiki, 1991)

For overcoming the instability of the generator and the time delay of exciter, the AVR controller must have the ability to react very fast. For acquiring this feature, (D. Hee Lee, 2007) presented a variable gain control scheme of Digital Automatic Voltage Regulator as shown in Figure 2.4, for AC brushless generator. They also used a PID controller with a simple gain adjustor for improving steady state performance and dynamic response. And the gains of PID were updated by the terminal voltage and load current for improving the dynamic response and stability. The proposed gain adjuster was designed by applying a simple linear function and thereafter increasing the gain in proportionally to terminal voltage and load current. Due to the usage of DSP or microprocessors recently, and in order to increase the power control performance, flexibility and low cost DAVR systems were presented to handle such conflicts. The DAVR main function is to regulate various output voltages of AC generator by controlling the exciter field voltage, additionally, Simple variable gain control scheme for the AC brushless generator system were used and simulated, including the conventional PID controller and a simple gain adjuster in order to produce good results.

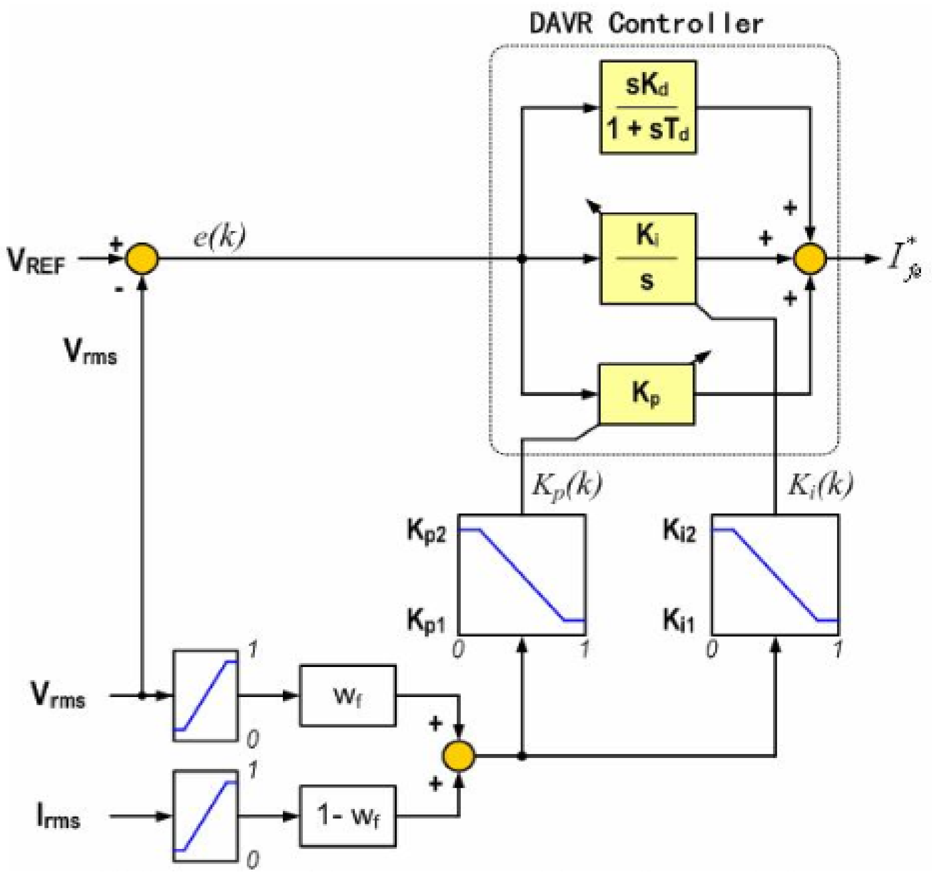

Figure 2.4. Block Diagram of the Proposed Variable Gain Control Scheme (D. Hee Lee, 2007)

In other research, adaptive design of an AVR for synchronous generator was presented by (G. Fusco, 2008). In this study the obtained transfer function depends on the estimated parameters yielded by a recursive least-squares algorithm subject to constraints deriving from the Thevenin circuit. The AVR design is based on the pole-assignment technique while the phasor estimation is performed by two Klman filters. In this study, the implemented block diagram shows how the applied system yielded accurate result as shown in Figure 2.5. This method has the ability of providing adequate voltage control performance in the varying condition of power system operation

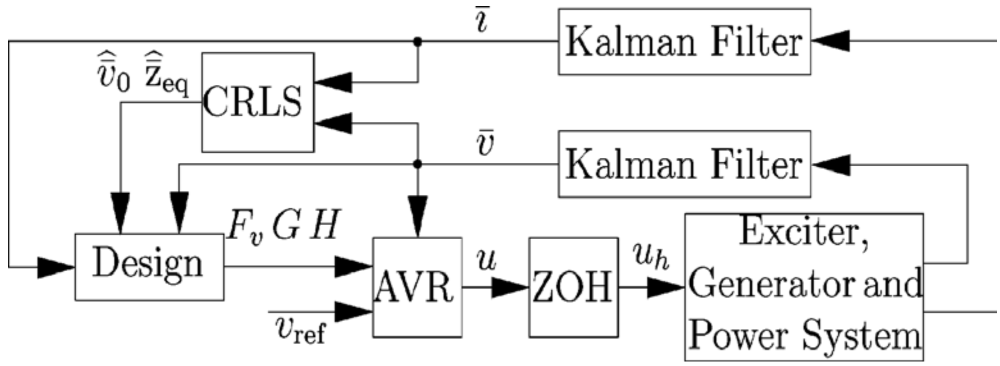

Figure 2.5. Adaptive AVR System (G. Fusco, 2008)

Microprocessor-based identification system applied to synchronous generator with voltage regulator, is presented by (R. D. Lang, 2006). This involves the identification of individual generator and voltage regulator parameters as well as system modes of oscillation and damping. In the paper, an identification technique involving pseudo-random ternary noise injection and cross correlation is assessed and applied to power systems. Operating the system in a normal mode, and obtaining the machine parameters along with its voltage regulator is discussed. The technique is examined, to show how its performance is in real time using a dedicated microprocessor. The following Figure 2.6 illustrates how the components are connected to another. The identification technique is tested on a simple micro-alternator connected to a noisy power system through a transmission line.

In another paper that presented by (W.Li, 2010), a novel digital automatic voltage regulator for synchronous generator is proposed. Analysis and development the proposed regulator is accomplished by both computer simulations and DSP implementation. Steady-state and dynamic control performance of the regulator have been examined on different operating conditions (e.g. Voltage establishment, load connection and disconnection). The used DSP as a microprocessor is installed on a hardware platform of the AVR. Examination test results represent the good stability of the simulation results.

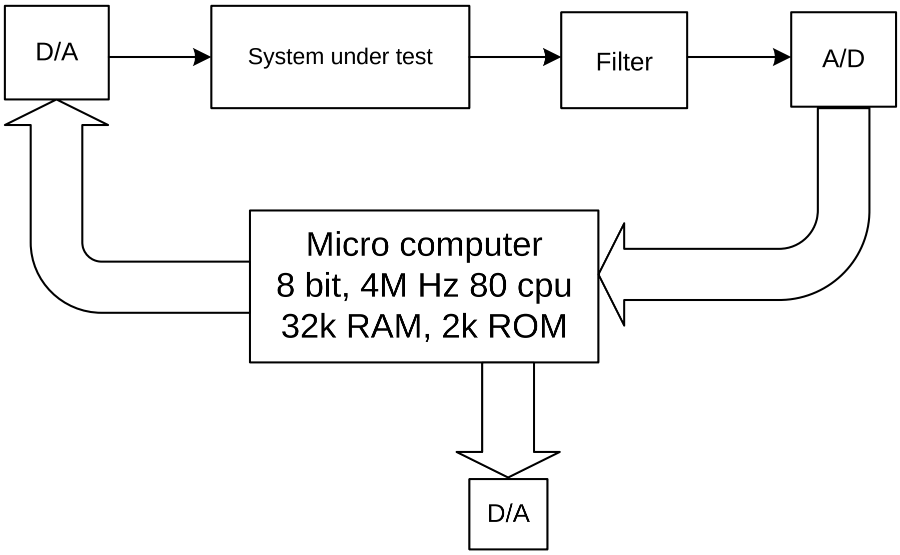

Figure 2.6. Identification System (R. D. Lang, 2006)

In this study a basic function of the AVR is presented to keep the output voltage changes within a desired range. A three loop control is adopted as shown in Figure 2.7 that the internal feedback loop controls the excitation current of the exciter for having larger gain and bandwidth, further, the external feedback loop produce the basic voltage regulation. An additional disturbance rejection loop compensates the changes in output voltage which induced by the generator load situation. The proposed controller's analysis and data acquisition are done with DSP in Saber simulator platform. To improve the dynamic response of an AVR, in particular, during the load disconnection, a novel excitation circuit is adopted in this article. The novel excitation circuit is represented in Figure 2.8.

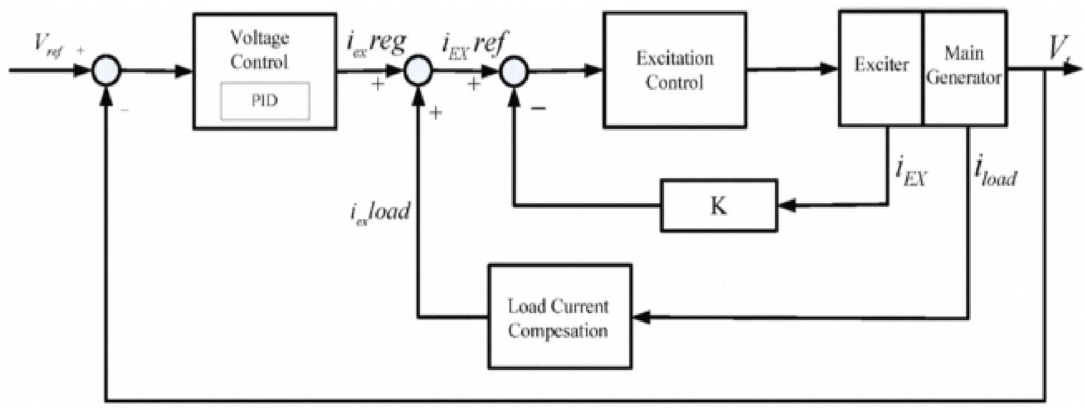

Figure 2.7. Control Structure (W.Li, 2010)

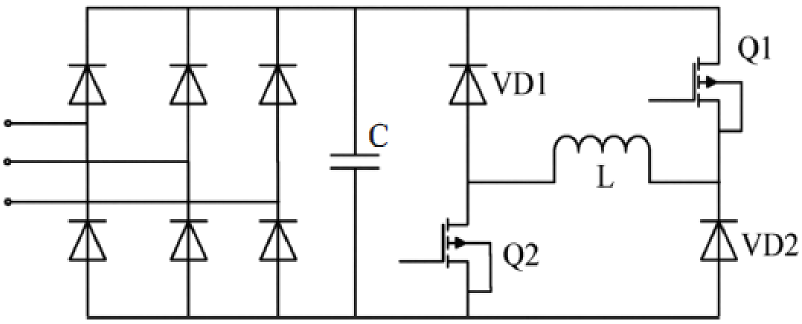

Figure 2.8. Novel Excitation Circuit (W.Li, 2010),

Conventional launch of a generator sets is performed when the engine is at its normal hot operating temperature. Cooper (2011) presented temperature-dependent voltage regulator operation for optimal load acceptance of a diesel generator. A novel voltage regulator design which utilizes engine temperature as a supplementary control input is presented, providing an improvement in a gen-set's cold load acceptance performance without compromising its standard hot performance.

A significant improvement is provided using the voltage regulator to a gen-set's cold load acceptance and decrease the possibility of engine stall without the gen-set's hot performance.

According to some researches, automatic voltage regulators are controllers that are used to sustain constant voltage at the generator terminals. Dealing with neural networks for designing an automatic voltage regulator of a synchronous generator, which is concerned with the development of a feedforward multilayer perceptron (MLP) presented by (L. N. Magangane, 2012), and it is used as an automatic voltage regulator with power system stabilizer (PSS).

In this paper the development of the ANN is comprised of three subjects; first one is, determining the applicable input signals to use input feature and second one is, determining the best activation function to use for neuron and the third one is, determining of optimum number of neurons in the hidden layer.

For doubly salient electro-magnetic generator with an improved PID sliding mode control strategy with constant switching frequency for the voltage regulator has been proposed in this study. An improved PID sliding mode control strategy with constant switching frequency for the voltage regulator of doubly salient electro-magnetic generator has been proposed in this paper. The approach presented by (W. Dai et al, 2014), deal with a control law with constant switching frequency and stability analysis, the method value selection of the sliding mode coefficient was created. Eventually, a voltage regulation system with a field circuit co-simulation model for doubly salient electro-magnetic generator using the PID sliding mode control, is designed.

Doubly salient electro-magnetic generator (DSEG) is also nonlinear. Thus, with a variation of rising exciting current and ambient temperature the parameters are being changed. Therefore, in this study a voltage regulation system is designed based on PID sliding mode (PIDSM) control. The structure of this controller is, the combination of the voltage error and the switch itself sliding characteristic. Calculation method of several parameters is done by Lyapunov function and other constraints.

2.2. Conclusion of Literature Survey

Several studies about automatic voltage regulator with different methods, in the literature were carried out. Some of them used experimental techniques and others used simulation analysis. These studies mainly focused on keeping the stability of generators output and control topologies. Also a different controlling method to obtain the best control optimization was searched.

Although there are many control circuits, it is obviously seen that the controlling methods are limited. These are mostly dealt with transient and dynamic response, on the other hand, providing steady state stability, voltage ripple and voltage drop. In this thesis, PID controller through a Buck-Boost convertor, as an automatic voltage regulator for synchronous generator is used.

The aim of using two switch three state buck-boost convertor the development of a new automatic voltage regulator is, its operation in the PCCM and also providing an additional degree of control freedom by the inductor current freewheeling stage that allows the splitting controller to make its design much easier. Another reason is, having fast transient and dynamic response compared with other converters such as DSM and CCM. Also by decreasing the inductor current, the stress current of switching are decreased. Besides, the two switch three state buck-boost convertor does not need additional power switch and has high power efficiency. The advantages of this study are the configuration simplicity and low cost.

3. MATERIAL AND METHOD

3.1. Material

3.1.1. Synchronous Generator (Alternator)

3.1.1.1. Principle of Synchronous Generator

In terms of electrical energy synchronous generators are considered an overall primary source, which convert the mechanical power output of steam turbines, gas turbines, reciprocating engines, hydro turbines into electrical power to the grid. Their size varies, some can have power reaching 1500 MW. They are referred to the synchronous because their rotor's speed is synchronized with the supply frequency of the synchronous generator.

In the revolving type the field system is on the rotor and the armature winding is on the stator, but in the stationary type the armature winding is on the rotor and field system is on the stator. In terms of shape of the field, synchronous machines can be classified as cylindrical-rotor machines and salient-pole machines.

3.1.1.2. Principle of Operation

To drive a synchronous generator, its rotor is connected to devices such as diesel motors, hydro turbines, steam turbines, gas turbines, etc. which generation of electrical energy plays a crucial role in their selection with a constant speed of n_s that by supplying a DC current I_f to the rotor generates a DC flux ϕ_f. This DC current in the rotating field flux induced a voltage in the stator winding and also the frequency of the induced voltage depends on the speed, the relation of the frequency-speed is; $f = (P/120)n = pn/120$ that P is the number of pole

The below Figure 3.5 is shown how to operate

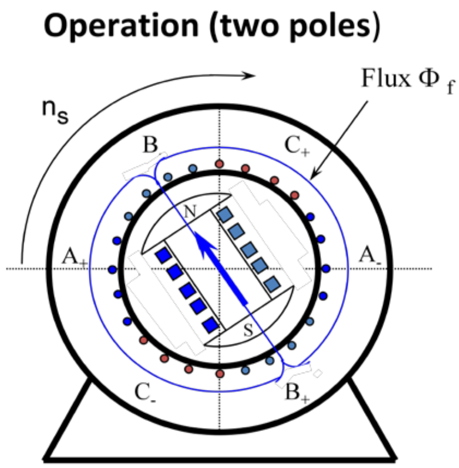

Figure 3.1. Operation Concept (S .Ibrahim)

The induced voltage is calculated by rms value;

$$E_{an} = E_{rms}e^{ideg} \tag{3.1}$$

$$E_{bn} = E_{rms}e^{-i120deg} \tag{3.2}$$

$$E_{cn} = E_{rms}e^{-i240deg} \tag{3.3}$$

Where

$$E_{rms} = \frac{k_w \omega N_a \phi_f}{\sqrt{2}} = 4.44 f N_a \phi_f k_w \tag{3.4}$$

$k_w = 0.85 - 0.95$ is the winding factor

3.1.1.4. Salient Pole Synchronous Generator

In some generators like hydroelectric generator, armature reactance is depended on rotor position which make complicated analysis and for facilitating, mmf and flux are separated to two component. The two components are coordinated with the direct axis and quadrature axis of the machine that the direct axis is aligned with the field winding and the quadrature axis leads direct axis by90°.

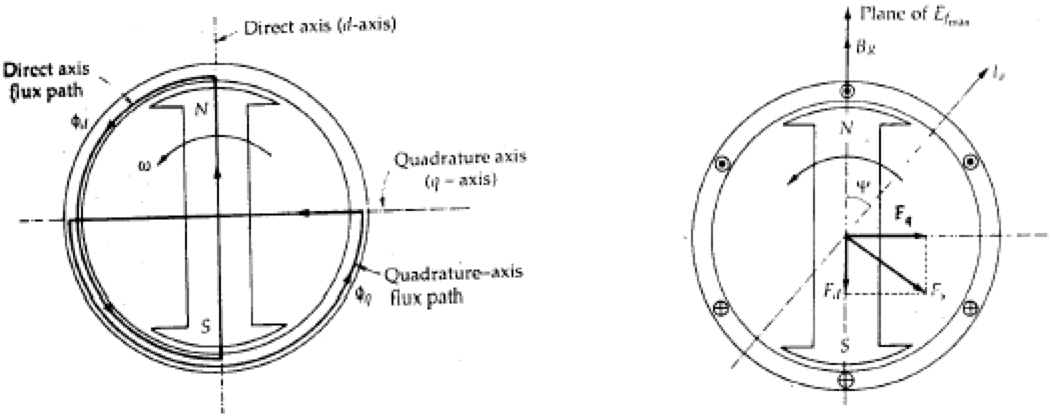

Figure 3.2. The direct and quadrature axis (S .Ibrahim)

Where

E_{ad} = Direct-axis component of armature reaction voltage
E_{aq} = Quadrature-axis component of armature reaction voltage

Due to every armature reaction voltage is proportional to its current and lags the stator current by90°. Thus, the armature reaction voltage is written as

$$E_{ad} = -jX_{ad}I_d \tag{3.5}$$

$$E_{aq} = -jX_{aq}I_q \tag{3.6}$$

Where

E_{ad}= armature reaction reactance in the direct axis in per phase
E_{aq}= armature reaction reactance in the quadrature in per phase

With the sum of the emf induced by the field excitation and these two emfs the total voltage induced is established, that is

$$\acute{E} = E_f + E_{ad} + E_{aq} \tag{3.7}$$

$$\acute{E} = E_f - jX_{ad}I_d - jX_{aq}I_q \tag{3.8}$$

Sum of the voltage terminal V, leakage reactance of the armature and voltage drop in the resistance is equal with $\acute{E}$ therefore, that

$$\acute{E} = V + R_aI_a + jX_lI_a \tag{3.9}$$

The armature current I_a is shown with two component that is split, one in phase with excitation voltage E_f and other one in phase with quadrature

If

I_q = The q axis component of I_a

I_d = The d axis component of I_a

$$I_a = I_d + I_q \tag{3.10}$$

With combination of (3.13) and (3.14)

$$E_f = V + R_aI_a + jX_lI_a + jX_{ad}I_d + jX_{aq}I_q \tag{3.11}$$

$$E_f = V + R_a(I_d + I_q) + jX_l(I_d + I_q) + jX_{ad}I_d + jX_{aq}I_q \tag{3.12}$$

$$= V + R_a(I_d + I_q) + j(X_l + X_{ad})I_d + j(X_l + X_{aq})I_q \tag{3.13}$$

$$X_d = X_l + X_{ad} \tag{3.14}$$

$$X_q = X_l + X_{aq} \tag{3.15}$$

The X_d is referred direct-axis synchronous reactance and the $X_q$is referred quadrature-axis synchronous reactance

By combining of Equations (3.18), (3.19) and (3.20) gives

$$E_f = V + R_a I_d + R_a I_q + jX_d I_d + jX_q I_q \tag{3.16}$$

$$E_f = V + R_a I_a + jX_d I_d + jX_q I_q \tag{3.17}$$

3.1.1.5. Field Excitation and Exciter

One of the most important part of the synchronous generator is, design of field excitation. The duty of the excitation is not only to ensure being a stable AC at terminal voltage, rather, response to sudden load changes is important as well.

The purposes of excitation system are to approximate the output to the steady state stability by controlling voltage and preserve voltage under load variation in order to protect equipment. Other one is to facilitate the reactive load sharing among machines in parallel mode.

3.1.2. PID Controller

3.1.2.1. Proportional Control

A proportional controller is defined to be one in which output ratio is simply proportional to the input, where the constant of proportionality is the gain of the controller. Initially consider the first-order system with a disturbance input as shown in Figure 3.8

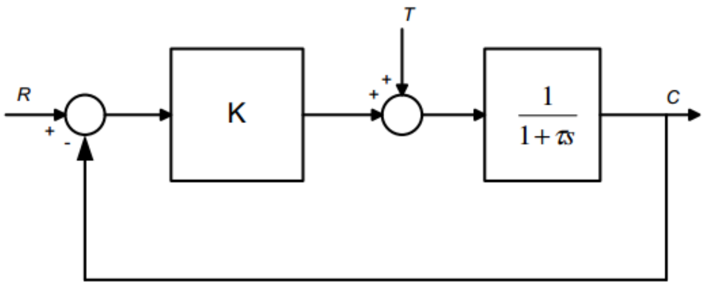

Figure 3.3. First Order System With Disturbance (Driels, 1996)

The transfer function for the two inputs R and T and output C are

$$\frac{C}{R}=\frac{K/(1+K)}{1+\tau s/(1+K)}$$

(3.18)

If K is done major, the device make the output for unit R almost unity and for T is close to zero, while this is a good result, but the error cannot be equal to zero due to practical limits on the magnitude of K. Consider a second order system, also subjected to external disturbances, as follow in Figure (3.9)

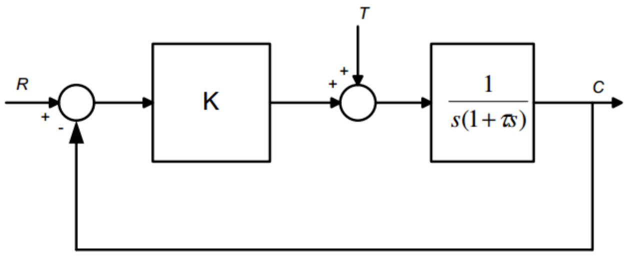

Figure 3.4. Second order system with disturbance (Driels, 1996)

The transfer functions from two inputs T and R to the output C as

$$\frac{C}{R}=\frac{K}{\tau s^{2}+s+K} \tag{3.19}$$

As expected the steady-state error for regular input is zero, but disturbance generates a finite error. The small error can be done by providing large K. Simple proportional control is of limited success is trying to obtain good performance in terms of steady-state error, disturbance rejection and transient response (Driels, 1996).

3.1.2.2. Proportional - Integral Control

A proportional – integral controller, where the output is proportional to the input plus the integral value of the input. This type of control is called two-mode control. The transfer function is shown as follow

$$\theta_0 = \left[K_p + \frac{K_i}{s} \right] \theta_i \tag{3.20}$$

Consider this controller recovers with proportional controller in the first order system. The new system seems like that shown in Figure 3.10. The new transfer function corresponding the output to two input is as

$$\frac{C}{R} = \frac{K_p s + K_i}{\tau s^2 + s(1 + K_p) + K_i} \tag{3.21}$$

$$\frac{C}{T} = \frac{s}{\tau s^2 + s(1 + K_p) + K_i} \tag{3.22}$$

The steady-state out C becomes as (3.34) for a unit step input R

$$c_{ss}(t) = 1 \tag{3.23}$$

And the steady-state output for unit T is

$$c_{ss}(t) = 0 \tag{3.24}$$

The steady-state errors is reduced to zero in proportional-integral controller and refused entirely external disturbances.

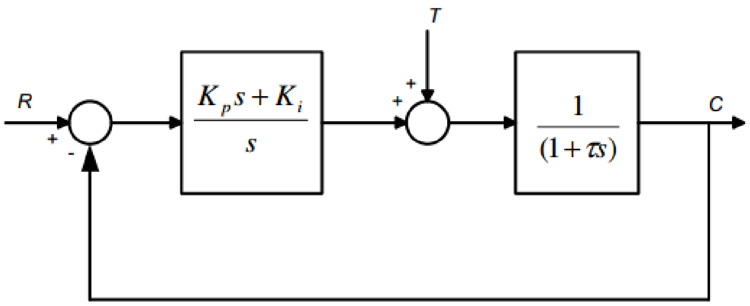

Figure 3.5. PI Control of First-Order System (Driels, 1996)

The transfer function for the second-order system is written as follow

$$\frac{C}{R} = \frac{K_p s + K_i}{\tau s^3 + s^2 + sK_p + K_i} \tag{3.25}$$

$$\frac{C}{T} = \frac{s}{\tau s^3 + s^2 + sK_p + K_i} \tag{3.26}$$

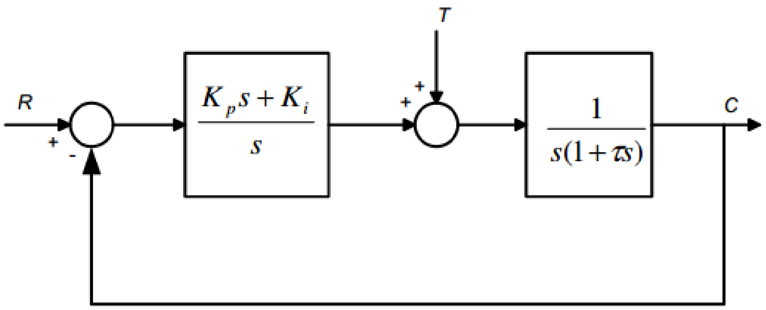

Figure 3.6. PI Control of Second Order System (Driels, 1996)

Letting R be a unit step generates

$$c_{ss}(t) = 1 \tag{3.27}$$

And for the unit disturbance

$$c_{ss}(t) = 0 \tag{3.28}$$

Using the open-loop transfer function

$$GH(s) = \frac{K_p s + K_i}{s^2(1+\tau s)} \tag{3.29}$$

From the transfer function, it has seen that the pair of poles of the system at the origin, and another pole at, and a zero at $s = 1/\tau$, and a zero at $s = -K_i / K_p$. In order for the system to be stable, the system zero must be closer to the imaginary axis than the system pole.

$$\left|\frac{1}{\tau}\right| > \left|\frac{K_i}{K_p}\right| \tag{3.30}$$

This puts some constraints on the proportional and integral gain selection (Driels, 1996).

3.1.2.3. Proportional – Integral – Derivative Control

A PID (Proportional-Integral-Derivative) has the transfer function that can be written as

$$\frac{\theta_o}{\theta_i} = K_p + \frac{K_i}{s} + K_d s \tag{3.31}$$

Adjusting the performance of the PID control system is very effective, and added a straight path of a control system to improve the performance that they are convenient as a commercial component. Choice of values for K_p, K_i and K_d is known as tuning the controller and it may be carried out in several ways. The transfer function can be written as (Driels, 1996).

$$\frac{\theta_o}{\theta_i} = K_p(1 + \frac{1}{T_i s} + T_d s) \tag{3.32}$$

3.1.3. Buck – Boost Converter

3.1.3.1. Principle of Buck – Boost Converter

The output voltage of Buck-Boost is either greater than or less than the size of input, furthermore, the buck- boost is a type of DC – DC convertor. The simplest form of the convertor is shown below in Figure 3.12. The main power switch is shown as a bipolar transistor, however, a power MOSFET, or any other device such as controlled manner (on or off) can be chosen.

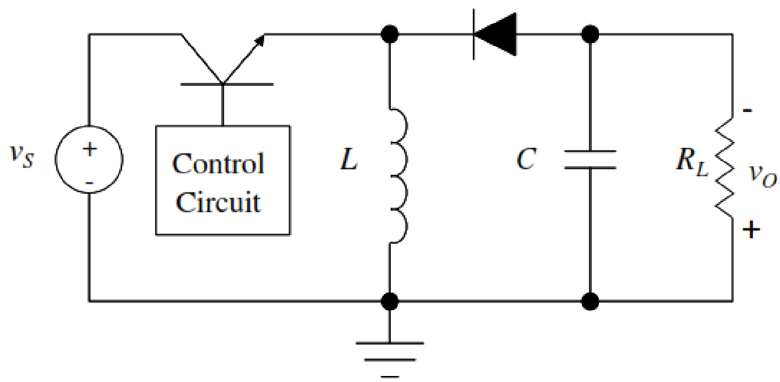

Figure 3.7. Buck – Boost Convertor (D.J. Shortt, 2002)

In general, this circuit works with "square wave" technology to transfer power from input to output, that is, produces waveforms with sharp edges. In fact, i_L represent the inductor current in the buck-boost convertor of Figure 3.12, i_D represent the diode current and,i_C the capacitor current as follow Figure 3.13. The convertor's operation is nonlinear and discrete.

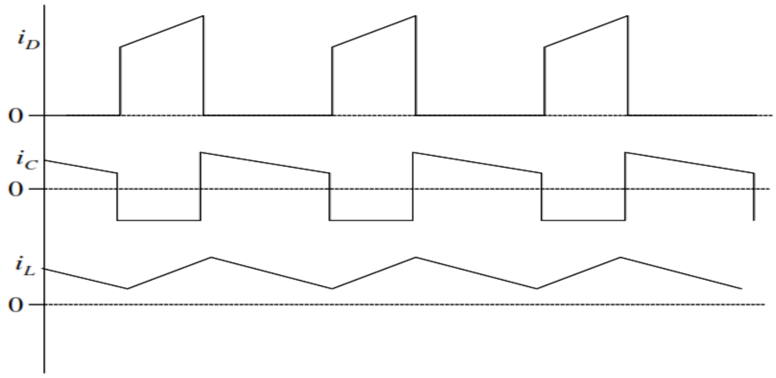

Figure 3.8. Typical Current Waveform in a Buck-Boost Convertor (D.J. Shortt, 2002)

3.1.3.2. Circuit Analysis

The buck-boost converter's topology is changed periodically according to the switching of semiconductor device, during a cycle of operation. The main power switch is on and off, and diode response to this switching is vice versa.

- **Continuous-Current Mode**

The topology which is shown in Figure 3.14, the main power switch is on and the diode is reverse-biased, therefore, it is off. For the purpose of illustration the semiconductor devices are assumed to be ideal. There are two independent state variables that contain the information describing the operation of this circuit: the inductor current, i_L, and the capacitor voltage, v_C . Two differential equations in terms of these variables, the output voltage, v_O, and the source voltage, v_S, for the designated topology are shown below;

$$\frac{d_{iL}}{dt} = \frac{v_S}{L} \tag{3.33}$$

$$\frac{d_{VC}}{dt} = \frac{V_O}{R_L C} \tag{3.34}$$

The inductor is charging up by the source while the capacitor is discharging into the output load, R_L, and the output voltage is falling.

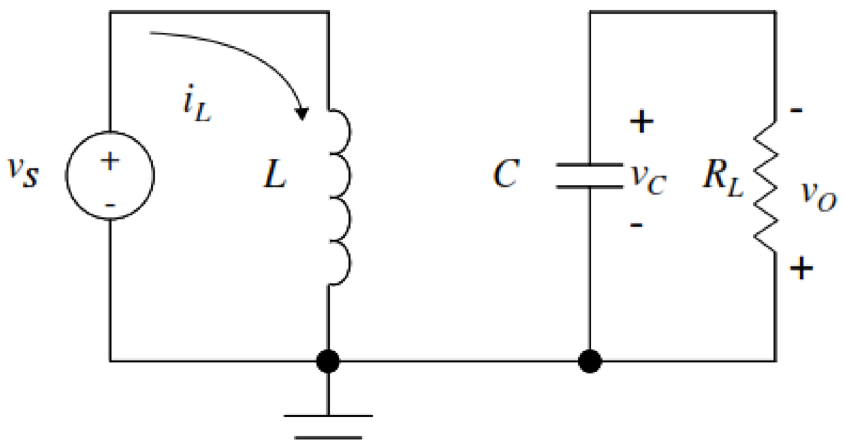

Figure 3.9. Topology 1 For The Buck-Boost Convertor (D.J. Shortt, 2002)

In other hand, as shown in Figure 3.15 when the main power is turning off the topology is changing as well, and the inductor keep the current in the same direction, therefore, the diode is forward based.

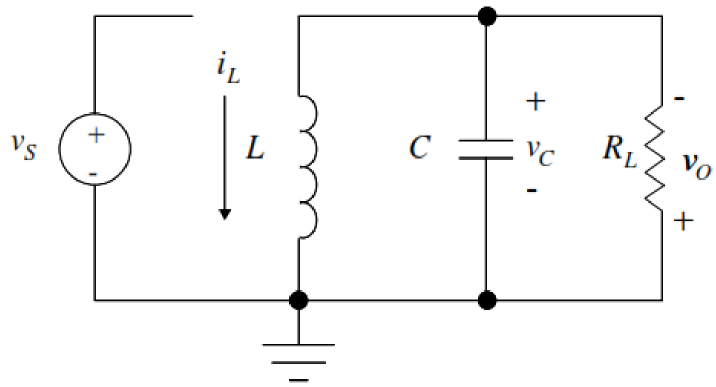

Figure 3.10. Topology 2 For The Buck-Boost Converter (D.J. Shortt, 2002)

For the topology 2 the equations are shown below, note that the inductor is transferring the obtained energy from the source into capacitor, and the capacitor is charged up and the inductor is discharged and the output voltage is growing up.

$$\frac{d_{iL}}{dt} = -\frac{V_C}{L} \tag{3.35}$$

$$\frac{d_{VC}}{dt} = \frac{i_L}{C} + \frac{v_O}{R_L C} \tag{3.36}$$

Another case of a topology change is, transferring all of the inductor energy into capacitor. In this circumstance the inductor current decline to zero. To express the state of the buck-boost convertor, four linear time-invariant differential equations are considered. Power level analysis, is linear for each range, however, for full operation cycle, it becomes a piecewise linear problem. Varying the on time and off time of main power switch, is different from cycle to cycle of the loop, which make further complicated analysis. In fact, there are two methods: numerical (global) and analytical (mathematical) technique. The analytical method, closed form expression representing the action of the convertor is obtained, which enables qualitative analysis to be performed. The numerical technique using different algorithms to produce an accurate quantitative results. Analytical techniques can be described in two different systems, discrete and continuous. Description of discrete system makes no assumptions based on simple converter operation. This explanation may be used in any application where a linear change of structure is evaluated. This method is accurate, but very complicated.

For each interval, the averaging technique in the cycle is represented by state space (differential equation), Figure 3.16 shows the waveform of the continuous, instantaneous inductor current, (i_L is not zero in each mark time) and average inductor current for buck-boost converter.

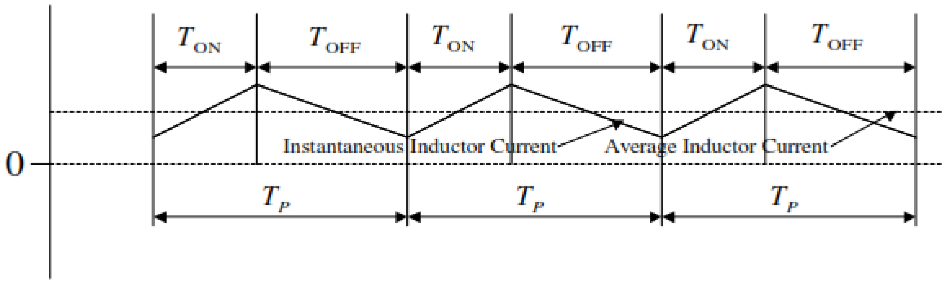

Figure 3.11. Continuous Inductor Current (D.J. Shortt, 2002)

The time period of the instantaneous current, $T_P s$ is cyclic and the$T_{on}s$, T_{off} of the main power switch are as shown in Figure 3.16.

Where the average variable are i_L and,v_C, $d = T_{on}/T_p$ and $\acute{d} = T_{off}/T_p$ please note: $d + d' = 1$.

Inductor current perturbation is shown as figure 3.17 represent the changing which T_{on} and T_{off} differ from each other cycle by cycle.

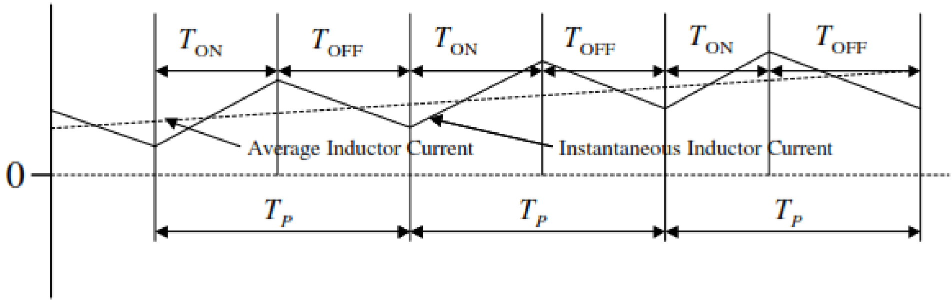

Figure 3.12. Inductor Current Perturbation (D.J. Shortt, 2002)

The equations

$$\frac{V_C}{V_S} = -\frac{D}{D'} \tag{3.37}$$

$$\Rightarrow V_C = -V_O$$

$$\frac{V_O}{V_S} = \frac{D}{D'} \tag{3.38}$$

The equation (3.63) represent the ratio of the output DC voltage to input DC voltage, considering the ratio of on time and off time of the main power switch, the inductor current is expressed as below

$$I_L = -\frac{V_O}{D'R_L} \tag{3.39}$$

- **Discontinuous – Current Mode**

In the buck-boost converter for discontinuous current waveform demonstrate in Figure (3.18) as shown below

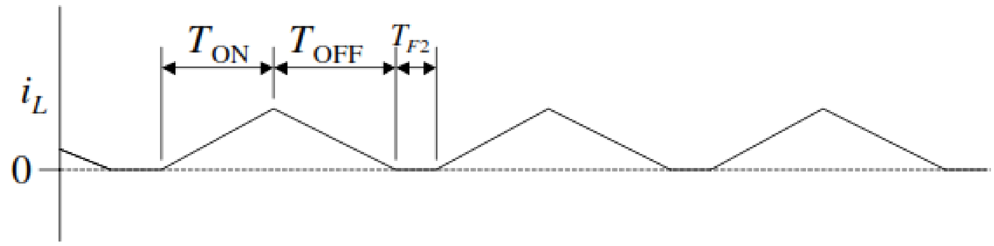

Figure 3.13. Discontinuous Inductor Current (D.J. Shortt, 2002)

As shown in Figure 3.18 the inductor current is equal to zero in interval of T_{F2} that cause to change the topology to following figure

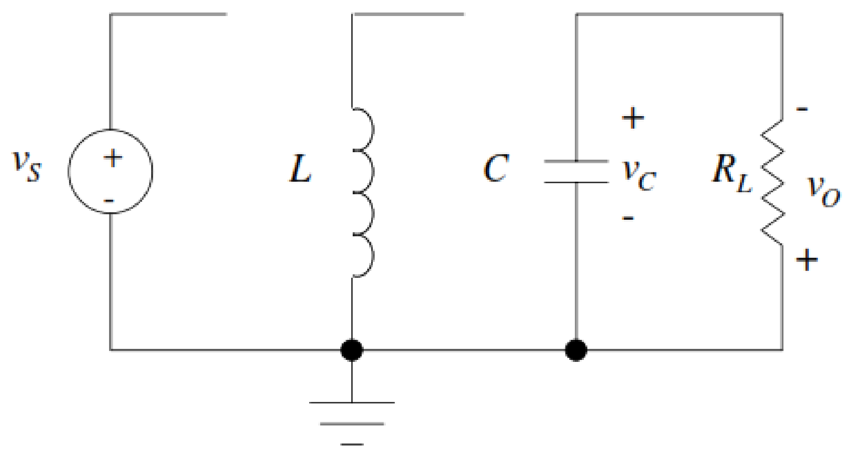

Figure 3.14. Topology 3 (Discontinuous Mode) For Buck-Boost Convertor (D.J. Shortt, 2002)

Also there exist just one state equation which can be determined as following equation

$$\frac{dv_C}{dt} = \frac{v_O}{R_L C} \tag{3.40}$$

In addition, this equation shows, the capacitor is discharging to the load resistor R_L and output voltage is descending. The general inductor current in discontinuous mode that is illustrated in finger 3.20 and represent the equations of T_{on} interval time which is same as Eqs. (3.44) and (3.45) in continuous mode. (D.J. Shortt, 2002).

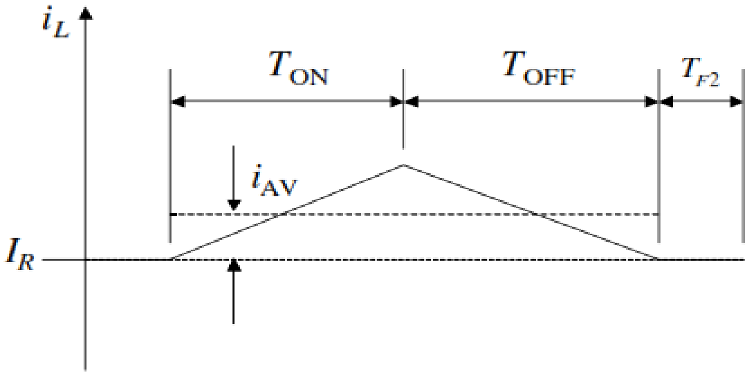

Figure 3.15. General Form of Discontinuous Inductor Current (D.J. Shortt, 2002)

Let

$$d_1 = \frac{T_{ON}}{T_P}$$
$$d_2 = \frac{T_{OFF}}{T_P} \qquad (3.41)$$
$$d_3 = \frac{T_{F2}}{T_P}$$

And

$$d_1 + d_2 + d_3 = 1$$

$$i_{AV} = \frac{1}{2}\frac{v_S}{L}T_{ON} \qquad (3.42)$$

Where

$$T_{ON} = \frac{V}{V_S}\sqrt{\frac{2LT_P}{R_L}} \tag{3.43}$$

$$T_{OFF} = \sqrt{\frac{2LT_P}{R_L}} \tag{3.44}$$

$$\frac{V_C}{V_S} = \frac{D_1}{D_2} \tag{3.45}$$

3.2. Method

The main goal of this study is to increase the performance of an automatic voltage regulator (AVR) and to enhance the startup response as well as the steady state performance of AVRs by using switching regulators. Many approaches have been proposed to improve the maintaining constant output voltage of the synchronous generator performance under load conditions. In the previous researches, per-knowledge about some path of regulating of output voltage is assumed. However, some of them is not applicable under load to have rapid dynamic and transient response. Consequently, a classifying method to maintain output voltage of synchronous generator and also provide a direct current as an excitation system at the same time is required. The buck-boost is well known as DC-DC converter as well as power factor correction.

In this study, buck-boost power factor correction convertor using two switch three states (M.He, 2013) performing in pseudo-continuous conduction mode along with a PI controller in term of an automatic voltage regular are used. Furthermore, the proposed converter does not need an added power switch and decrease the complication by independent control loop, speedy dynamic response. In the paper unity power factor is achieved using additional degree of control freedom which introduced by inductor current freewheeling.

3.2.1. Two – Switch Tri – State Buck – Boost Convertor

In the conventional boost converter which has been generally used, there exists some problem such as oscillation at voltage when the load drops actively, harmonic distortion at low input current, and restriction of power range ($<250W$). Additionally, universal root-mean-square (RMS) input applications with the input line voltage in the range of 90-265 V AC, the PFC boost converter is extremely oversized for the most enormous input RMS current. On the other hand, PFC converter for obtaining variable DC output voltage, flexibility and rapidity is proposed that the topology of the convertor should have the ability of both step up and step down conversions.

Whereas, the conventional buck-boost converters such as inverting buck-boost, flyback, SEPIC and Cuk have the component stress and the content of energy storage device more than a boost PFC converter. Thus, they are not adequate for high input devices due to high switch stress. For this purpose, independently controlled two switch buck-boost is designed to decrease, but to control the convertor in buck mode and boost mode smoothly is not easy due to discontinuity and non-linearity of transfer function because of the effective maximum and minimum duty cycle.

Apart from CCM and DCM modes of operation, the consistent switching frequency convertor can also work in pseudo-continuous conduction mode (PCCM). Like DCM, PCCM has three action stage in every switching cycle and also has bigger load-bearing capability than DCM and faster dynamic response than CCM converter. In previous research faster dynamic response and expanded load range is introduced, however, for establishing the PCCM mode in boost convertor mode the extra power switch is needed, in which the performance of the three states is affected. This causes a complicated design.

In this study that presented by (M.He, 2013) in order to perform the conventional buck-boost converter in PCCM mode, the switch states are mixed with three operation stages in every switching cycle. The conventional buck-boost with a single switch to switch and is shown in Figure 3.21. In addition, the inductor current during a freewheeling time range, in the two switch tri-state buck-boost PFC converter flow a path through a diode and a power switch, instead of two diodes when the inductor current ramps down during range. In addition, the efficiency is higher than two switch DCM and CCM buck-boost converter, furthermore, the independent voltage control loop of the current control loop benefits with an additional degree of control freedom that cause to design much simpler. Despite, a massive inductance using in PCCM operation, the ripple of the inductor current in the two switch Tri state buck-boost is lower than the two switch DCM buck-boost PFC converter.

3.2.1.1. Principle Operation of Buck – Boost Converter

The general topology of the single phase PFC convertor is usually used for boost convertor, however a variable DC output voltage is considered related to performance requirement, a buck–boost convertor must be employed. As shown in Figure 3.21 a single-switch and two switch buck-boost convertor is used, respectively. The useful buck-boost convertor which is shown in Figure 3.21, is two switch buck-boost convertor that is composed of Diode Bridge, filter inductor L_f, filter capacitor C_f, buck power switch S_1, freewheeling diode D_1, boost power switch S_2, boost inductor L, output diode D_2 and output capacitor C. For all operations of the two switch buck-boost with two power switch has $2^2 = 4$ switch states: (1) $S_1$is turned on and S_2 turned off (2) $S_1$is turned off and S_2 is turned on (3) both S_1 and S_2 are turned on and (4) both $S_1$and S_2 are turned off as shown in Figure 3.22 (M.He, 2013)

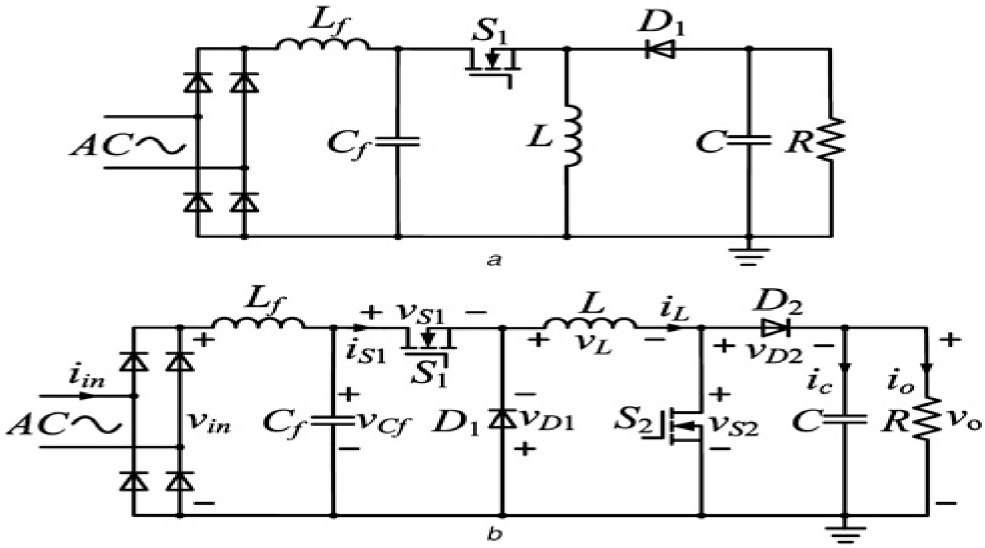

Figure 3.16. Buck-Boost Converter (M.He, 2013)
a. Single-switch buck-boost PFC converter
b. Two-switch buck-boost PFC converter

Unlike two switch DCM and CCM buck-boost converter that have two switch states in every switching cycle, both switching S_1 and S_2 are turned on or turned off as shown 3.22 *c-d*, PCCM converter has three switch states in each switch cycle by producing inductor current freewheeling state. The Inductor current $i_L(t)$, during the freewheeling interval time, is maintained at constant in terms of $i_{ref}(t)$ not at zero same as DCM. According to the Figure 3.22 *b*, by utilizing inductor current freewheeling stage, the two switch buck-boost is operated in the tri-state PCCM, and also it is well known, additional power switch is not used to provide the additional degree of control freedom that cause to increase the efficiency. The three operational state of the two switch tri-state buck-boost is shown in Figure 3.22 *b-d.* Inductor current $i_L(t)$ in these three operation stages, rise up and ramp down and maintain at the reference inductor current $i_{ref}(t)$, respectively. Figure 3.23 represents the two switch Tri state buck-boost waveform in steady state which $d_1(t)$, $d_2(t)$ and $d_3(t)$ define the time interval of the three operation in a switch cycle and the drive pulse of the switch S_1andS_2 is shown with $Q_1$and Q_2, respectively.

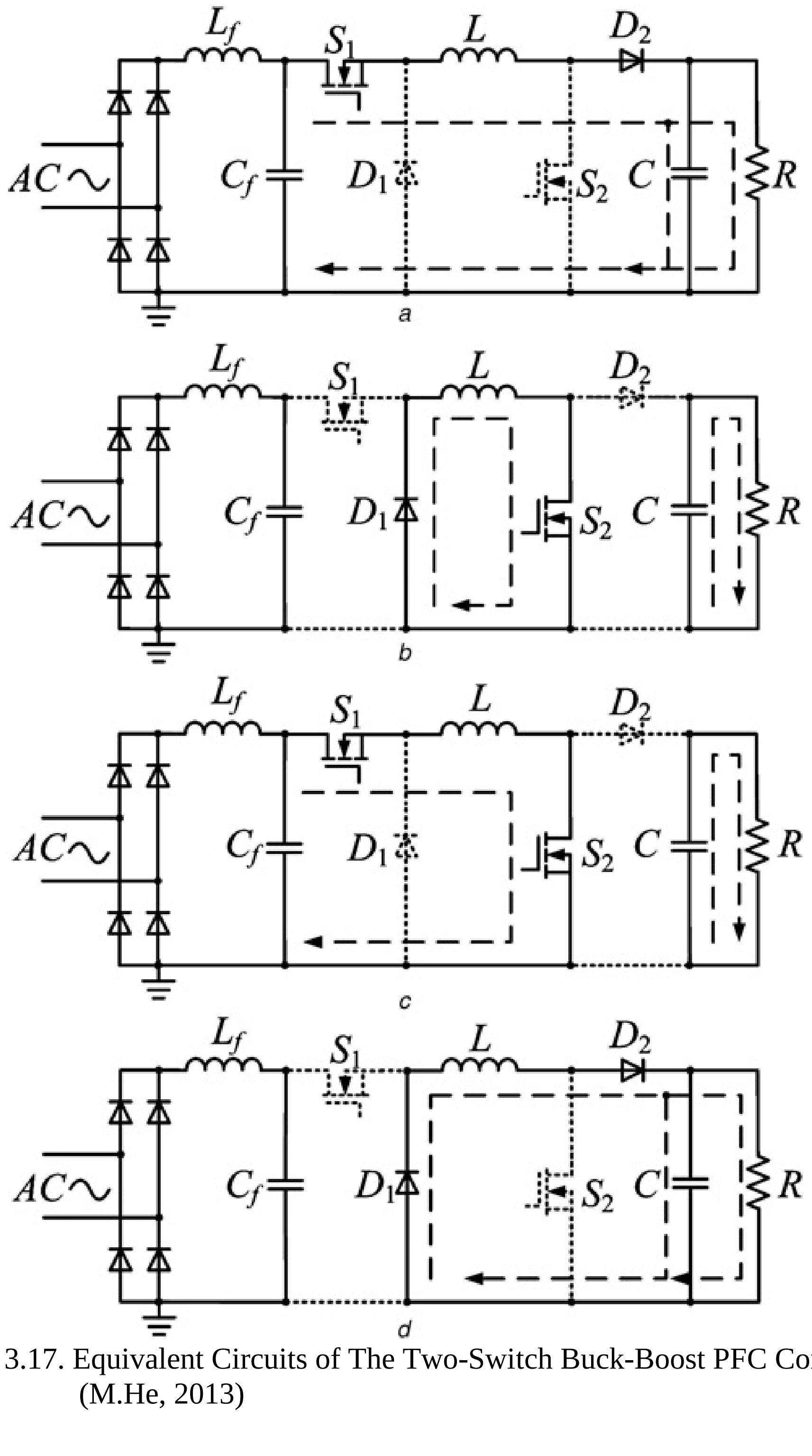

Figure 3.17. Equivalent Circuits of The Two-Switch Buck-Boost PFC Convertor (M.He, 2013)

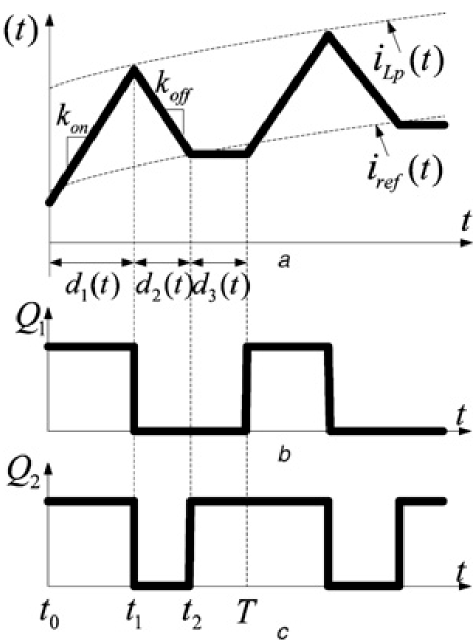

Figure 3.18. Steady Operation of Two-Switch Tri-State Buck-Boost PFC Convertor (M.He, 2013)

The equation of that should be shown as

$$d_1(t)+d_2(t)+d_3(t)=T \tag{3.46}$$

3.2.1.2. Operation of the Two – Switch Tri – State PFC Convertor

The following equation is obtained by rectifier application which the rectified input voltage is shown by

$$v_{in}(t)=V_M\left|\sin\omega t\right|\cong v_{Cf}(t) \tag{3.47}$$

Where $V_M$is the peak input voltage, $v_{cf}(t)$ is the voltage across the input filter capacitor C_f. The input current is proportional to the input voltage that is,

$$i_{in}(t)=v_{in}(t)/R_e \tag{3.48}$$

Where the emulate resistance R_e is constant for a given output power. The output voltage is regulated to a constant voltage V_O.

As shown in Figure 3.24, a separated schematic for the control strategy of the two switch tri state buck-boost PFC converter is considered that voltage control loop is designed for adjusting the output voltage and current control loop for controlling the reference inductor current $i_{ref}(t)$ to make in phase with $v_{in}(t)$ and wave shape to obtain unity power factor. As can be seen from the Figure 3.24 the voltage control loop and current control loop are independent, therefore it causes to design simpler. The difference between v_o and v_{ref}, makes the voltage error $v_e$which feeds the PI controller to produce control pulse Q_1 to control switch S_1. Moreover D_1that refers to the steady state ratio of switch S_1, is constant within one AC line cycle.

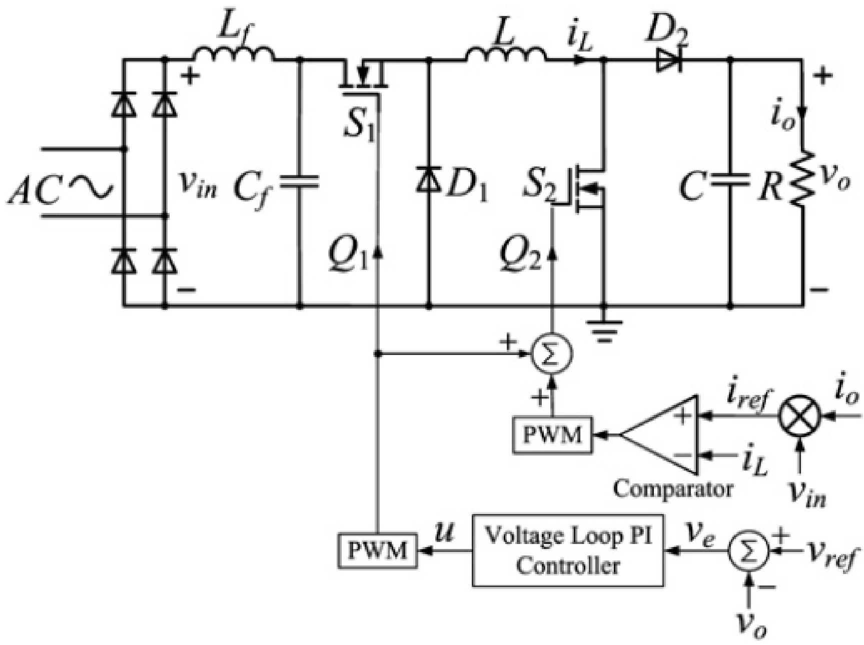

Figure. 3.19. Controlled Two-Switch Tri-State Buck-Boost PFC Converter (M.He, 2013)

Due to the peak inductor current is specified by $i_{Lp}(t)=i_{ref}(t)+\left(v_{Cf}(t).D_1T\right)/L$, where line voltage $v_{in}(t)\cong v_{Cf}(t)=V_M.\sin\omega t$ is sinusoidal, D_1T and input inductance L are constant. Thus, the inductor current $i_{LP}(t)$ is followed to sinusoidal using the line voltage waveform if the reference current $i_{ref}(t)$ is sinusoidal. Conforming to the hysteresis band control, the $i_L(t)$ is carried out to implement the current control loop.

By implying to Figure 3.21-3.23, following equation through switch S_1, $i_{S1}(t)$, input current is given as

$$i_{S1}(t) = \begin{cases} i_L(t) & t_0 \le t < t_0 + d_1 T \\ 0 & t_0 + d_1 T \le t < t_0 + (d_1 + d_2)T \\ 0 & t_0 + (d_1 + d_2)T \le t < t_0 + T \end{cases} \quad (3.49)$$

When switch S_1starts its on-time, t_0 shows the time instant, thus the time average I_{S1} through $S_1$is given as;

$$I_{S1} = d_1(t) I_L = D_1 I_L \quad (3.50)$$

Where the steady state duty cycle represented by D_1, and $I_L$is the average inductor current .

$$\begin{aligned} i_{S1\_av}(t) &= \frac{1}{T}\int_0^T i_{S1}(t)\,dt = \frac{1}{T}\left(i_{ref} d_1(t) T + \frac{1}{2}\frac{v_{Cf(t)}}{L} d_1^2(t) T^2 \right) \\ &= D_1 i_{ref} + \frac{1}{2}\frac{D_1^2}{L} v_{Cf}(t) \cong D_1 i_{ref} + \frac{1}{2}\frac{D_1^2 T}{L} v_{in}(t) \end{aligned} \quad (3.51)$$

Since the input voltage $v_{in}(t)$ is sinusoidal, steady-state duty ratioD_1, switching cycle T and input inductance L are constant. Therefore in the freewheeling stage, by controlling the reference inductor current $i_{ref}(t)$ to make it in wave-shape to, and in phase with the input voltage$v_{in}(t)$, the average currents $i_{S1\_av}(t)$ is also sinusoidal. Through the input low-pass filter, the average input current $i_{in}(t)$ is sinusoidal and unity power factor can be achieved. The $i_{ref}(t)$, that is the reference inductor current, plays very important role in the current control loop that should be huger than the load output current $i_O(t)$ to assure PCCM operation. The big reference inductor current makes the big freewheeling interval time $d_3(t)$ which should be as small as possible to make it a short time. Therefore, $i_{ref}(t)$ by multiplying $v_{in}(t)$, for having sinusoidal, and $i_O(t)$ in order to be proportional with load is proposed. Also, to enhance the dynamic response capability of the two switch tri state buck boost converter. For generating the control pulse to turn on switch S_2 by comparator until off-time of switch S_2, the inductor current $i_L(t)$ has to decrease to the inductor current reference $i_{ref}(t)$.

The output voltage of the two switch tri state buck-boost in the steady state is regulated to constant voltage V_O. Referring to the Figure 3.21-3.23, the inductor voltage $V_L(t)$ is given as;

$$v_L(t) = \begin{cases} v_{Cf}(t) & t_0 \le t < t_0 + d_1 T \\ -v_O(t) & t_0 + d_1 T \le t < t_0 + (d_1 + d_2)T \\ 0 & t_0 + (d_1 + d_2)T \le t < t_0 + T \end{cases} \tag{3.52}$$

So the average inductor voltage $V_L(t)$ is given as;

$$V_L = d_1(t)V_{Cf} - d_2(t)V_O \simeq D_1 V_M - (1 - D_2)V_O \tag{3.53}$$

The steady state duty cycle is shown by D_2 of switch S_2. And also time averaged current I_C and the input current I_{in} is given as;

$$\begin{aligned} I_C &= d_2(t) I_L - I_O = (1 - D_2) I_L - I_O \\ I_{in} &= I_{S1} = d_1(t) I_L = D_1 I_L \end{aligned} \tag{3.54}$$

And considering the $V_L = 0$ and $I_C = 0$ according to the equivalence principle, the input, output relationship of the two switch Tri state buck boost is obtained as;

$$\frac{V_O}{V_M} = \frac{I_{in}}{I_O} = \frac{D_1}{1 - D_2} \tag{3.55}$$

Hence, the control circuit has to establish the steady state duty cycle D_1 and D_2 between 0 and 1 and on the other hand, the sum of D_1 and $D_2 < 1$.

The switch current stress can be analyzed in the interval time $[0, T_{line}/4]$, considering the input voltage waveform is periodic with $T_{line}/2$ (half cycle) and symmetric with relation $T_{line}/4$. Due to the frequency of the switching that is higher than the AC line frequency, by assuming quasi-steady state operation which, the switch duty cycle as operation of time can be obtained from the DC steady state conversion.

$$\frac{d_1(t)}{1 - d_2(t)} = \frac{V_O}{V_m \sin \omega t} \tag{3.56}$$

As shown in Figure 3.22-3.23, $i_L(t)$ will circulate to the load if switch S_2 is turned off, so the average inductor current $i_{L\_av}(t)$ in a switching period is given as;

$$i_{L\_av}(t) = \frac{I_O}{d_2(t)} = \frac{1}{d_2(t)} \frac{V_m^2 \sin^2(\omega t)}{V_O R_e} \tag{3.57}$$

Also the total RMS of the inductor L current is given as;

$$\begin{aligned} I_{L\_rms} &= \sqrt{\frac{4}{T_{line}} \int_0^{T_{line}/4} i_{L\_av}^2(t) dt} \\ &= \sqrt{\frac{4}{T_{line}} \frac{V_m^4}{R_e^2} \int_0^{T_{line}/4} \frac{\sin^4 \omega t}{(V_O - D_1 V_M \sin \omega t)^2} dt} \end{aligned} \tag{3.58}$$

The currents are flowing via switches S_1 and S_2 when the switch $S_1$and S_2 are turned on, then the total RMS of these is given as;

$$I_{S1\_rms} = \sqrt{\frac{4}{T_{line}}\int_0^{T_{line}/4} d_1(t) i_{L\_av}^2(t)\,dt} = \sqrt{\frac{4}{T_{line}}\frac{V_m^4}{D_1 R_e^2}\int_0^{T_{line}/4}\frac{\sin^4 \omega t}{\left(V_O - D_1 V_M \sin\omega t\right)^2}dt} \tag{3.59}$$

$$I_{S2\_rms} = \sqrt{\frac{4}{T_{line}}\int_0^{T_{line}/4} d_2(t) i_{L\_av}^2(t)\,dt} = \sqrt{\frac{4}{T_{line}}\frac{V_m^4}{V_O R_e^2}\int_0^{T_{line}/4}\frac{\sin^4 \omega t}{V_O - D_1 V_M \sin\omega t}dt} \tag{3.60}$$

With equal the steady state input power P_{in} and the steady state output P_{out} of two switch tri state of buck-boost converter, the peak input current I_M is given, from (3.76), (3.77) and (3.84) as follows;

$$I_M = V_O I_O / V_M \tag{3.61}$$

And the peak input current is given, from (3.80) as;

$$I_M = K D_1 V_M I_O + \frac{1}{2L} D_1^2 T V_M \tag{3.62}$$

From (3.90) -(3.91), the steady state duty cycle $D_1$of the two switch Tri state buck-boost is obtained, where K is the sampling coefficient of the current loop.

$$D_1 = \frac{-K V_M I_O L + \sqrt{K^2 V_M^2 I_O^2 L^2 + 2 T V_O I_O L}}{T V_M} \tag{3.63}$$

And the inductor current ripple ΔI_{L_PCCM} of the two switch Tri state buck-boost is obtained by referring to Figure (3.23) as;

$$\Delta I_{L\_\mathrm{PCCM}}(t) = \frac{v_{Cf}(t)}{L} D_1 T \tag{3.64}$$

Compared with PCCM, the inductor current ripple ΔI_{L_DCM} of the two-switch DCM buck-boost PFC converter is presented,

$$\Delta I_{L\_DCM}(t) = \frac{v_{Cf}(t)}{L} DT \tag{3.65}$$

Where

$$D = \frac{\sqrt{2TV_O I_O L}}{TV_M} \tag{3.66}$$

Considering the steady state duty cycle, D of the two switch DCM buck-boost and using of (3.92) and (3.95) is presented as

$$D - D_1 = \frac{\sqrt{2TV_O I_O L} + KV_M I_O L - \sqrt{2TV_O I_O L + K^2 V_M^2 I_O^2 L^2}}{TV_M} > 0 \tag{3.67}$$

Thus, by regarding to (3.65), (3.66) and (3.67) equations, it can be shown that the inductor current ripple ΔI_{L_PCCM} of the two-switch tri-state buck-boost PFC convertor is very small compared with the two switch DCM buck-boost PFC converter in the same conditions and parameters. Besides, the big amount of inductor can be used in the two switch tri state buck –boost PFC converter, also the inductor current ripple can be decreased. Therefore, the power restriction of the two switch DCM buck-boost PFC converter is eliminated, and the power handling capability is achieved in buck-boost tri state buck-boos PFC converter.

4. MODELING OF NEW AUTOMATIC VOLTAGE REGULATOR USING TWO - SWITCH TRI - STATE BUCK – BOOST CONVERTER

4.1. NEW AUTOMATIC VOLTAGE REGULATOR USING TWO – SWITCH THREE – STATE BUCK – BOOST CONVERTER

In this chapter, the design and parameter of components of the new voltage regulator like two switch three state buck-boost converter, synchronous generator and PI controller will be described. The design of the new AVR is made by the PSCAD software program including actual values. Parameters value that were used in the simulation part are also actual value as well. Hence, both the two switch tri state buck-boost PFC converter (M.He, 2013) and PI controller were combined as an AVR in order to keep constant output voltage of the synchronous generator and excite the synchronous generator's field winding. The essential purpose of this simulation is to establish an AVR infrastructure. Afterwards, the results were obtained by using varying loads such as resistive and inductive loads in different percentages of the amount. It is aimed to enhance the startup response and the steady state performance, the proposed AVR is shown below;

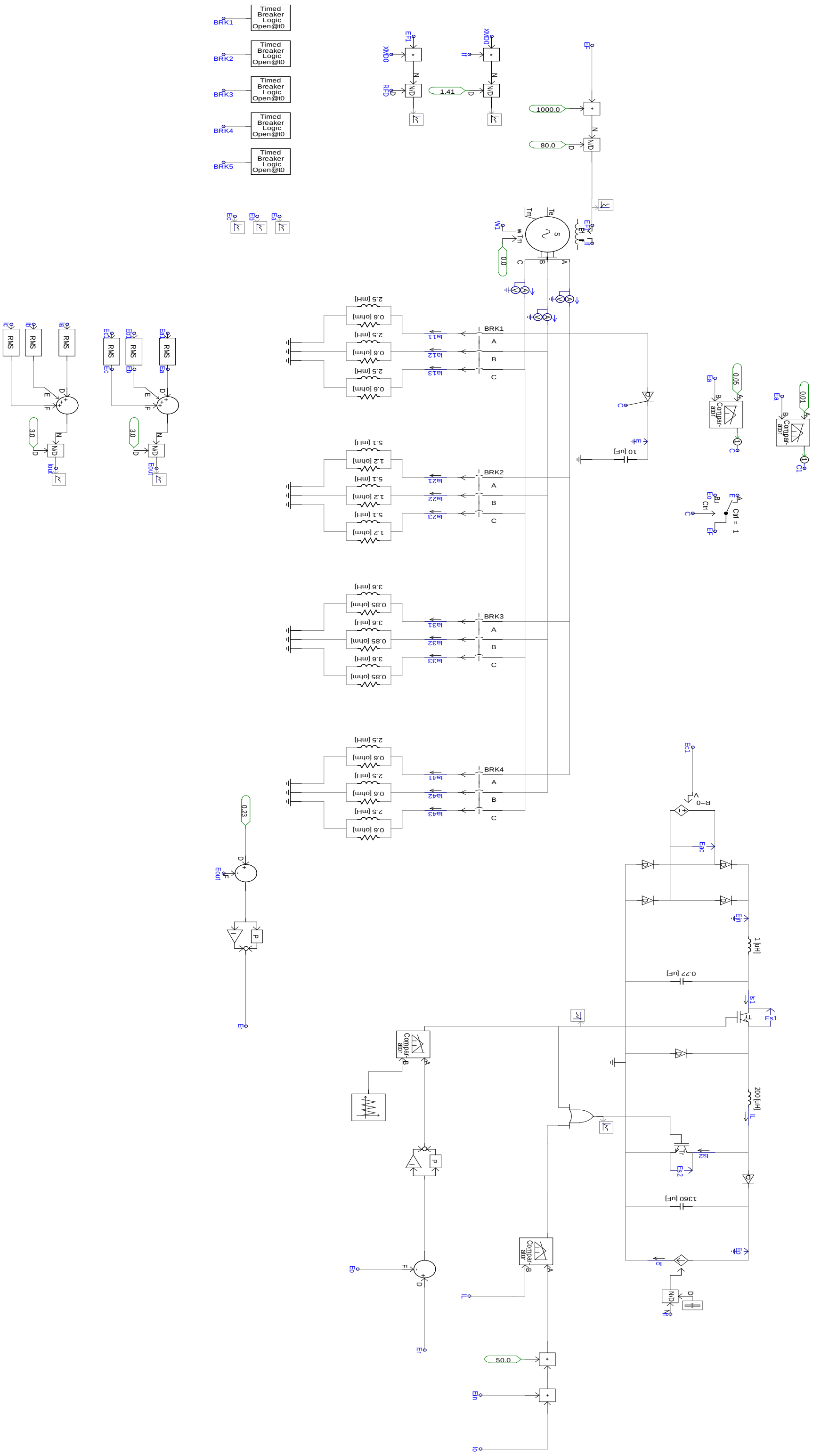

Figure 4.1. Proposed AVR

4.1.1. TWO – SWITCH TRI – STATE BUCK – BOOST PFC CONVETER

The design and the tuned parameters of the proposed two switch Tri state buck-boost converter presented by (M.He, 2013) are described and simulated. In this study, the advantages and analysis of two switch Tri state buck-boost PFC converter which was mentioned in the section above along with the operating in PCCM, is described in terms of an automatic voltage regulator. In the implementation of PSCAD program the circuit parameters of the two switch Tri state buck-boost converter are: $L_f = 1\ \mu H$, $C_f = 0.22\ \mu F$, C=1360 μF, f= 50 KHz, L=200 μH , besides, v_{in} of the two switch three state buck-boost in this study depends on the output of the synchronous generator and its v_O depends on the needed voltage to excite the field winding. As well as, the inductor current variation of two switch Tri state buck-boost converter is much smaller than the DCM converter, for this purpose, a medium amount of inductor is used for representing the advantage of PCCM converter.

The controller is represented by a PI controller with ($K_p = 4, \tau_i = 0.01s$) that generates the signal of switch S_1 through pulse-width-modulated (PWM) by subtracting the v_{ref} andv_O. Also, as shown in Figure 4.1, in order to generate the signal for turning off the switch S_2 current feedback is used.

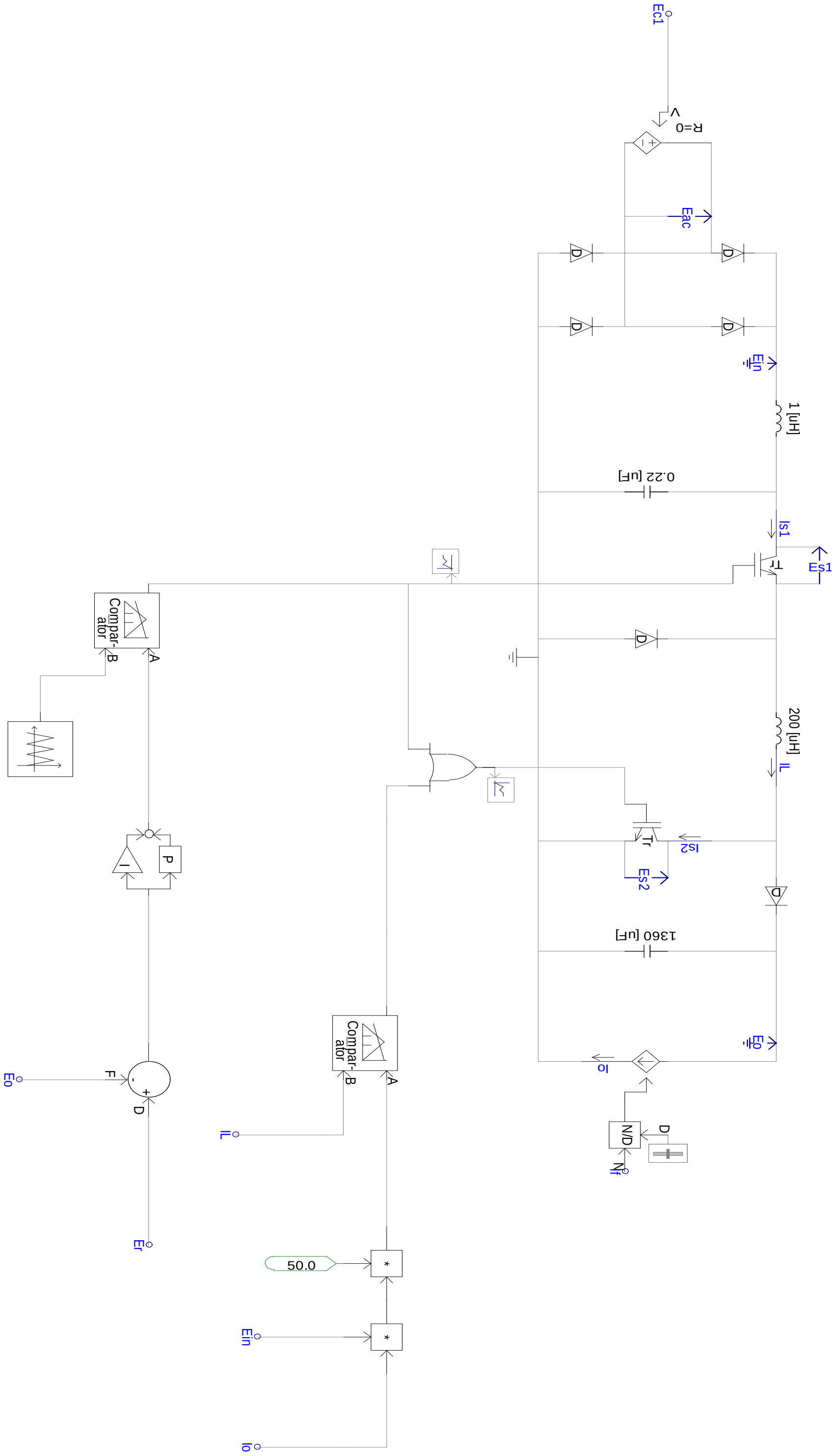

Figure 4.2. Two Switch Tri State Buck-Boost Converter PSACD

4.2. SYNCHRONOUS GENERATOR ON PSCAD

The implemented synchronous generator in this study is described below:

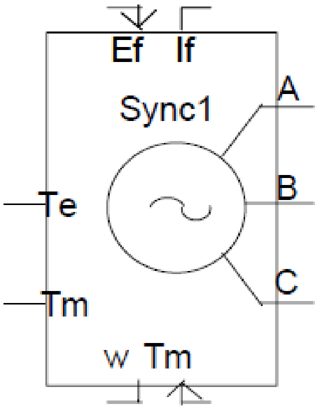

Figure 4.3. Synchronous Generator

I / O	Definition	Description
Ef	Input	The exciter voltage (p.u.)
Tm	Input, output	The mechanical torque (p.u.)
If	Output	The exciter current (p.u.)
Te	Output	The electrical torque (p.u.)
w	Output	The speed of the generator (p.u.)
A,B,C	Output	The voltage (KV)

INPUT/OUTPUT synchronous generator

- **Computation of parameter**

Rated speed at 50Hz $\omega = 2\pi * f = 314\, rad/s$

Rated power $S_n = 330\ KVA$

Rated voltage $V_n = 230\ V$

Rated current $I_n = 478.26\ A$

Real power $P_{3\phi} = 3V_p I_p \cos\varphi$

$= 3*230*478.26*0.8 = 264Kw$

Reactive power

$$Q_{3\phi} = 3V_P I_P \sin\varphi$$
$$= 3 * 230 * 478.26 * 0.6 = 198K\,\text{var}$$

Rated load

$$P_T = 3P_\phi \Rightarrow P_\phi = 88Kw$$
$$P_\phi = \frac{V^2}{R} = \frac{230^2}{R} \Rightarrow R = 0.6\Omega$$

$$Q_T = 3Q_\phi \Rightarrow Q_\phi = 66K\,\text{var}$$
$$Q_\phi = \frac{V^2}{XL} = \frac{230^2}{XL} \Rightarrow XL = 0.8\Omega$$
$$L = \frac{XL}{\omega} = \frac{0.8}{314} = 2.5mH$$

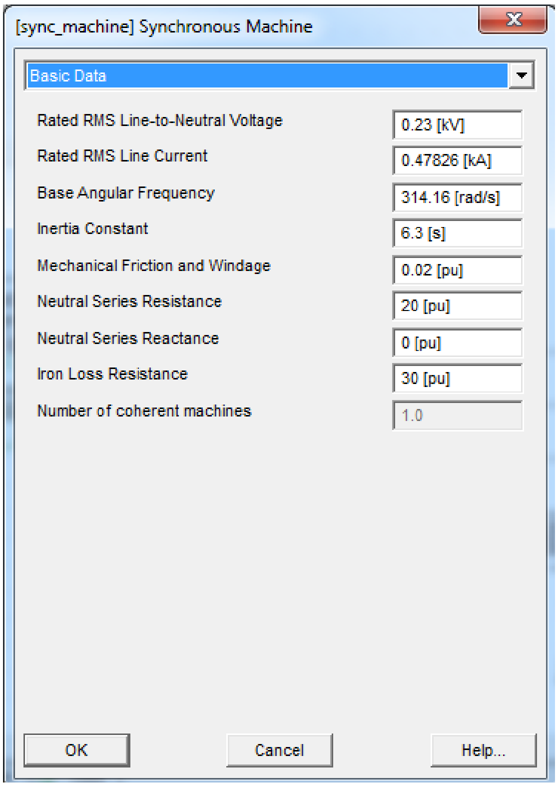

Figure 4.4. Basic Information of Synchronous Generator on PSCAD

4.3. THE PARAMETERS OF P-I CONTROLLER ON PSCAD

In this chapter, the tuned parameter and operation of the P-I (proportional-integral) controller for this study is described. The output value of the main P-I controller denotes the reference value for the two switch Tri state buck-boost converter. The main controller generates the required control signal, by subtracting a reference value with the feedback value. The reference value of the main controller is 230 volts which is considered to be the appropriate value at the terminal voltage of the synchronous generator under each condition of the load. And also, the mentioned feedback is the output voltage of the synchronous generator. Afterward, the generated control signal is sent to buck-boost as a reference value, for generating the required output.

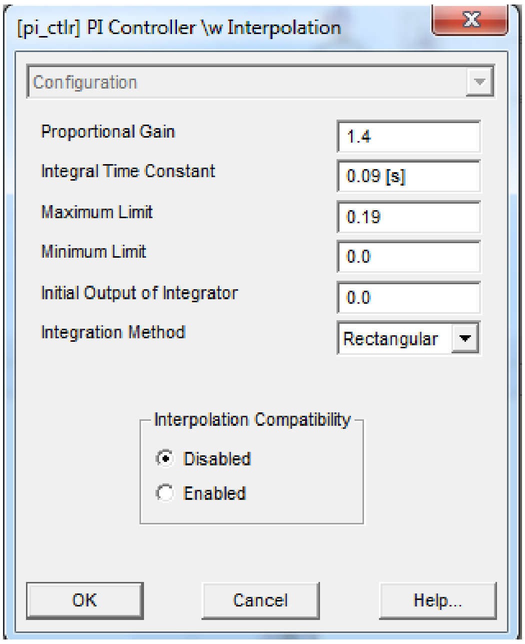

Figure 4.5. Basic Information on P-I Controller

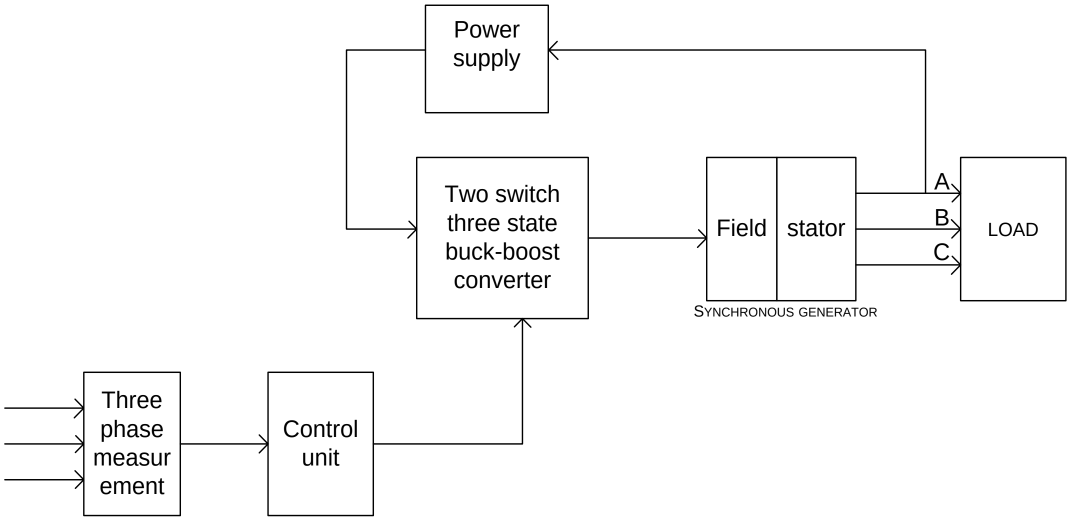

Figure 4.6. The Proposed New Automatic Voltage Regulator Block Diagram

5. SIMULATION AND EXPERIMENTAL RESULTS

In this chapter, experimental and implementation setups along with their several case studies on different conditions of the synchronous generator loads will be considered. These loads consist of resistive and inductive load in varied situation. After applying the parameters that were mentioned earlier to the modeling of AVR, the results of the proposed new automatic voltage regulator using two three state buck-boost converter will be shown.

The proposed new automatic voltage regulator implemented on the PSCAD. In the beginning the used synchronous generator supplies itself by using residual voltage until a value of 50 volts of the A phase through a thyristor, and then the thyristor is turned off by a comparator. Afterwards, the synchronous generator's field winding is excited by the two switch three state buck-boost for increasing the dynamic and start up response. And also the input power supply of the two switch three state buck-boost is connected to C phase of the synchronous generator output in order to be independent of external power supply. The output of the buck-boost is controlled by its P-I controller, in which the controller generates the pulse signal for turning on the switch S_1. The controller's error signal is obtained from the difference between the output voltage of buck-boost and reference voltage that is provided by the main P-I controller. The error signal of P-I controller is obtained from the difference between the reference voltage (230) with the sum of the three RMS (Root Mean Square) voltage of the phase (A, B, C) of the synchronous generator

In this thesis, some cases are investigated in order to examine the system in detail and to see the effects of proposed infrastructure on the system, generally these assumptions are considered:

- Case 1: no load

- Case 2: unbalanced load with R
  30% of rated load at phase A, 50% of rated load at phase B, 50% of rated load at phase C

- Case 3: unbalanced load with R
  50% of rated load at A phase, 30% of rated load at phase B, 50% of rated load at phase C

- Case 4: unbalanced load with R
  50% of rated load at phase A, 70% of rated load at phase B, 100% of rated load at phase C

- Case 5: unbalanced load with L
  30% of rated load at phase A, 50% of rated load at phase B, 50% of rated load at phase C

- Case 6: unbalanced load with L
  %50 of rated load at phase A, 30% of rated load at phase B, 50% of rated load at phase C

- Case 7: unbalanced load with L
  50% of rated load at phase A, 70% of rated load at phase B, 100% rated load at phase C

- Case 8: unbalanced load with RL
  30% of rated load at phase A, 50% of rated load at phase B, 50% of rated load at phase C

- Case 9: unbalanced load with RL
  50% of rated load at phase A, 30% of rated load at phase B, 50% of rated load at phase C

- Case 10: unbalanced load with RL
  50% of rated load at phase A, 70% of rated load at phase B, 100% rated load at phase C

- Case 11: balanced load with R
  30% of rated load

- Case 12: balanced load with R
  50% of rated load

- Case 13: balanced load with R
  70% of rated load

- Case 14: balanced load with R
  100% of rated load

- Case 15: balanced load with L
  30% of rated load

- Case 16: balanced load with L
  50% of rated load

- Case 17: balanced load with L
  70% of rated load

- Case 18: balanced load with L
  100% of rated load

- Case 19: balanced load with R-L
  30% of rated load

- Case 20: balanced load with R-L
  50% of rated load

- Case 21: balanced load with R-L
  70% of rated load

- Case 22: balanced load with R-L
  100% of rated load

These cases are examined and simulated one by one and will be shown the results as follows

Table 5.1. Test results

Tested cases	V_a	V_b	V_c	V_f	I_f
Case 1	229.9	229.9	229.9	9.12	1.29
Case 2	258	215	213	10.63	1.53
Case 3	212	258	215	10.80	1.53
Case 4	260	236	200	12.45	1.75
Case 5	258	214	210	13.48	1.9
Case 6	210	260	214	13.48	1.92
Case 7	264	234	198	16.35	2.3
Case 8	261	214	212	14.13	1.99
Case 9	210	264	214	14.78	2.12
Case 10	262	238	190	19.08	2.7
Case 11	230	230	230	10.08	1.42
Case 12	230	230	230	11.33	1.61
Case 13	230	230	230	13.28	1.87
Case 14	229.7	229.7	229.7	16.47	2.32
Case 15	230	230	230	12.27	1.73
Case 16	229.6	229.1	229.1	14.24	2.03
Case 17	230	230	230	16.54	2.32
Case 18	230	230	230	19.74	2.8
Case 19	229.7	229.4	229.1	12.88	1.84

Case 20	229.8	229.2	229.2	16.09	2.26
Case 21	230	229.2	229.3	19.11	2.73
Case 22	229.3	229.7	230	21.05	3

Besides, some tests such as, changing the rated load from %50 to % 100 of rated load, [70 % to 100 %], [100 % to 70 %], [30 % to 50 %], and [100 % to 50 %] of rated load is done that according to ISO 8528 technical specifications all of the test cases are obeyed as following;

- Permanent voltage regulation:
  When a full load is applied to an alternator, after temporary voltage variance, regulation of the permanent voltage of the alternator should not exceed % $\pm$1.

- Temporary voltage regulation:
  In regulated voltage, the changing from full load to non-load and vice versa, the temporary voltage should not exceed % 15 of nominal voltage and the voltage should be close to the % 5 of nominal voltage limitation within 1 second.

Simulation parameters & analysis

- Duration of run: 13 s
- Solution time step: 1 μs
- Channel plot step: 5 μs
- Startup method: standard

Considering to the test cases that is done above, some tests is also established by using R-L load in order to illustrate the results as waveforms in below Figures. The cases are from {0 to 100%}, {0 to 70%}, {0 to 50%}, {0 to 30%}, {0 to %100% to 70%}, {0 to 100% to 50%}, {0 to 70% to 100%}, {0 to 50% to 100%}, {0 to 30% to 50%}, respectively.

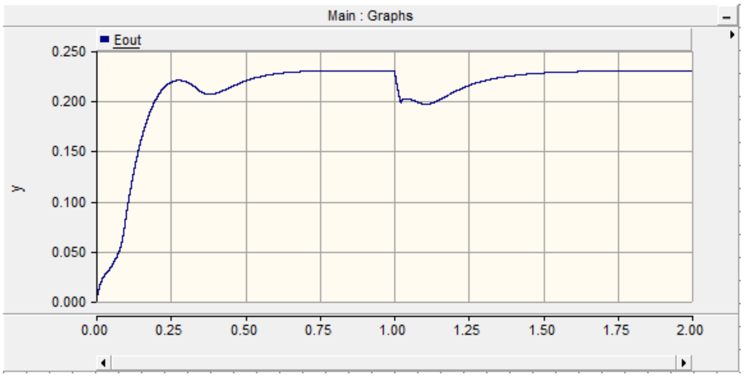

Figure 5.1. Changing the Load From 0 to 100% of Rated Load

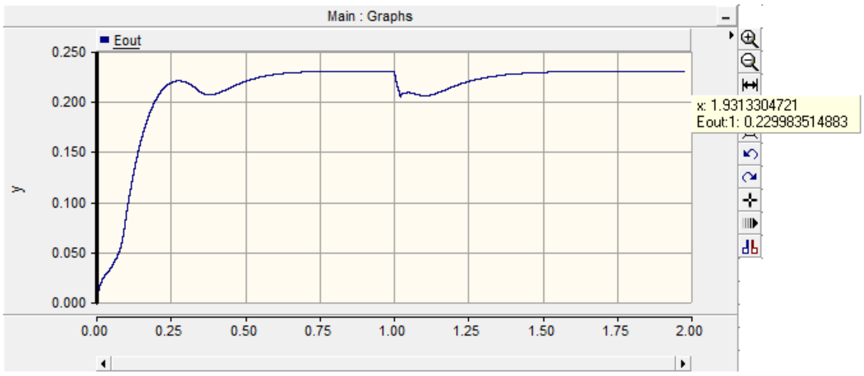

Figure 5.2. Changing the Load From 0 to 70% of Rated Load

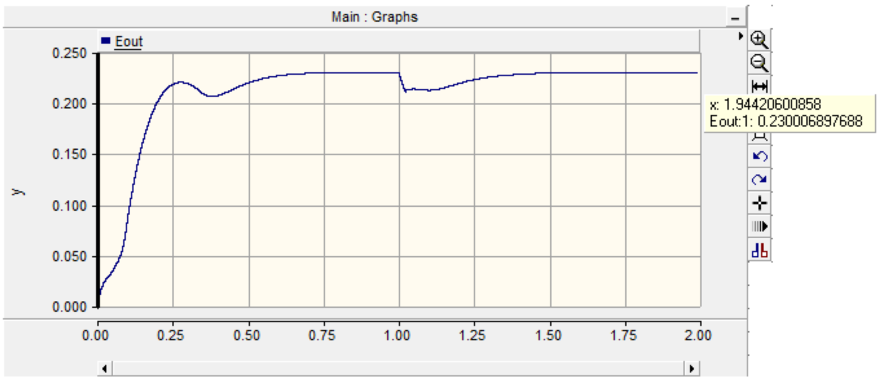

Figure 5.3. Changing the Load From 0 to 50% of Rated Load

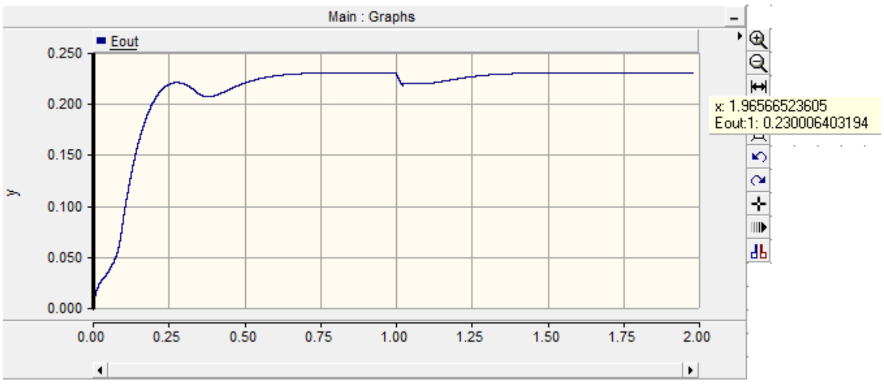

Figure 5.4. Changing the Load From 0 to 30% of Rated Load

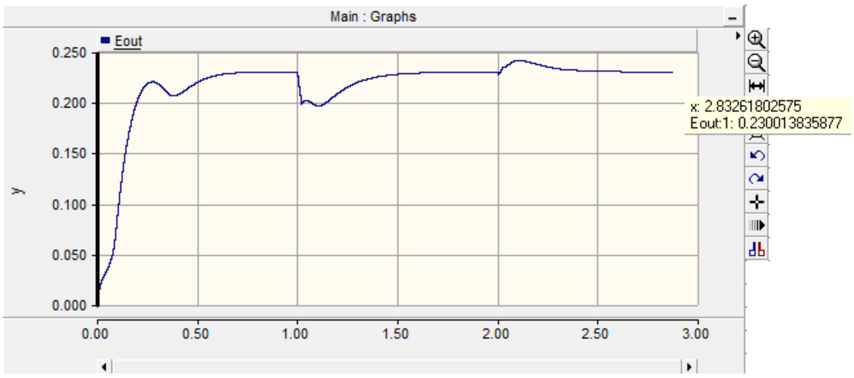

Figure 5.5. Changing the Load From 0 to 100% to 70% of Rated Load

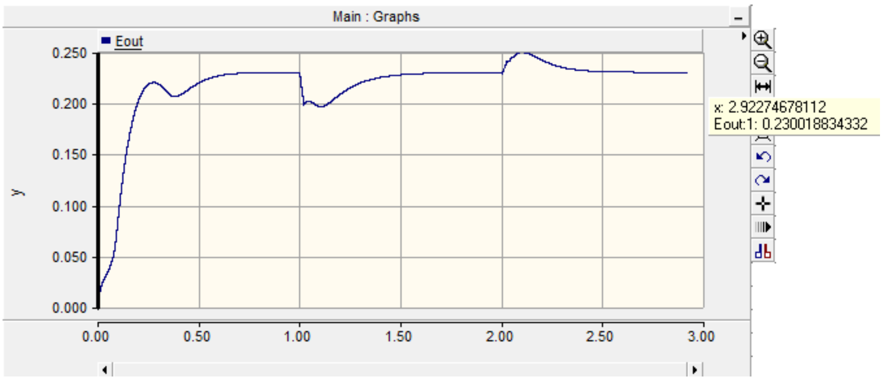

Figure 5.6. Changing the Load From 0 to 100% to 50% of Rated Load

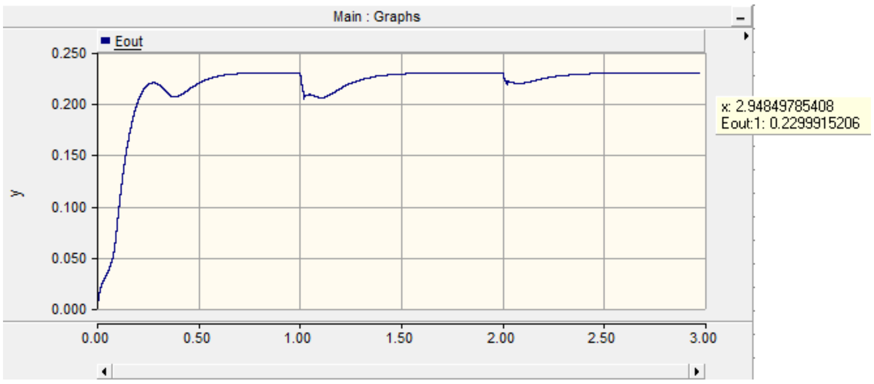

Figure 5.7. Changing the Load From 0 to 70% to 100% Rated of Load

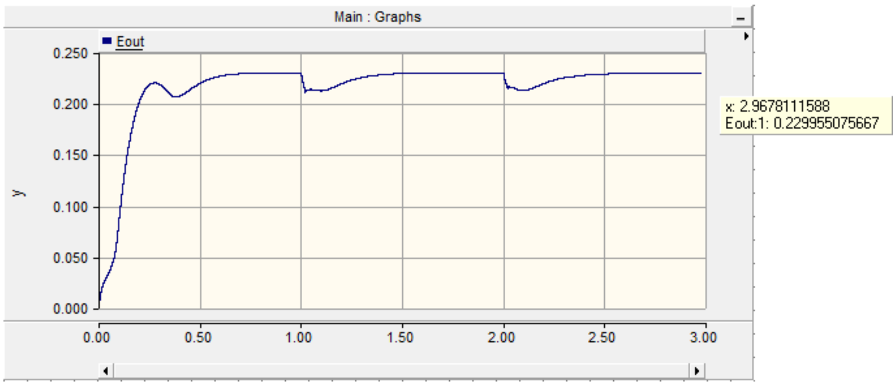

Figure 5.8. Changing the Load From 0 to 50% to 100% Rated of Load

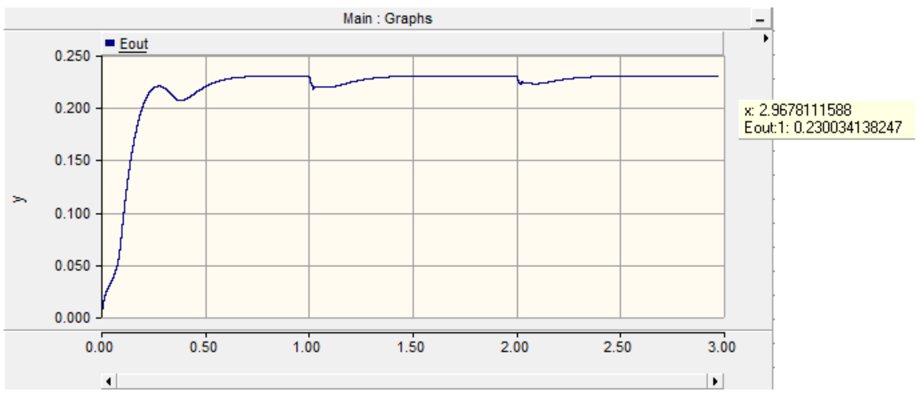

Figure 5.9. Changing the Load From 0 to 30% to 50% Rated of Load

6. CONCLUSION

Nowadays, the demand for exciting the field winding by varied approach is increased. Several manufactories have concentrated their research and development activities on the synchronous generator excitation. The number of the used methods for automatic voltage regulator on the market is increasing day by day. Therefore, the excitation system infrastructure technologies along with automatic voltage regulator are also being developed. Some of the new technology infrastructures used for developing are: DC- DC converters, PWM technique, etc.

In this thesis, a new automatic voltage regulator based on two switch three state buck-boost converter are examined. Related modeling and simulation studies were performed in PSCAD. Also, some regulating method of synchronous generator's output voltage is discussed with their topology. Their control system is reviewed and the most appropriate one is chosen among them. This chosen controller system is proportional-integral (P-I). The main feature and the best advantage of this controller system is, its simplicity and its utilities. However, as an automatic voltage regulator system, the two switch three state buck-boost converter along with the P-I controller are considered in this study.

The main aim of using two switch three state buck-boost for establishing a new automatic voltage regulator is, its operation in the PCCM and also providing the additional degree of control freedom by the inductor current freewheeling stage that causes the splitting controller to make its design much easier. Another reason, is for having so fast transient and dynamic response compared with other converters. In addition, by decreasing the inductor current, the stress current of switching are decreased. Besides, the two switch three state buck-boost converter does not need an additional power switch and has power efficiency.

In this thesis, the advantages of using the two switch three state buck-boost converter to make a new automatic voltage regulator are presented. Afterwards by reviewing the results, it has been noticed that the studied system along with its values, were found to be suitable.

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BIOGRAPHY

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