# CONTROL OF ELECTRIC POWER GENERATORS AND THEIR SYNCHRONIZATION

**A MASTER'S THESIS**

**IN**

**ELECTRICAL AND ELECTRONIC ENGINEERING**

**ATILIM UNIVERSITY**

**by**

**ZAIDOON WALEED JAWAD ALSHAMMARI**

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# CONTROL OF ELECTRIC POWER GENERATORS AND THEIR SYNCHRONIZATION

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Approval of the Graduate School of Natural and Applied Sciences, Atılım University.

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I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

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This is to certify that we have read the thesis "Control of electric power generators and their synchronization" submitted by "Zaidoon Waleed Jawad Alshammari" and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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# ABSTRACT

## CONTROL OF ELECTRIC POWER GENERATORS AND THEIR SYNCHRONIZATION



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We present a simulation based study focusing on the application of a nonlinear control technique to stabilize and control the terminal voltage and power angle of a small synchronous generator driven by a steam turbine engine. The control technique is based on integrator back-stepping techniques which is an application of the second method of Lyapunov to the states of a nonlinear dynamical system one-by-one recursively. The theory is applied to two cases. The first one is the combined control of power angle and terminal voltage of a single generator. The second one is the synchronization of the power angles and terminal voltages of multiple generators (two or more). Upon obtaining a successful and stable generator control system for a main generator, we replicated the controller for another generator and feed the second generator's reference inputs from the first generator's outputs (power angle and terminal voltage of the main generator). The second generator has the same controller design. The same approach is applied to a three generator case. All the generators are assumed identical and same controller designs can be applied. Simulations are presented to verify the approaches developed in this research. Results showed that the control algorithms work satisfactorily in both single generator and multiple generator cases. In the synchronization of multiple generators, the second and later generators have a very small delay.



Keywords: Control of Synchronous Generator, Steam Turbine, Back-stepping Control, Terminal voltage control, Power angle control, Synchronization.

# ÖZ


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Bu çalışmada buhar türbini ile çalışan küçük senkronize alternatif akım jeneratörleri için doğrusal olmayan denetim yöntemleri geliştirilmektedir. Söz konusu denetimin amacı rotor açısı (ya da güç açısı) ve uçbirim (terminal) gerilimini istenen düzeyde tutmaktır. Bu amaçla geri adımlamalı denetim yöntemine başvurulmuştur. Bu metod, Lyapunov'un ikinci kararlılık yönteminin bir uzantısı olup modeldeki her durum değişkenini teker teker kararlaştırmayı amaçlar. Teorik olarak geliştirilen yaklaşımlar, iki değişik probleme uygulanmaktadır. Bunlardan birincisi tek bir üretecin rotor açısı ve uçbirim geriliminin kontrol edilmesi diğeri ise birden çok üretecin bir ana üretecin rotor açısı ve uçbirim gerilimini takip etmesini sağlamaktır. İkinci problemde tüm üreteçlerin aynı olduğu varsayılmıştır. Bu nedenle her bir üreteç için aynı denetleç tasarımları kullanılabilmektedir. Çalışmanın performansını inceleyebilmek için benzetimler yapılmış ve sonuçlar göstermiştir ki ister tek üreteç olsun ister senkronizasyon amaçlı olsun tasarımlar oldukça başarılı olarak görevlerini yerine getirmektedirler. Çoklu üreteçlerin birbirini takibinde çok az bir gecikme söz konusu olmakla beraber bu uygulama açısından herhangi bir sorun teşkil etmemektedir.



Anahtar Kelimeler: Senkronize Üreteç Denetimi, Buhar Türbini, Geri-Adımlamalı Denetim, Son Uç Gerilimi Denetimi, Güç Açısı Denetimi, Senkronizasyon.

To My Parents and my family

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Finally, This graduation is a gift to my dear father, and I wish to thank my family and specially my old brother khaldoon and my mother for their patience and contribution during the years of my study.

***Zaidoon Waleed Alshammari***

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## TABLE OF SYMBOLS

| | Parameter | Definition |
|---|---|---|
| 1 | PID | Proportional, integral and derivative |
| 2 | CLF | Control Lyapunoc function |
| 3 | LFC | Load frequency control |
| 4 | GRC | Generation rate constraints |
| 5 | PI | Proportional – integral |
| 6 | DFL | Direct feedback linearization |
| 7 | SMIB | Single machine infinite bus |
| 8 | PI LFC | Proportional, integral load frequency control |
| 9 | PSS | Power system stabilizers |
| 10 | AVR | Automatic voltage regulator |
| 11 | MIMO | Multi input – multi output |
| 12 | $\omega_o$ | Speed of the generator |
| 13 | M | Inertia coefficient of the generator |
| 14 | $P_{mo}$ | Initial power supplied by the turbine |
| 15 | D | Damping constant |
| 16 | $V_s$ | Infinite bus voltage |
| 17 | $x_d$ | Synchronous reactance of the d-axis |
| 18 | $x_q$ | Synchronous reactance of the q-axis |
| 19 | $x'_d$ | Transient reactance in d-axis |
| 20 | $x_s$ | Reactance of the transmission line |
| 21 | $x_T$ | Reactance of the transformer |
| 22 | $T_{do}$ | The field short circuit time constant |
| 23 | $T'_d$ | Transient field short circuit time constant |

| | | |
|---|---|---|
| 24 | $T_s$ | Equivalent time constant of the steam turbine |
| 25 | $x'_{ds}$ | $x'_d$+$x_T$+$x_s$ |
| 26 | $x_{qs}$ | $x_q$+$x_T$+$x_s$ |
| 27 | $i_d$ | Generator current in d-axis |
| 28 | $i_q$ | Generator current in q-axis |
| 29 | $V_d$ | Generator terminal voltage d-axis |
| 30 | $V_q$ | Generator terminal voltage q-axis |
| 31 | $V_t$ | Generator terminal voltage (over all) |
| 32 | $E_q$ | Internal voltage of q-axis |
| 33 | $x_1$ | Power angle |
| 34 | $x_2=\acute{\omega}$ | Angular velocity |
| 35 | $x_3$ | Transitional q-axis voltage |
| 36 | $u_4$ | Mechanical power |
| 37 | $u_1= u_f$ | Field excitation voltage |
| 38 | $u_2= u_p$ | Electrical control signal to the steam pressure control valve |

# CHAPTER ONE
# INTRODUCTION

## 1.1 Introduction

Synchronous generators are responsible for the bulk of the electrical power generated in the world today. They are mainly used in power stations. These generators are usually connected to the infinite bus where a terminal voltages are held at a constant value by the ‘momentum’ of all the another generators also connected to it [4,9,16,19,56,57]. Synchronous generators [38] are a type of alternating current voltage generating devices often driven by a steam or gas turbine or by hydroelectric means. Regardless of the mechanical energy source, the common input to all generators is the mechanical power generated by utilization of the associated resources. The angular velocity of the generator rotor which determines the frequency of the generated AC voltage depends on the mechanical power supplied. Thus, it can be considered as an actuating input concerning control systems engineering. In addition to the mechanical power, as one can understand from[10] the field voltage excitation might also be controlled to increase the efficiency of the control systems. Moreover, increasing the number of inputs to the generator dynamic will be better as more variables can be manipulated. In order to design a linear or nonlinear control system for a synchronous generator assembly one should first consider the dynamical model of the generator. It has a similarity to AC electric motors in the general sense. They are generally highly nonlinear models describing the angular velocity of the shaft, d- and q-axis voltages, terminal voltage, field voltages and mechanical power variation. In addition, certain inductance parameters such as d- and q-axis reactance are also existent. Linear controllers such as classical proportional-integral-derivative approaches are possible on such models provided that one can propose certain conditions which will allow a linearization of the model. Such assumptions often involve a small power angle which helps the simplification of the generators dynamics by converting some states to constant in the equations. Such a modification, will ease the controller design, but harsh working conditions might be a problem where deviation from the linearization assumptions will be an issue. More recent studies generally involve advanced techniques such as adaptive control [39,45,49], passivity based approaches [21], feedback linearization [28,44], robust control techniques such as $H_\infty$ [35,40,47], neural networks [50] and other various control techniques [46,48,53]. Nonlinear control techniques are expected to bring better performances as they do not need any approximations on the model dynamics. Of course, the technical issues such as the sensor noise or actuation limits will always be present, but are out of scope of this research. In this research, we will also design a nonlinear controller to asymptotically stabilize the terminal voltage and power angle of the synchronous generator. We will employ the integrator back-stepping techniques [27,29,43,51] which will apply the famous second method of Lyapunov to the states of a nonlinear dynamical system one-by-one. One can also incorporate the output of the dynamical system in the phases of back-stepping. Upon obtaining a successful generator control system, we will replicate the controller for another generator and feed the second generator's reference inputs from the first generators outputs which will yield an automatically controlled generator synchronization. In the control system point of view, this reminds studies on synchronization of chaotic systems where a controller is designed to match the states of two identical chaotic nonlinear systems by stabilizing the error dynamics between their states. Generally Lyapunov based techniques are employed in such approaches, a member of which is back-stepping. The difference of our approach is that we only synchronize the terminal voltage and power angle. Stability of the controllers are ensured through the Lyapunov's second method in the back-stepping procedure. In order to demonstrate the performance of the overall designs we will present simulations performed in MATLAB. The goal of case study is to achieved by backstepping control technique which is a recursive application of Lyapunov method. The research problem, we have a model of a small single generator, synchronize two generators and synchronize three generators which is driven by steam turbine system. The model requires a multi-input, multi-output controller design. The problem is simplified by decoupling the turbine dynamics and obtaining a cascaded controller design by placing turbine controller in the center of the cascaded control scheme. The research is contributed to the literature by applying nonlinear backstepping technique to the generator control problem. This is a novel contribution to the literature. Over last few years, the considerable amount of researches have been done in the area of the application of conventional controllers and power system stabilizers to enhance the stability and transient response of the terminal voltage and frequency deviation of synchronous generator. The problems of the most widely applied controller in power system control which is an well-known proportional, integral, and derivative (PID) controller; The parameters tuning is the complex exercise because it depends mainly on a classical techniques which are always time consuming and manually done depending on a classical method and sometimes on a human experts of the operators [37,42]. As the result of a newly huge demands of electrical power, since it works near the maximum demand margins, thus making a system more vulnerable to disturbances [29,32]. The presence of poorly damped modes of oscillation, and continuous variation in power system operating conditions arises some limitations in a conventional controllers (PID) application to a complicated and dynamical system like power system. These limitations have motivated research to design nonlinear control laws to stabilize the generated voltage of asynchronous generators and can be performed automatically.

We can classify the stability in power system into three types which are;

1. Rotor angle stability [26], refers to the ability of synchronous machines of the interconnected power system to remain in synchronism after being subjected to the disturbance. It depends on an ability to restore/maintain equilibrium between mechanical torque and electromagnetic torque of all synchronous machines in a system.

2. Frequency stability [26], refers to the ability of the power system to keep steady frequency following a severe system upset resulting in a significant imbalance between load and generation. It depends on an ability to restore/maintain equilibrium between load and system generation, with minimum unintentional loss of load.

3. Voltage stability [26], refers to the ability of the power system to keep steady voltages at all buses in the system after being subjected to the disturbance from the given initial operating condition. It depends on the ability to restore/maintain equilibrium between load supply and load demand from the power system.

## 1.2 Aim of the work

The main aims of the present work is to design a nonlinear control laws to stabilize the rotor (power) angle and generated voltage of a small single generator, synchronize multiple generators (two or more).

## 1.3 Thesis Structure

The thesis is organized as follow:

**Chapter One**

The general introduction presents an introduction to the problem, aims of the work and thesis Structure**.**

**Chapter Two**

This chapter presents a literature review and historical perspective for the control of synchronous generator that can controllers about the power angle, terminal voltage and frequency response of a synchronous generator in a power system.

**Chapter Three**

In this chapter the mathematical model of the work that will be used throughout this thesis is presented. The mathematical model includes the theoretical background, Lyapunov stability analysis, recursive control design overview, backstepping approach, theory behind backstopping, generic nonlinear system, back-stepping transformation, backstepping control, Backstepping methods, modeling small synchronous AC generators, control of a synchronous AC generators by backstepping.

**Chapter Four:**

The designs presented in chapter three are completed. In this chapter the Simulation system and results for the single generator, synchronize multiple generators(two or more), will introduced and the obtained results are well compared.

**Chapter Five**

Provides conclusions with suggestions for future work.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1: classification of power system stability

The power system is stable if it will regain stable operation after a system disturbance. Generally, there are three main categories of stability analysis. They are namely steady state stability, transient stability and dynamics stability.

1. Steady state stability is defined as the capability of the power system to maintain synchronism after a gradual change in power caused by small disturbances (associated with small perturbations slow variation on loads) [54].

2. Transient stability refers to as the capability of a power system to maintain synchronism when subjected to a severe and sudden disturbance. This disturbance in the network connections is brought about by faults and by sudden large increment of loads (associated with great perturbations line faults, loss of a generating unit, sudden application of a big load, fault in equipment) [54].

3. The third category of stability, which is the dynamic stability, is an extension of steady state stability, it is concerned with the small disturbances lasting for a long period of time [54].

## 2.2: The types of power system stability

In spite of the above classification in 2.1, there are another type concern with the stability nature which also divide into three types which are;

### 2.2.1 Rotor angle stability

For convenience in analysis and for gaining useful insight into a nature problems of stability, it is useful to characterize rotor angle stability in terms of a following two subcategories:

- Small-disturbance (or small-signal) rotor angle stability is concerned with the ability of the power system to keep synchronism under small disturbances. The disturbances are considered to be small enough that the linearization of system equations is allowable for analysis aims [26].

- Large-disturbance rotor angle stability or transient stability, as it is commonly referred to, is concerned with the ability of the power system to keep synchronism while subjected to the heavy disturbance, like the short circuit on the transmission line. The resulting system response include big excursions of generator rotor angles and is affected by the nonlinear power-angle relationship [26].

### 2.2.2 Voltage stability

It is useful to classify voltage stability into the following subcategories:

- Large-disturbance voltage stability refers to the system's ability to keep steady voltage following big disturbances like system faults, loss of generation, or circuit contingencies. This ability is determined by a system and load characteristics, and an interaction of both continuous and discrete controls and protections [26].

- Small-disturbance voltage stability refers to the system's ability to keep steady voltages when subjected to small perturbations like incremental changes in system load. This form of stability is influenced by the characteristics of loads, continuous controls, and discrete controls at the given instant of time [26].

### 2.2.3 Frequency stability

Frequency stability [26], refers to the ability of a power system to keep steady frequency following the heavy system upset resulting in a significant imbalance between load and generation. It depends on the ability to restore/maintain equilibrium between load and system generation, with minimum unintentional loss of load. Instability that may result happens in the form of sustained frequency swings leading to tripping of generating units and/or loads. During frequency excursions, the characteristic times of a device and processes this is activated will range from a fraction of seconds, corresponding to the response of devices like under frequency load shedding and generator controls and protections, to several minutes, corresponding to a response of devices like prime mover energy supply systems and load voltage regulators. Thus, frequency stability may be the long-term or the short-term phenomenon.

## 2.3 Historical perspectives

The problem of the small synchronous generators stability and control has been extensively discussed and developed by several researchers. Because the complexity of the structure of synchronous generators, a wide variety of models have been utilized and several control techniques have been proposed. A review of many previously published works is presented as follows:-

**J. W. Chapman, et al, 1993 [56]:** in this research, the excitation generator control system is defined that utilizes the collection of feedback linearization and an observation decoupled state space. This controller builds can be realistically performed utilizing just local measurements, the execution is consistent by respect to change in the power transfer conditions, load and network configuration. In this respect a control is change from the constant linear gain controller like stabilizers power system.

**H. Su Ryu, et al 2002 [3]:** in this research, they present the extended integral control to the speed-governor system for damping power system oscillations. To control the surplus energy, LFC (Load Frequency Control) loop can be used the direct method. A proposed controller is also based on an extend integral control which is applied to speed-governor to damp out the local mode oscillations. And so a proposed controller give a very good execution under presence of a singularities of speed-governor like limits on GRC and valve position.

**S. Noguchi, et al 2006 [24]:** in this research, they present improvements to the control high side voltage that increases power system stability (both terminal voltage and power angle). The high side voltage control can either be interfaced with exiting automatic voltage regulator or in redesigned can be integrated the functions.

**A. Noco´n and S. Paszek, 2006 [41]:** in this research, they present the method for multiple criteria design the voltage regulator in synchronous generators. A voltage regulator results are compromise sets for the classical control type (proportional-integral). The genetic algorithm is utilized to solve the polyoptimization problem.

**Tushar Kanti Roy, 2016 [12]:** In this research, it is based on the adaptive backstepping approach, this research suggests the control design new coordinated where the coordinate is apply between a steam-valve control of turbine-governor systems and the excitation control of synchronous generators in the multiple machine power system by considering unknown both critical parameters systems. The new control coordinated design can guarantee a stability of multiple machine power systems during a control Lyapunov functions and the adaptation laws derive to determine an parameters unknown in a design process to demonstrate the convergence of power systems utilizing control Lyapunov functions. The stability theoretical of multiple machine power systems is demonstrated during a negative semi-definiteness of the derivative of control Lyapunov functions.

**Qinmin Yang, Bo Fan, 2016 [11]:** In this research, two excitation controls are suggested for power systems with time-varying output constraints. A direct feedback linearization and a transformation tracking error techniques are suggested to transfer an nonlinear original system with limit error to the new without constraints. A stability of a new system guarantees satisfied a time-varying constraints of an original system. We have carefully shown that an output constraint is completed, so a performance of transient can be shaped arbitrarily in transient processes and steady-state. A doubts of dynamics system include inertia constant and damping coefficient are also considered and compensated by adaptive strategies.

**T.K.Roy, M.A.Mahmud, 2015 [8]:** In this research, The problem of stability in the power systems with synchronous generators is discussed and a new adaptive backstepping excitation controller is designed for guaranteeing the transient stability in case of large disturbances. The controls are designed by consider most of a critical parameters of synchronous generators as unknown parameters and adaptive law is considered to determine these stability sensitive parameters. The control design is employed to control various physical properties of synchronous generators like rotor angle, power output, speed of synchronous and terminal voltage. The execution of a controller is estimated by applying short circuit faults three-phase at different positions of a single machine infinite bus system.

**Carlo Cecati, Hamed Latafat, 2012 [7]:** In this research, it has presented a comparative survey of various techniques in estimating transient stability. The transient stability of two machine infinite bus system without or with decentralized nonlinear control was considered whereas a system was influenced by big disturbances during the application of time domain approach and of the direct method of Lyapunov function. In disparity to the time-domain approach, the direct method of Lyapunov define system stability directly based on energy functions.

**Sandeep Jain, 1993 [14]:** In this research, the controller designs based on the nonlinear differential equation model nwant to be considered. The power system model like a nonlinear multi-input multi-output system utilizing state-space formulation has been done. The controller design based on the direct feedback linearization technique may not be robust to handle varying power-system configurations. To robustify the execution, the adaptive extension of the feedback linearization design to achieve the asymptotically exact cancellation of terms is considered. The modeling of power-system has been expressed in the form where a fields of nonlinear vector are linear in a doubts. Parameter adaptation and stability and convergence proofs utilizing an adaptive control design applied to power systems are established. The suggested design is applied to the two-generator, infinite bus system.

**Liying SUN, Jan ZHAO, 2010 [6]:** In this research, the nonlinear main steam valve controller for the single machine infinite bus power systems with the damping coefficient and an equivalence reactance doubts has been derived by means of novel adaptive backstepping technique. A suggested controller preserves a coupling terms including a beneficial error information and error terms of state guaranteeing a concourse properties of subsystems. The closed-loop systems are ensured to be an asymptotically stable utilizing the Lyapunov method and parameters updating law is obtained simultaneously.

**Heon-Su Ryu, 2002 [3]:** In this research, it presented the extended integral control to a speed-governor systems so as to damp out the oscillations of power system. The proportional-integral controls techniques are applied to speed-governor systems for control of load frequency design. The conventional proportional-integral load frequency control design does not yield sufficient controller execution with consideration of a singularities of speed-governor like generation rate constraints and valve position limits. Hence, an extended integral controls are advanced for a proportional-integral controls of a speed governors. An extended integral controls supplies a good controls execution even with presence of an original singular characteristics of a speed-governors, like generation rate constraints and steam valve position limit. It has been conducted for a multiple machine systems with changes a big load.

**SARBESHWAR PRUSTY 1972 [2]:** In this research, The nonlinear transient stability of the synchronous generator connect to the big power systems by the direct method of Lyapunov. Lyapunov function can provide the exact stability limit. We have a trial has been made by the author in formulating Lyapunov function for a different type of model of a synchronous generator joined to the big power systems. Strict mathematical analysis for a presence of, the method of finding, an optimum value of Lyapunov functions parameter is included a problem of transient stability. This makes a present method of constructing a Lyapunov functions for an obtain a region of asymptotic stability rational and systematic.

**Youssef A. Smaili, Ali T. Alouani, 1992 [13]:** In this research, studies the application $H_\infty$ optimal control theory to designs the supplementary excitation and governor control system to increase the stability and execution robustness of the electric power systems. It is based on the single machine infinite bus system. A controller was applied utilizing a nonlinear plant model. The control systems are robust in face of various kinds of disturbances that the power system can be subject to like change in power reference level or voltage and the short circuit in three phase happened at an terminal infinite bus. The potential of this technique in terms of execution and stability robustness. This allow the controller to work well over the wide range of potential operating points.

**Ben WANG, Zongyang MAO, 2007 [22]:** In this research, it proposed the set of a novel nonlinear variable structure stabilizer for the synchronous generator. Basic idea is the global linearization is utilized to transfer a dynamic equation from the nonlinear system to the linear one. Thereafter, an index asymptotic variable structure control techniques are utilized. The systematic procedures are utilized to find a switch function of a variable structure control. A dynamic systems are nonlinear, by strict mathematic deductive process, we can get a very simple proportional excitation control; in the same time, and so obtain other control steam valve nonlinear. After applying a two controls in combination to the single generator infinite bus power system, A dynamic quality of the system execution and robustness of a stabilizers against system disturbances is much more effective.

**H.Chen, H. B. Ji, B. Wang, 2006 [21]:** In this research, the steam-valving and dual-excited controls for synchronous generators are proposed to obtain voltage stability and rotor angle stability. The steam valving controls are designed by backstepping techniques, while dual excited controls are based on coordinated passivation. A passivity based controls can be obtained to guarantee the closed loop systems are asymptotically stable. A control design is effectiveness. We have utilized a coordinated passivation design tool to design a steam-valving and dual excited controller of synchronous generator to ensure the systems are asymptotically stable.

**J. De Leon-Morales, K. Busawon, 2001 [20]:** In this research, the nonlinear control observer design has been developed and applied to a synchronous generator model. A controls design are based on a sliding mode and singular perturbation techniques. An observers design are based on the recent approach which does not require the solution of a differential equation to update its gain. It assumed the states of a system are available during the observer, the control of composite tracking was first designed for the generator utilizing a sliding mode techniques. It assumed just a rotor angular position is available state variable, the observers were design to find the angular speed and the value of $E_q'$. We found a good performance of the combined observer controller.

**Zairong Xi, Daizhan Cheng, 2000 [18]:** In this research, we considered conservative quantity of a power system excitation controls. It showed that the systems has no common conservative quantity for both the closed-loop and unforced systems. It implies that the closed-loop system has different conservative quantity from the unforced system, it has no relative equilibrium to the power systems.

**Alexander G. loukianov, J. Cabrere-Vazquez, 2000 [17]:** In this research, it designed the nonlinear observer based excitation controllers for power systems comprising the single synchronous generator joined to the exciter system and the infinite bus systems. A controllers proposed are based on an utilizing variable structure system and singular perturbation system concept, and block control principle. The nonlinear observer for calculation of rotor fluxes and mechanical torque, is included. This combined approach enables to compensate the original nonlinearities of the generator and to reject external disturbances. A designs process, including analysis of stability, are discussed. A formulation employed makes simple to design the nonlinear observer that exhibits the good performance for a power system with unmodeled dynamic and discontinuous controls.

**J.Machoeski, J.W.Bialek, 1998 [15]:** In this research, the optimal excitation controls strategy has been derived for a nonlinear generator infinite busbar systems. By utilizing the direct method of Lyapunov in conjunction with the energy type Lyapunov function, an optimal control strategy has been derived, which maximises the speed with which Lyapunov function decreases, therefore, maximising energy dissipation in the system. By utilizing a model of nonlinear system, a controls strategy are optimal over the wide range of rotor angle and swing frequency changes. And so it achieves the same positive damping, regardless of the value of the transmission network parameter. In a standard system the main voltage controllers are the automatic voltage regulator.

# CHAPTER THREE

# THEORETICAL BACKGROUND

## 3.1 Introduction

The purpose of this chapter is to present the theoretical background behind the control approaches of this research. The theory of backstepping and input output feedback linearization are presented in a form suited for the control [44]. In control theory [27], backstepping is a technique developed for designing stabilizing controls for a special class of nonlinear dynamical systems. The process terminates when the final external control is reached. Therefore, this process is known as backstepping.

## 3.2 Lyapunov stability analysis

For a given control system, stability is usually the most important thing to be determined [30,33,34]. If the system is linear and time invariant, many stability criteria are available. Among them are the Routh's stability criterion and Nyquist stability criterion. If the system is linear or nonlinear but time varying, however, then such stability criteria do not apply. The direct method of Lyapunov which is also called the second method of Lyapunov for determination of the stability of nonlinear and/or time varying system. This method, of course, applies to determination the stability of linear, time-invariant systems. And so, for solving quadratic optimal control problems we can use the direct method of Lyapunov.

The methods of Lyapunov, In 1892, A. M. Lyapunov presented two methods, ( first method and second method) for determining a stability of dynamics systems.

The first method of Lyapunov is consists of all procedures in which an explicit form of the solutions in differential equations is used for analysis.

The second method of Lyapunov is on the other hand, does not require the solutions of differential equations. This is, by using the second method of Lyapunov, we can determine the stability of the system without solving the state equations.

System: the system we consider is defined by

$$\dot{x} = f(x , t) \qquad (3.1)$$

Where x is a state vector (n – vector) and f ( x , t ) is an n – vector whose elements are function of $x_1$ , $x_2$ , . . . . , $x_n$ and t, and so suppose the system of equation (3.1) has a unique solution beginning at the given initial condition.

Equilibrium state: at the system of equation (3.1) , a state $x_e$

where

$$f(x_e,t) = 0 \qquad \text{For all t} \tag{3.2}$$

It is named an equilibrium state of the system. If in the linear time invariant system, that is, if Ax = f(x,t), thereafter there exists just one equilibrium state if A is nonsingular and there exist infinitely many equilibrium states if A is singular. The solution of differential equations of the system, equation (3.1) it does not involve to determination of the equilibrium states, but the equation (3.2) just we can solution the equation.

**Asymptotic stability**

In the system of equation (3.1) the equilibrium state $x_e$ is said to be asymptotically stable if it is stable in the sense of Lyapunov and if all solution beginning within S($\delta$) converges, without leave S(Ɛ), to $x_e$ as t increases indefinitely.

In practice, the asymptotic stability is more important than stability. And also, since asymptotic stability is a local concept, simply to establish asymptotic stability may not mean the system will work properly. The size of the largest region of asymptotic stability is necessary (usually). The name of this region is a domain of attraction [30].

**Second method of Lyapunov**

From the classical theory of mechanics, we know the vibratory system is stable if its total energy (positive – definite function) is continually decreasing (this means the time derivative of the total energy should be negative definite) until the equilibrium state is reached.

The second method of Lyapunov is based on the generalization of this fact: if a system has asymptotically stable equilibrium state, thereafter the stored energy of the system displaced within the domain of attraction decays with increasing time until it lastly suppose its smallest value at the equilibrium state. In fact, any scalar function satisfying the hypotheses of Lyapunov's stability theorem (theorem 3-1 , 3-2) can serve as Lyapunov functions. (in the simple systems, we may be able to guess suitable Lyapunov functions; but finding a Lyapunov function may be very difficult, for a complicated system).

### 3.3 Lyapunov's main stability theorem

It can be shown that if a scalar function v(x), where x is the n – vector, is positive definite, thereafter the states x that satisfy

$$v(x) = C$$

Where C is a positive constant, lie on a closed hypersurface in the n – dimensional state space, at least in the neighborhood of the origin. If $v(x) \rightarrow \infty$ as $\| X \| \rightarrow \infty$, thereafter such closed surfaces extend over the entire state space. The hypersurface $v(x) = C_1$ lies entirely inside the hypersurface $v(x) = C_2$ if $C_1 < C_2$.

For the given system, can be found if a positive – definite scalar function v(x) such that its time derivative taken along a trajectory is ever negative, thereafter as time increases v(x) takes smaller and smaller values of C. As time increases, v(x) lastly shrinks to zero, and therefore x so shrinks to zero. Lyapunov's main stability theorem, which is a generalization of the foregoing fact, gives an enough condition for asymptotic stability. This theorem may be stated as follows:

**Theorem 3 – 1** suppose that a system is described by:

$$\dot{x} = f(x , t)$$

Where

$$f(0,t) = 0 , \quad \text{for all } t$$

If there exists a scalar function v(x, t) having continuous, first partial derivatives and satisfying the conditions

1. V (x , t) is a positive definite
2. $\dot{V}(x , t)$ is a negative definite

Thereafter the equilibrium state at the origin is uniformly asymptotically stable. If $v(x, t) \rightarrow \infty$ as $\| X\| \rightarrow \infty$ , thereafter the equilibrium state at the origin is uniformly asymptotically stable in the large. Though theorem (3–1) is the basic theorem of a second method of Lyapunov, somewhat restrictive because $\dot{V}(x , t)$ should be negative definite. If restriction is imposed on $\dot{V}(x, t)$ this it not vanish identically along any trajectory except at the origin, thereafter it is possible to replace the requirement of $\dot{V}(x , t)$ being negative definite by stating that $\dot{V}(x, t)$ be negative semidefinite.

**Theorem 3 – 2** suppose that the system is described by

$$\dot{x} = f(x , t)$$

Where

$$f(0,t) = 0 , \qquad \text{for all } t \geq t_o$$

If there exists a scalar function $v(x , t)$ having continuous, first partial derivatives and satisfying the conditions

1. $V(x , t)$ is a positive definite.
2. $\dot{V}(x , t)$ is a negative semidefinite.

Thereafter the equilibrium state at the origin of the system is uniformly asymptotically stable in the large. If $\dot{V}(x , t)$ is not negative definite, but just negative semidefinite, thereafter the trajectory of a representative point can become tangent to some particular surface $v(x , t) = C$. If there exists a positive – definite scalar function $v(x , t)$ same this $\dot{V}(x , t)$ is identically zero, thereafter the system can remain in a limit cycle. In this case, the equilibrium state at the origin is said to be stable in the sense of Lyapunov [30].

**Instability:** If the equilibrium state $x = 0$ of the system is unstable, thereafter there exists a scalar function $W(x , t)$, which determines the instability of the equilibrium state. The theorem of instability in the following [30].

**Theorem 3 – 3** Suppose that the system is described by

$$\dot{x} = f(x, t)$$

Where

$$f(0,t), \quad \text{for all } t \geq t_o$$

If there exists a scalar function W(x , t) having continuous, first partial derivatives and satisfying the conditions

1. W(x , t) is a positive definite in some region about the origin.
2. $\dot{W}$(x , t) is a positive definite in the same region.

Then the equilibrium state at the origin is unstable [30].

## 3.4 Backstepping approach

The backstepping approach gives a recursive method for stabilizing the origin of a system in strict – feedback form [27]. This is, treat a system of the form

$$\dot{x} = f_x(x) + g_x(x)\, z_1$$

$$\dot{z}_1 = f_1(x, z_1) + g_1(x, z_1)\, z_2$$

.

.

$$\dot{z}_i = f_i(x, z_1, z_2, \ldots, z_{i-1}, z_i) + g_i(x, z_1, z_2, \ldots, z_{i-1}, z_i)\, z_{i+1} \qquad \text{for } 1 \leq i \leq k-1$$

.

.

$$\dot{z}_{k-1} = f_{k-1}(x, z_1, z_2, \ldots, z_{k-1}) + g_{k-1}(x, z_1, z_2, \ldots, z_{k-1})\, z_k$$

$$\dot{z}_k = f_k(x, z_1, z_2, \ldots, z_{k-1}, z_k) + g_k(x, z_1, z_2, \ldots, z_{k-1}, z_k)\, u$$

Where

- $X \in R^n$ with $n \geq 1$ ,
- $z_1$ , $z_2$ , . . . , $z_i$ , . . . , $z_{k-1}$ , $z_k$ are scalars ,
- $u$ is a scalar input to the system ,
- $f_x$ , $f_1$ , $f_2$ , . . . , $f_i$ , . . . , $f_{k-1}$ , $f_k$ vanish at the origin

($f_i$ (0,0, . . . . ,0) = 0) ,

- $g_1$ , $g_2$ , . . . , $g_i$ , . . . , $g_{k-1}$ , $g_k$ are nonzero over the domain of interest ( $g_i$(x, $z_1$, . . . , $z_k$ ) ≠ 0 for $1 \le i \le k$ ).

And so suppose the subsystem

$$\dot{x} = f_x(x) + g_x(x)\, u_x(x)$$

The backstepping approach concludes whereby to stabilize the x subsystem using $z_1$ , and thereafter proceeds with concludes whereby to make the next state $z_2$ drive $z_1$ to the control desired to stabilize x. Therefore, the process "steps backword" from x out of the strict – feedback form system until the final control $u$ is designed.

### 3.5 Theory Behind Backstepping

Backstepping is a modular method of control. Descriptively, it is a recursive or step by step completion of the design process. This is generally performed through a partition of the state vector of the dynamical plant model. The sub – states obtained from that partition are stabilized one by one in each step [58].

#### 3.5.1 Generic Nonlinear System

The models used in the design procedures of this work must be in affine form such as the one shown below:

$$\dot{x}_1 = f_1(x_1)\, x_2$$

$$\dot{x}_2 = f_2(x_1, x_2) + g(x)\, u \qquad (3.3)$$

Where $x_{1,2} \in R^m$ , $u \in R^m$ , $x = [x_1^T \ x_2^T]^T \in R^{n=2m}$, $g$ (x) $\in R^{mxm}$, $f_1$(x) $\in R^{mxm}$ and $f_2(x_1 , x_2) \in R^m$ .

It is supposed that $f_1(x_1)$ and $g$ (x) are invertible matrices. The example is designed as a tracking problem where $x_1$(t) must track the desired trajectory defined by $x_{1d}$ (t) [59].

### 3.5.2 Back – stepping Transformation

The back – stepping transformation is a state transformation mechanism to Obtain the states of the closed loop after the solution of the problem. For tracking problems it will be convenient to choose a new state variables as the additive errors of the states [59]. For the current example, the new state variables are obtained from the following transformation:

$$z_1 = x_1 - x_{1d}$$
$$z_2 = x_2 - \alpha_1 \tag{3.4}$$

Where the new term $\alpha_1$ is an artificial command input to produce an internal control loop. The next step is to differentiate them with respect to time and substitute the necessary functions from the system equation in (3.3).

### 3.5.3 Backstepping Control

Differentiating the first virtual state variable $z_1$ [58,59] and substituting the first equation from (3.3) leads to:

$$\dot{z}_1 = \dot{x}_1 - \dot{x}_{1d} = f_1(z_1 + x_{1d})\, x_2 - \dot{x}_{1d} \tag{3.5}$$

Thereafter substitute $x_2$ from (3.4) to obtain:

$$\dot{z}_1 = f_1(z_1 + x_{1d})\,(z_2 + \alpha_1) - \dot{x}_{1d} \tag{3.6}$$

For the sake of simplicity the term $f_1(z_1 + x_{1d})$ will be written as $f_1(x_1)$ throughout this section. The real control design procedure begins with the definition of the Lyapunov function corresponding to $z_1$. This can be a quadratic Lyapunov function similar shown below:

$$v_1 = \frac{1}{2} z_1^T z_1 \tag{3.7}$$

And,

$$\dot{V}_1 = \frac{1}{2}\dot{z}_1^T z_1 + \frac{1}{2} z_1^T \dot{z}_1 \tag{3.8}$$

Also, substituting $\dot{z}_1$ from (3.6) yields:

$$\dot{V}_1 = \frac{1}{2}\left[(\alpha_1^T + z_2^T)\, f_1^T(x_1) - \dot{x}_{1d}^T\right] z_1 + \frac{1}{2} z_1^T\left[f_1(x_1)(z_2 + \alpha_1) - \dot{x}_{1d}\right] \tag{3.9}$$

A useful expansion of the above function is shown below:

$$\dot{V}_1 = \frac{1}{2}[(\alpha_1^T) f_1^T(x_1) - \dot{x}_{1d}^T] z_1 + \frac{1}{2} z_1^T [f_1(x_1)(\alpha_1) - \dot{x}_{1d}] + \frac{1}{2} z_2^T f_1^T(x_1) z_1$$

$$+ \frac{1}{2} z_1^T f_1(x_1) z_2 \quad (3.10)$$

To obtain a stable dynamics on variable $z_1$ one must obtain a negative definite quadratic function of $z_1$. The remaining section (the terms involving $z_2$) is eliminated in the second step. One can do the following for this purpose:

$$\alpha_1^T f_1^T(x_1) - \dot{x}_{1d}^T = - z_1^T K_1$$

&

$$f_1(x_1)\alpha_1 - \dot{x}_{1d} = - K_1 z_1 \quad (3.11)$$

This is the replacement of the term $f_1(x_1)\,\alpha_1 - \dot{x}_{1d}$(and thus its transposed version in the other half) with $-K_1 z_1$. One can solve for $\alpha_1$ here and obtain:

$$\alpha_1 = f_1^{-1}(x_1)\,\dot{x}_{1d} - f_1^{-1}(x_1)\,K_1 z_1 \quad (3.12)$$

As a result the Lyapunov derivative is:

$$\dot{V}_1 = -z_1^T K_1 z_1 + \frac{1}{2} z_2^T f_1^T(x_1) z_1 + \frac{1}{2} z_1^T f_1(x_1) z_2 \quad (3.13)$$

It could be understood from the above, the matrix $K_1$ should be positive definite and symmetric. Now we can continue through the second step beginning with the differentiation of the second virtual variable $z_2$:

$$z_2 = x_2 - \alpha_1$$

$$\dot{z}_2 = \dot{x}_2 - \dot{\alpha}_1 \quad (3.14)$$

From the system equation (3.3) and obtain:

$$\dot{z}_2 = f_2(x_1, z_2 + \alpha_1) + g(x_1)\,u - \dot{\alpha}_1 \quad (3.15)$$

Same equation (3.6) the term $f_2(x_1, z_2 + \alpha_1)$ will be become as $f_2(x_1, x_2)$. The second Lyapunov function (on $z_2$) can be also a quadratic Lyapunov function similar $z_1$ (first step) and add to $V_1$. This is:

$$v_2 = v_1 + \frac{1}{2} z_2^T P_2 z_2 \quad (3.16)$$

With $P_2$ being positive definite. Differentiating $V_2$ and substituting from (3.15) yields:

$$\dot{V}_2 = - z_1^T K_1 z_1 + \frac{1}{2} z_2^T f_1^T(x_1)\, z_1 + \frac{1}{2} z_1^T f_1(x_1)\, z_2 + \frac{1}{2}\{ u^T g^T (x) + f_2^T (x_1, x_2) - \dot{\alpha}_1^T \}$$

$$P_2 z_2 + \frac{1}{2} z_2^T P_2 \{ f_2 (x_1,x_2) + g (x)\, u - \dot{\alpha}_1 \} \tag{3.17}$$

And,

$$\dot{V}_2 = - z_1^T K_1 z_1 + \frac{1}{2}\{ u^T g^T (x)\, P_2 + f_2^T (x_1, x_2)\, P_2 - \dot{\alpha}_1^T P_2 + z_1^T f_1(x_1) \}\, z_2$$

$$+ \frac{1}{2} z_2^T \{ P_2\, f_2 (x_1,x_2) + P_2\, g (x)\, u - P_2 \dot{\alpha}_1 + f_1^T(x_1) z_1 \} \tag{3.18}$$

Similar the first step of the procedure, it is required to replace the non quadratic terms in the above function with negative definite terms also one can do the following:

$$P_2 f_2 (x_1,x_2) + P_2\, g(x)\, u - P_2 \dot{\alpha}_1 + f_1^T(x_1)\, z_1 = - K_2 z_2$$

$$u^T g^T(x)\, P_2 + f_2^T (x_1, x_2)\, P_2 - \dot{\alpha}_1^T P_2 + z_1^T f_1(x_1) = - z_2^T K_2 \tag{3.19}$$

And the control input $u$ now can be obtained as shown in below:

$$u = - g^{-1} (x)( P_2)^{-1} \{ K_2 z_2 + P_2\, f_2 (x_1,x_2) + f_1^T(x_1)\, z_1 - P_2\, \dot{\alpha}_1 \} \tag{3.20}$$

Also the total Lyapunov derivative is:

$$\dot{V}_2 = - z_1^T K_1 z_1 - z_2^T K_2 z_2 \tag{3.21}$$

If $K_2$ is a symmetric and positive definite matrix, the closed loop system is globally stable.

Also The differentiated value of $\alpha_1$ must be obtained through the system state equation. This can be done by for example:

$$\dot{\alpha}_1 = \frac{\partial \alpha_1}{\partial x}\, \dot{x} \tag{3.22}$$

Where $\dot{x}$ is replaced by the right hand side of the state equation in (3.3). Finally, the closed loop system equations are:

$$\dot{z}_1 = f_1(x_1)\, z_2 + K_1 z_1$$

$$\dot{z}_2 = -p_2^{-1} K_2 z_2 - p_2^{-1} f_1^T ( x_1)\, z_1 \tag{3.23}$$

The aim of the example given in this section is to present the main procedure of backstepping. Of course in the realistic applications, the selection of the Lyapunov functions and control inputs may be different. They could be changed according to the design requirements. In the control laws of (3.12) and (3.20) the state variables $x_1, x_2$ and the errors $z_1, z_2$ are computed from the sensing system.

### 3.6 Backstepping methods

Back-stepping method is developed by [27,28,29,43] which allows the asymptotic stabilization of a nonlinear system through the implementation of the second method of Lyapunov on each element of its state vector individually. The interconnection of each state is maintained through introduction of virtual control inputs to the dynamics associated with the considered state.

#### 3.6.1 Lyapunov's second method

Consider a dynamical system of the form [1,36]:

$$\dot{x} = f(x, u) \tag{3.24}$$

One should also suppose that $f(0,0) = 0$ which means that the above system has an equilibrium at the origin. In addition, one should define a control Lyapunov function (CLF) V(x) which bears the following properties:

1. V(x) should be positive definite: $V(x) > 0$.
2. $V(0) = 0$.
3. V(x) should be radially unbounded: $\lim_{x\to\infty} V(x) = \infty$.
4. $\frac{\partial v(x)}{\partial x} f(x,u) < 0$: The variation of the V(x) along the trajectories of the nonlinear system should be decreasing.

If the properties above are all satisfied by V(x), $x = 0$ is asymptotically stable in the sense of Lyapunov. If V(x) is a CLF for $\dot{x} = f(x, -k(x))$, the closed loop system formed by the feedback $u=-k(x)$ is also asymptotically stable in the sense of Lyapunov. The latter is the main approach utilized in the back-stepping based controller development.

#### 3.6.2 Relative Degree

In order to define the vector relative degree concept, it will be convenient to rewrite (3.24) as a affine nonlinear system form:

$$\dot{x} = f(x) + g(x)\,u \qquad (3.25)$$

$$y = h(x) \qquad (3.26)$$

Where x Є $R^n$ is the state vector, $u$ Є $R^p$ is the vector of inputs, and y Є $R^m$ is the vector of outputs.

#### 3.6.2.1 Concept of Lie Derivative

Lie derivative is a mathematical operator to define the variation of a function on the trajectories of a differential equation. Consider the time derivative of the output $y$ in (3.25), which we can compute using the chain rule,

$$\dot{y} = \frac{d\,h(x)}{dt} = \frac{d\,h(x)}{dx}\,\dot{x}$$

$$= \frac{d\,h(x)}{dx} f(x) + \frac{d\,h(x)}{dx} g(x)u \qquad (3.27)$$

Now we can define the Lie derivative of $h(x)$ along $f(x)$ as:

$$L_f h(x) = \frac{d\,h(x)}{dx} f(x) \qquad (3.28)$$

And similarly, the Lie derivative of h(x) along $g(x)$ as:

$$L_g h(x) = \frac{d\,h(x)}{dx} g(x) \qquad (3.29)$$

With this notation, we may express $\dot{y}$ as $\dot{y} = L_f h(x) + L_g h(x)u$. It should be noted that the notation of Lie derivatives is convenient when we take multiple derivatives with respect to either the same vector field or a different one.

Namely:

$$L_f^{\,2} h(x) = L_f\, L_f\, h(x) = \frac{d(L_f\, h(x))}{dx} f(x)$$

$$L_g\, L_f\, h(x) = \frac{d(L_f\, h(x))}{dx} g(x) \qquad (3.30)$$

#### 3.6.2.2 The Relative Degree of a Nonlinear System

Using (3.30) paradigm, one can continue differentiation as shown below:

$$L_g L_f^{\,k}\, h(x) = 0 \qquad \text{x and x} \leq r - 2$$

$$L_g L_f^{\,r-1}\, h(x_o) \neq 0 \tag{3.31}$$

Considering this definition of relative degree ($r$) in light of the expression of the time derivative of the output y, we can consider the relative degree of our system (3.25) to be the number of times we have to differentiate the output y before the input $u$ appears explicitly. In a linear system, the relative degree is the difference between the number of its poles and zeros. If $r$ = n, the system in (3.25) is said to be of full relative degree. In back-stepping control approaches, best results are obtained when one has a full relative degree dynamical system. In multi input-multi output system each relative output should be considered separately and the resultant relative degree should be summed up to find the total vector relative degrees. The inputs to appear in this evaluation is not critical. In the next section, one will be eligible to see how back-stepping controllers are designed through a very simple example.

### 3.7 Backstepping by Example

Here we will introduce the methodlogy of the backstepping by a very simple example that will help the readers to understand the method of backstepping without being confused by too many generic equations. At this time, one should introduce a simple nonlinear system of full relative degree such as the one shown below:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= -x_2\cos(x_1) + u \\ y &= x_1 \end{aligned} \tag{3.32}$$

The output y = $x_1$ and when one takes its derivative $\dot{y} = \dot{x}_1 = x_2$ and second time $\ddot{y} = \ddot{x}_1 = \dot{x}_2 = -x_2\cos(x_1) + u$ where the input $u$ appears first time after differentiating y two times. This means that the relative degree of the system equals to $r$ = 2. Being a full relative degree system one can implement a backstepping controller on (3.32) easily.

#### 3.7.1 First step: definition of an output tracking error

First step of a backstepping controller involves the definition of a tracking error between the output state y = $x_1$ and a reference input $y_r$ or $x_{1r}$. The reference can be assumed constant.

$$e_1 = y - y_r = x_1 - x_{1r} \tag{3.33}$$

Taking the time derivative of the above to find an error dynamics:

$$\dot{e}_1 = \dot{x}_1 - \dot{x}_{1r} = \dot{x}_1 = x_2 \tag{3.34}$$

As $x_{1r}$ is assumed constant. Now one should define a CLF satisfying the properties presented in section 3.6.1. This can be $w_1(e_1) = \frac{1}{2}e_1^2$. Taking its time derivative:

$$\dot{w}_1(e_1) = e_1\dot{e}_1 = e_1 x_2 \tag{3.35}$$

Now in order to link the above with the second step one has to define a tracking error between second state $x_2$ and a newly defined virtual control input $x_{2r}$ as:

$$e_2 = x_2 - x_{2r} \tag{3.36}$$

Rewriting this as $x_2 = e_2 + x_{2r}$ and substituting into (3.35):

$$\dot{w}_1(e_1) = e_1\dot{e}_1 = e_1\{e_2 + x_{2r}\} = e_1 e_2 + e_1 x_{2r} \tag{3.37}$$

In the above, we have to separate the error term related to $e_2$ as it is related to step 2 section 3.7.2**.** Now if one defines a virtual control law as $x_{2r} = -k_1 e_1$ we will have:

$$\dot{w}_1(e_1) = e_1 e_2 - k_1 e_1^2 \tag{3.38}$$

Assuming $e_2 \rightarrow 0$ the error $e_1$ will decay to zero. We will handle the error $e_2$ in the next step.

### 3.7.2 Second Step: Derivation of the Control Law

Now, one should reconsider the error $e_2 = x_2 - x_{2r}$ and differentiate to time as shown below:

$$\dot{e}_2 = \dot{x}_2 - \dot{x}_{2r} = -x_2\cos(x_1) + u + k_1\dot{e}_1$$

$$= -x_2\cos(x_1) + u + k_1\dot{x}_1 = -x_2\cos(x_1) + u + k_1 x_2 \tag{3.39}$$

Now defining the new CLF as:

$$W_2(e_1, e_2) = W_1(e_1) + \frac{1}{2} e_2^2 \tag{3.40}$$

And its derivative:

$$\dot{w}_2(e_1, e_2) = \dot{w}_1(e_1) + e_2\dot{e}_2$$

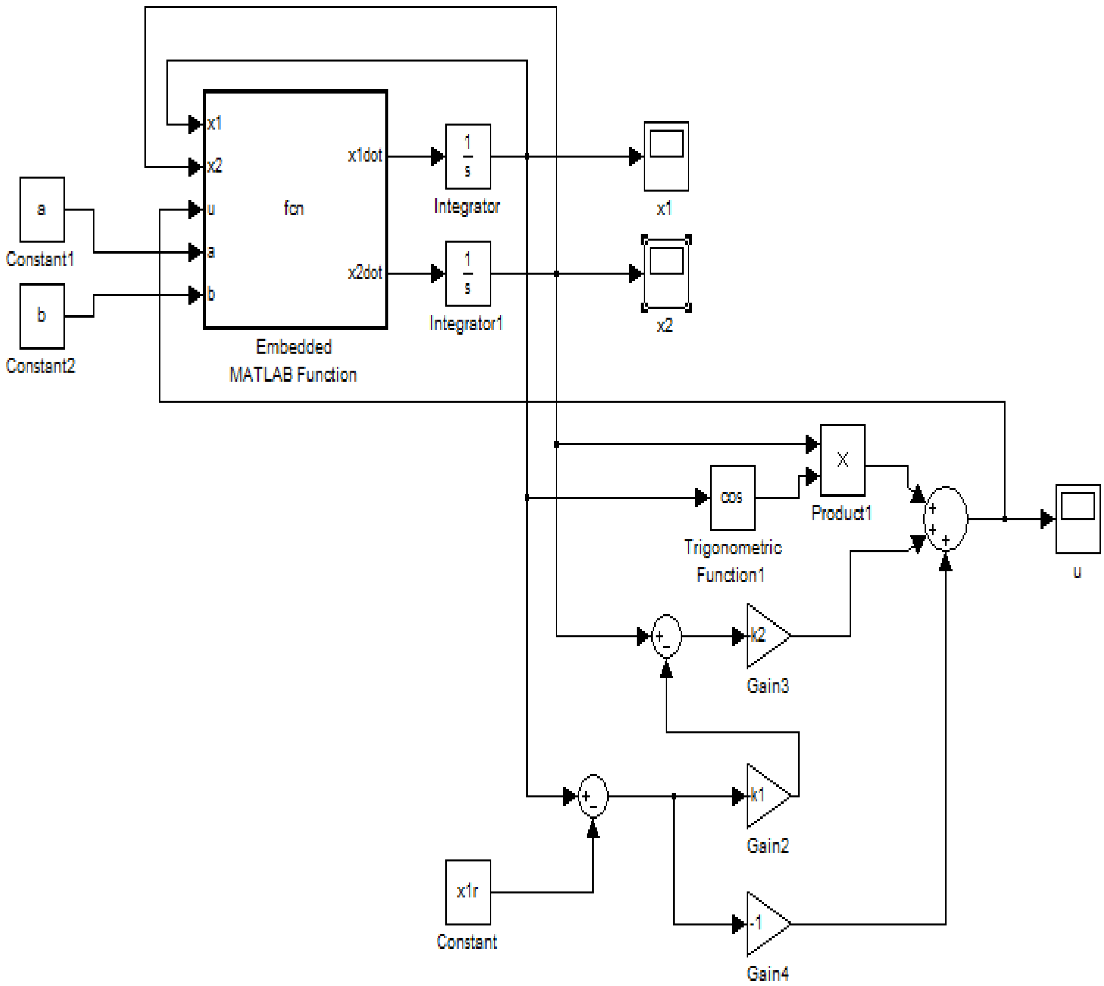
$$= -k_1 e_1^2 + e_1 e_2 + e_2(-x_2\cos(x_1) + u + k_1 x_2)$$

$$= -k_1 e_1^2 + e_2(e_1 - x_2\cos(x_1) + u + k_1 x_2) \tag{3.41}$$

Link in step 1 section 3.7.1. We should do a nonlinearity cancellation here and should obtain $\dot{\mathrm{w}}_2$ something like $\dot{\mathrm{w}}_2(\mathrm{e}_1, \mathrm{e}_2) = -\mathrm{k}_1\mathrm{e}_1^2 - \mathrm{k}_2\mathrm{e}_2^2$. This can be performed by choosing a control law *u* as:

$$u = -\mathrm{k}_2\mathrm{e}_2 - \mathrm{e}_1 + \mathrm{x}_2\cos(\mathrm{x}_1) - \mathrm{k}_1\mathrm{x}_2 \quad (3.42)$$

Now one can say that the closed loop control of (3.32) is asymptotically stable in the sense of Lyapunov. Now one can apply, backstepping control to generator control and synchronization.



### 3.7.3 First step: definition of an output tracking error

First step of a backstepping controller involves the definition of a tracking error between the output state $x_1$ and a reference input $x_{1r}$. The reference can be assumed constant.

$\dot{x}_1 = x_2$

$\dot{x}_2 = ax_1 + bx_2 + u$

$e_1 = x_1 - x_{1r} \quad \rightarrow \quad e_1 = 0$

$x_1(t)$: is the variable to be controlled

$x_{1r}$: step function, external reference (constant)

Taking the time derivative of the above to find an error dynamics:

$$\dot{e}_1 = \dot{x}_1 - \dot{x}_{1r} = \dot{x}_1 = x_2$$

Now one should define a CLF satisfying the properties presented in section 3.6.1. This can be $w_1 = \frac{1}{2}e_1^2$. Taking its time derivative:

$$\dot{w}_1 = e_1\dot{e}_1 = e_1\,[\dot{x}_1 - \dot{x}_{1r}]$$

$$\dot{w}_1 = e_1\,[x_2 - \dot{x}_{1r}]$$

$$\dot{w}_1 = e_1\dot{e}_1 = e_1\,x_2$$

Now in order to link the above with the second step one has to define a tracking error between second state $x_2$ and a newly defined virtual control input $x_{2r}$ as

$$e_2 = x_2 - x_{2r}$$

Rewriting this as $x_2 = e_2 + x_{2r}$

$$\dot{w}_1 = e_1\,[e_2 + x_{2r} - \dot{x}_{1r}]$$

$$\dot{w}_1 = e_1e_2 + e_1x_{2r} - e_1\dot{x}_{1r}$$

As $x_{1r}$ is assumed constant.

$\dot{x}_{1r} = 0$

$$\dot{w}_1 = e_1\dot{e}_1 = e_1\{e_2 + x_{2r}\} = e_1e_2 + e_1\,x_{2r}$$

In the above, we have to separate the error term related to $e_2$ as it is related to step 2 section 3.7.4**.** Now if one defines a virtual control law as $x_{2r} = -k_1e_1$ we will have

$$\dot{w}_1 = e_1e_2 - k_1e_1^2$$

Assuming $e_2 \rightarrow 0$ the error $e_1$ will decay to zero. We will handle the error $e_2$ in the next step.

### 3.7.4 Second Step: Derivation of the Control Law

Now, one should reconsider the error $e_2 = x_2 - x_{2r}$ and differentiate to time as shown below:

$$\dot{e}_2 = \dot{x}_2 - \dot{x}_{2r}$$

$$\dot{e}_2 = ax_1 + bx_2 + u + k_1\dot{e}_1$$

$$= ax_1 + bx_2 + u + k_1x_2$$

Now defining the new CLF as:

$$W_2 = W_1 + \frac{1}{2}e_2^2$$

And its derivative:

$$\dot{w}_2 = \dot{w}_1 + e_2\dot{e}_2$$

$$= -k_1e_1^2 + e_2e_1 + e_2\dot{e}_2$$

$$\dot{w}_2 = -k_1e_1^2 + e_2\,[e_1 + ax_1 + bx_2 + u + k_1x_2]$$

Link in step 1 section 3.7.3. We should do a nonlinearity cancellation here and should obtain $\dot{w}_2$ something like $\dot{w}_2 = -k_1e_1^2 - k_2e_2^2$. This can be performed by choosing a control law *u* as:

$k_1>0$ (constant)

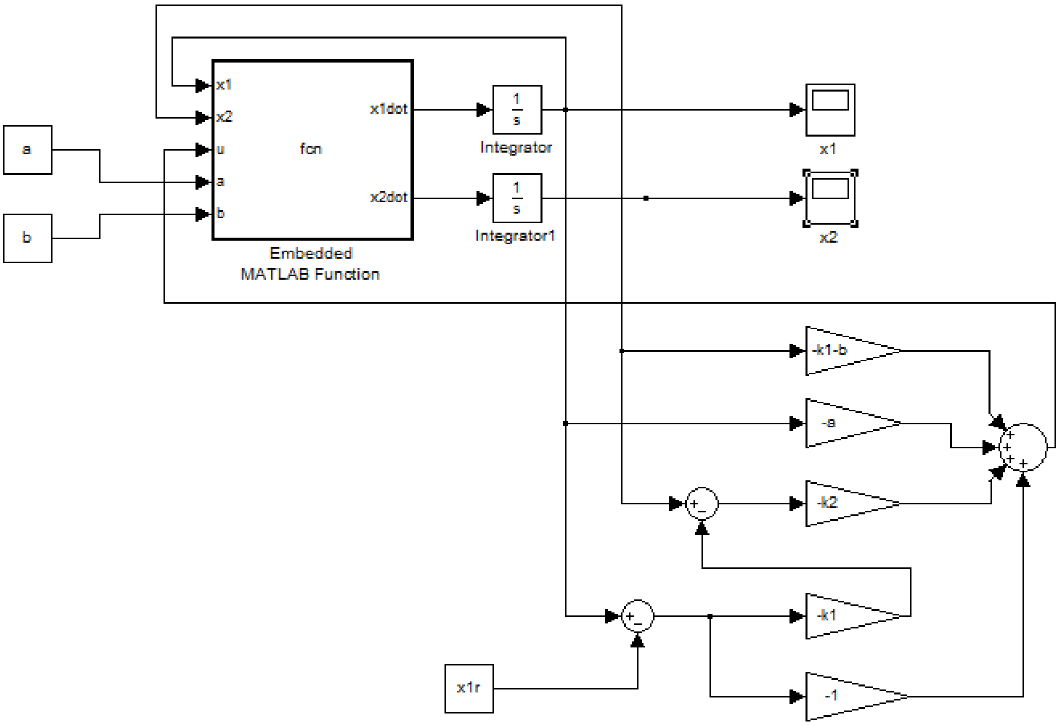
$k_2>0$ (constant)

$W_2^{\circ}< 0$

$$-k_2e_2 = e_1 + ax_1 + bx_2 + u + k_1x_2$$

$$u = -k_2e_2 - e_1 - ax_1 - bx_2 - k_1x_2$$

Now one can say that the closed loop control is asymptotically stable in the sense of Lyapunov. Now one can apply, backstepping control to generator control and synchronization.



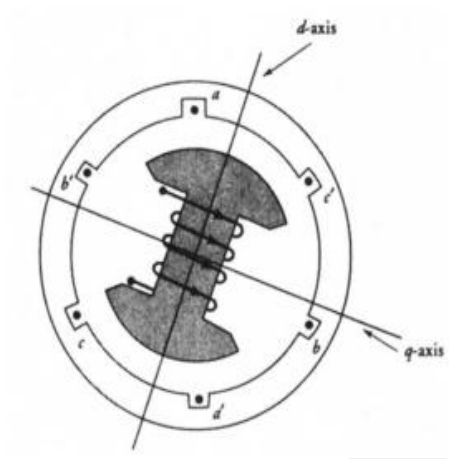

## 3.8 Modeling Small Synchronous AC Generators

In this section we will present the generator model used in this research. The explanations of the states and parameters will all be presented. The model is compiled from various sources which will be shown where appropriate. In general, a synchronous electric generator should involve the power angle ($\delta$) in radians, angular velocity ($\omega$) of the rotor shaft in radians per second (rad/sec), internal transient voltage of the q-axis $E'_q$ in per unit, and the mechanical power supplied by the turbine to the generator $P_m$ in per unit. It will now be convenient to present the four state nonlinear dynamical model. For the detailed development of the model readers are strongly encouraged to read the works [31,32]. The mathematical model is shown below:

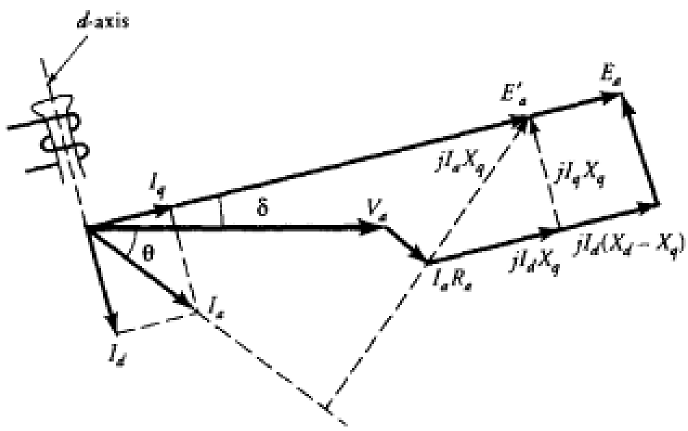
- $\dot{\delta} = \omega - \omega_o$
- $\dot{\omega} = -\frac{D}{M}(\omega - \omega_o) + \frac{\omega o}{M} P_m - \frac{\omega o E'_q V_s}{M x'_{ds}} \sin(\delta)$
- $\dot{E}'_q = -\frac{1}{T'_d} E'_q + \frac{1}{T_{do}} \frac{x_d - x'_d}{x'_{ds}} V_s \cos(\delta) + \frac{1}{T_{do}} u_f$ (3.43)
- $\dot{P}_m = \frac{1}{T_s}(-P_m + P_{mo}) + \frac{1}{T_s} u_p$

**Table 3.1**: The definitions and values of the parameters and variable in (3.43) ([31],[32])

| Parameter | Definition | Unit | Value |
|---|---|---|---|
| $\omega_o$ | Speed of the generator | rad/s | $2\pi f_o$ (here $\omega_o$ =1) |
| M | Inertia coefficient of the generator | Seconds | 7.6 |
| $P_{mo}$ | Initial power supplied by the turbine | Per unit | 1 |
| D | Damping constant | Per unit | 3 |
| $V_s$ | Infinite bus voltage | Per unit | 1.5 |
| $x_d$ | Synchronous reactance of the d-axis | Per unit | 0.9 |
| $x_q$ | Synchronous reactance of the q-axis | Per unit | 0.6 |
| $x'_d$ | Transient reactance in d-axis | Per unit | 0.36 |
| $x_s$ | Reactance of the transmission line | Per unit | 0.36 |
| $x_T$ | Reactance of the transformer | Per unit | 0.12 |
| $T_{do}$ | The field short circuit time constant | Seconds | 5 |
| $T'_d$ | Transient field short circuit time constant | Seconds | 5 |
| $T_s$ | Equivalent time constant of the steam turbine | Seconds | 5 |
| $x'_{ds}$ | $= x'_d + x_T + x_s$ | Per unit | 0.84 |
| $x_{qs}$ | $= x_q + x_T + x_s$ | Per unit | 1.08 |
| $i_d$ | Generator current in d-axis | Per unit | $\frac{1}{x'_{ds}}(E'_q - V_s \cos(\delta))$ |
| $i_q$ | Generator current in q-axis | Per unit | $\frac{V_s \sin(\delta)}{x_{qs}}$ |
| $V_d$ | Generator terminal voltage d-axis | Per unit | $x_q i_q$ |
| $V_q$ | Generator terminal voltage q-axis | Per unit | $E'_q - x'_d i_d$ |
| $V_t$ | Generator terminal voltage (over all) | Per unit | $\sqrt{V_d^2 + V_q^2}$ |
| $E_q$ | Internal voltage of q-axis | Per unit | $E'_q + (x_d - x'_d)\, i_d$ |
| $x_1$ | Power angle | rad | |
| $x_2 = \dot{\omega}$ | Angular velocity | rad/s | $\omega - \omega_o$ |
| $x_3$ | Transitional q-axis voltage | Per unit | |
| $u_4$ | Mechanical power | Per unit | |
| $u_1 = u_f$ | Field excitation voltage | Per unit | |
| $u_2 = u_p$ | Electrical control signal to the steam pressure control valve | Per unit | |

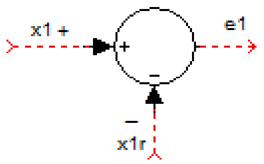



d-axis and q-axis in synchronous generator

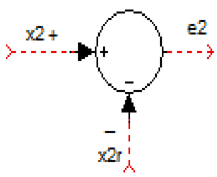



Phasor diagram of synchronous generator

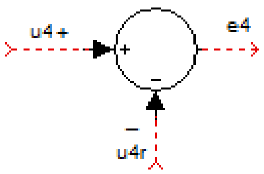
$$e_1 = x_1 - x_{1r}$$



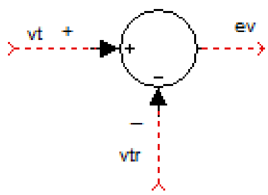

$$e_2 = x_2 - x_{2r}$$




$$e_4 = u_4 - u_{4r}$$




$$e_v = V_t - V_{tr}$$



The parametric definitions of the model are given in **Table 3.1**: in the application, controlled variables will initially be power angle $\delta$ and the terminal voltage $V_t$. The control laws will manipulate the field voltage $u_f$ and turbine pressure valve signal $u_p$.

In order to manipulate the model equations in (3.43) it will be convenient to rewrite them in a more generic form as suggested by. That is shown below:

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= a x_4 - b x_2 - c x_3 \sin(x_1) \\
\dot{x}_3 &= -p_1 x_3 + p_2 \cos(x_1) + u_1 \\
\dot{x}_4 &= -f x_4 + h + u_2
\end{aligned} \tag{3.44}$$

In the above,

$x_1 = \delta$ , $x_2 = \omega - \omega_o$ , $x_3 = E'_q$ , $x_4 = P_m$ ,

$a = \frac{\omega o}{M}$ , $b = \frac{D}{M}$ , $c = \frac{\omega o}{M x'_{ds}} V_s$ , $u_1 = \frac{1}{T_{do}} u_f$ , $P_1 = \frac{1}{T'_d}$ ,

$p_2 = \frac{1}{T_{do}} \frac{x_d - x'_d}{x'_{ds}} V_s$ , $f = \frac{1}{T_s}$ , $h = \frac{1}{T_s} P_{mo}$ , $u_2 = \frac{1}{T_s} u_p$

Looking at (3.44), one will be able to notice that the mechanical power ($x_4$) equation is a self contained equation and does not depends on any other states. This is an advantage in the design process as it can be decoupled from the rest of the model. In that case, the term $x_4$ in the second equation becomes a power input directly. So it can be denoted as $u_4$ instead of $x_4$ which will be a mechanical power input to the generator shaft. So the equation (3.44) can be rewritten as:

$$\begin{aligned}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= a u_4 - b x_2 - c x_3 \sin(x_1) \\
\dot{x}_3 &= -p_1 x_3 + p_2 \cos(x_1) + u_1 \\
\dot{u}_4 &= -f u_4 + h + u_2
\end{aligned} \tag{3.45}$$

Here there are no changes in the dynamics, but a variable which appears as an input in certain parts of the model.

## 3.9 Control of a Synchronous AC Generator by Backstepping

### 3.9.1 Preliminaries and Relative Degree

The control of a generator modeled by (3.45) can be performed by control laws designed by backstepping methodology introduced in Section 3.6. The model in (3.45) together has two external inputs which are $u_1$ and $u_2$ (definitive field voltages and turbine valve signals). From basic control theory it is well known that, satisfactory control actions can be obtained if the number of controlled outputs and available inputs to the plant are equal. The controlled variables are the power angle ($x_1 = \delta$) and the terminal voltage $V_t$=$f$ ($E'_q$). So concerning the input-output relationships we do not have any issues. The next point to consider is the relative degree of (3.45). From Section 3.6.2 One can evaluate the vector relative degree for outputs $x_1$ and $V_t$ as 3 ($u_2$ appears after differentiating $x_1$ three times) and 1 ($V_t$ is a function of $E'_q$ and $u_1$ appears when differentiated once) respectively. So the total relative degree appears as 4. So the dynamics of the synchronous generator is a full relative degree nonlinear system. However, the computational complexity of the derivation of the control law is obvious when looked at the (3.45). Because of that we will decouple the turbine dynamics ($u_4$ or $x_4$) from rest of the model in (3.45).

### 3.9.2 Control of the Turbine Dynamics

The turbine dynamics itself is a first order differential equation as shown so controller can directly by designed by the second method of Lyapunov. To start one should define an error between the mechanical power $u_4$ and desired mechanical power from the generator $u_{4r}$ as:

$$\dot{x}_4 = -f\,x_4 + h + u_2 \quad \rightarrow \quad x_4 = P_m \qquad \text{(Mechanical power generation dynamics)}$$

$$\rightarrow \quad h = \frac{1}{T_s} P_{mo}$$

Mechanical power $x_4$ is only existent in power angle dynamics $(x_1, x_2)$ because of that one can treat ( $x_4$ ) in ( $\dot{x}_2$) equation as an input and call as $u_4$.

$\dot{u}_4 = -f\,u_4 + h + u_2$ $\quad\rightarrow\quad$ (Is the dynamics of mechanical power generation)

$$e_4 = u_4 - u_{4r} \tag{3.46}$$

And its dynamics form (3.45) will be

$$\dot{e}_4 = \dot{u}_4 - \dot{u}_{4r} = -f\,u_4 + h + u_2 - \dot{u}_{4r} \tag{3.47}$$

Here we do not consider $\dot{u}_{4r}$= 0 as it is the desired mechanical power that is to be supplied from the generator control system. We will take care of this part in the next section, control of power angle. Now we should define the CLF for this problem which is:

$$W_4 = \frac{1}{2} e_4^2 \tag{3.48}$$

And its derivative will be:

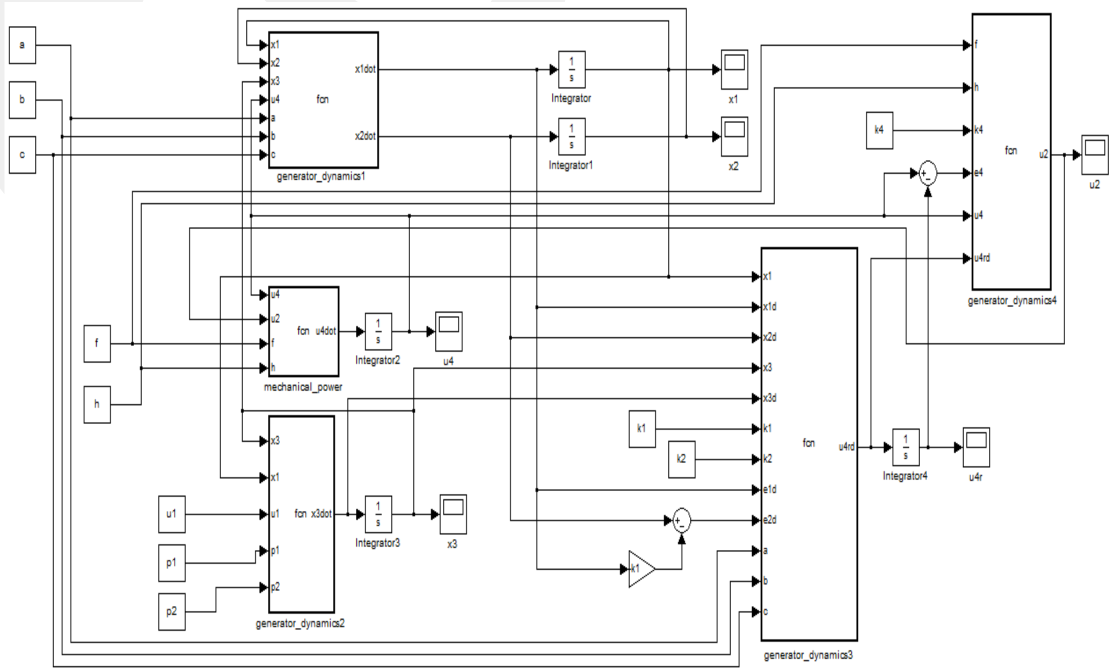
$$\dot{W}_4 = e_4\,\dot{e}_4 = e_4\,[-f u_4 + h + u_2 - \dot{u}_{4r}] \tag{3.49}$$

If one applies the following control law $u_2$ then $\dot{W}_4$ will be $\dot{W}_4 = -k_4 e_4^2$

$$-k_4 e_4 = -f\,u_4 + h + u_2 - \dot{u}_{4r}$$

$$u_2 = -k_4 e_4 + f\,u_4 - h + \dot{u}_{4r} \tag{3.50}$$

Where $\dot{u}_{4r}$ will be driven in the power angle control.



### 3.9.3 Control of the Power Angle

As the turbine dynamics is decoupled from (3.45), we will make use of the dynamics of the variables $x_1$ and $x_2$ and obtain the desired mechanical power as a control law. So the dynamics associated with this section are:

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = a u_{4c} - b x_2 - c x_3 \sin(x_1) \qquad (3.51)$$

$u_4$ : is the mechanical power.

Controlling the power angle part ($x_1 = \delta$) ($x_2 = \omega - \omega_o$).

$\omega$o: Is the constant rotational speed (initial adjustment).

$\omega$: Is the actual speed.

Here, we replace $u_4$ by $u_{4c}$ to stress the fact that mechanical power is a control input to (3.51). Starting with the definition of the power angle tracking error $e_1$ as:

$$e_1 = x_1 - x_{1r} \qquad (3.52)$$

And its dynamics as:

$$\dot{e}_1 = \dot{x}_1 - \dot{x}_{1r} = \dot{x}_1 = x_2 \qquad (3.53)$$

In the above, we can safely assume that $\dot{x}_{1r} = 0$ because the power angle is desired to be constant at steady state. In order to proceed, we should define the tracking error for $x_2$ against a virtual control input $x_{2r}$ as:

$$e_2 = x_2 - x_{2r} \qquad (3.54)$$

In this context, we have to write the above equation as $x_2 = e_2 + x_{2r}$ to substitute into (3.53) as:

$$\dot{e}_1 = \dot{x}_1 - \dot{x}_{1r} = \dot{x}_1 = e_2 + x_{2r} \qquad (3.55$$

Defining the CLF as $w_1 = \frac{1}{2} e_1^2$ and taking its derivative

$$\dot{w}_1 = e_1 \dot{e}_1 = e_1 (e_2 + x_{2r}) = e_1 e_2 + e_1 x_{2r} \qquad (3.56)$$

So a virtual control law as $x_{2r} = -k_1 e_1$ will yield:

$$\dot{w}_1 = e_1 \dot{e}_1 = e_1 (e_2 + x_{2r}) = e_1 e_2 - k_1 e_1^2 \qquad (3.57)$$

The term $e_1 e_2$ will be treated next. Now, reconsider the tracking error $e_2 = x_2 - x_{2r} = x_2 + k_1 e_1$ and differentiate as:

$$\dot{e}_2 = \dot{x}_2 + k_1 \dot{e}_1 = a u_{4c} - b x_2 - c x_3 \sin(x_1) + k_1 x_2 \qquad (3.58)$$

The CLF for the second step will be $W_2 = W_1 + \frac{1}{2} e_2^2$ and

$$\dot{W}_2 = \dot{W}_1 + e_2\dot{e}_2 \quad \rightarrow \quad e_1e_2 - k_1e_1^2 + e_2\dot{e}_2 \quad \rightarrow \quad -k_1e_1^2 + e_2 [e_1 + \dot{e}_2]$$

$$\dot{W}_2 = -k_1e_1^2 + e_2 [e_1 + au_{4c} - bx_2 - cx_3\sin(x_1) + k_1x_2] \qquad (3.59)$$

$$-k_2e_2 = e_1 + au_{4c} - bx_2 - cx_3\sin(x_1) + k_1x_2$$

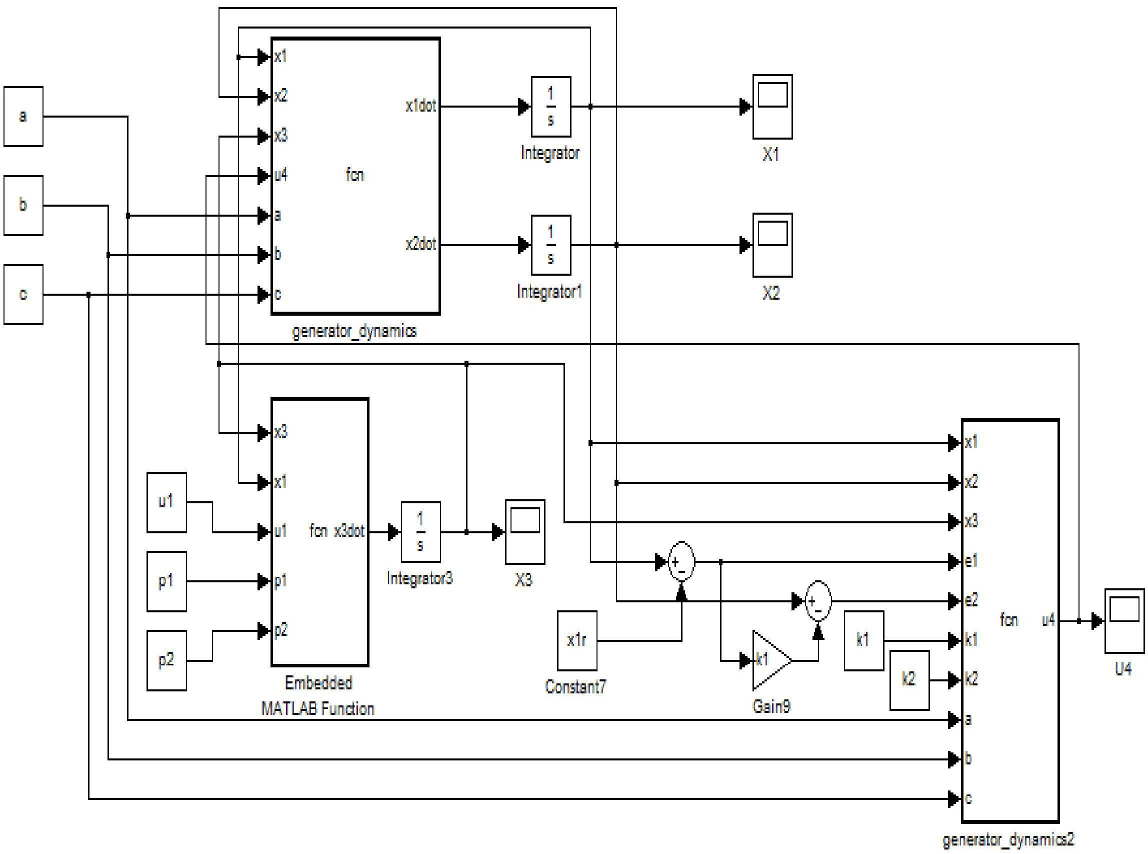
$x_{2r}$: virtual input to $x_2$ dynamics.

W: Lyapunov functions.

$u_4$: Is the required mechanical power to set power angle $(x_1)$ to the desired value.

If we assign the mechanical power control law $u_{4c}$ as:

$$u_{4c} = \frac{-k_2e_2 - e_1 + bx_2 + cx_3\sin(x_1) - k_1x_2}{a} \quad \rightarrow \quad \text{supplied as } u_{4r} \qquad (3.60)$$



$\dot{w}_2$ will be $\dot{w}_2 = -k_1 e_1^2 - k_2 e_2^2$. So one obtained an asymptotically stable power angle controller. The above control law will be provided as $u_{4r}$ to the turbine controller designed in section 3.9.2. The response of the closed loop turbine controller ($u_4$) will be forwarded to the power angle controller as mechanical power input $u_{4c}$. So we have a cascaded controller scheme here. $u_4$ is generated by the turbine. So control the turbine to here this $u_4$. Thus, this $u_4$ becomes $u_{4r}$ because it is the needed(desired) mechanical power. We want to obtain this amount of mechanical power from turbine.

$$u_4 = u_{4r}$$

$$u_{4r} = \frac{-k_2 e_2 - e_1 + b x_2 + c x_3 \sin(x_1) - k_1 x_2}{a}$$

So $u_4$ which is actual mechanical power from the turbine will be controlled. So that it is at $u_{4r}$

$$e_4 = u_4 - u_{4r}$$

$$e_4 = 0 \text{ by turbine controller}$$

In section 3.9.2. It is mentioned that $\dot{u}_{4r}$ is not zero and needed to be derived. It is given below:

$$\dot{u}_{4r} = \frac{1}{a}(-k_2 \dot{e}_2 - \dot{e}_1 + b\dot{x}_2 + c\dot{x}_3 \sin(x_1) + c x_3 \cos(x_1)\dot{x}_1 - k_1 \dot{x}_2) \quad (3.61)$$

The control input $u_1$ will be designed in the terminal voltage control.

### 3.9.4 Control of Terminal Voltage

Like in all previous steps we will define a tracking error on the terminal voltage dynamics:

$$V_d = x_q i_q$$

$$V_q = E'_q - x'_d \, i_d$$

$$V_t = \sqrt{V_d^2 + V_q^2} \quad , \quad e_v = V_t - V_{tr} \quad (3.62)$$

With its dynamics as (from Table 1):

$$\dot{e}_v = \dot{V}_t - \dot{V}_{tr} = \dot{V}_t = \frac{1}{2\sqrt{V_d^2 + {V_q}^2}} [2V_d \dot{V}_d + 2V_q \dot{V}_q] \quad (3.63)$$

Note that $V_{tr}$ is the reference terminal voltage, ($V_{tr}$ : constant). Equation (3.63) can be rewritten as:

$$\dot{e}_v = \frac{1}{\sqrt{V_d^2+V_q^2}}[V_d\dot{V}_d + V_q\dot{V}_q] \quad (3.64)$$

With $i_q$ and $i_d$ being:

$$i_q = \frac{V_s sin(x_1)}{x_{qs}}$$

$$i_d = \frac{1}{x'_{ds}}(x_3 - V_s\cos(x_1))$$

$$\dot{V}_d = x_q \dot{i_q} \quad \rightarrow \quad \dot{i_q} = \frac{V_s\cos(x_1)\dot{x}_1}{x_{qs}}$$

$$\dot{V}_d = \frac{x_q}{x_{qs}} V_s\cos(x_1)x_2$$

$$\dot{V}_q = \dot{E}'_q - x'_d\dot{i_d} \quad \rightarrow \quad \dot{V}_q = \dot{x}_3 - x'_d\dot{i_d}$$

$$\dot{i_d} = \frac{1}{x'_{ds}}(\dot{x}_3 + V_s\sin(x_1)\,\dot{x}_1)$$

$$\dot{V}_q = -p_1x_3 + p_2\cos(x_1)+u_1 - \frac{x'_d}{x'_{ds}}(\dot{x}_3 + V_s\sin(x_1)x_2)$$

$$= -p_1x_3 + p_2\cos x_1 + u_1 - \frac{x'_d}{x'_{ds}}(-p_1x_3+p_2\cos(x_1)+u_1 + V_s\sin(x_1)x_2)$$

$$\dot{V}_q = p_1[\frac{x'_d}{x'_{ds}} - 1]\,x_3 + p_2[1 - \frac{x'_d}{x'_{ds}}]\cos x_1 + [1 - \frac{x'_d}{x'_{ds}}]u_1 - \frac{x'_d}{x'_{ds}}V_s\sin(x_1)x_2 \quad (3.65)$$

Substituting $\dot{x}_3$ from (3.45) and compiling (3.64) and (3.65) together one can write the terminal voltage error dynamics $\dot{e}_v$ as:

$$\dot{e}_v = \frac{1}{\sqrt{V_d^2+V_q^2}}[\frac{V_d\,V_s\,x_q}{x_{qs}}\cos(x_1)x_2 + \{p_1[\frac{x'_d}{x'_{ds}} - 1]x_3 + p_2[1 - \frac{x'_d}{x'_{ds}}]\cos(x_1)$$

$$+[1 - \frac{x'_d}{x'_{ds}}]u_1 - \frac{x'_d}{x'_{ds}}V_s\sin(x_1)x_2\}V_q] \quad (3.66)$$

To complete the procedure, we will need to define the last CLF which is for $e_v$. It will be simply $W_v = \frac{1}{2}e_v^2$ and its derivative is:

$$\dot{W}_v = e_v\dot{e}_v \quad (3.67)$$

With $\dot{e}_v$ being given in (3.66). If we choose a field voltage control law as:

$$\rightarrow\ e_v\{\frac{1}{\sqrt{V_d{}^2+V_q{}^2}}[\frac{V_d V_s x_q}{x_{qs}}\cos(x_1)x_2 + \{p_1V_q[\frac{x'_d}{x'_{ds}}-1]x_3 + p_2V_q[1-\frac{x'_d}{x'_{ds}}]\cos(x_1)$$

$$+V_q[1-\frac{x'_d}{x'_{ds}}]u_1 - \frac{x'_d}{x'_{ds}}V_qV_s\sin(x_1)x_2]\} \quad \rightarrow$$

$$\frac{V_d V_s x_q}{x_{qs}}\cos(x_1)\,x_2 + p_1V_q[\frac{x'_d}{x'_{ds}}-1]x_3 + p_2V_q[1-\frac{x'_d}{x'_{ds}}]\cos(x_1) + V_q[1-\frac{x'_d}{x'_{ds}}]\,u_1$$

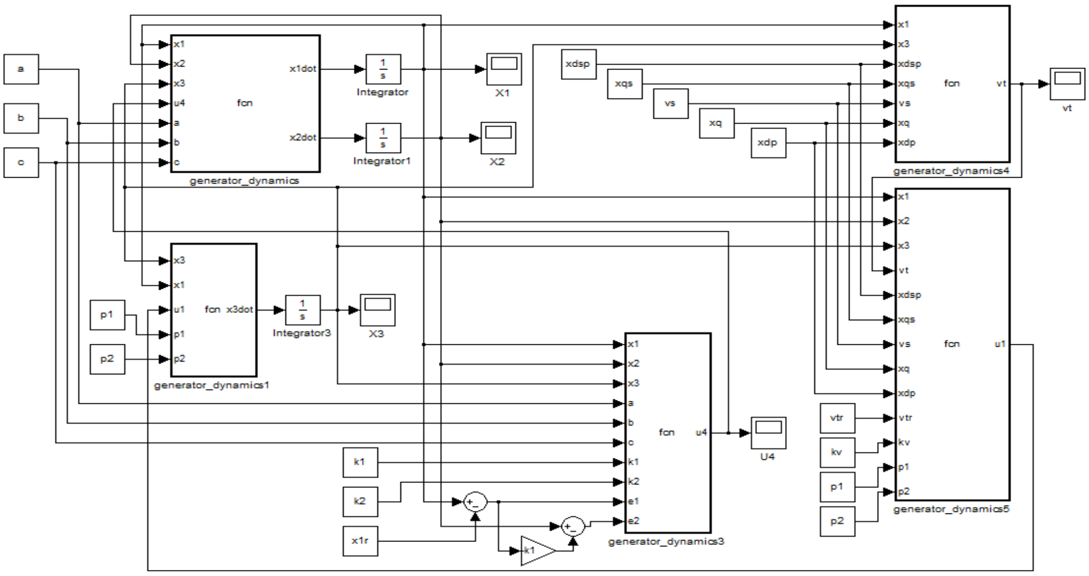
$$-\frac{x'_d}{x'_{ds}}V_qV_s\sin(x_1)\,x_2 = -k_ve_v \quad \rightarrow$$

$$u_1 = \frac{-k_ve_v - \frac{V_d V_s x_q}{x_{qs}}\cos(x_1)x_2 - P_1V_q\left[\frac{x'_d}{x'_{ds}}-1\right]x_3 - P_2V_q\left[1-\frac{x'_d}{x'_{ds}}\right]\cos(x_1) + \frac{x'_d}{x'_{ds}}V_qV_s\sin(x_1)x_2}{V_q[1-\frac{x'_d}{x'_{ds}}]} \tag{3.68}$$

(3.67) will take the following form:

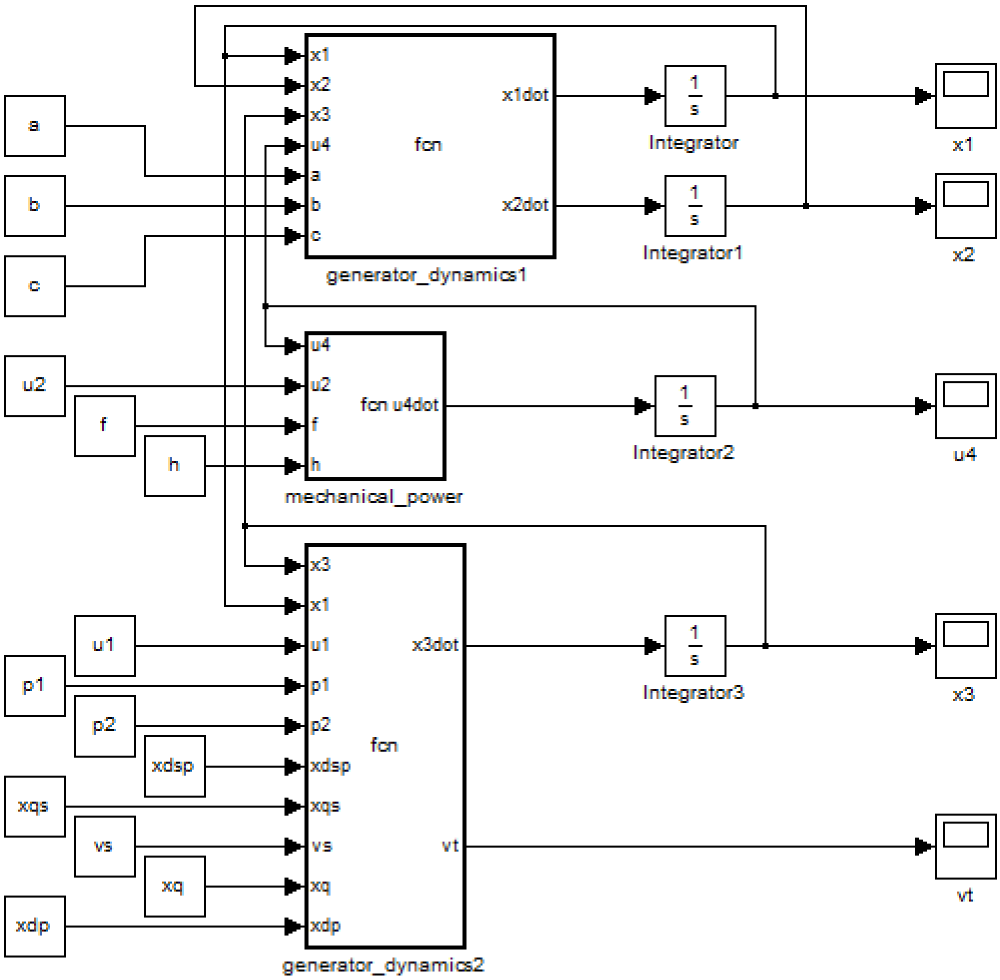
$$\dot{W}_v = -\frac{k_ve_v^2}{\sqrt{V_d^2+V_q^2}} \tag{3.69}$$

So we have an asymptotically stable terminal voltage controller in the sense of Lyapunov. Note that, the terminal voltage controller receive measurements from other steps such as power angle $x_1$ and angular velocity $x_2$ although we have designed the power angle and terminal voltage controllers separately. In all of the controllers, the coefficients $k_1, k_2, k_4$ and $k_v$ should be positive.



### 3.10 Synchronization of Two Generators

In this research synchronization of two identical generators are considered. Here the synchronization concept is inspired from certain research works on the topic of synchronizing two identical chaotic nonlinear systems using nonlinear control techniques. Here we will feed the outputs of the main generator( power angle $x_1 = \delta$ and terminal voltage $V_t$ ) as reference signals to the controllers of the second generator module. The second generator has the same controllers, but it may or may not been tuned by the same gains ($k_i$'s). We will show the results in the chapter four.



# CHAPTER FOUR

# NUMERICAL APPLICATIONS AND SIMULATIONS

## 4.1: Numerical Results

Here we will present a numerical simulation of the theoretical development in chapter three. We will present the simulations of power angle and terminal voltage controller for three cases. The first one presents the result of controller for a single generator, the second one will present the results of controller for synchronization two generators and the third one will present the results of controller for synchronization three generators.

The Modeling of Small Synchronous AC Generators

- $\dot{\delta} = \omega - \omega_o$
- $\dot{\omega} = -\frac{D}{M}(\omega - \omega_o) + \frac{\omega o}{M} P_m - \frac{\omega o E'_q V_s}{M x'_{ds}} \sin(\delta)$
- $\dot{E}'_q = -\frac{1}{T'_d} E'_q + \frac{1}{T_{do}} \frac{x_d - x'_d}{x'_{ds}} V_s \cos(\delta) + \frac{1}{T_{do}} u_f$
- $\dot{P}_m = \frac{1}{T_s}(-P_m + P_{mo}) + \frac{1}{T_s} u_p$

## 4.2: parameters

**Table 4.1**: The definitions and values of the parameters and variable ([31],[32])

| Parameter | Definition | Unit | Value |
|---|---|---|---|
| $\omega_o$ | Speed of the generator | rad/s | $2\pi f_o$ (here $\omega_o$ =1) |
| M | Inertia coefficient of the generator | Seconds | 7.6 |
| $P_{mo}$ | Initial power supplied by the turbine | Per unit | 1 |
| D | Damping constant | Per unit | 3 |
| $V_s$ | Infinite bus voltage | Per unit | 1.5 |
| $x_d$ | Synchronous reactance of the d-axis | Per unit | 0.9 |
| $x_q$ | Synchronous reactance of the q-axis | Per unit | 0.6 |
| $x'_d$ | Transient reactance in d-axis | Per unit | 0.36 |
| $x_s$ | Reactance of the transmission line | Per unit | 0.36 |
| $x_T$ | Reactance of the transformer | Per unit | 0.12 |
| $T_{do}$ | The field short circuit time constant | Seconds | 5 |
| $T'_d$ | Transient field short circuit time constant | Seconds | 5 |
| $T_s$ | Equivalent time constant of the steam turbine | Seconds | 5 |
| $x'_{ds}$ | $= x'_d + x_T + x_s$ | Per unit | 0.84 |
| $x_{qs}$ | $= x_q + x_T + x_s$ | Per unit | 1.08 |

| | | | |
|---|---|---|---|
| $i_d$ | Generator current in d-axis | Per unit | $\frac{1}{x'_{ds}}(E'_q - V_s \cos(\delta))$ |
| $i_q$ | Generator current in q-axis | Per unit | $\frac{V_s \sin(\delta)}{x_{qs}}$ |
| $V_d$ | Generator terminal voltage d-axis | Per unit | $x_q i_q$ |
| $V_q$ | Generator terminal voltage q-axis | Per unit | $E'_q - x'_d\, i_d$ |
| $V_t$ | Generator terminal voltage (over all) | Per unit | $\sqrt{V_d^{2} + V_q^{2}}$ |
| $E_q$ | Internal voltage of q-axis | Per unit | $E'_q + (x_d - x'_d)\, i_d$ |
| $x_1$ | Power angle | rad | |
| $x_2 = \dot{\omega}$ | Angular velocity | rad/s | $\omega - \omega_o$ |
| $x_3$ | Transitional q-axis voltage | Per unit | |
| $u_4$ | Mechanical power | Per unit | |
| $u_1 = u_f$ | Field excitation voltage | Per unit | |
| $u_2 = u_p$ | Electrical control signal to the steam pressure control valve | Per unit | |

**Table 4.2**: Control of single generator simulations

| Case | Time | $x_{1r}$ | $V_{tr}$ |
|---|---|---|---|
| 1 | 300 | 70 | 5 |
| 2 | 300 | 70 | 10 |
| 3 | 300 | 80 | 5 |
| 4 | 300 | 80 | 10 |

**Table 4.3**: Control of synchronize two generators simulations

| Case | Time | $x_{1r}$ | $V_{tr}$ |
|---|---|---|---|
| 1 | 300 | 70 | 5 |
| 2 | 300 | 70 | 10 |
| 3 | 300 | 80 | 5 |
| 4 | 300 | 80 | 10 |

**Table 4.4**: Control of synchronize three generators simulations

| Case | Time | $x_{1r}$ | $V_{tr}$ |
|---|---|---|---|
| 1 | 300 | 70 | 5 |
| 2 | 300 | 70 | 10 |
| 3 | 300 | 80 | 5 |
| 4 | 300 | 80 | 10 |

### 4.3: results of the single generator simulations.

In this section the results of a single generator simulations for the cases of **Table (4.2)**.

**4.3.1: results of case (1) table (4.2), in this case the target is $x_{1r}$= 70° , $V_{tr}$ = 5.**

**Table 4.5**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_v$ | 0.2 | Controller Gain v |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 70 | Desired Power Angle (°) |
| $V_{tr}$ | 5 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.5** are shown in **Figures 1 to 7** when the conditions are applied.

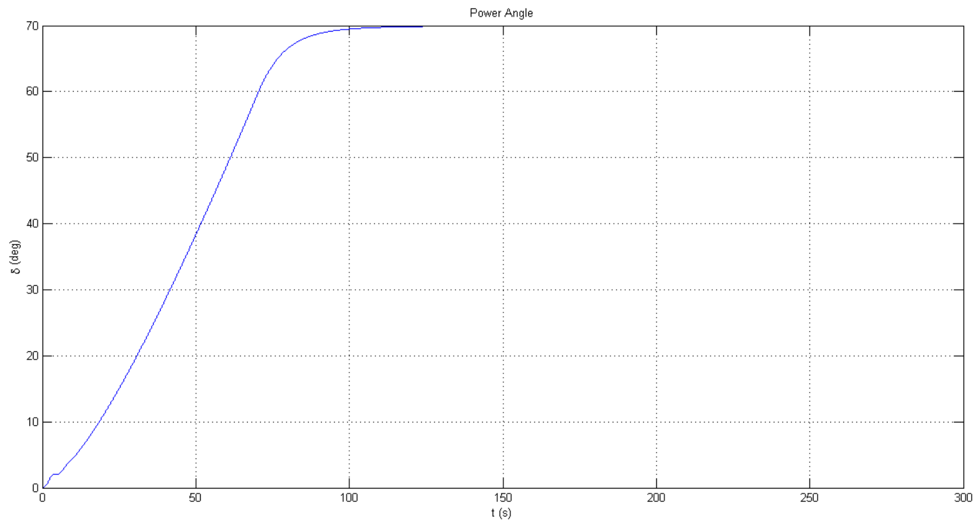



Figure 4-1: The variation of power angle (Single Gen.)

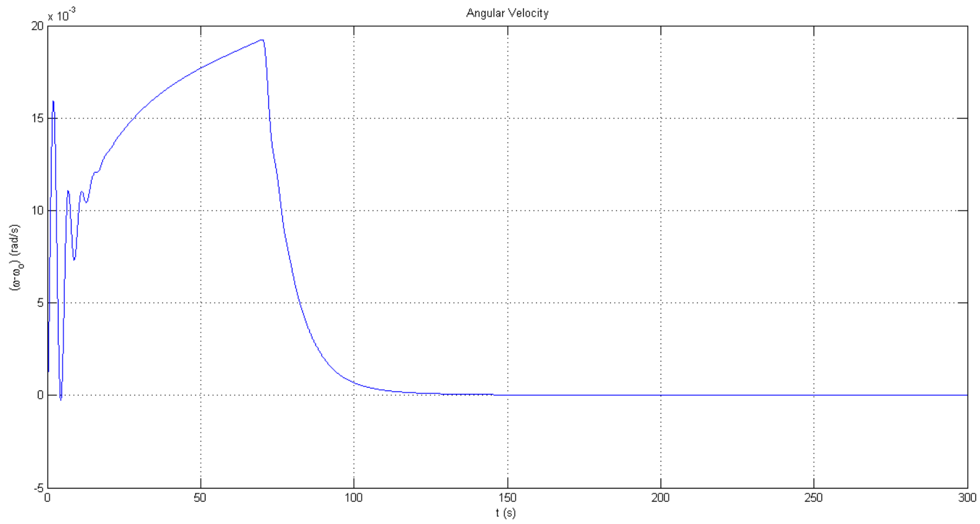



Figure 4-2: The variation of angular velocity ( $\omega - \omega_o$) (Single Gen.)

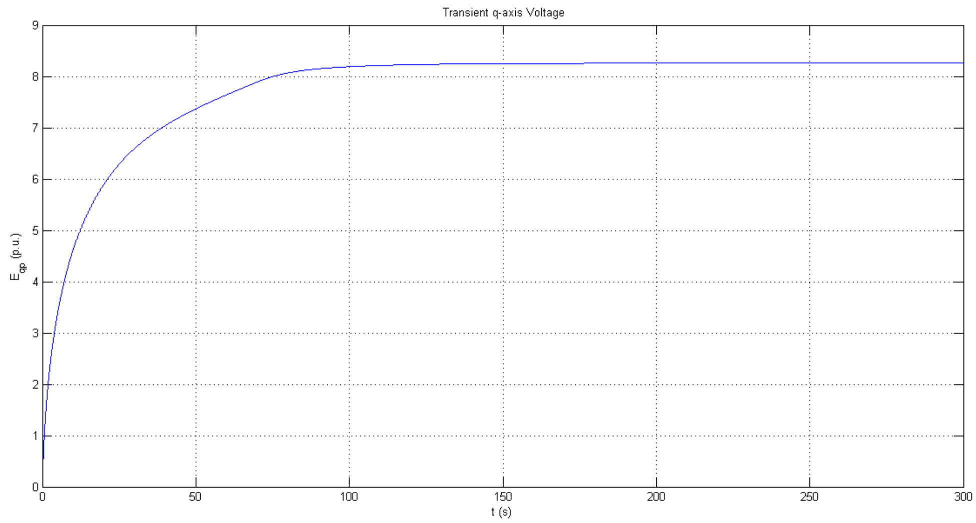



Figure 4-3: The variation of transitional q-axis voltage (Single Gen.)

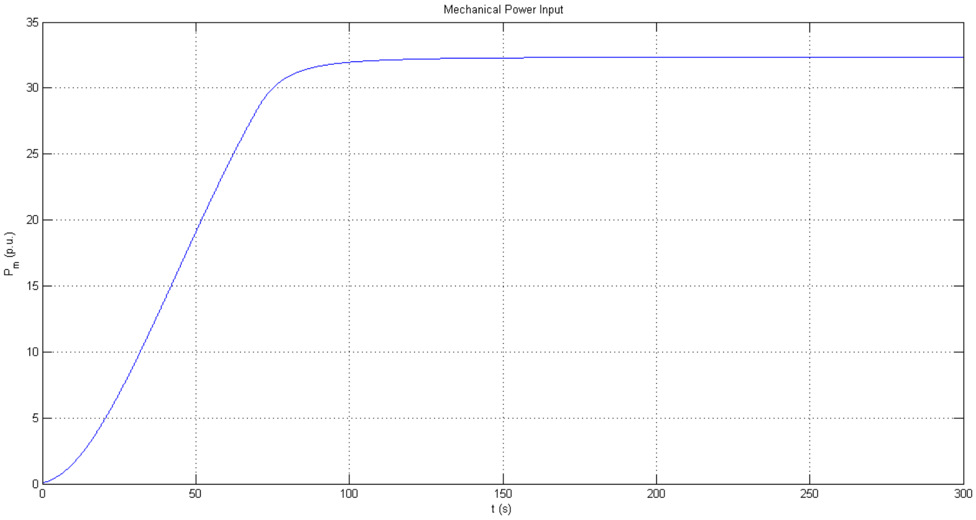



Figure 4-4: The variation of mechanical power input (Single Gen.)

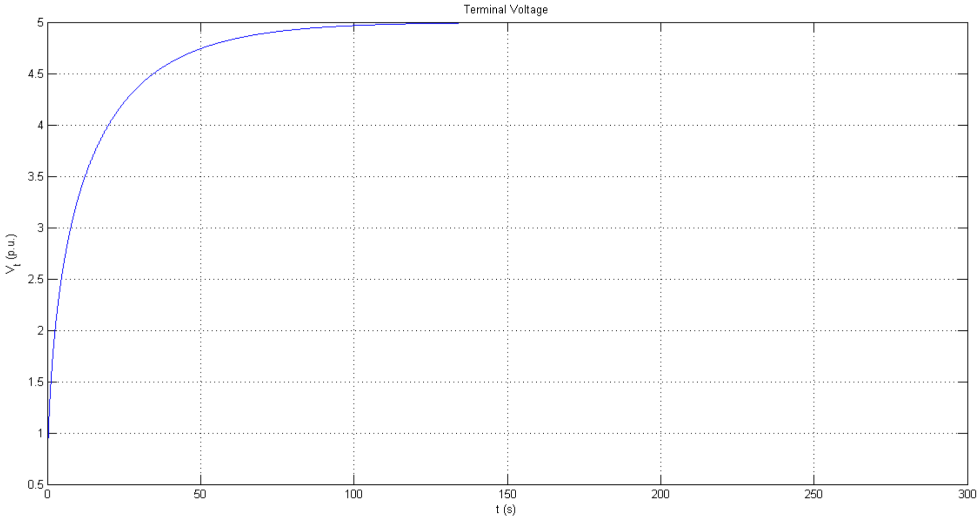



Figure 4-5: The variation of terminal voltage (Single Gen.)

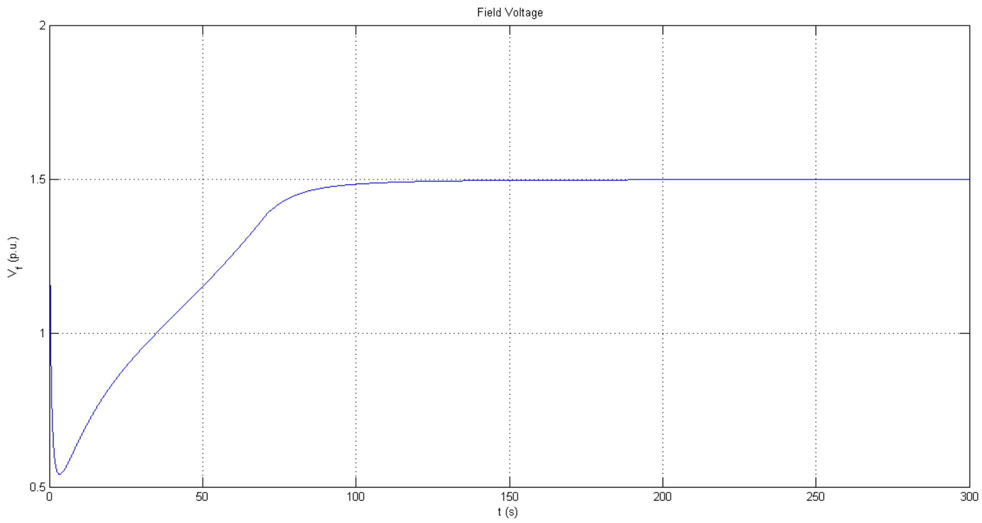



Figure 4-6: The variation of field excitation voltage (Single Gen.)

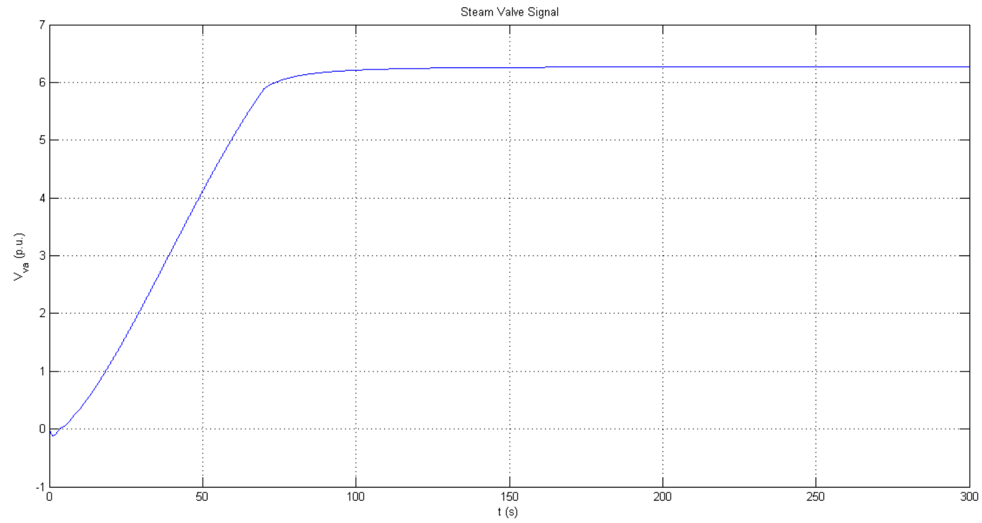



Figure 4-7: The variation of steam valve signal (Single Gen.)

**4.3.2: results of case (2) table (4.2), in this case the target is $X_{1r}$=70°, $V_{tr}$=10.**

**Table 4.6**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_v$ | 0.2 | Controller Gain v |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 70 | Desired Power Angle (°) |
| $V_{tr}$ | 10 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.6** are shown in **Figures 8 to 14** when the conditions are applied.

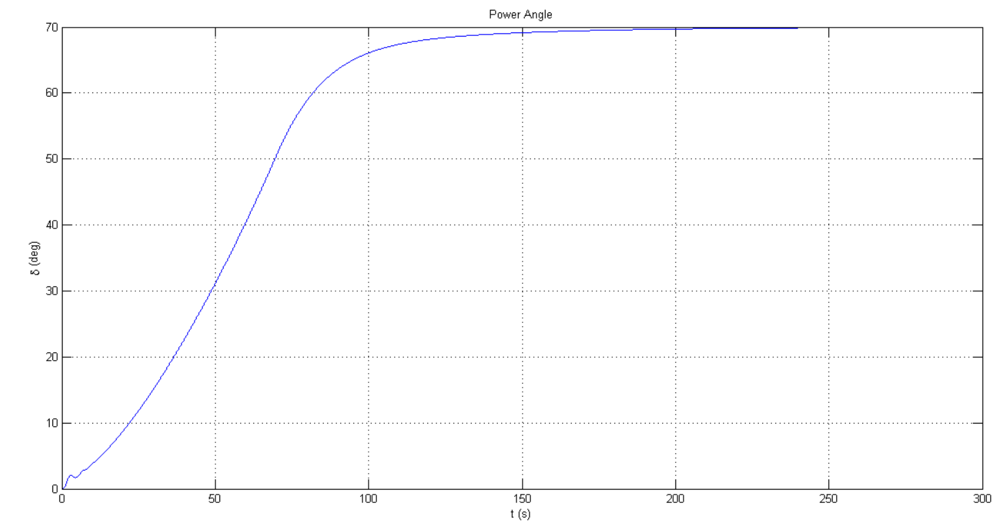



Figure 4-8: The variation of power angle (Single Gen.)

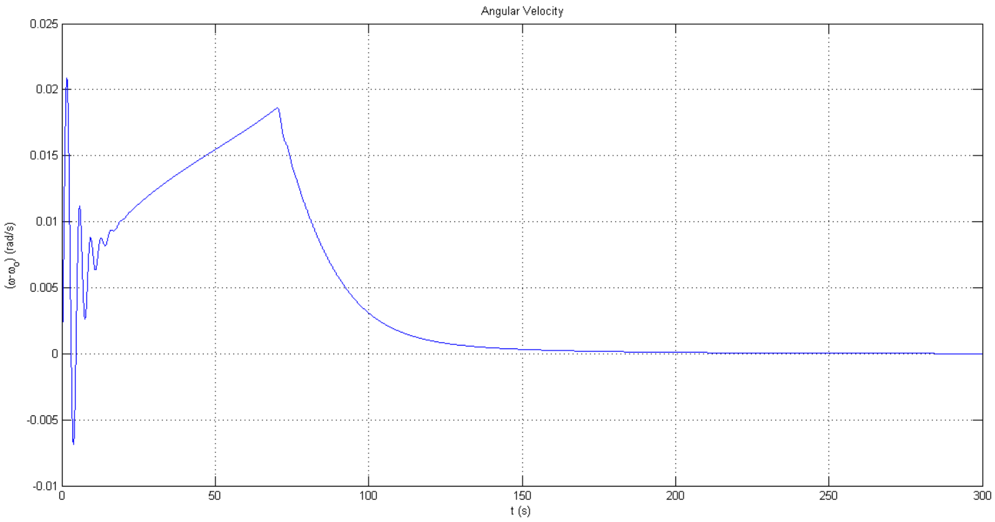



Figure 4-9: The variation of angular velocity ($\omega - \omega_o$) (Single Gen.)

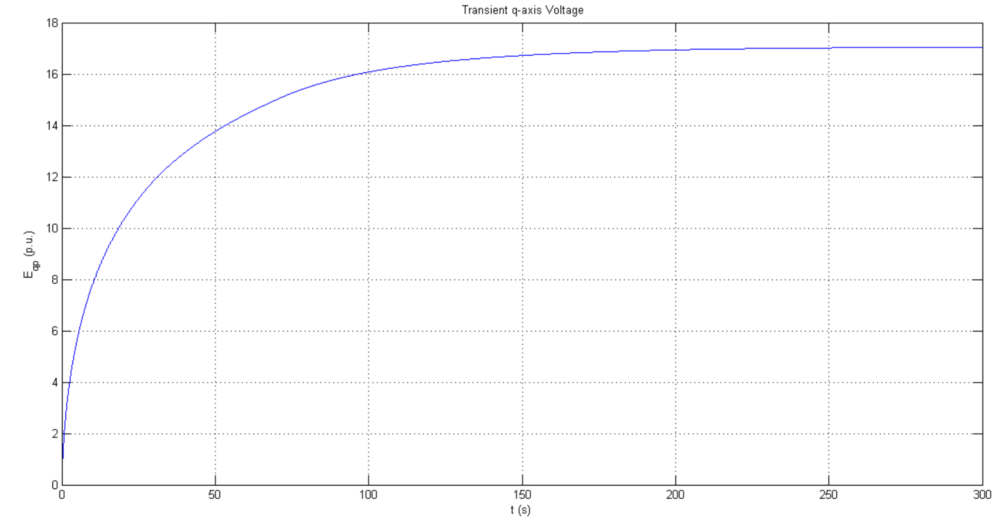



Figure 4-10: The variation of transitional q-axis voltage (Single Gen.)

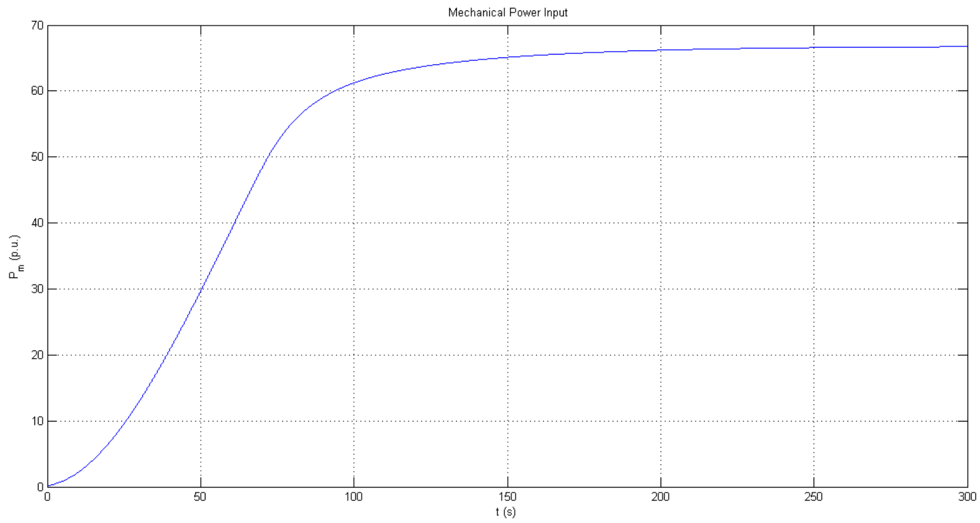



Figure 4-11: The variation of mechanical power input (Single Gen.)

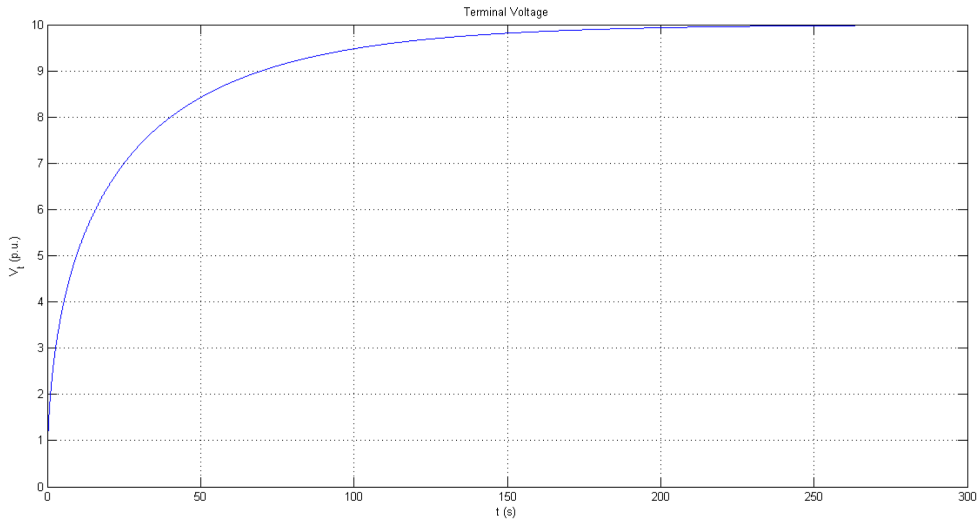



Figure 4-12: The variation of terminal voltage (Single Gen.)

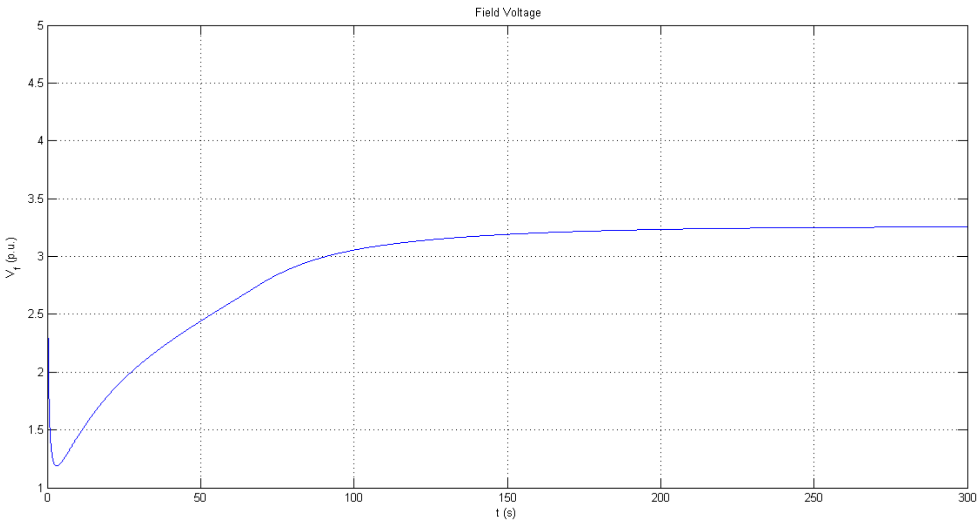



Figure 4-13: The variation of field excitation voltage (Single Gen.)

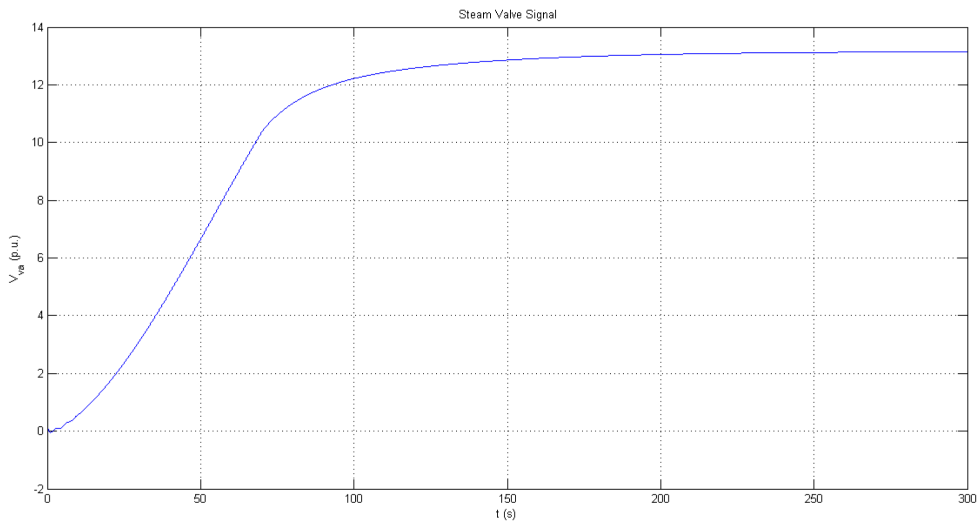



Figure 4-14: The variation of steam valve signal (Single Gen.)

**4.3.3: results of case (3) table (4.2), in this case the target is $X_{1r}$= 80°, $V_{tr}$ = 5.**

**Table 4.7**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_v$ | 0.2 | Controller Gain V |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 80 | Desired Power Angle (°) |
| $V_{tr}$ | 5 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.7** are shown in **Figures 15 to 21** when the conditions are applied.

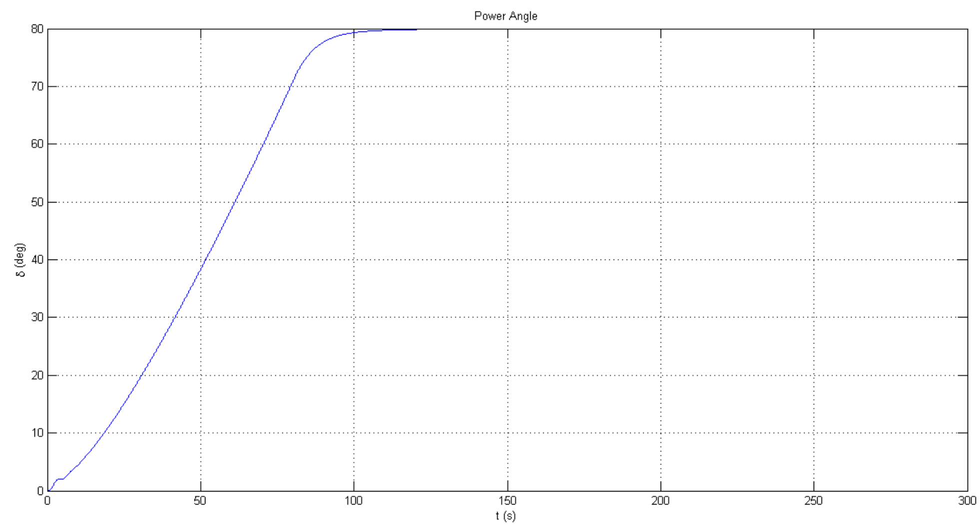



Figure 4-15: The variation of power angle (Single Gen.)

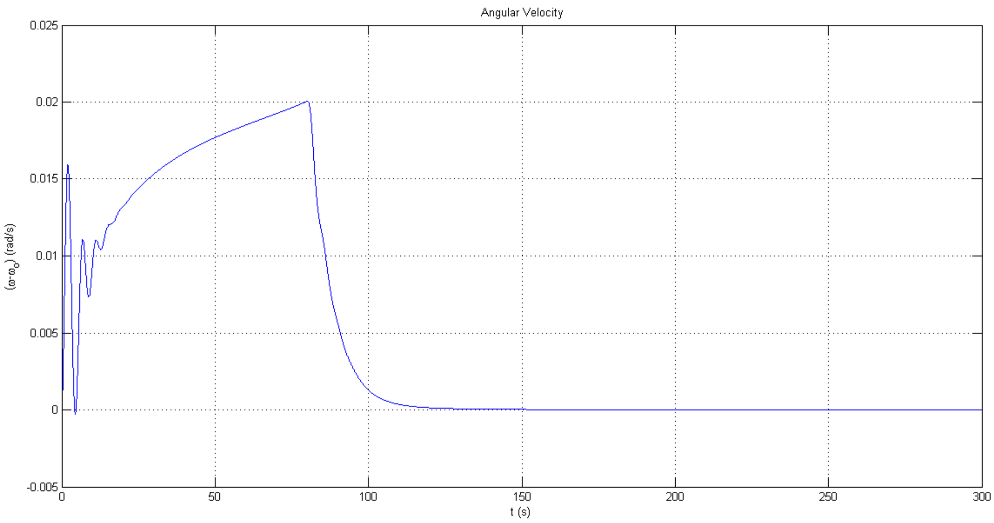



Figure 4-16: The variation of angular velocity ($\omega - \omega_o$) (Single Gen.)

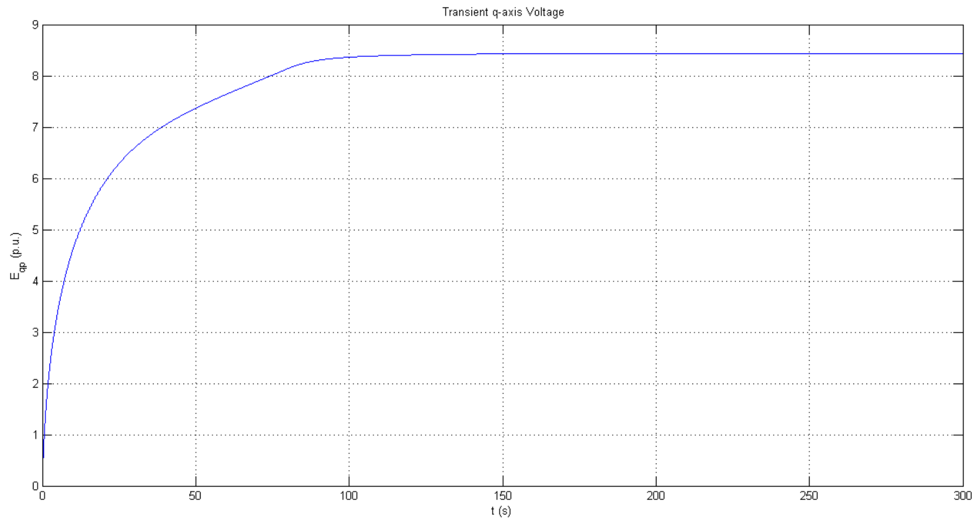



Figure 4-17: The variation of transitional q-axis voltage (Single Gen.)

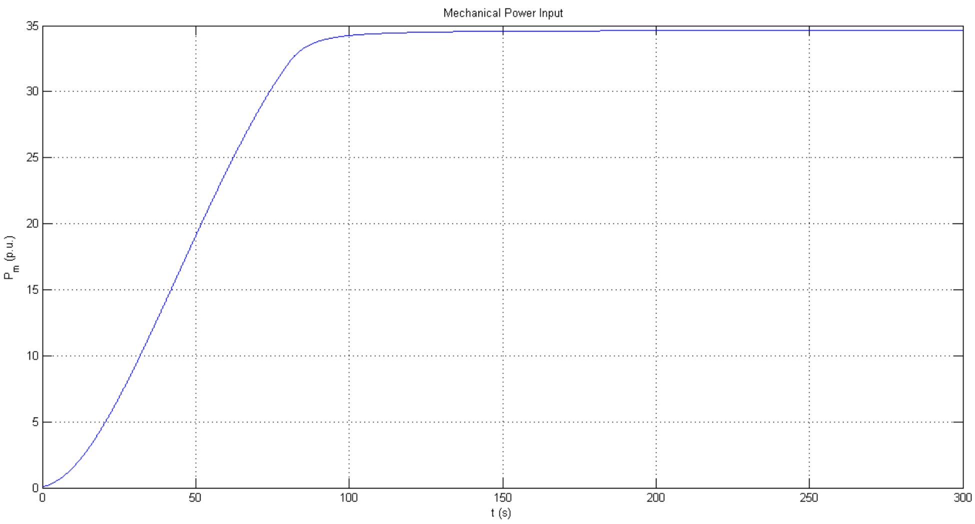



Figure 4-18: The variation of mechanical power input(Single Gen.)

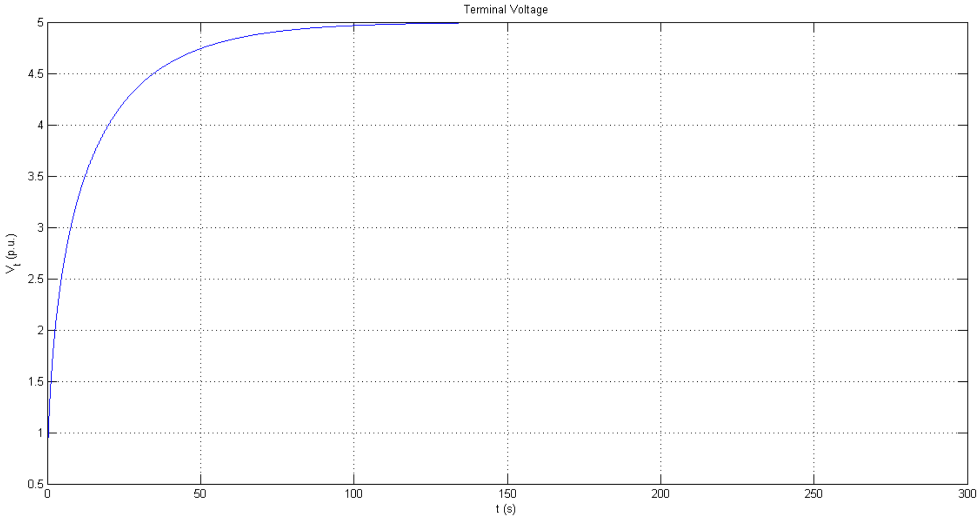



Figure 4-19: The variation of terminal voltage(Single Gen.)

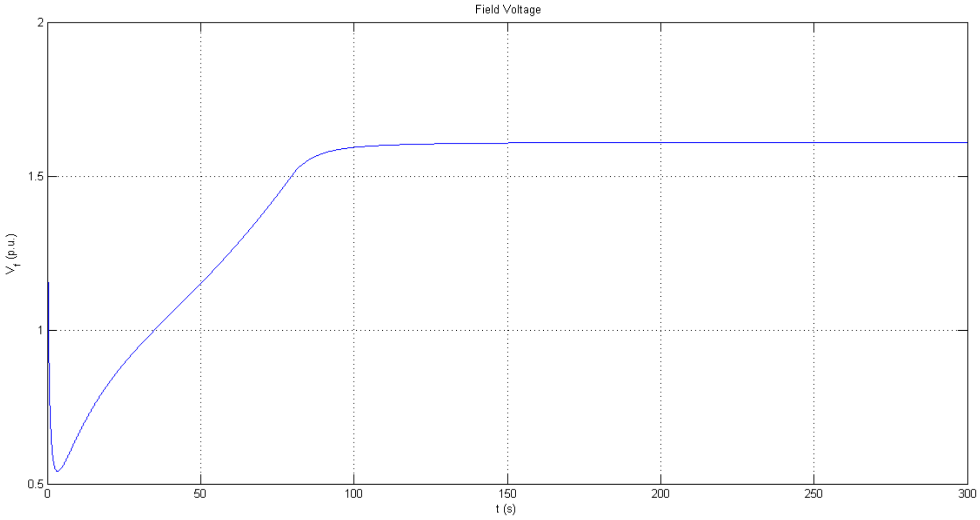



Figure 4-20: The variation of field excitation voltage (Single Gen.)

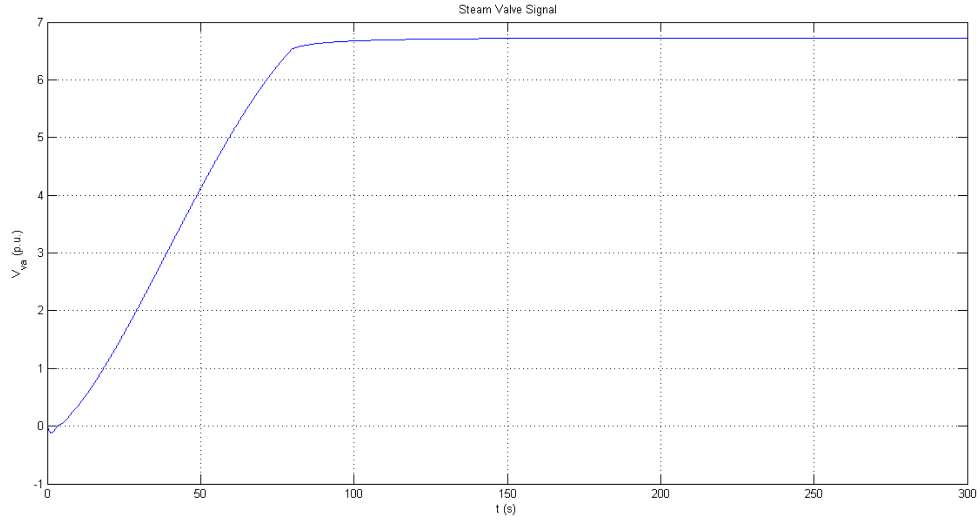



Figure 4-21: The variation of steam valve signal (Single Gen.)

**4.3.4: results of case (4) table (4.2), in this case the target is $X_{1r}$ = 80°, $V_{tr}$=10.**

**Table 4.8**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_v$ | 0.2 | Controller Gain V |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 80 | Desired Power Angle (°) |
| $V_{tr}$ | 10 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.8** are shown in **Figures 22 to 28** when the conditions are applied.

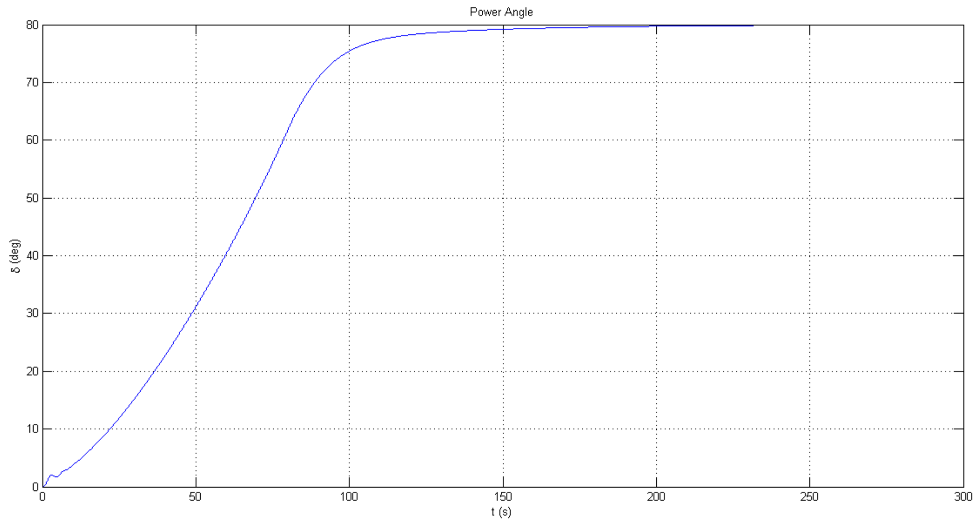



Figure 4-22: The variation of power angle (Single Gen.)

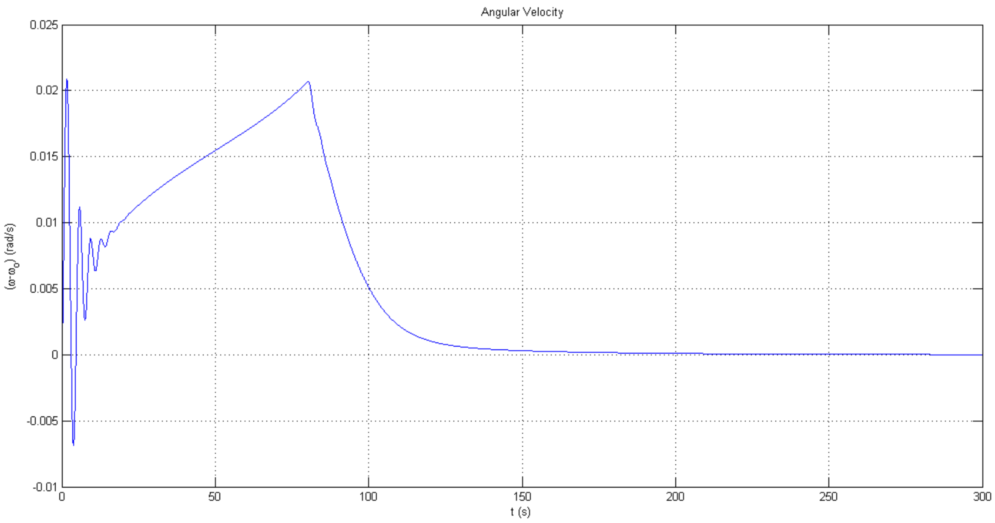



Figure 4-23: The variation of angular velocity $(\omega - \omega_o)$ (Single Gen.)

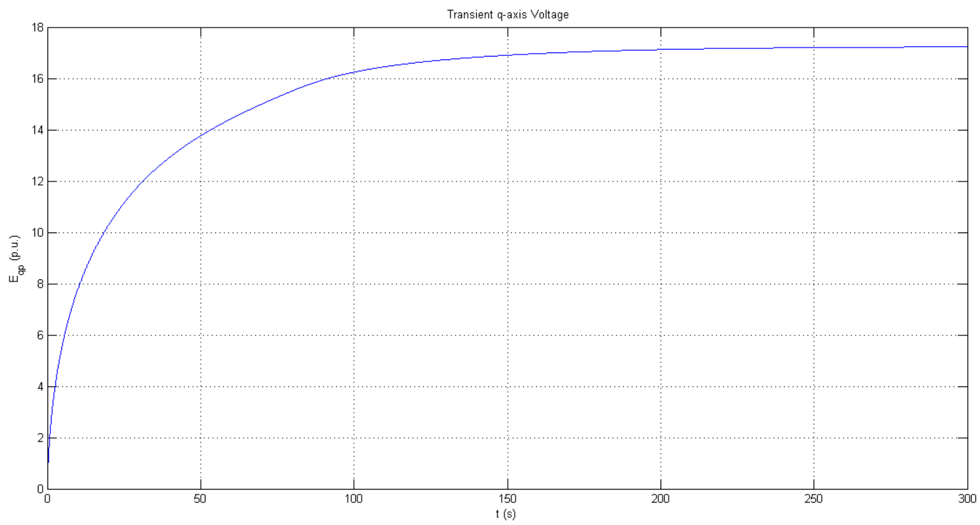



Figure 4-24: The variation of transitional q-axis voltage (Single Gen.)

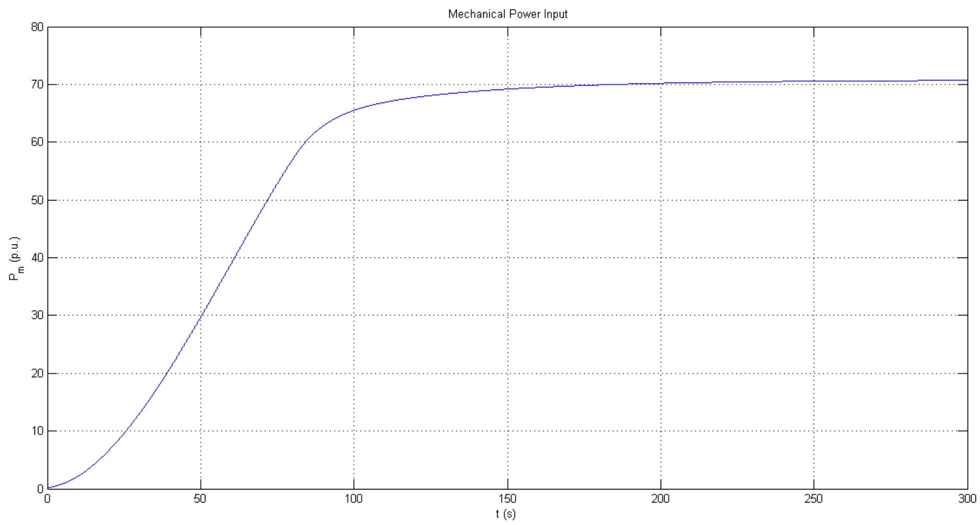



Figure 4-25: The variation of mechanical power input(Single Gen.)

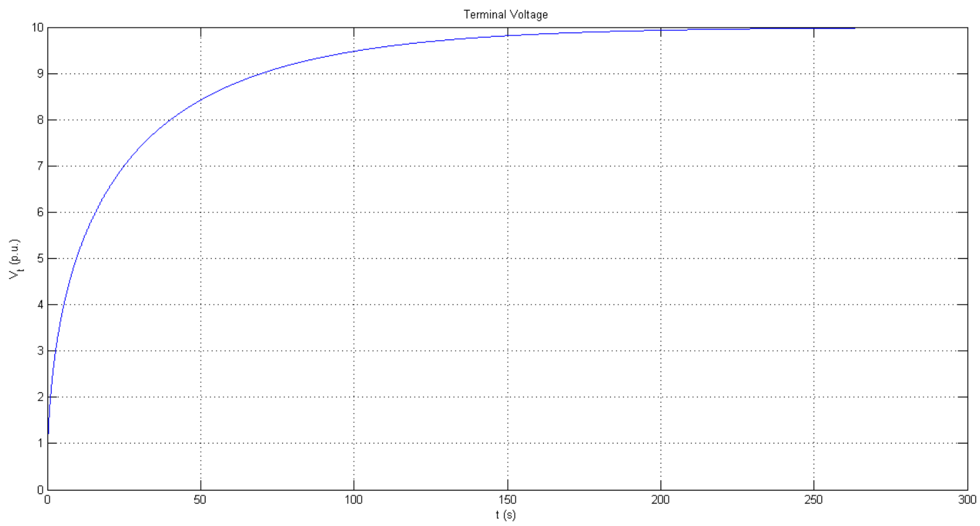



Figure 4-26: The variation of terminal voltage(Single Gen.)

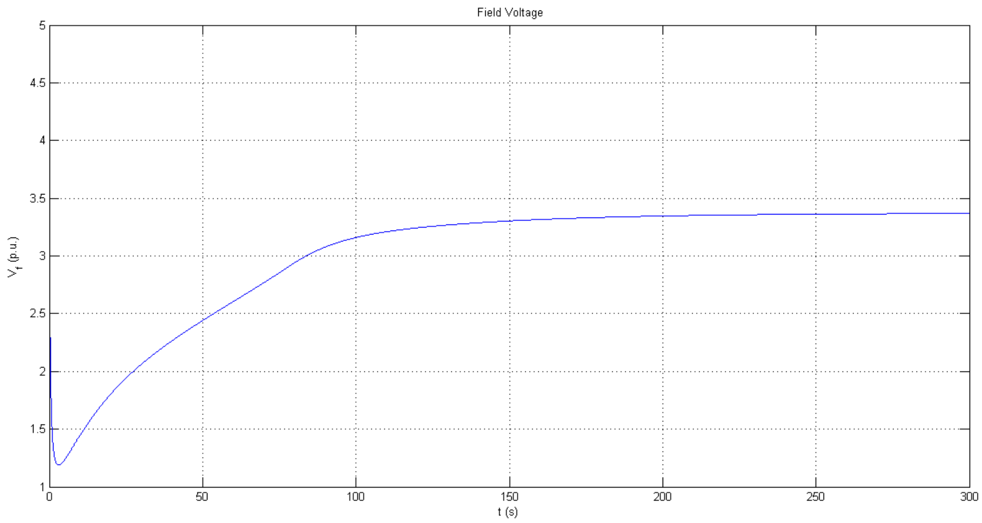



Figure 4-27: The variation of field excitation voltage (Single Gen.)

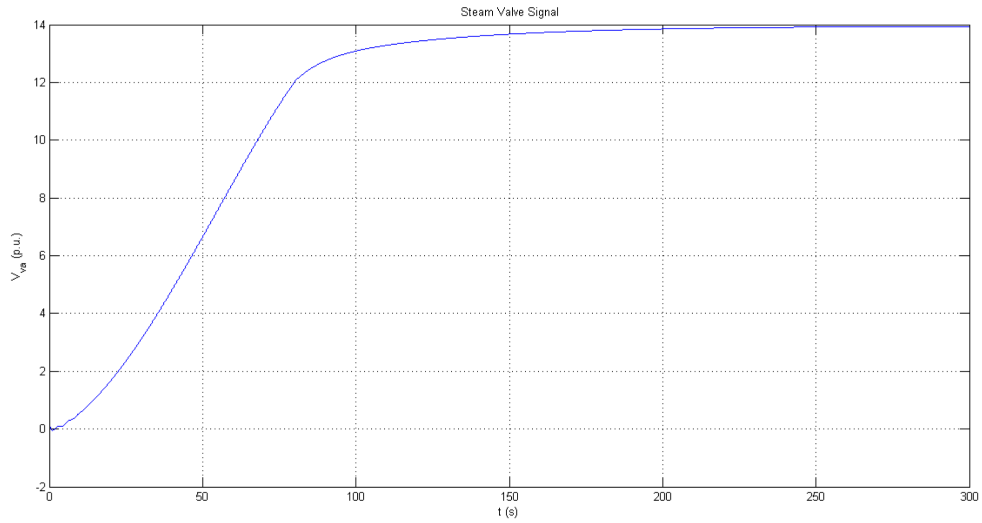



Figure 4-28: The variation of steam valve signal (Single Gen.)

The results showed that, in this case control of power angle and terminal voltage of the single generator, the generator control laws worked satisfactorily. The simulation results did not show an unexpected behavior after the transients, they all converged to the steady states which are equal to the desired values of the power angle and terminal voltages The power angle and terminal voltage converged to their desired values $X_{1r}$ and $V_{tr}$ without any steady state error for all scenarios in this case (single generator). The other states are also reached an acceptable level of the steady state. Concerning the control point of view, the back-stepping controllers appeared to reach thier goals very well. The turbine power controller worked well and handle the mechanical power requests flawlessly. This is understood from the results obtained for different scenarios. So it is expected that the designs work in a realistic environment without any hassles. The control of power angle is more dependent on the mechanical part of the overall system. So $u_2$ (Steam control signal) seems to be more effective. The control of $V_t$ is dependent both on power angle and field voltage. So $u_1$ will be more dependent on the requested $V_t = V_{tr}$ due to mentioned relationship.

The steady state value of the state vriables, inputs and outputs of single generator.

| Parameters | Definition |
|---|---|
| $x_3$ | Transitional q-axis voltage (first generator) |
| $u_4$ | Mechanical power (first generator) |
| $V_t$ | Generator terminal voltage (over all) (first generator) |
| $u_1 = u_f$ | Field excitation voltage (first generator) |
| $u_2 = u_p$ | Electrical control signal to the steam pressure control valve (first generator) |

**Table 4.9** the result for single generator

| | $x_3$ | $u_4$ | $u_1$ | $u_2$ | $V_t$ |
|---|---|---|---|---|---|
| $X_{1r}$ = 70°, $V_{tr}$ = 5 | 8.2572 | 32.3302 | 1.4975 | 6.2660 | 5.0000 |
| $X_{1r}$ = 70°, $V_{tr}$ = 10 | 17.0448 | 66.7203 | 3.2551 | 13.1457 | 10.0000 |
| $X_{1r}$ = 80°, $V_{tr}$ = 5 | 8.4360 | 34.6158 | 1.6090 | 6.7232 | 5.0000 |
| $X_{1r}$ = 80°, $V_{tr}$ = 10 | 17.2289 | 70.6882 | 3.3677 | 13.9392 | 10.0000 |

## 4.4: results of the synchronization two generators simulations.

In this section the results of a synchronous two generators simulations for the cases of **Table (4.3)**

### 4.4.1: results of case (1) table (4.3), in this case the target is $X_{1r}$=70°, $V_{tr}$=5.

**Table 4.10**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_v$ | 0.2 | Controller Gain V |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 70 | Desired Power Angle (°) |
| $V_{tr}$ | 5 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.10** are shown in **Figures 29 to 35** when the conditions are applied.

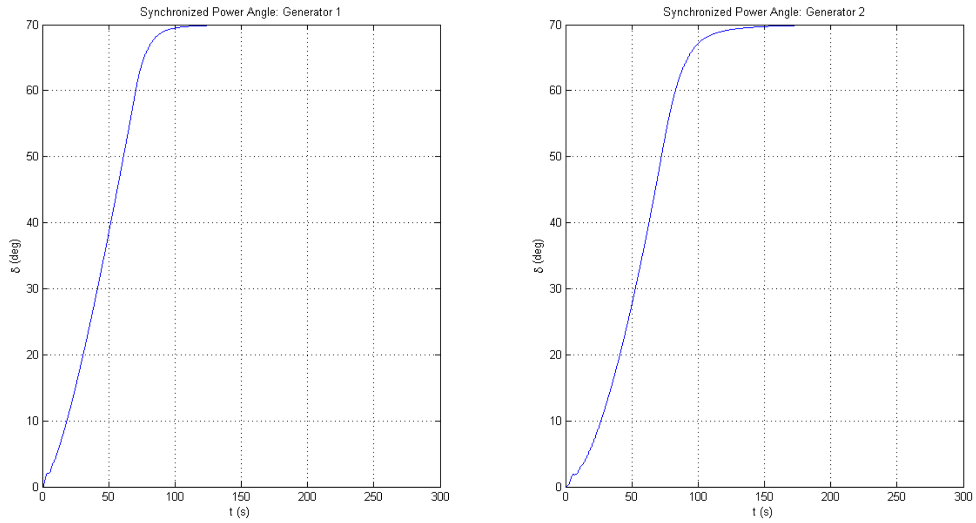



Figure 4-29: The variation of two synchronized generators power angles

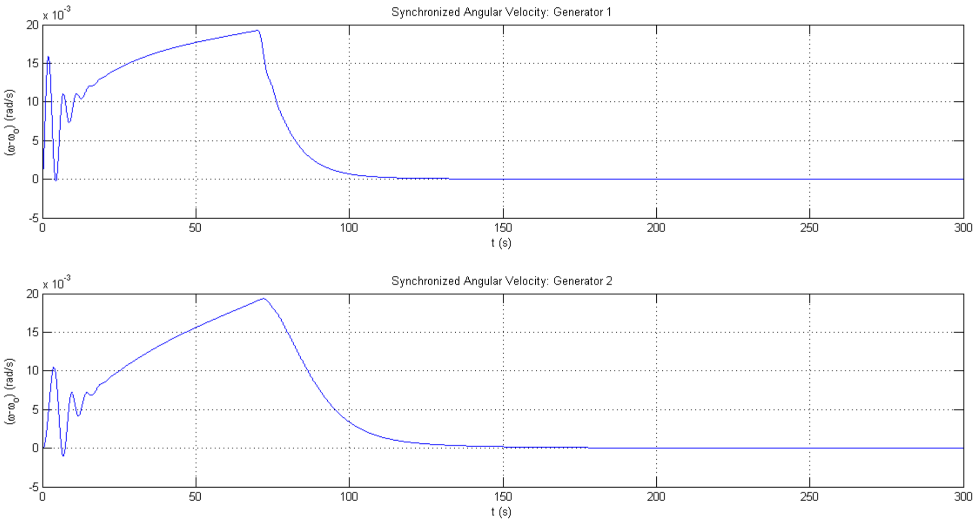



Figure 4-30: The variation of two synchronized generators angular velocity $(\omega - \omega_o)$

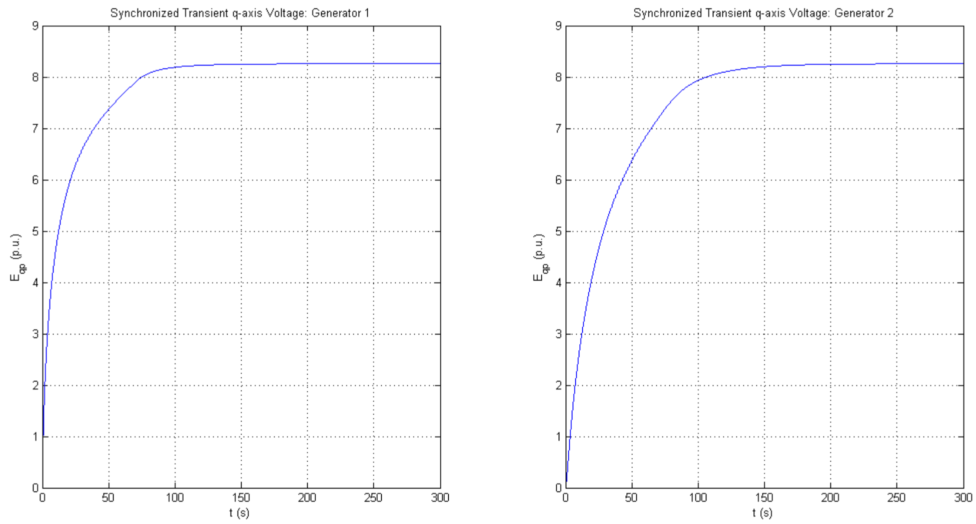



Figure 4-31: The variation of two synchronized generators transitional q-axis voltages

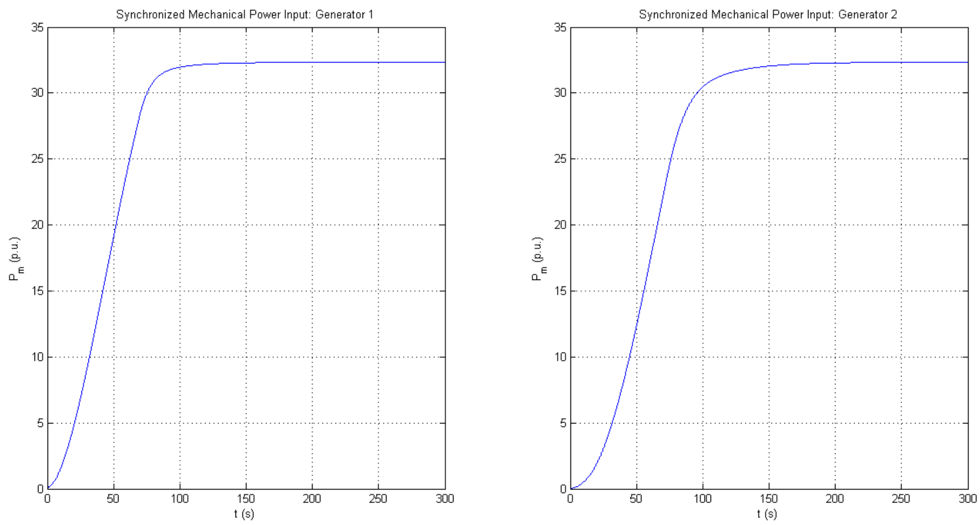



Figure 4-32: The variation of two synchronized generators mechanical power input

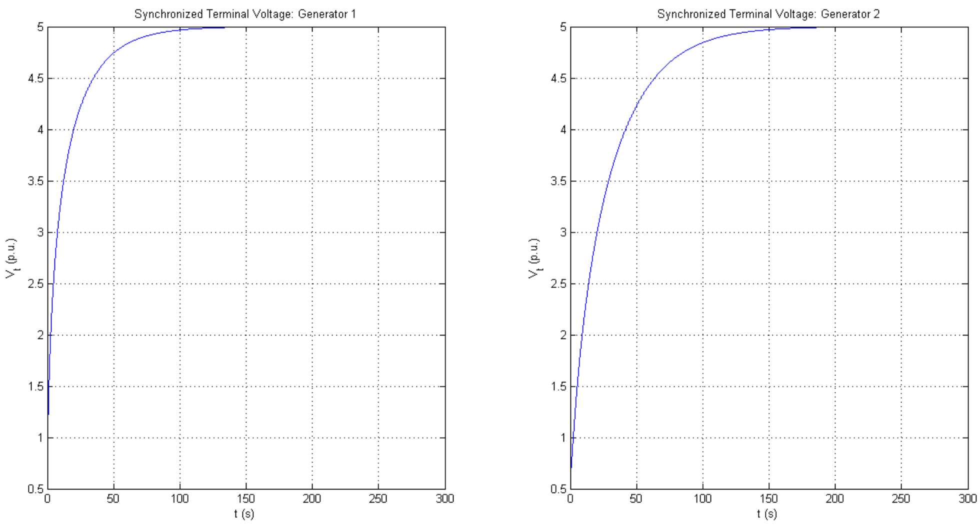



Figure 4-33: The variation of two synchronized generators terminal voltages

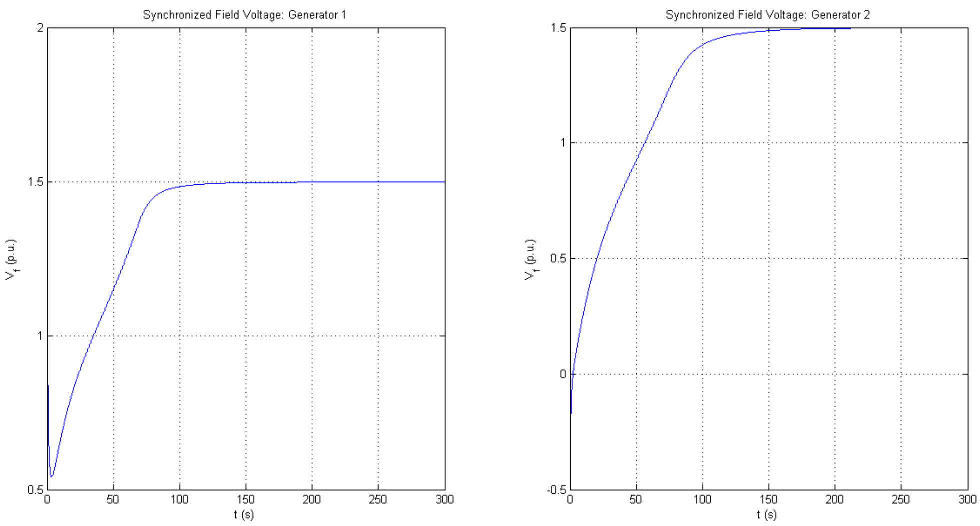



Figure 4-34: The variation of two synchronized generators field excitation voltages

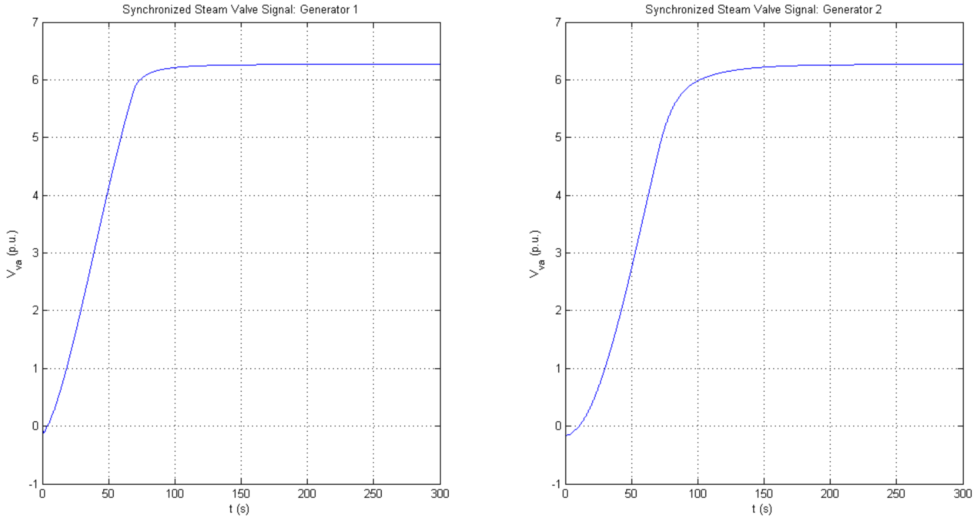



Figure 4-35: The variation of two synchronized generators steam valve signals

**4.4.2: results of case (2) table (4.3), in this case the target is $X_{1r}$ = 70°, $V_{tr}$ = 10.**

**Table 4.11**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_v$ | 0.2 | Controller Gain V |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 70 | Desired Power Angle (°) |
| $V_{tr}$ | 10 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.11** are shown in **Figures 36 to 42** when the conditions are applied.

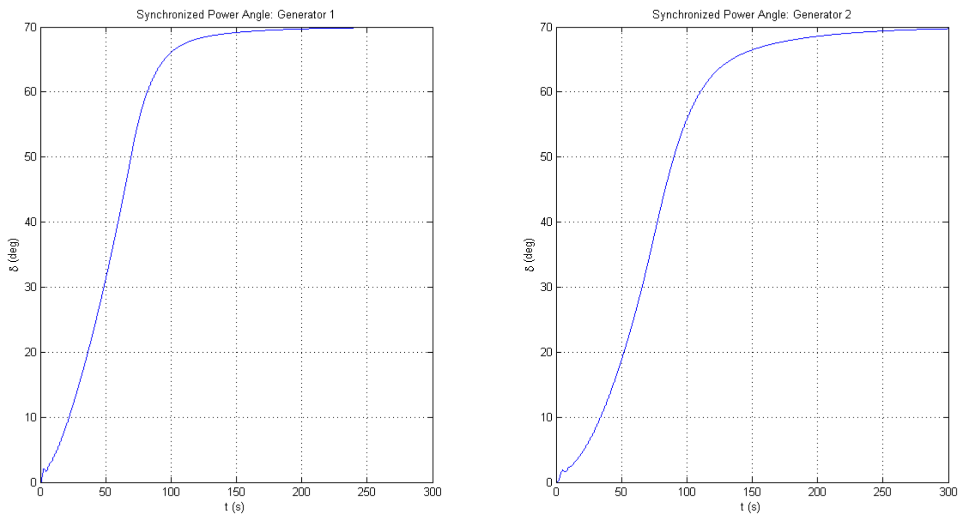



Figure 4-36: The variation of two synchronized generators power angles

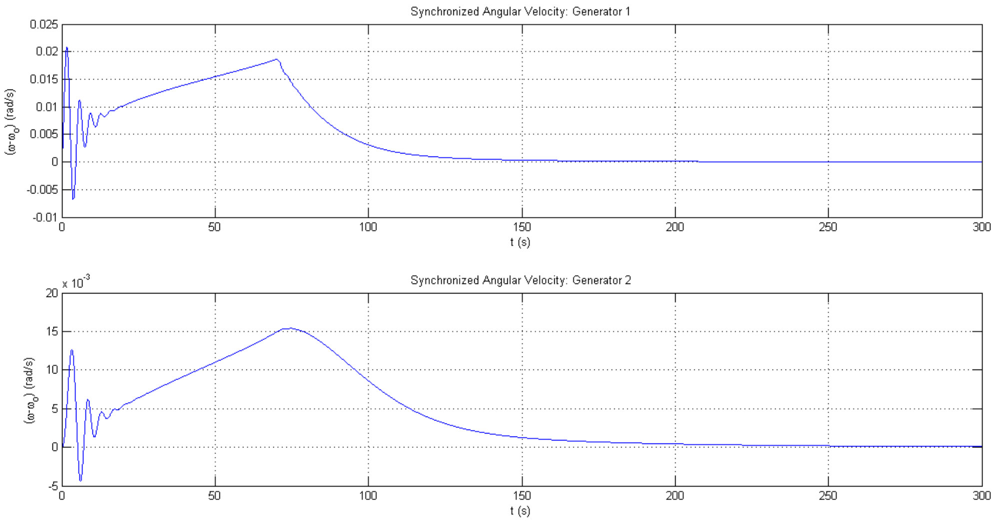



Figure 4-37: The variation of two synchronized generators angular velocity $(\omega - \omega_o)$

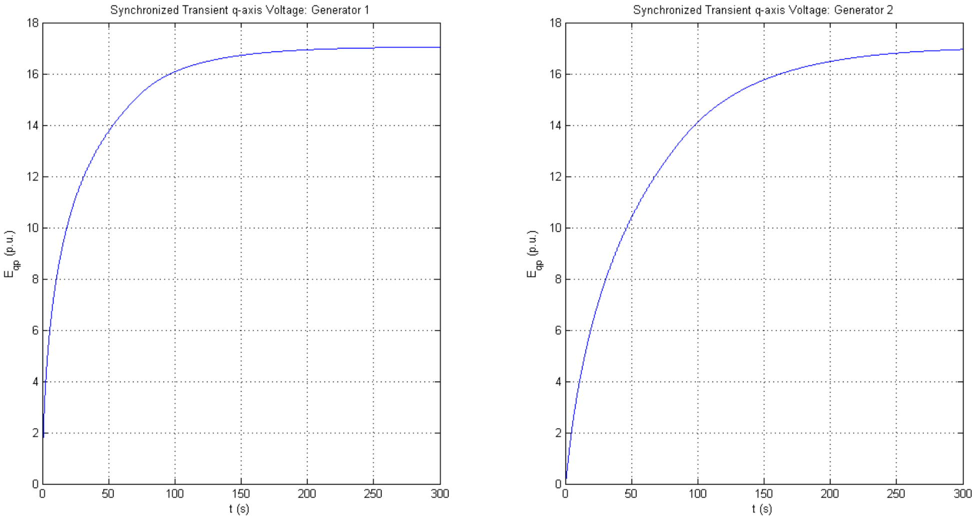



Figure 4-38: The variation of two synchronized generators transitional q-axis voltages

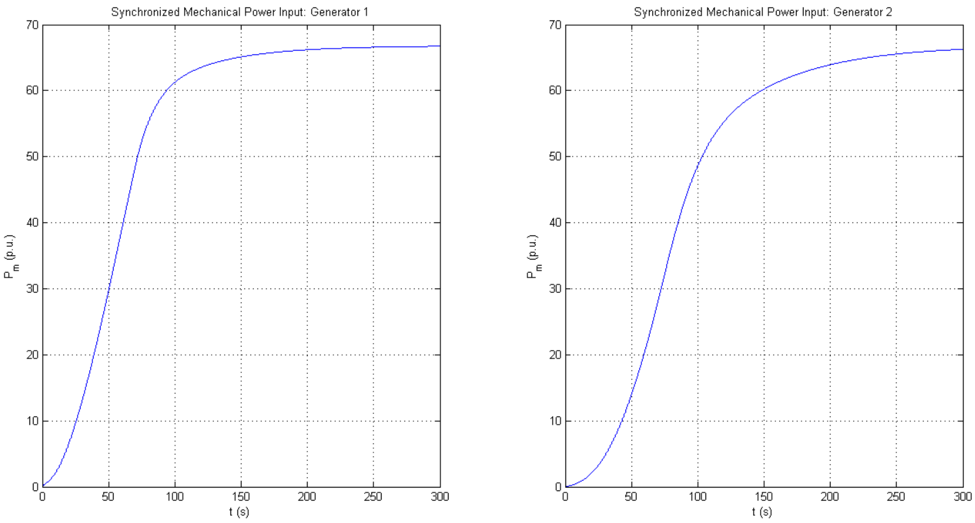



Figure 4-39: The variation of two synchronized generators mechanical power input

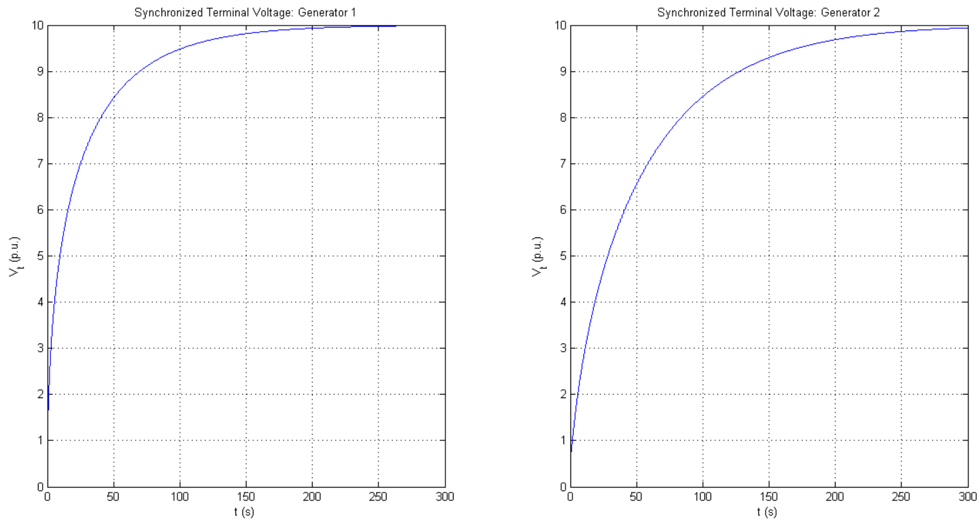



Figure 4-40: The variation of two synchronized generators terminal voltages

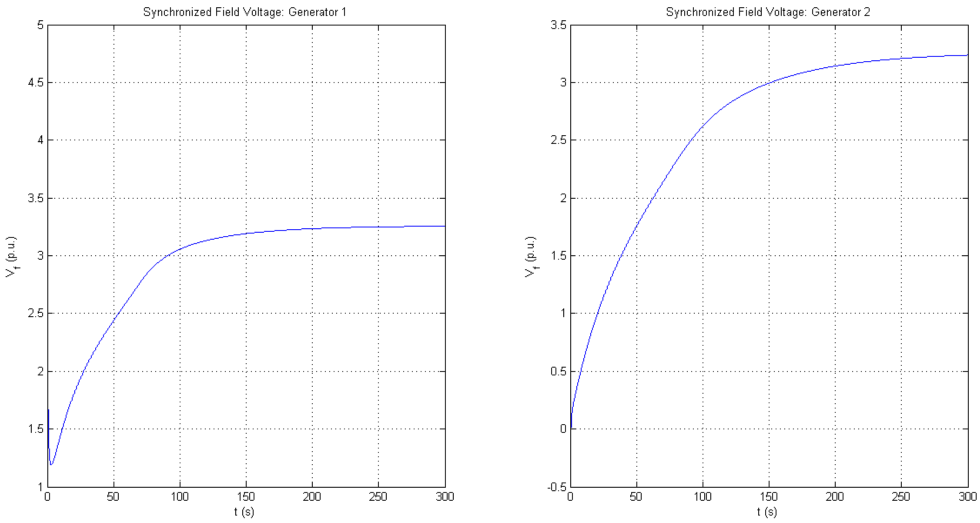



Figure 4-41: The variation of two synchronized generators field excitation voltages

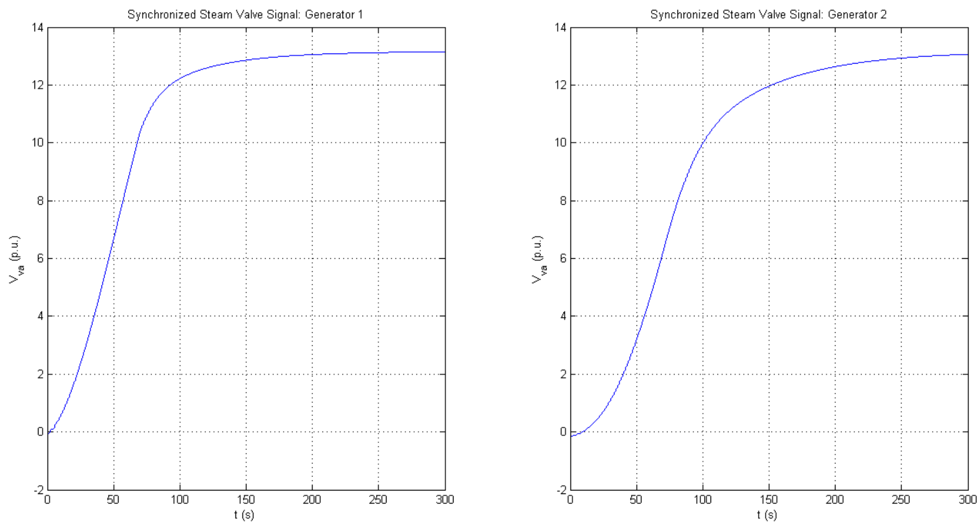



Figure 4-42: The variation of two synchronized generators steam valve signals

**4.4.3: results of case (3) table (4.3), in this case the target is $X_{1r}$ = 80°, $V_{tr}$ = 5.**

**Table 4.12**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_v$ | 0.2 | Controller Gain V |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 80 | Desired Power Angle (°) |
| $V_{tr}$ | 5 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.12** are shown in **Figures 43 to 49** when the conditions are applied.

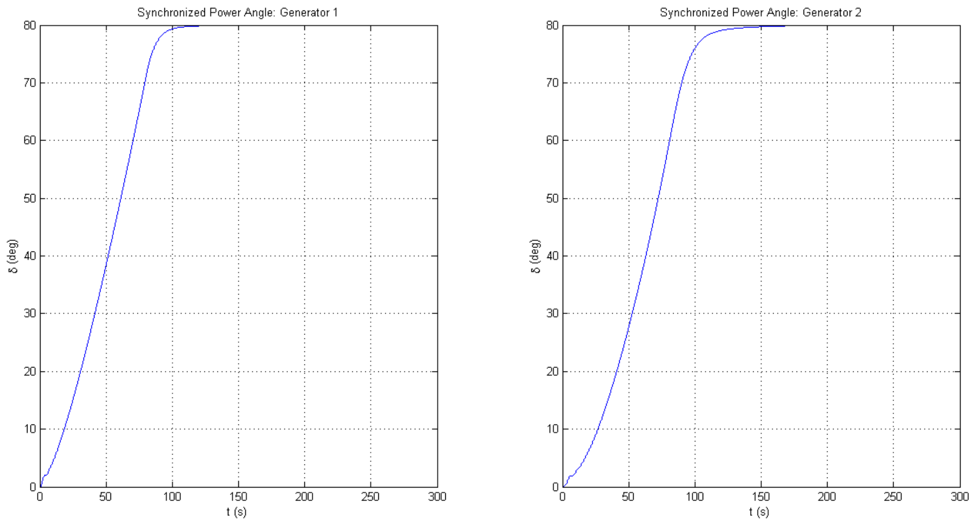



Figure 4-43: The variation of two synchronized generators power angles

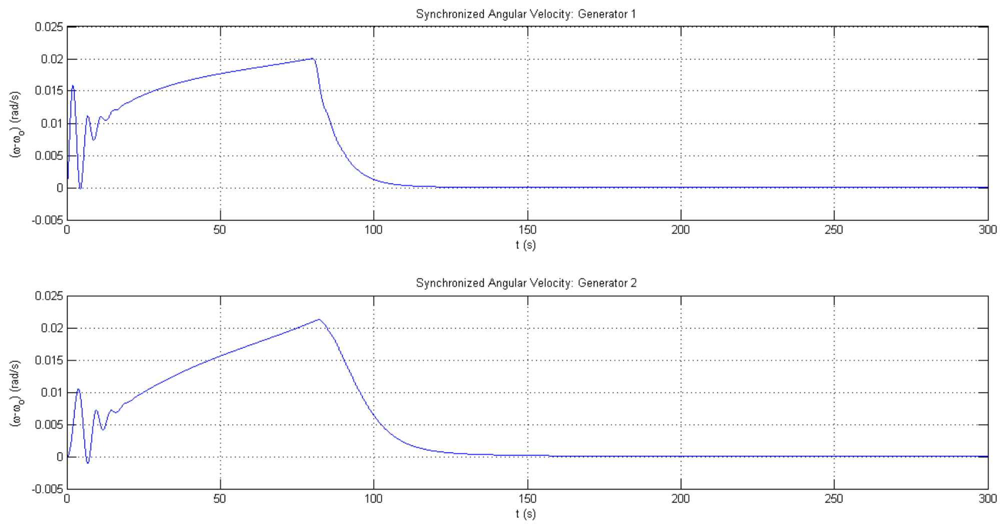



Figure 4-44: The variation of two synchronized generators angular velocity $(\omega - \omega_o)$

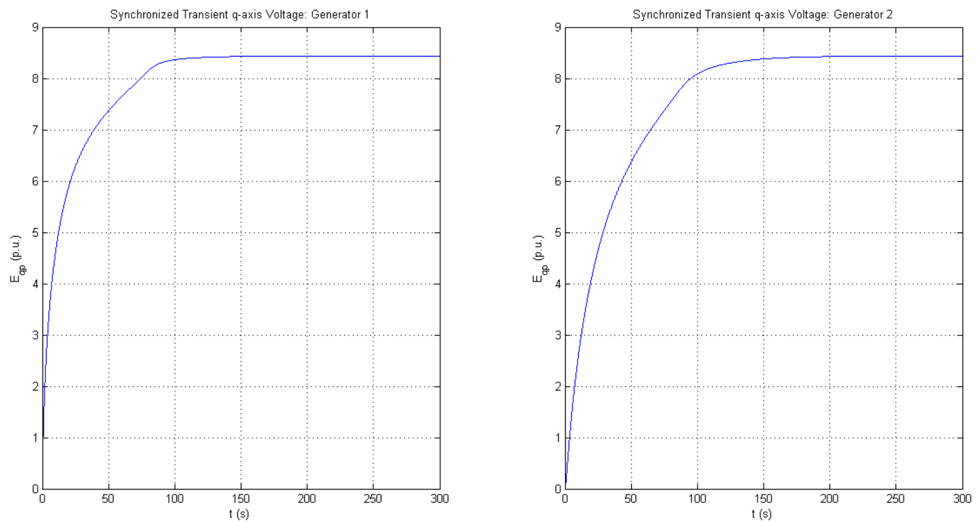



Figure 4-45: The variation of two synchronized generators transitional q-axis voltages

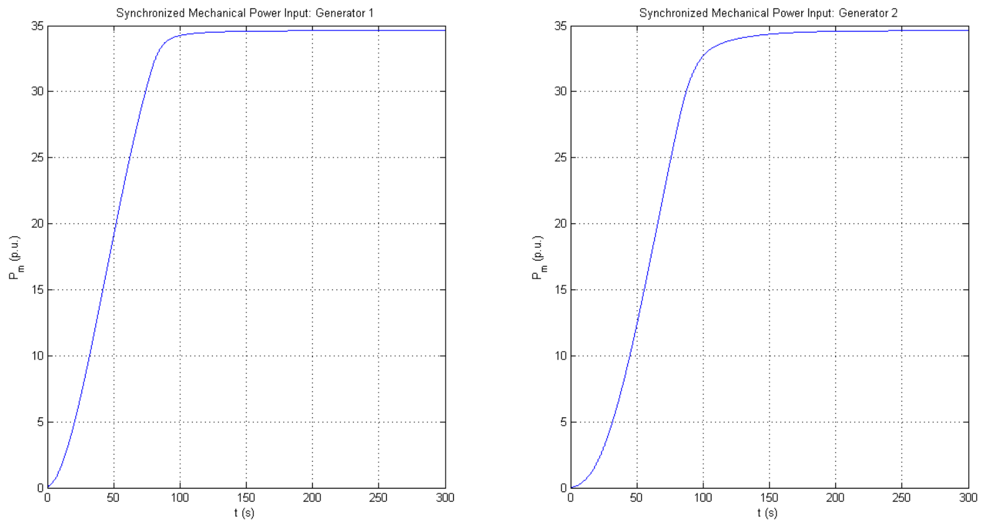



Figure 4-46: The variation of two synchronized generators mechanical power input

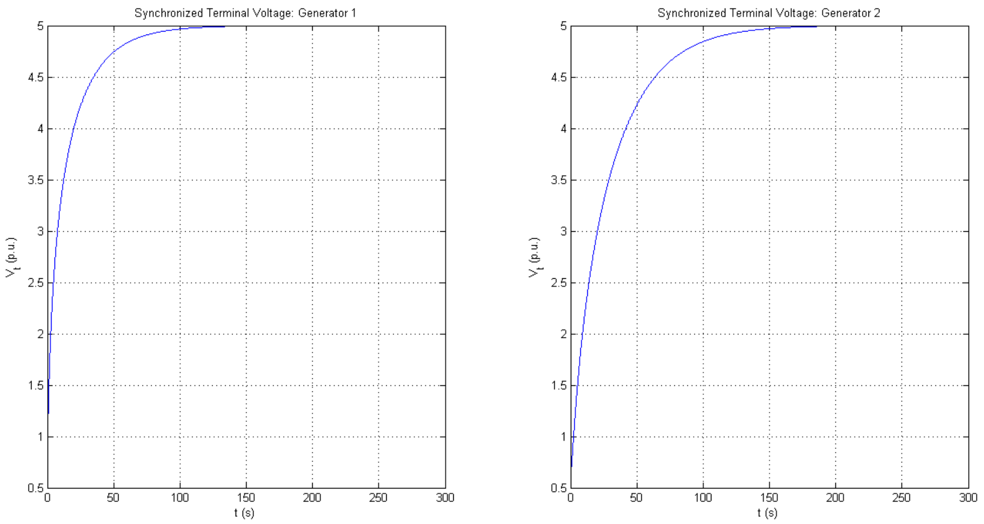



Figure 4-47 : The variation of two synchronized generators terminal voltages

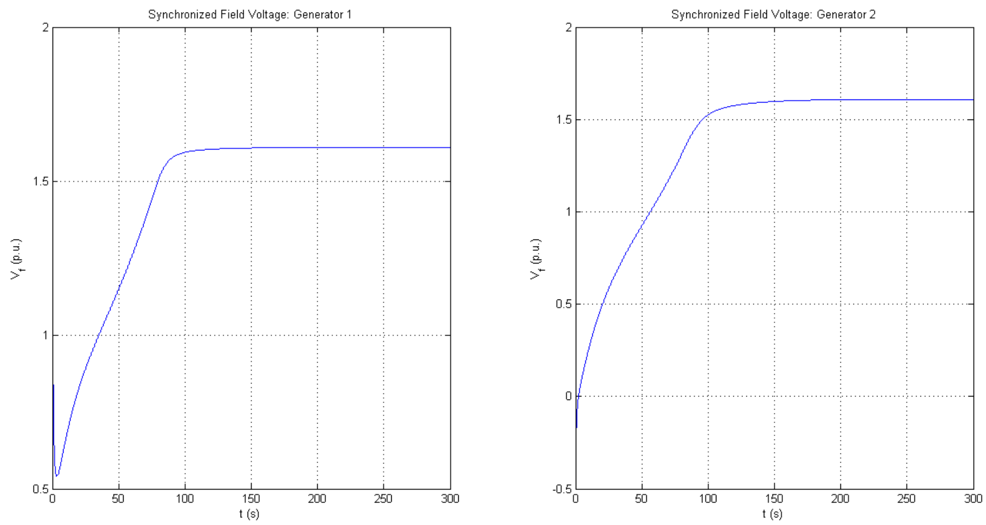



Figure 4-48 : The variation of two synchronized generators field excitation voltages

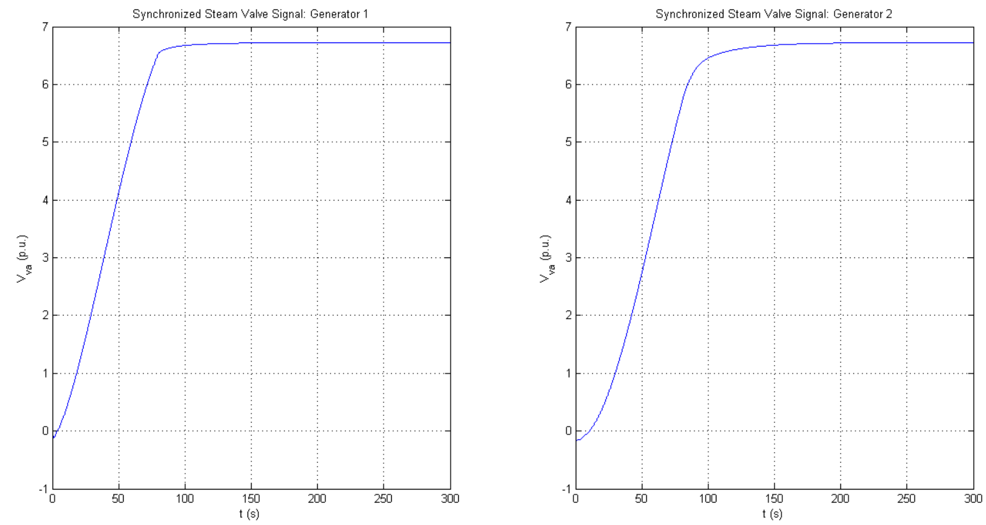



Figure 4-49 : The variation of two synchronized generators steam valve signals

**4.4.4: results of case (4) table (4.3), in this case the target is $X_{1r}$ = 80°, $V_{tr}$ = 10.**

**Table 4.13**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_v$ | 0.2 | Controller Gain V |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 80 | Desired Power Angle (°) |
| $V_{tr}$ | 10 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.13** are shown in **Figures 50 to 56** when the conditions are applied.

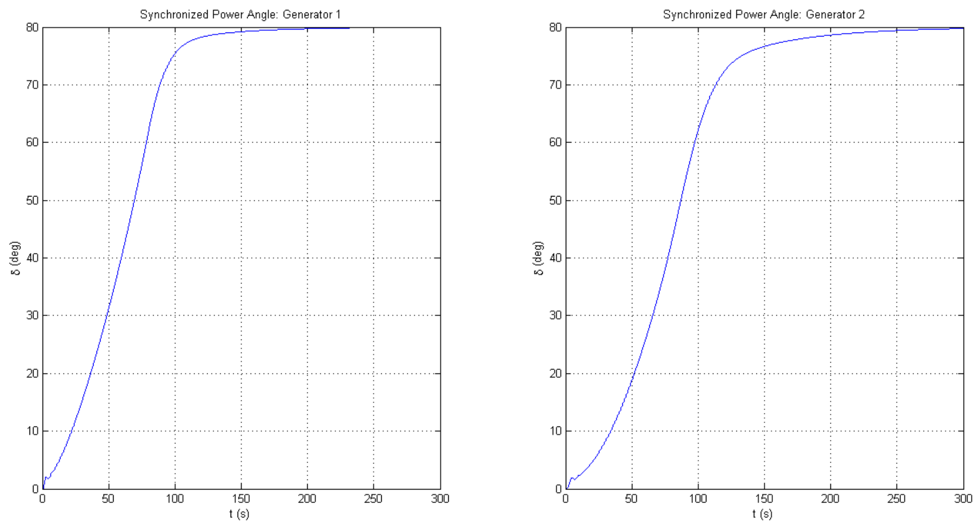



Figure 4-50: The variation of two synchronized generators power angles

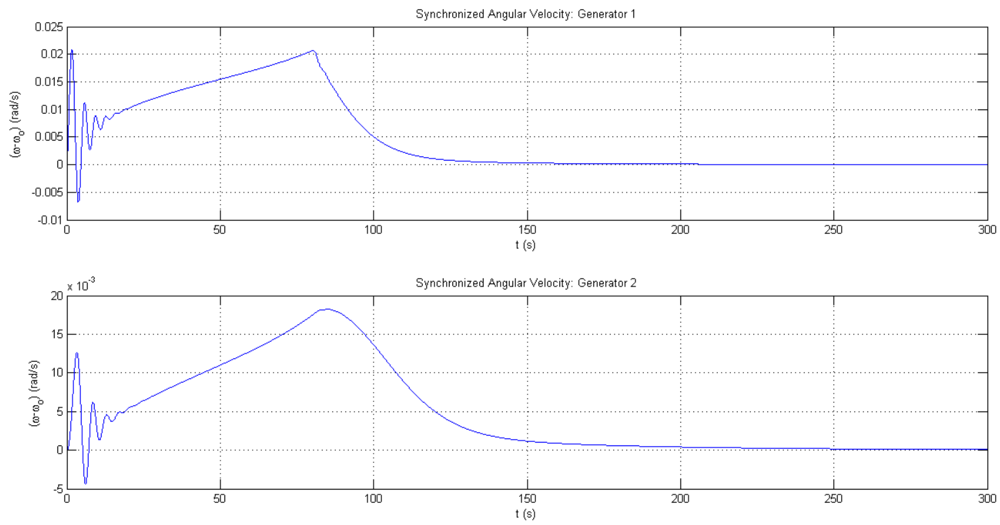



Figure 4-51: The variation of two synchronized generators angular velocity $(\omega - \omega_o)$

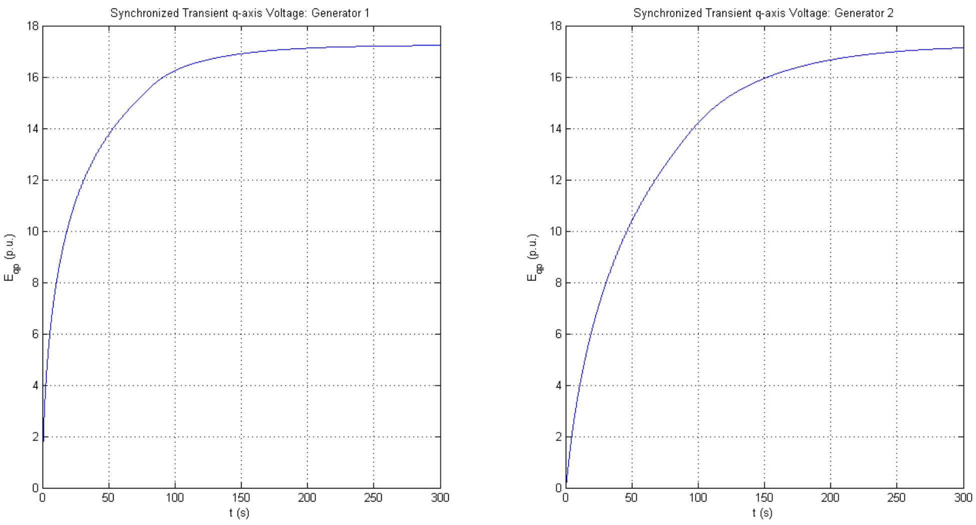



Figure 4-52: The variation of two synchronized generators transitional q-axis voltages

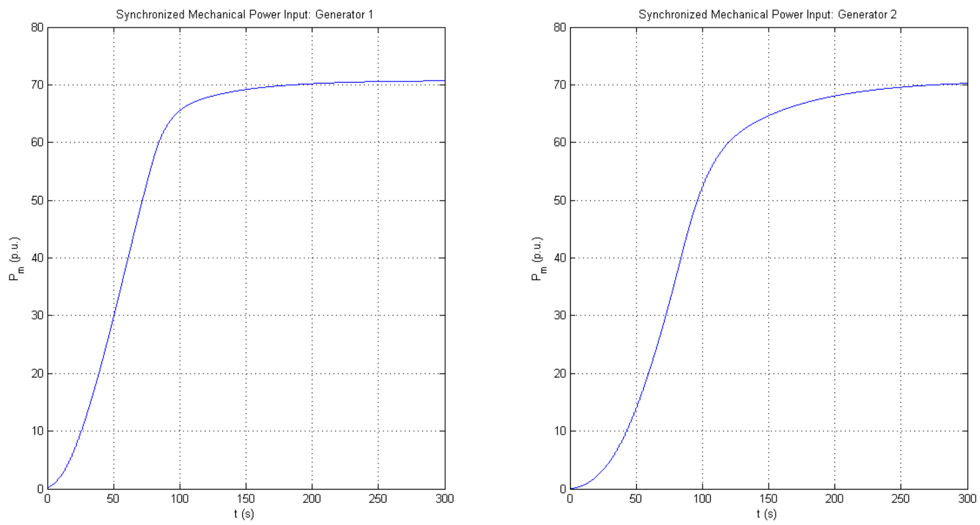



Figure 4-53: The variation of two synchronized generators mechanical power input

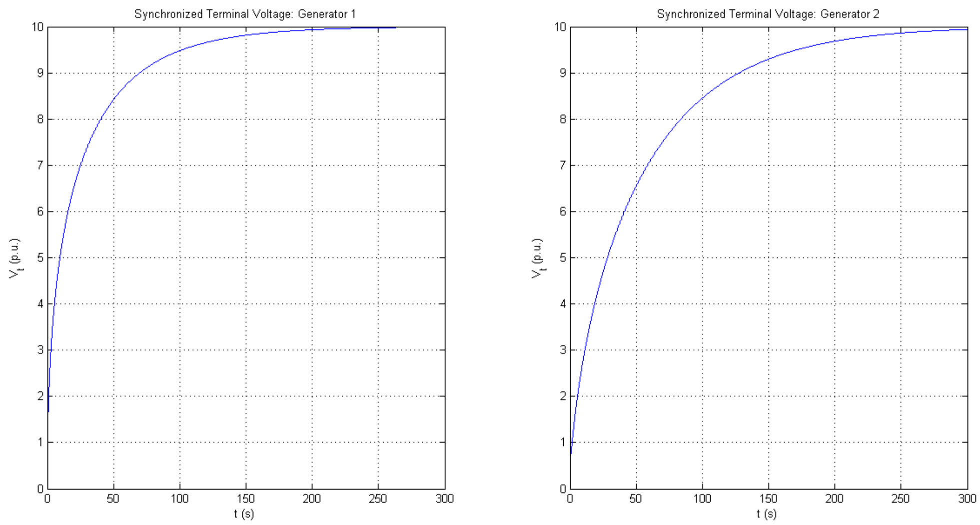



Figure 4-54: The variation of two synchronized generators terminal voltages

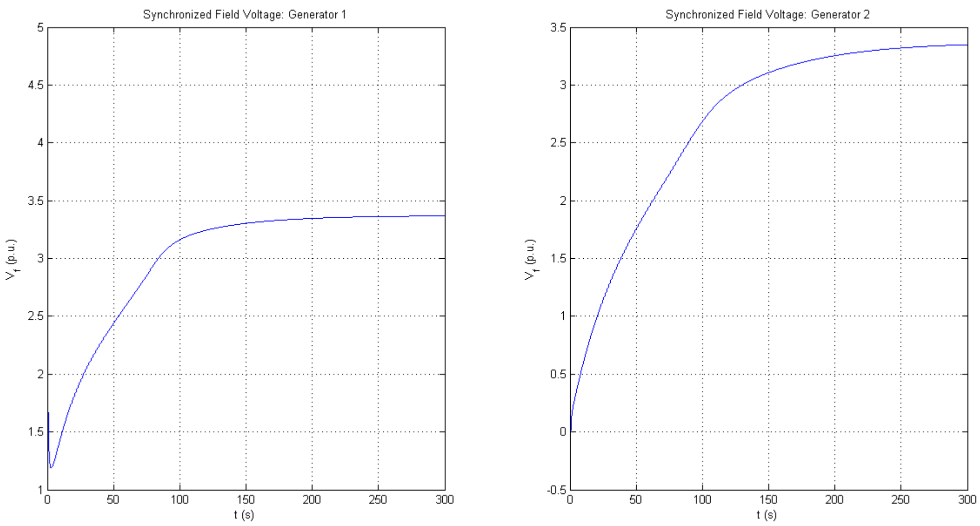



Figure 4-55: The variation of two synchronized generators field excitation voltages

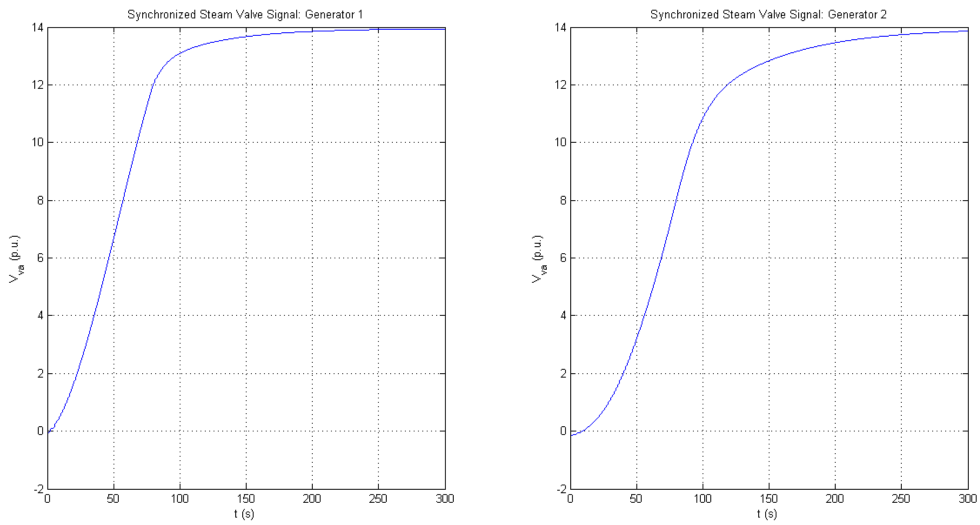



Figure 4-56: The variation of two synchronized generators steam valve signals

The results showed that, The synchronization of the power angles and terminal voltages of the multiple synchronous generators (synchronization of two generators). The generator control laws worked satisfactorily. The synchronization of the generators based on the cascaded strategy. The first generator acted as a controlled "main generator" and the rest follows the power angle and terminal voltage outputs of the main generator. The controller designs are same for all generators and the second generators receive the outputs of the first generator as reference. The simulation results did not show an unexpected behavior after the transients, they all converged to the steady states which are equal to the desired values of the power angle and terminal voltages The power angle and terminal voltage converged to their desired values $X_{1r}$ and $V_{tr}$ without any steady state error for all scenarios in this case (synchronous two generators). The second generator followed the output of the first one without any steady state errors. So synchronization also works perfectly for power angle and terminal voltage. Similar outcome is obtained from the synchronized control. The other states are also reached an acceptable level of the steady state. Concerning the control point of view, the back-stepping controllers appeared to reach thier goals very well. As an expected fact, the synchronization of multiple generators introduced a small delay. This due to the fact that, the design assumes the power angle and terminal voltage references are constants (or step function). However, the synchronized generators (second and the rest) receives a transient change where the other generators need more time to recover. This issue can partially be solved by increasing the controller gains of the second and subsequent generators. The turbine power controller worked well and handle the mechanical power requests flawlessly. This is understood from the results obtained for different scenarios. So it is expected that the designs work in a realistic environment without any hassles. The control of power angle is more dependent on the mechanical part of the overall system. So $u_2$ (Steam control signal) seems to be more effective. The control of $V_t$ is dependent both on power angle and field voltage. So $u_1$ will be more dependent on the requested $V_t = V_{tr}$ due to mentioned relationship.

The steady state value of the state vriables, inputs and outputs of two synchronized generators.

| Parameters | Definition |
|---|---|
| $x_3$ | Transitional q-axis voltage (first generator) |
| $z_3$ | Transitional q-axis voltage (second generator) |
| $u_4$ | Mechanical power (first generator) |
| $w_4$ | Mechanical power (second generator) |
| $u_1$ | Field excitation voltage (first generator) |
| $w_1$ | Field excitation voltage (second generator) |
| $u_2$ | Electrical control signal to the steam pressure control valve (first generator) |
| $w_2$ | Electrical control signal to the steam pressure control valve (second generator) |
| $V_t$ | Generator terminal voltage (over all) (first generator) |
| $Y_t$ | Generator terminal voltage (over all) (second generator) |

**Table 4.14** the result for synchronized two generators

| | $x_3$ | $z_3$ | $u_4$ | $w_4$ | $u_1$ | $w_1$ |
|---|---|---|---|---|---|---|
| $X_{1r}$=70°, $V_{tr}$=5 | 8.2572 | 8.2572 | 32.3302 | 32.3302 | 1.4975 | 1.4975 |
| $X_{1r}$=70°, $V_{tr}$=10 | 17.0448 | 17.0448 | 66.7203 | 66.7203 | 3.2551 | 3.2551 |
| $X_{1r}$=80°, $V_{tr}$=5 | 8.4360 | 8.4360 | 34.6158 | 34.6158 | 1.6090 | 1.6090 |
| $X_{1r}$=80°, $V_{tr}$=10 | 17.2289 | 17.2289 | 70.6882 | 70.6882 | 3.3677 | 3.3677 |

| | $u_2$ | $w_2$ | $V_t$ | $Y_t$ |
|---|---|---|---|---|
| $X_{1r}$=70°, $V_{tr}$=5 | 6.2660 | 6.2660 | 5.0000 | 5.0000 |
| $X_{1r}$=70°, $V_{tr}$=10 | 13.1457 | 13.1457 | 10.0000 | 10.0000 |
| $X_{1r}$=80°, $V_{tr}$=5 | 6.7232 | 6.7232 | 5.0000 | 5.0000 |
| $X_{1r}$=80°, $V_{tr}$=10 | 13.9392 | 13.9392 | 10.0000 | 10.0000 |

### 4.5: results of the synchronization for Powr Angle and Terminal Voltage of three generators simulations.

In this section the results of a synchronize three generators simulations for the cases of the **Table (4.3).**

#### 4.5.1: results of case (1) table (4.4), in this case the target is $X_{1r}$ = 70°, $V_{tr}$ = 5.

**Table 4.15**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_v$ | 0.2 | Controller Gain V |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 70 | Desired Power Angle (°) |
| $V_{tr}$ | 5 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.15** are shown in **Figures 57 to 63** when the conditions are applied.

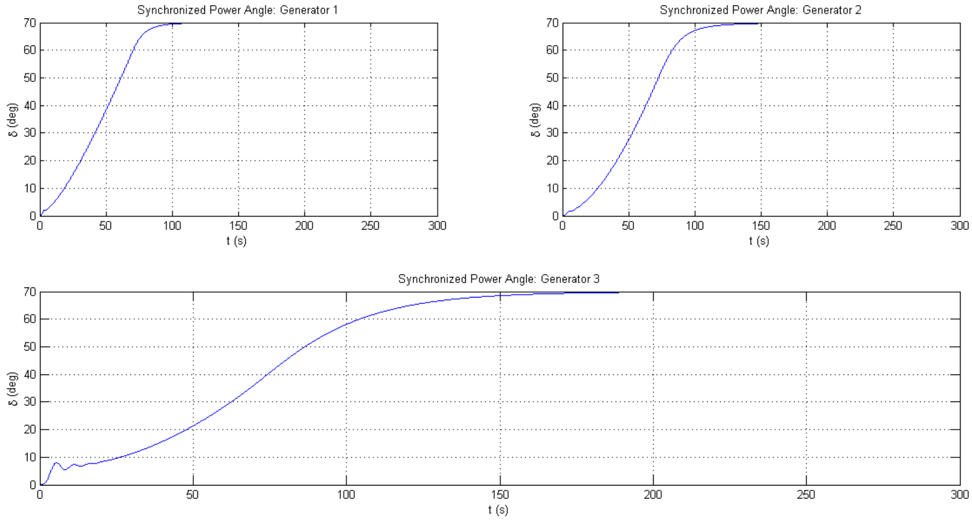



Figure 4-57: The variation of three synchronized generators power angles

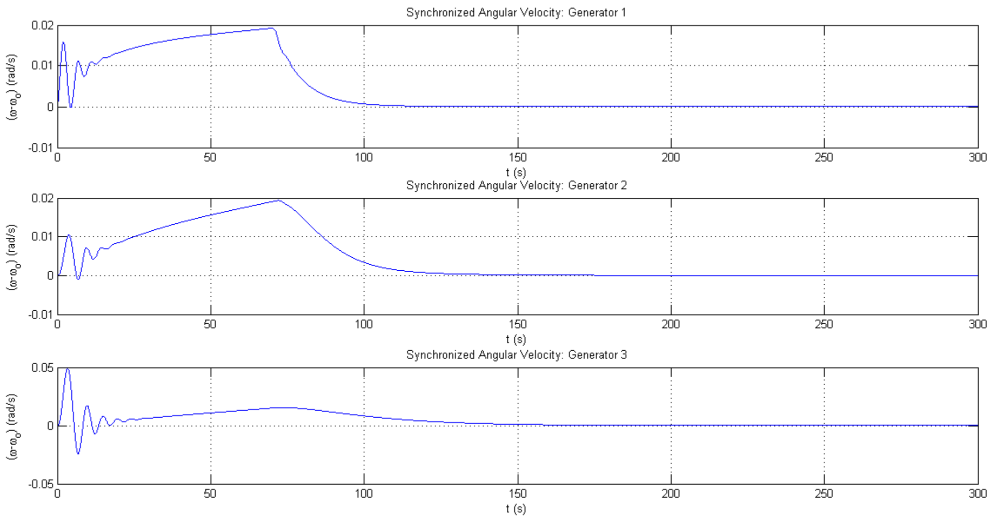



Figure 4-58: The variation of three synchronized generators angular velocity $(\omega - \omega_0)$

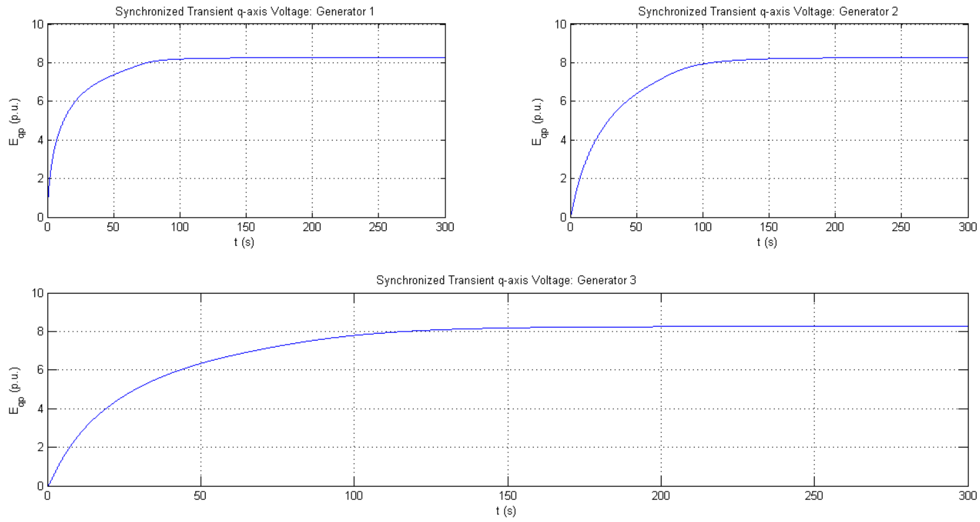



Figure 4-59: The variation of three synchronized generators transitional q-axis voltages

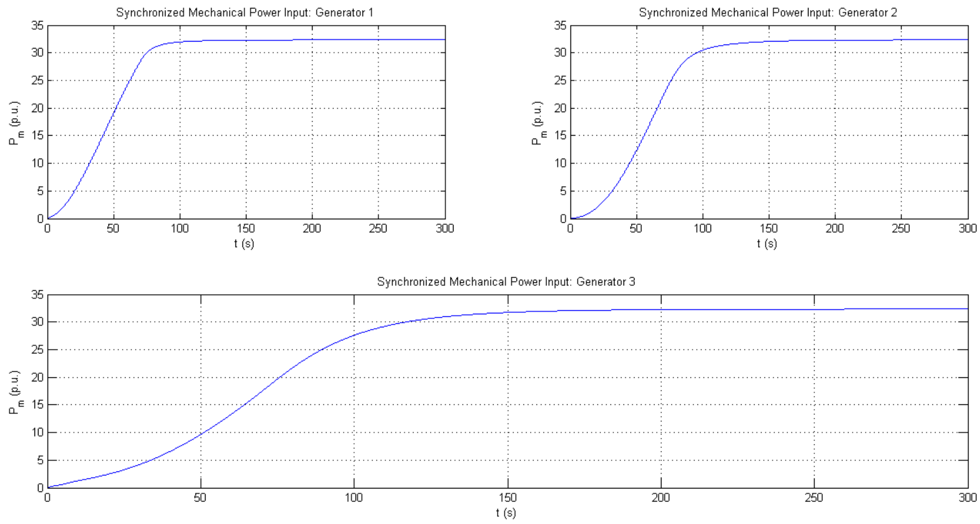



Figure 4-60: The variation of three synchronized generators mechanical power input

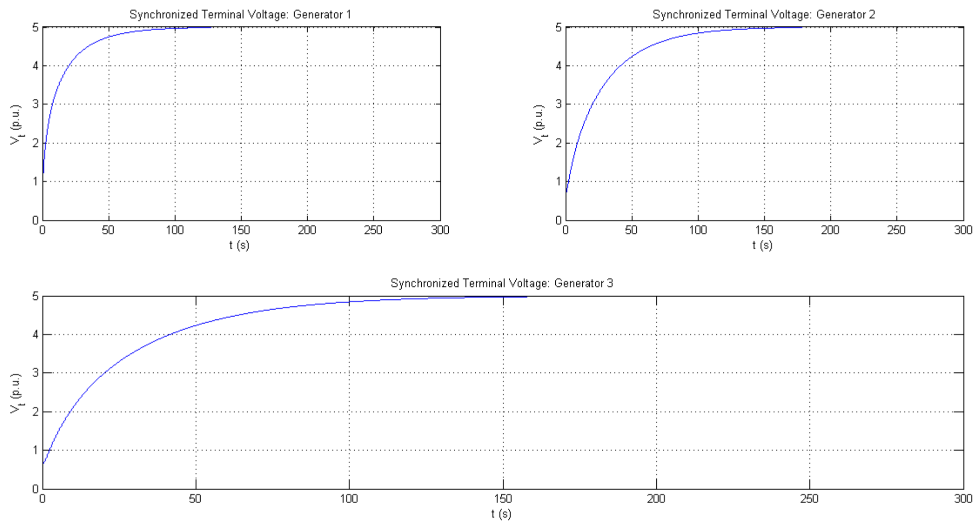



Figure 4-61: The variation of three synchronized generators terminal voltages

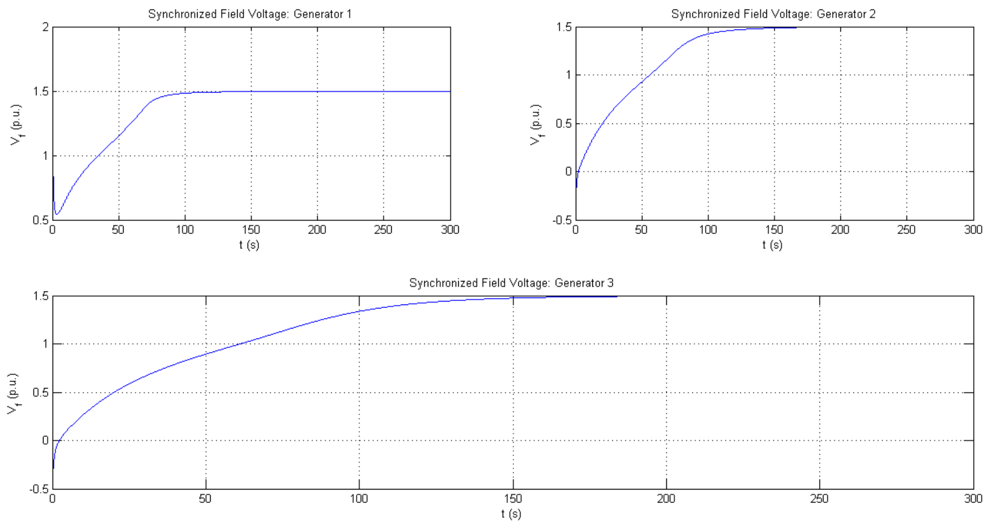



Figure 4-62: The variation of three synchronized generators field excitation voltages

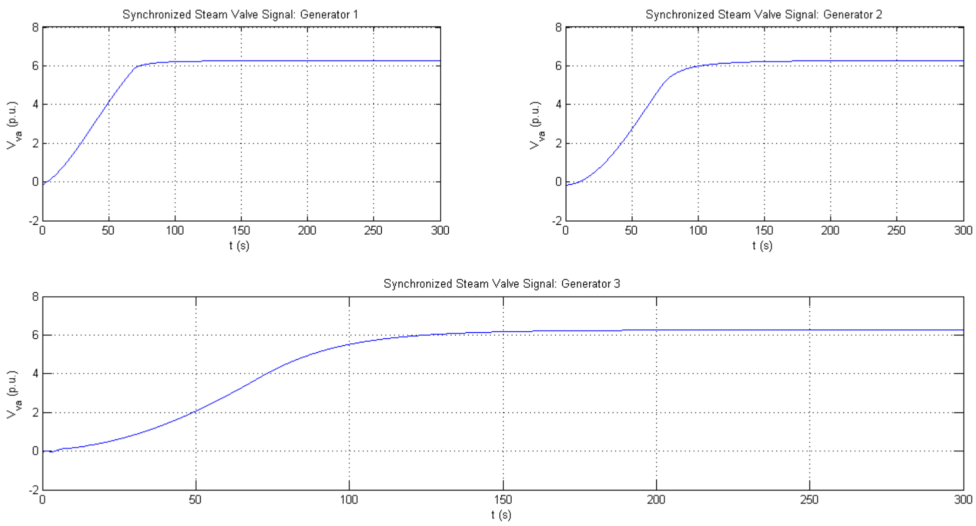



Figure 4-63: The variation of three synchronized generators steam valve signals

**4.5.2: results of case (2) table (4.4), in this case the target is $X_{1r}$ = 70°, $V_{tr}$=10.**

**Table 4.16**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_V$ | 0.2 | Controller Gain V |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 70 | Desired Power Angle(°) |
| $V_{tr}$ | 10 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.16** are shown in **Figures 64 to 70** when the conditions are applied.

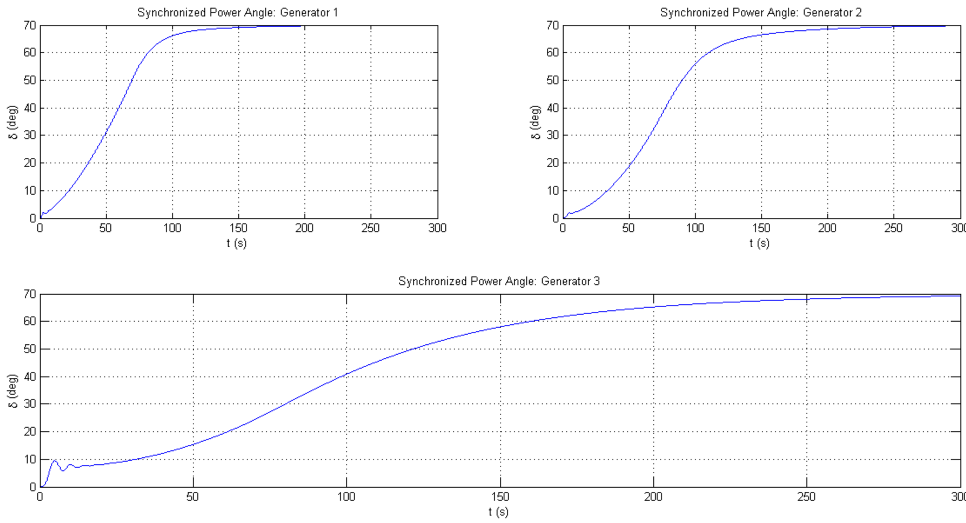



Figure 4-64: The variation of three synchronized generators power angles

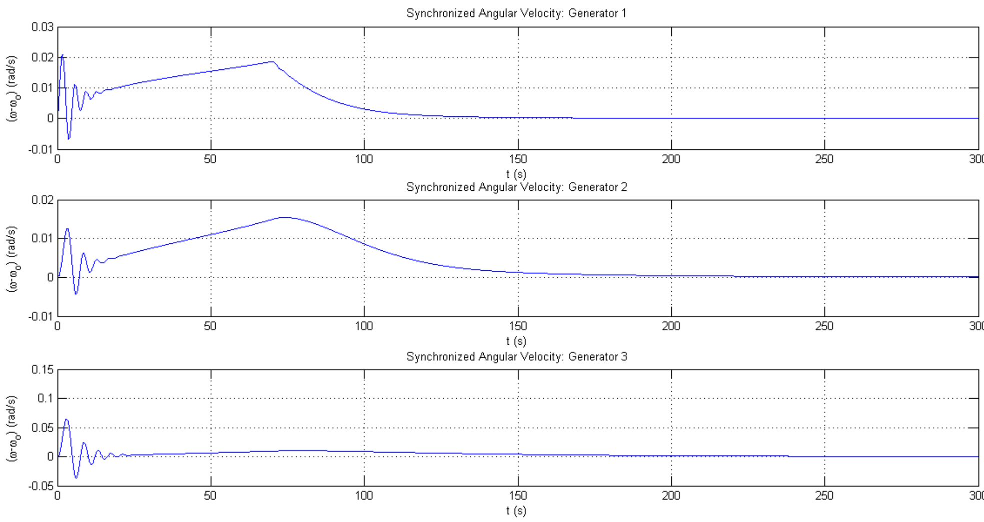



Figure 4-65: The variation of three synchronized generators angular velocity $(\omega - \omega_o)$

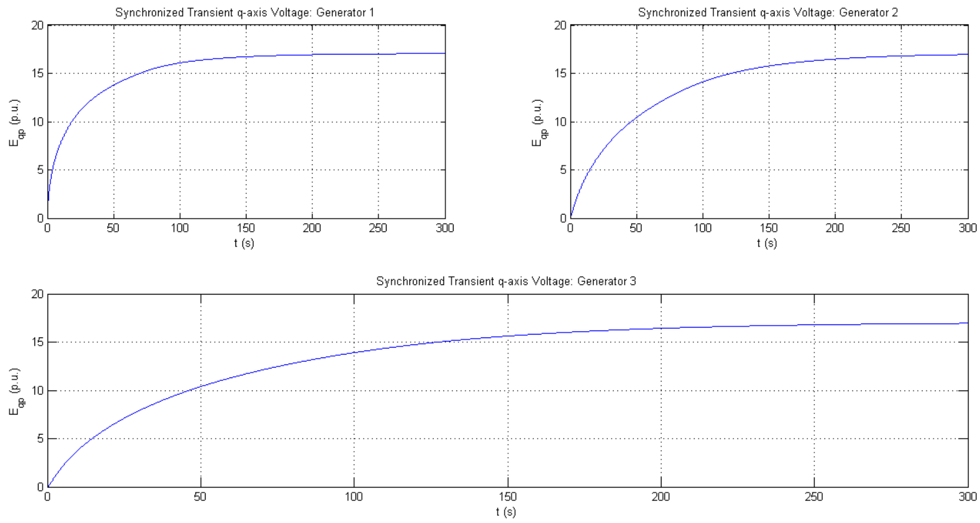



Figure 4-66: The variation of three synchronized generators transitional q-axis voltages

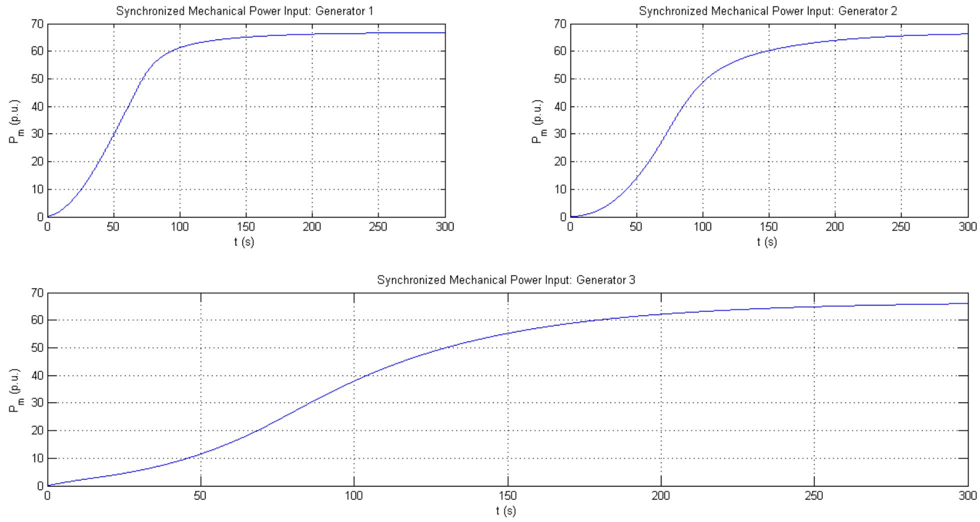



Figure 4-67: The variation of three synchronized generators mechanical power input

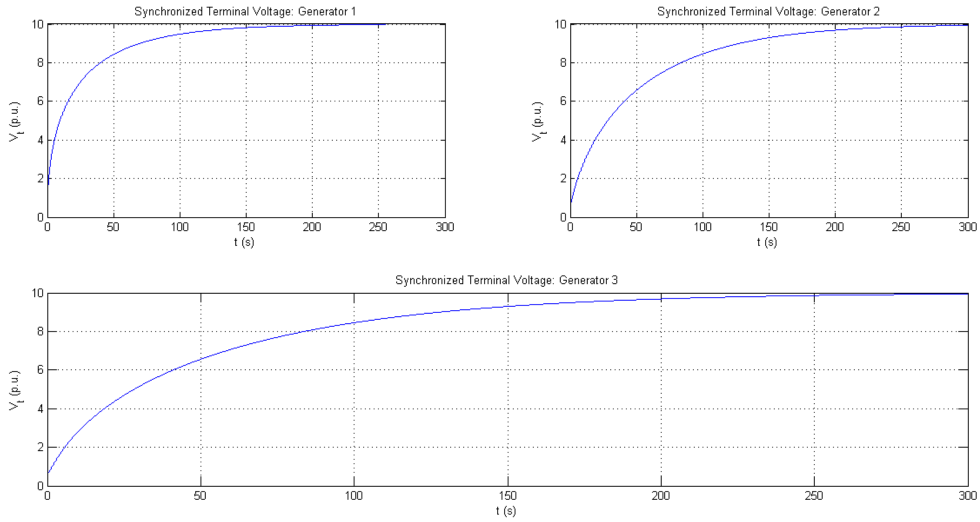



Figure 4-68: The variation of three synchronized generators terminal voltages

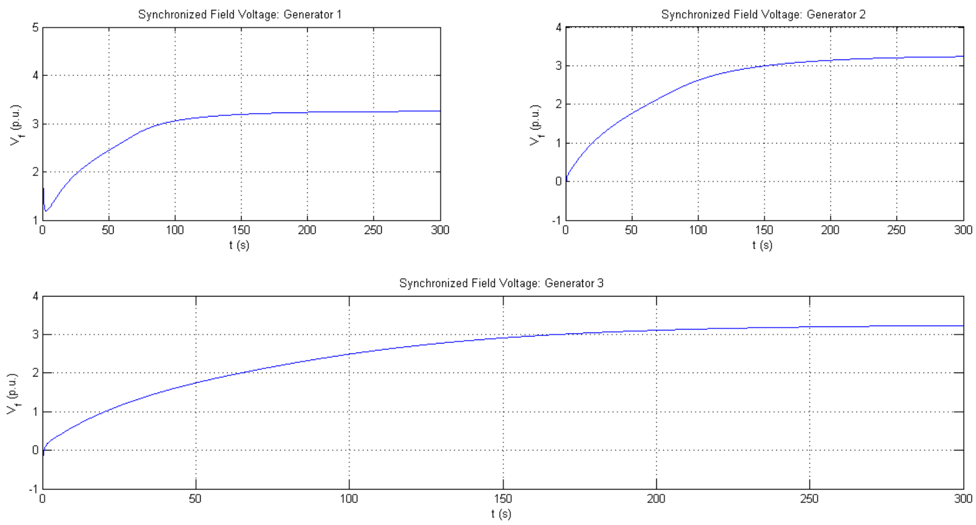



Figure 4-69: The variation of three synchronized generators field excitation voltages

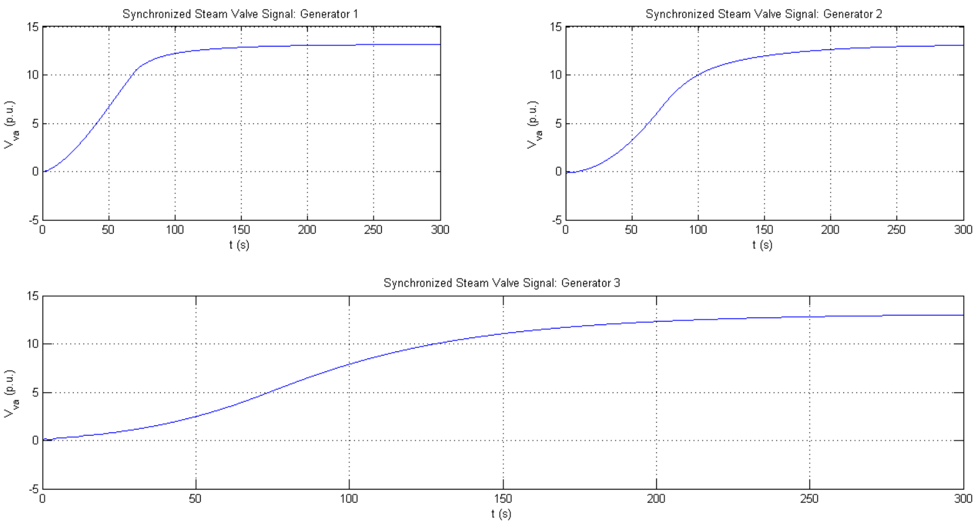



Figure 4-70: The variation of three synchronized generators steam valve signals

**4.5.3: results of case (3) table (4.4), in this case the target is $X_{1r}$ = 80°, $V_{tr}$ = 5.**

**Table 4.17**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_v$ | 0.2 | Controller Gain V |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 80 | Desired Power Angle (°) |
| $V_{tr}$ | 5 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.17** are shown in **Figures 71 to 77** when the conditions are applied.

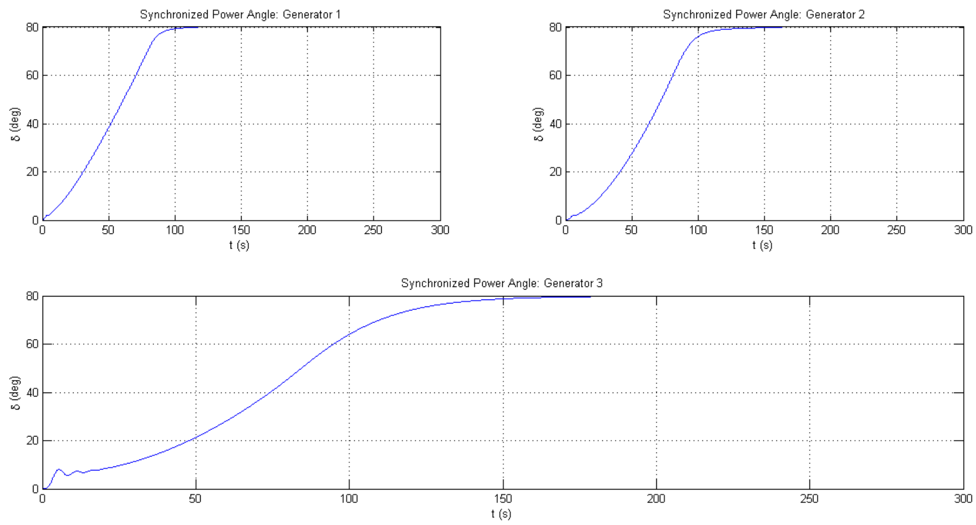



Figure 4-71: The variation of three synchronized generators power angles

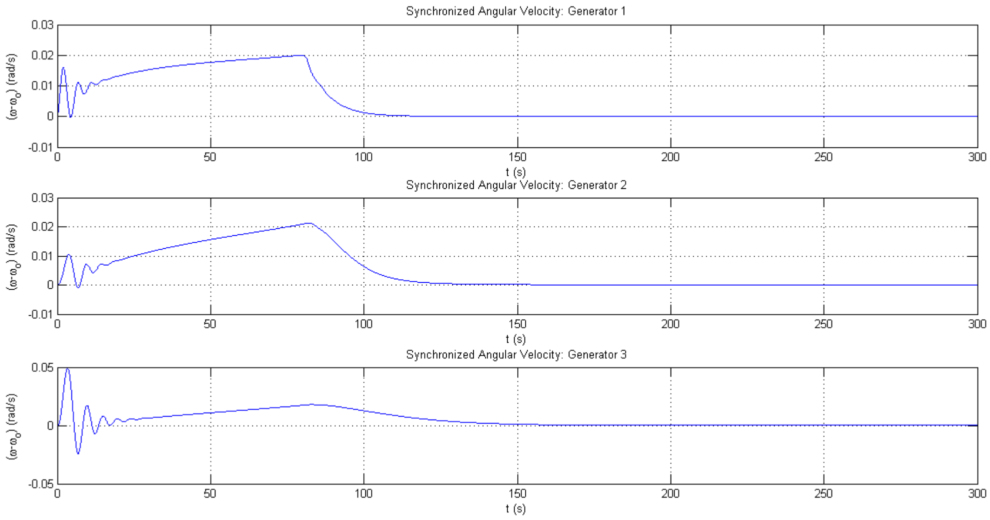



Figure 4-72: The variation of three synchronized generators angular velocity $(\omega - \omega_o)$

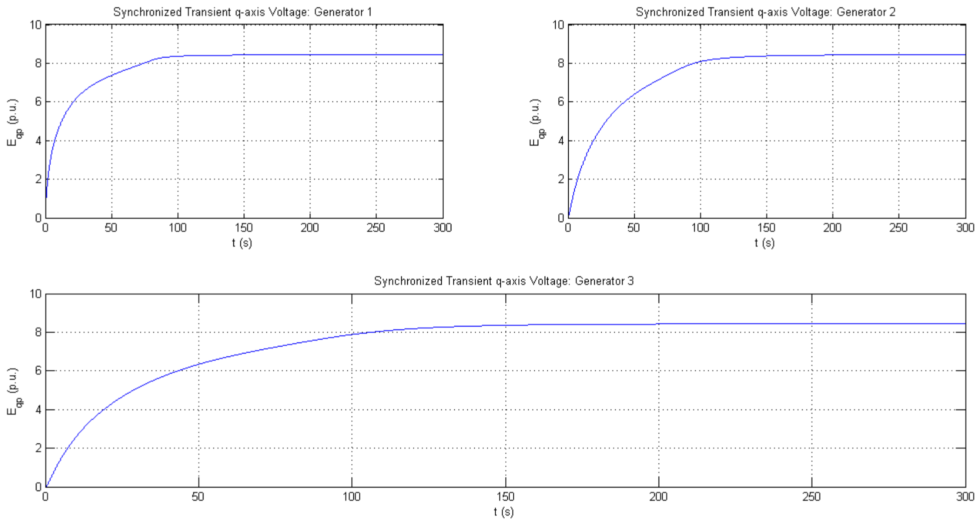



Figure 4-73: The variation of three synchronized generators transitional q-axis voltages

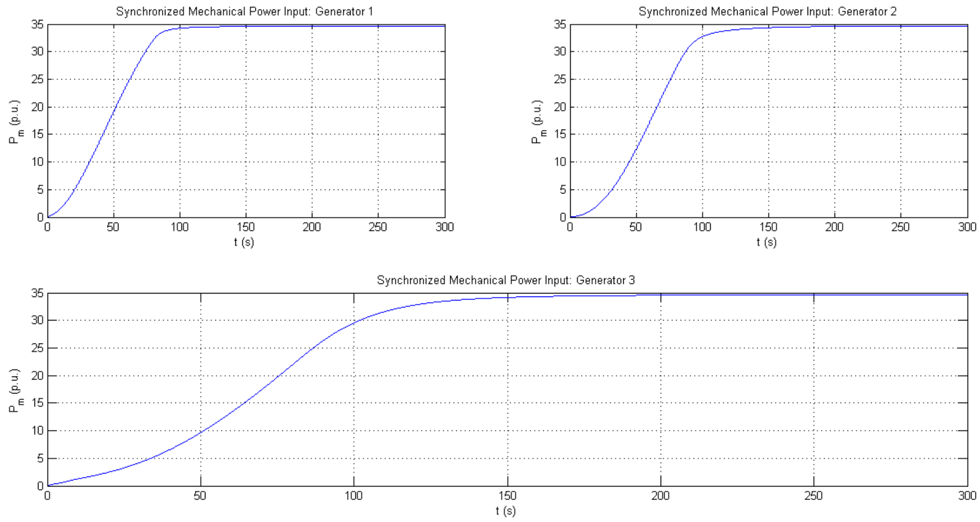



Figure 4-74: The variation of three synchronized generators mechanical power input

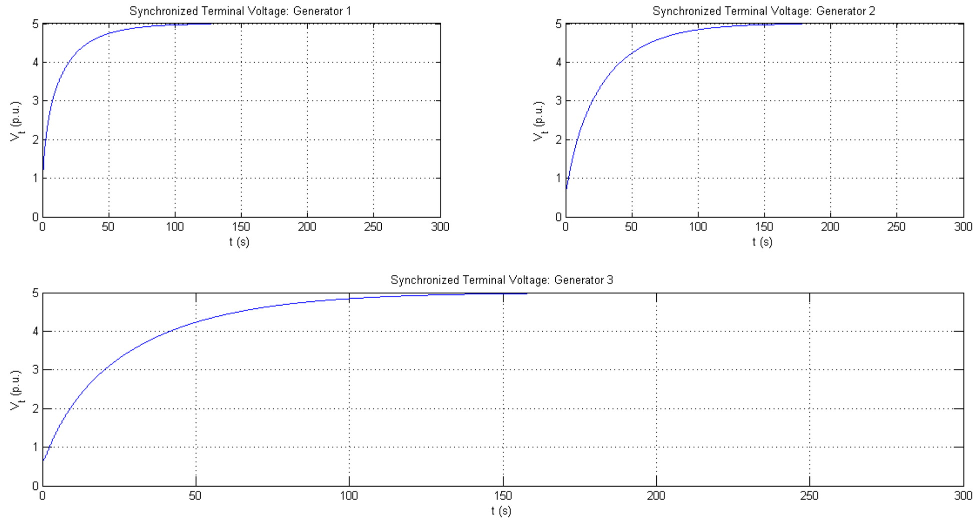



Figure 4-75: The variation of three synchronized generators terminal voltages

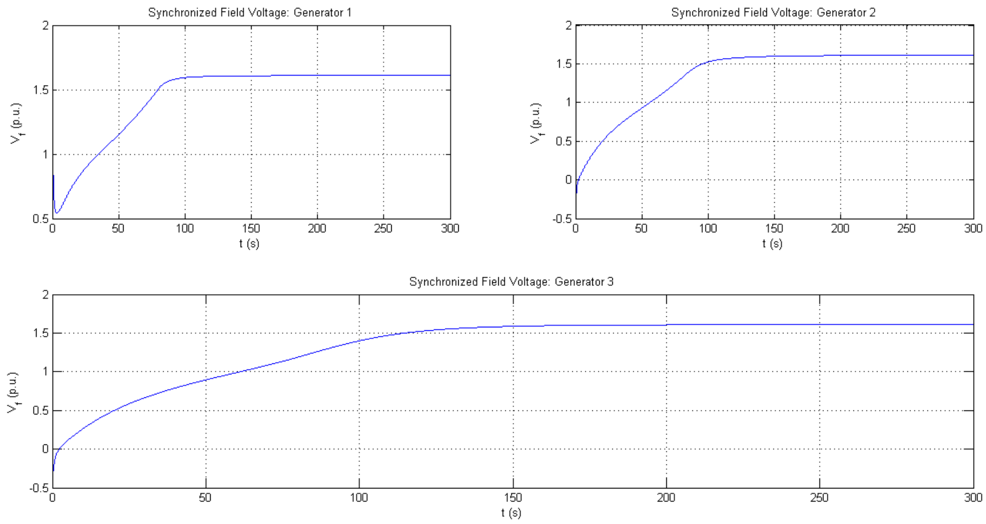



Figure 4-76: The variation of three synchronized generators field excitation voltages

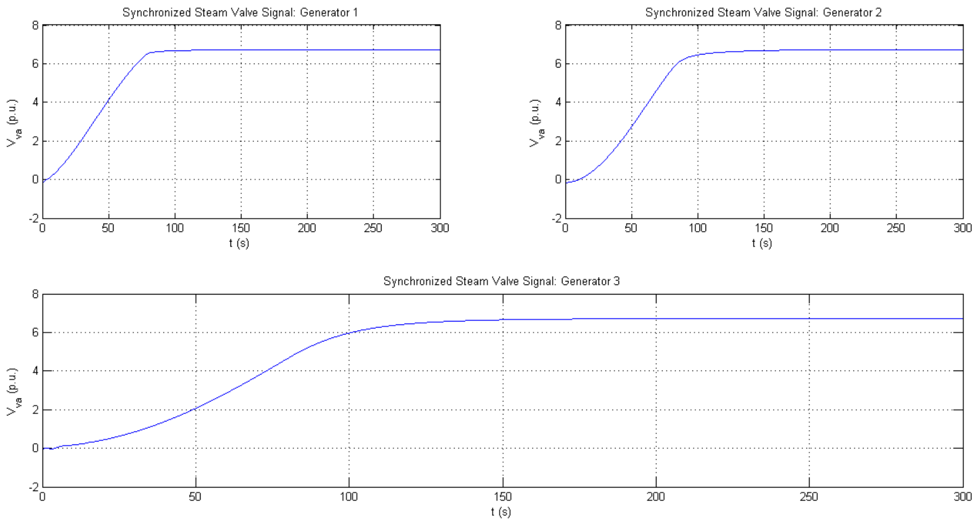



Figure 4-77: The variation of three synchronized generators steam valve signals

**4.5.4: results of case (4) table (4.4), in this case the target is $X_{1r}$ = 80°, $V_{tr}$ = 10.**

**Table 4.18**: Control and simulation parameters for power angle and terminal voltage

| Parameter | Value | Definition |
|---|---|---|
| $k_1$ | 0.5 | Controller Gain 1 |
| $k_2$ | 1 | Controller Gain 2 |
| $k_4$ | 0.2 | Controller Gain 3 |
| $k_V$ | 0.2 | Controller Gain V |
| $T_f$ | 300 | Simulation Time (s) |
| $\delta_r$ | 80 | Desired Power Angle (°) |
| $V_{tr}$ | 10 | Desired Terminal Voltage (p.u.) |

One can see the results of the simulation in this case, according to the parameters in the **Table 4.18** are shown in **Figures 78 to 84** when the conditions are applied.

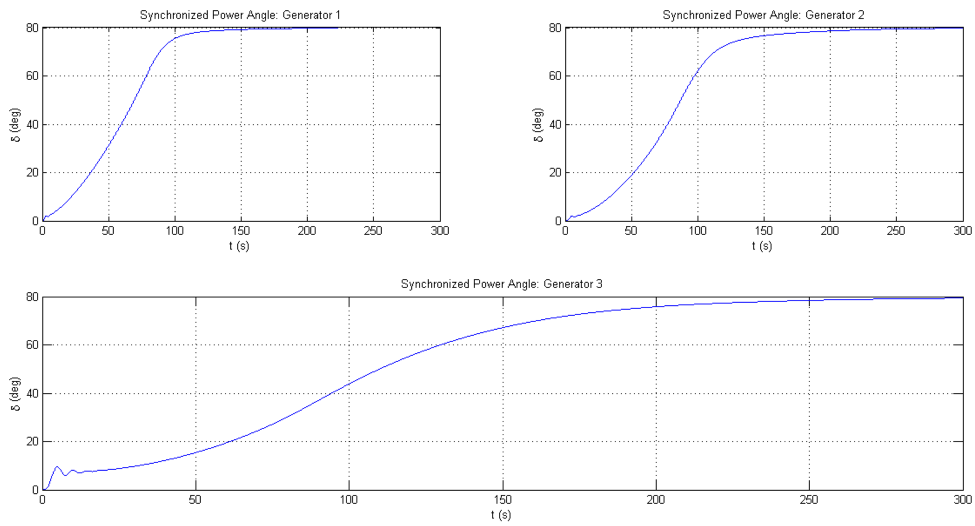



Figure 4-78: The variation of three synchronized generators power angles

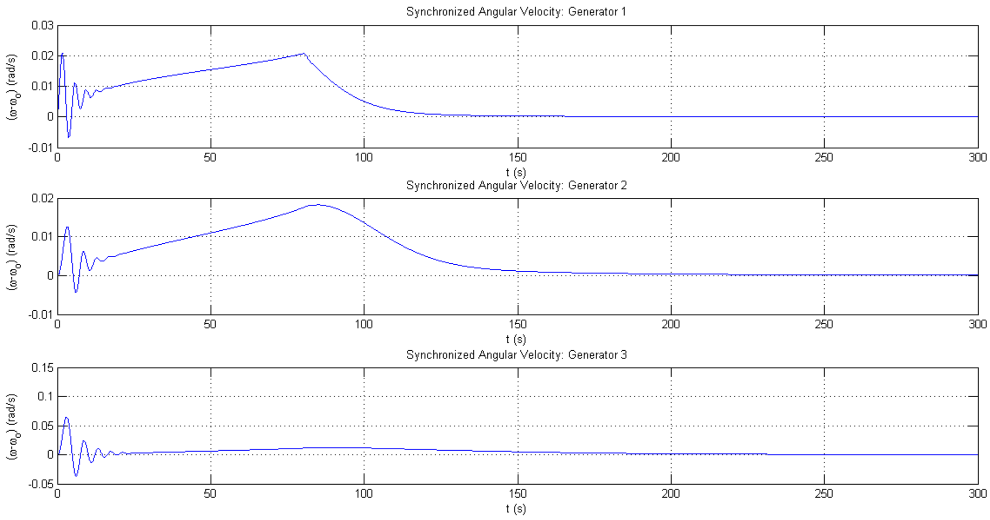



Figure 4-79: The variation of three synchronized generators angular velocity ($\omega - \omega_o$)

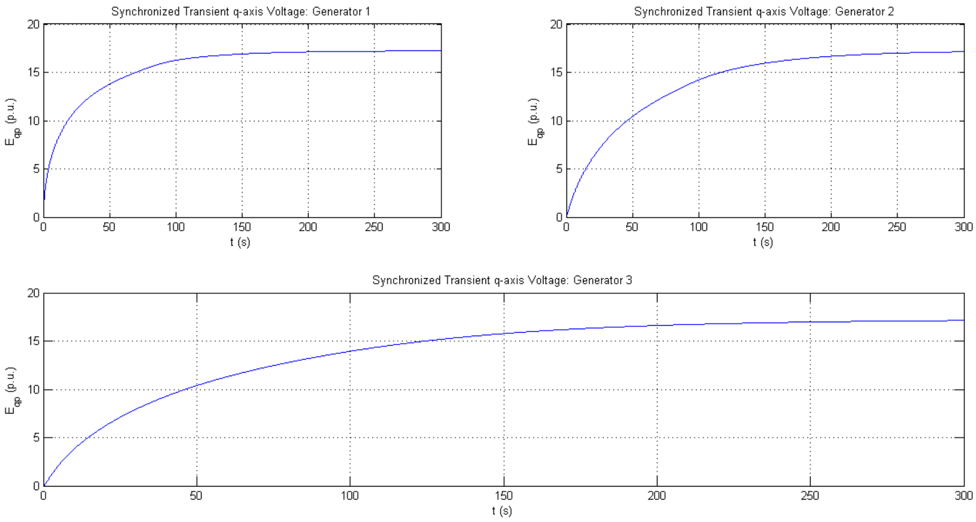



Figure 4-80: The variation of three synchronized generators transitional q-axis voltages

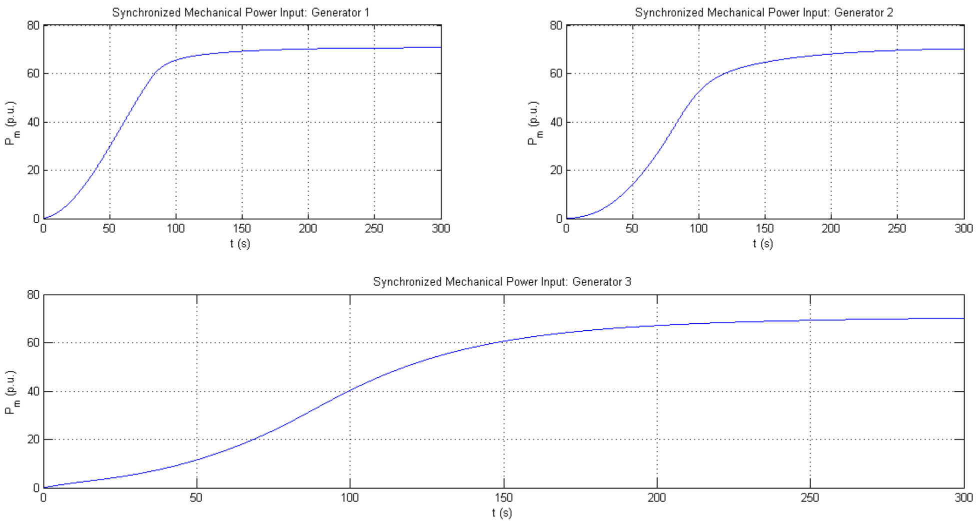



Figure 4-81: The variation of three synchronized generators mechanical power input

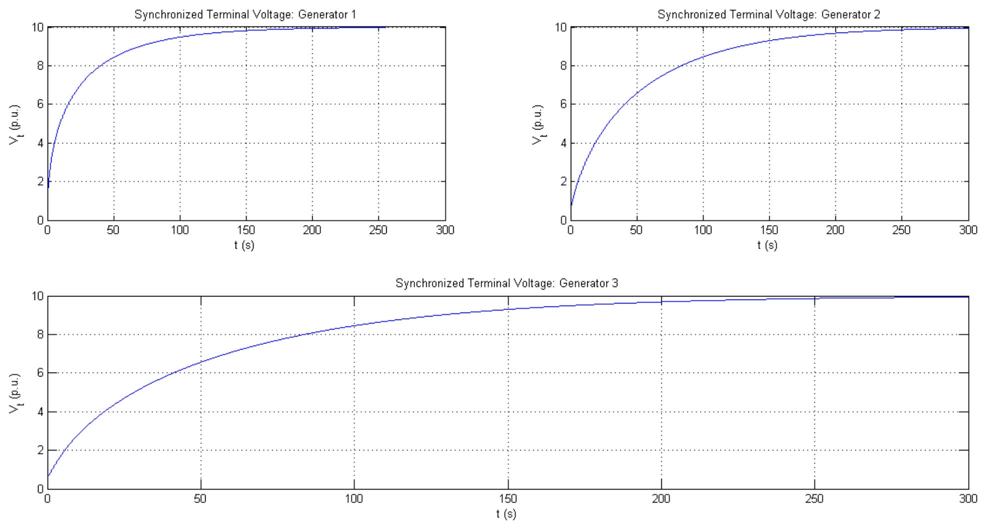



Figure 4-82: The variation of three synchronized generators terminal voltages

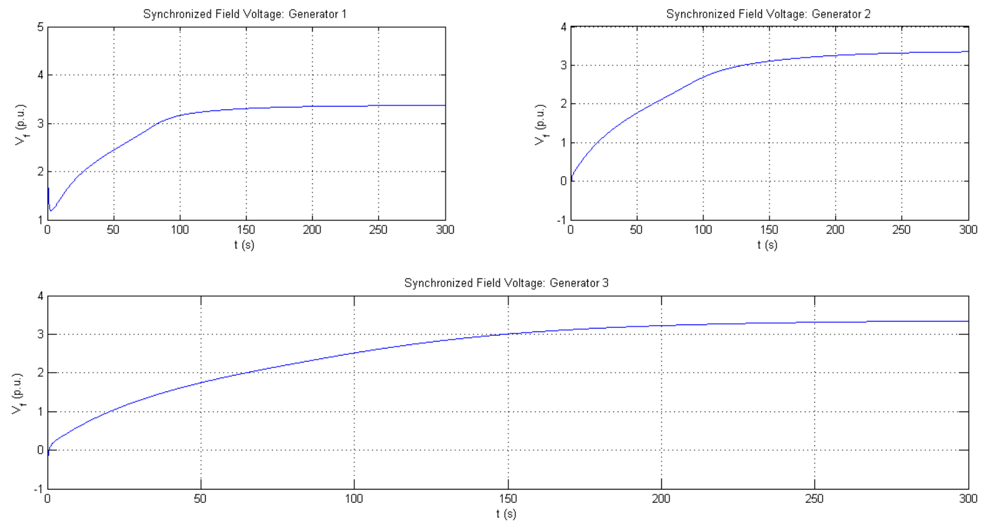



Figure 4-83: The variation of three synchronized generators field excitation voltages

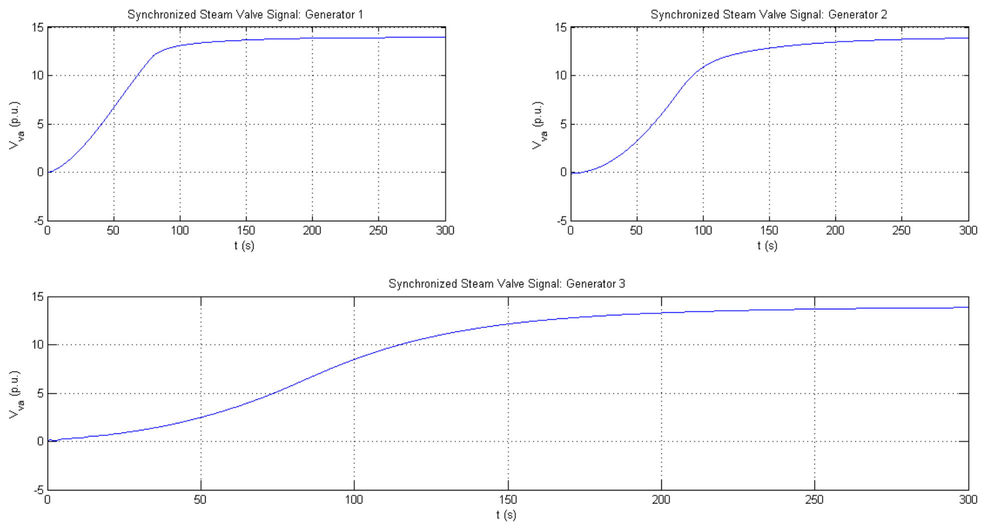



Figure 4-84: The variation of three synchronized generators steam valve signals

The results showed that, in this case, synchronization of the power angles and terminal voltages of the multiple synchronous generators (synchronization of three generators). The generator control laws worked satisfactorily. The synchronization of the generators based on the cascaded strategy. The first generator acted as a controlled “main generator” and the rest follows the power angle and terminal voltage outputs of the main generator. The controller designs are same for all generators and the second and subsequent generators receive the outputs of the first generator as reference. The simulation results did not show an unexpected behavior after the transients, they all converged to the steady states which are equal to the desired values of the power angle and terminal voltages. The power angle and terminal voltage converged to their desired values $X_{1r}$ and $V_{tr}$ without any steady state error for all scenarios in this case (synchronization three generators). The third generator followed the output of the second one and the second generator followed the output of the first one without any steady state errors. So synchronization also works perfectly for power angle and terminal voltage. Similar outcome is obtained from the synchronized control. The other states are also reached an acceptable level of the steady state. Concerning the control point of view, the back-stepping controllers appeared to reach thier goals very well. As an expected fact, the synchronization of multiple generators introduced a small delay. This due to the fact that, the design assumes the power angle and terminal voltage references are constants (or step function). However, the synchronized generators (second and the rest) receives a transient change where the other generators need more time to recover. This issue can partially be solved by increasing the controller gains of the second and subsequent generators. The turbine power controller worked well and handle the mechanical power requests flawlessly. This is understood from the results obtained for different scenarios. So it is expected that the designs work in a realistic environment without any hassles. The control of power angle is more dependent on the mechanical part of the overall system. So $u_2$ (Steam control signal) seems to be more effective. The control of $V_t$ is dependent both on power angle and field voltage. So $u_1$ will be more dependent on the requested $V_t = V_{tr}$ due to mentioned relationship.

The steady state value of the state vriables, inputs and outputs of three synchronized generators.

| Parameters | Definition |
|---|---|
| $x_3$ | Transitional q-axis voltage (first generator) |
| $z_3$ | Transitional q-axis voltage (second generator) |
| $z_{32}$ | Transitional q-axis voltage (third generator) |
| $u_4$ | Mechanical power (first generator) |
| $w_4$ | Mechanical power (second generator) |
| $w_{42}$ | Mechanical power (third generator) |
| $u_1$ | Field excitation voltage (first generator) |
| $w_1$ | Field excitation voltage (second generator) |
| $w_{12}$ | Field excitation voltage (third generator) |
| $u_2$ | Electrical control signal to the steam pressure control valve (first generator) |
| $w_2$ | Electrical control signal to the steam pressure control valve (second generator) |
| $w_{22}$ | Electrical control signal to the steam pressure control valve (third generator) |
| $V_t$ | Generator terminal voltage (over all) (first generator) |
| $Y_t$ | Generator terminal voltage (over all) (second generator) |
| $Y_{t2}$ | Generator terminal voltage (over all) (third generator) |

**Table 4.19** the result for synchronized three generators

| | $x_3$ | $z_3$ | $z_{32}$ | $u_4$ | $w_4$ | $w_{42}$ | $u_1$ | $w_1$ | $w_{12}$ |
|---|---|---|---|---|---|---|---|---|---|
| $X_{1r}$=70°, $V_{tr}$ =5 | 8.2572 | 8.2572 | 8.2572 | 32.3302 | 32.3302 | 32.3302 | 1.4975 | 1.4975 | 1.4975 |
| $X_{1r}$=70°, $V_{tr}$ =10 | 17.0448 | 17.0448 | 17.0448 | 66.7203 | 66.7203 | 66.7203 | 3.2551 | 3.2551 | 3.2551 |
| $X_{1r}$=80°, $V_{tr}$ =5 | 8.4360 | 8.4360 | 8.4360 | 34.6158 | 34.6158 | 34.6158 | 1.6090 | 1.6090 | 1.6090 |
| $X_{1r}$=80°, $V_{tr}$ =10 | 17.2289 | 17.2289 | 17.2289 | 70.6882 | 70.6882 | 70.6882 | 3.3677 | 3.3677 | 3.3677 |

| | $u_2$ | $w_2$ | $w_{22}$ | $V_t$ | $Y_t$ | $Y_{t2}$ |
|---|---|---|---|---|---|---|
| $X_{1r}$=70°, $V_{tr}$=5 | 6.2660 | 6.2660 | 6.2660 | 5.0000 | 5.0000 | 5.0000 |
| $X_{1r}$=70°, $V_{tr}$=10 | 13.1457 | 13.1457 | 13.1457 | 10.0000 | 10.0000 | 10.0000 |
| $X_{1r}$=80°, $V_{tr}$=5 | 6.7232 | 6.7232 | 6.7232 | 5.0000 | 5.0000 | 5.0000 |
| $X_{1r}$=80°, $V_{tr}$=10 | 13.9392 | 13.9392 | 13.9392 | 10.0000 | 10.0000 | 10.0000 |

# CHAPTER FIVE
# CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

## 5.1 Conclusions

In this research, the theoretical and simulation based study on control of synchronous AC generators with steam valve and field excitation controls system is presented. The control approach is based on integrator back-stepping techniques. The application of theory is performed in two cases. The first one is the combined control of power angle and terminal voltage of the single generator. The second one is the synchronization of the power angles and terminal voltages of the multiple synchronous generators (synchronization of two generators or more). The synchronization of the generators based on the cascaded strategy. The first generator acted as a controlled “main generator” and the rest follows the power angle and terminal voltage outputs of the main generator. The controller designs are same for all generators and the second and subsequent generators receive the outputs of the first generator as reference. The simulation results did not show an unexpected behavior after the transients, they all converged to the steady states which are equal to the desired values of the power angle and terminal voltages. Similar outcome is obtained from the synchronized control. The other states are also reached an acceptable level of the steady state. Concerning the control point of view, the back-stepping controllers appeared to reach thier goals very well. As an expected fact, the synchronization of multiple generators introduced a small delay. This due to the fact that, the design assumes the power angle and terminal voltage references are constants (or step function). However, the synchronized generators (second and the rest) receives a transient change where the other generators need more time to recover. This issue can partially be solved by increasing the controller gains of the second and subsequent generators. One drawback of this adjustment is an increase in the levels of the control inputs (steam valve control signal and field voltage). The actuators of the turbine and the field winding should be able to withstand those levels. In this study, there is one more controller which regulates the turbine power output. The turbine power controller worked well and handle the mechanical power requests flawlessly. This is understood from the results obtained for different scenarios. So it is expected that the designs work in a realistic environment without any hassles. And this system can be used in practice in the power station, the regulation of the voltage generated by the synchronous generator can be performed automatically.

### 5.2 Suggestions for future work

This section describes possible future suggestions and developments on the existing simulation model and controllers. Though a successful research is completed, there still are some issues not addressed. One can summarize them as shown below:

1. The Robustness of the closed loop generator controllers can be also discussed.

2. The model has noise inputs. The stability of close loop generator control system against these exogenous noises and disturbances can be assessed by using the input-to-state stability concept which can be applied by treating the external noises or disturbances as inputs to the closed loop.

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