NONLINEAR CONTROLLER DESIGN FOR POWER SYSTEMS SYNCHRONOUS GENERATOR

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

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Prof.Dr.Ali Kara

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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 “nonlınear controller desıgn for power systems synchronous generator” submitted by “Mohammed Shakir Al-akam” 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

NONLINEAR CONTROLLER DESIGN FOR POWER SYSTEMS SYNCHRONOUS GENERATOR

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This thesis reviews the control of synchrounous generetor connected to infinite bus in small electrical power system grid and introduces input-output feedback linearization in detail as a method in order to control the load angle (δ) and the terminal voltage (Vt) of synchrounous generetor. Involving simulation design, the application of the input-output feedback linearization method on our system was verified. The results approved that the algorithm works satisfactory.

Keywords: Power angle,Terminal voltage ,synchrounous generetor control, Input-output feedback linearization method

ÖZ

GÜÇ SİSTEMLERİ İÇİN DOĞRUSAL OLMAYAN SENKRON JENARATÖR DENETLEYİCİSİ TASARIMI

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Bu çalışma sonsuz bara bağlı ve küçük bir elektrik şebekesine bağlı senkron bir jenaratörün denetimi üzerinde durulacaktır. Bu noktada girdiden çıktıya geri beslemeye dayalı doğrusallaştırma yaklaşımı ile sistemler doğrusallaştırılmakta olup yük açısı ve sonuç voltajının denetimi yapılmaktadır. Yapılan çalışmaların performansı benzetimler yoluyla doğrulanmaktadır. Sonuçlar algoritmanın başarılı olduğunu göstermektedir.

Anahtar Kelimeler: Yük açısı, sonuç voltajı, senkron jenaratör denetimi, girdi-çıktı doğrusallaştırması

TO LIVES OF IRAQI MARTYRS

TO MY PARENTS

TO MY GREAT WIFE

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I express sincere appreciation to my supervisor **Assoc.Prof. Dr. Reşat Özgür DORUK** for his guidance and insight throughout the research.. To my parents and my great wife, SABA, I offer sincere thanks for their continuous support and patience during this diffeculit period. And also, offer sincere thanks to my best friend Mohammed Abdal hussen for his great support.

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CHAPTER ONE

INTRODUCTION

1.1 Introduction

In the world today the energy generation stations used mainly the synchronous generators which are responsible for generating huge electrical energy. When these generators connected to electrical grid or infinite bus the terminal voltages for these generators should be fixed at a constant value for all generator connected to the same grid or same infinite bus as well the load angle. However, there are two main studies in generator control systems the first one is a control system which is regulating the terminal voltage of generator and the second one is a control system which is regulating the speed of governor which provide mechanical energy to synchronous generator.

Both of these studies of control systems share the contribution of synchronous generator stability during any disturbance happens in electrical grid or governor perturbation in order to establish a reliable and integrated control system for generators connected to electrical grid. Therefore, trustworthy control systems sets is important to have stable and safe generators operation where these generators are integrated to stable whole electrical grid. There are various techniques to control a synchronous generator and suitability will depend on the type of generator and the conditions of operation [1].

Synchronous generators [2] which are driven by a gas or steam turbine or by a hydro power are type of alternating current voltage generating devices. Regardless of the type there should always be a prime mover or mechanical energy source to supply the necessary rotational energy to the generator.

The angular velocity for generator determines the frequency of the generated AC voltage. Thus, as explained in [3] we can control the excitation of the field voltage in order to increase generator control system efficiency that means to increase the plant's control inputs. More increasing the number of control inputs will allow more variables that can be steered properly.

However, to design a controller for such a plant (Synchronous generator connect to electrical grid via electrical power transformer and transmission line) firstly we should consider the dynamical model of the plant. These dynamics are generally nonlinear models characterize shaft angular velocity, generator voltages for both q-axis and d-axis, generator terminal and field voltages and the variation of mechanical power. They generally involve certain inductance parameters such as transformer reactance, transmission line reactance, q-axis and d-axis reactance.

On such models linear controllers are suitable for instance Proportional – integral – derivative approach but this will require the linearization of the dynamics of the plant (namely the synchronous generator).

Such hypothesis engage the load angle (δ) in order to simplify the dynamics of generator due to fixation of some state variables. Such assumption will make controller design easier but the difficult work conditions may be an issue due to the deviation from linearization conditions.

There are a lot of studies involve advanced methods such as adaptive controller [4], passivity based approach [5], neural networks [6] and other approaches [7, 8] these various method are expected to give the model good performance without any approximation on the model. Naturally, the noise of sensor and the limits of actuation are always presented but are out of the main topic of this research.

In this research will design two nonlinear controllers. The first one will be a unique implementation of PID controller which is proportional-derivative-second derivative (PDD2) type of controller in order to stabilize the load angle because of the high order integrative action of the linearized model. These controllers can be easily realized using either simple analog circuits or digital controllers and they are still preferred in commercial applications today as explain in [9].

The second controller used is only a Proportional controller for low order linearized model to stabilize the terminal voltage of generator.

We will use input–output feedback linearization method [10.] on the nonlinear synchronous generator model dynamics and establish a relation between inputs which are the electrical signal to steam valve and field voltage and outputs which are load angle (δ) and terminal voltage. Then compare between the nonlinear model and the fully linearized transfer function to study the influence of linearization if there are any effects of removing the nonlinear parts from the original model.

Finally, in this research stability of both controllers (terminal voltage controller and load angle controller) are also ensured through closed loop designs on the linear models obtained from input-output feedback linearization technique. Furthermore, we will demonstrate the overall performance of these controllers using MATLAB simulation of the developed approaches here.

The (PDD2) controller will be implemented in two ways. The first one uses direct differentiation using the derivative blocks in Simulink software. The second one on the other hand, implements each single derivative factor by a high-pass filter. This is also the approach implemented in the PID blocks of Simulink. However, we have to utilize it for (PDD2) controller which is not available as a specific block in Simulink library. The latter approach is recommended as derivative blocks are vulnerable to noise presence.

1.2 Objective of Our Work

The main goals of the present work is to design nonlinear control laws in order to maintain the terminal voltage of a synchronous generator at a specified level with respect to its stabilized value of load angle (δ).

1.3 Thesis Structure

The thesis is organized as follows:

Chapter One:

This chapter presents an introduction to the problem, Objectives of the work and thesis structure.

Chapter Two:

In this chapter will presented the literature review and historical perspective for synchronous generator control which uses different technique and methods in order to stabilize and control the load angle (δ) and terminal voltage for synchronous generator.

Chapter Three:

This chapter will focus on the mathematical framework that will used in this thesis. That framework includes introduction to theoretical control background, recursive control design overview, generic nonlinear system and input –output feedback linearization method.

Chapter Four:

In this chapter the mathematical calculations and control laws estimation will be presented. In addition, mathematical models will also be presented which includes the application of input output feedback linearization and relative degree concepts to the small synchronous generator model.

In addition, formulas needed in simulation will be developed for synchronous generator controllers using (PDD2) controller.

Chapter Five:

In this chapter we will present the simulation of the fully linearized system which is established by input-output feedback linearization using PDD2 and Proportional controllers. Possible effects that are likely to be seen due to the implementation of the (PDD2) controller will also be discussed.

Chapter Six:

Provide conclusions with the suggestions of possible future work

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Many methods (linear and nonlinear) have been suggested to evaluate and ensure power systems stability. There are a broad range of techniques to maintain the stability of synchronous generator connected to an infinite bus [11, 12]. Infinite bus assumption is a standard approach in the modeling of synchronous generators to be used in energy sector.

Stability of such a device can be maintained either by linear or nonlinear controllers. In order to design such controllers, it is crucial for the design to measure all or some of the state variables that define the physical state of the generator.

The difficulties related with unmeasured states which can be solved through different processes and methods used by researchers will be presented in this chapter in order to achieve better terminal voltage and load angle regulation with high stable system operation.

2.2 Historical Perspective For Synchronous Generator Control

In order to realize a good regulation of generator load angle and terminal voltage of the generator, a variety of control structures has been proposed in the last years especially in the field of automatic synchronous generator regulation for which synchronous generators play an essential role in power system stability.

Thus among these controller structures a reduced-order observer-based variable structure controller is proposed in [13]. In [14] a graphical observer design is presented aiming at monitoring of fault detection for large scale electrical power systems. It involves state estimation but the different thing in [14] is to identify new input to attain the goals of monitoring which is difficult for real systems.

Some methods aiming at power system stability are suggested in [15]. Here a high voltage bus which is considered as a reference bus that is different from various works that involve infinite bus connection. Also, all the power system state variables are achieved from the local measurements.

In [16], the calculation of the controller gains are performed in such a way that the controller can handle the influence of unmodelled power systems dynamics. A minimax LQG controller is suggested in [17] where it used the mean-value theorem in order to linearize the model of power system with dynamic load.

So far, It is well known that the power systems are nonlinear in nature [18, 19] and should be transformed into a fully linearized system using different strategies such as exact linearization [20, 21]. The exact linearization of a nonlinear system rely on the system relative degree which rely on the selection of system output function [20] (this is restricted by the design and aims).

Therefore, if nonlinear system output function is chosen in such a way that system relative degree equals to the system order, the system will be fully linearized [20]. If a nonlinear system converted to fully linearized, the linear control techniques can be used to develop a nonlinear control approach [23].

However, from the viewpoint of stability of power system dynamics, it is crucial to provide a device which is responsible for maintaining the synchronism of generators with a supplementary damping controller in order to alleviate the power system oscillations.

There are classical controllers such as Proportional–Integral–Derivative (PID), Proportional–Integral (PI) and other types have been employed in these devices as supplementary damping controller [25, 26]. But in [27] Proportional-Double Derivative (PDD2) controller was selected in order to promote all scale of transient stability improvement, including: little undershoot, little overshoot and little settling time.

Also derivative and second derivative terms (PDD2) are still favored in commercial applications today [30]. So, one of the successful study for (PDD2) in commercial sector is a study that implemented the same (PDD2) controller for ship stabilization which is by Kula [29]. In that work, a (PDD2) controller was used in stabilization of roll dynamics with an additional loop consisting of feedback of lift force in order to determine roll angle and velocity.

Nowadays, many applications as well as power systems using filters such as a high pass filter in Static Var Compensators (SVC) controls the high-side bus voltage to establish a specified level of V_{ref} as explained in [24].

But in our research will use a derivative filter to implement the derivative action in second order controller which this implementation provide a significant improvement of the controller performance especially for load angle of synchronous generator for the same reasons explain in [28].

Derivatives are implemented using finite differences in digital computers. However due to noise accumulation direct differentiation of signals are not recommended. As a result a band limited version which can be implemented as a high-pass-filter is suggested in [29]. We will utilize a similar implementation which is known to be used in PID controller blocks of MATLAB/Simulink.

CHAPTER THREE

THEORITICAL BACKGROUND

3.1 Introduction

This chapter will focus on the theoretical background behind the control approaches in this research. Input output feedback linearization and other theories are found in a form suited for tracking control which is an approach in nonlinear control design.

- The main idea of the approach is to algebraically transform the dynamics of nonlinear system into a fully or partly linear system so that one can apply a linear control method.

- This differs completely from conventional linearization (such as Jacobean linearization) in that the feedback generates a linear model without the need of a linear approximation of the dynamics.

- Feedback linearization method could be viewed as a way of converting the original system model into a simpler and equivalent model [31].

3.2 Input- Output Feedback Linearization

Generally, most of practical, dynamic systems are nonlinear. The traditional method in control system design, is to linearize the main system at one of its equilibrium points, in order to get its linearized mathematical model, which is in a form of a set linear state equations or a form of transfer function; after that the system can be analyzed according to the methods and technique of linear control theory [34].

One of the important methods used to linearize nonlinear systems into a linear ones is input-output linearization which is based on differentiate the output function (y) of the system repeatedly until the input (u) appears, after that design (u) in order to eliminate the nonlinearity[35]. In other word, the input-output linearization technique is based on the transformation of the nonlinear system into an equivalent linear system through a change of variables and an appropriately designed control law.

To illustrate the methodology, let consider the single-input-single-output system:

$$\dot{x} = f(x) + g(x)\,u \tag{3.1}$$

$$y = h(x) \tag{3.2}$$

Where *f*, *g*, and *h*are sufficiently smooth in a domain$D \subset R^n$.

The mappings$f: D \rightarrow\subset R^n$. And$g: D \rightarrow\subset R^n$are called vector fields on D.

At this point, one can differentiate the output of the system (y) constantly until the input (u) appears, and after that we will try to resolve u in order to omit the nonlinearity effect of the system.

The derivative is given by$\dot{y}$:-

$$\dot{y} = \frac{\partial h}{\partial x}[f(x) + g(x)u] = \frac{\partial h}{\partial x}f(x) + \frac{\partial h}{\partial x}g(x)u$$

$$= L_f h(x) += L_g h(x)u \tag{3.3}$$

Where

$\frac{\partial h}{\partial x}f(x) = L_f h(x)$is called Lie derivative of h with respect to f

And $\frac{\partial h}{\partial x}g(x) = L_g h(x)$is called Lie derivative of h with respect to g

If $L_g h(x)$= 0, then $\dot{y}$ =$L_f h(x)$, independent of u. Now, one can continue repeating the differentiation process and find the second derivative for (y) we get:-

$$\ddot{y} = \frac{\partial(L_f h)}{\partial x}[f(x) + g(x)u]$$

$$= L_f^2 h(x) + L_g L_f h(x)\,u \tag{3.4}$$

And again if $L_g L_f h(x) = 0$ then $\ddot{y} = L_f^2 h(x)$ independent from u, repeat this derivation process until $h(x)$ satisfies the below condition:-

$$L_g L_f^{r-1} h(x) = 0 \quad , i = 1,2,3 \dots\dots, r-1$$

$$L_g L_f^{r-1} h(x) \neq 0$$

Therefore, the input u does not appear in the previous expressions $y, \dot{y}, \ddot{y}, \ldots \ldots, y^{r-1}$ and appear in the following expression

$$y^{(r)} = L_f^r h(x) + L_g L_f^{r-1} h(x)\, u \tag{3.5}$$

So, from the above equation can find a control law that will linearize the nonlinear system in eq (3.1) which is equal to:-

$$y^{(r)} = u = \frac{1}{L_g L_f^{r-1} h(x)} \left(-L_f^r h(x) + V_{ctrl}\right) \tag{3.6}$$

So that:

$$y^{(r)} = V_{ctrl}$$

Which is a chain of r integrators. In this case, the integer r is called the ***relative degree*** of the system.

Relative degree is an important concept in nonlinear control theory. In linear systems relative degree can be interpreted as the difference between the number of poles (degree of denominator) and zeros (degree of numerator) of the transfer function of the considered system respectively.

But when r=n, the system is of full relative degree and there will be no remaining dynamics. On the other hand, if r <n, there will be a remaining dynamics and we have no control over it (the order of this remaining dynamics will be n-r). Having a full relative degree nonlinear system is best case concerning input/output linearization as we will have no uncontrolled dynamics which may or may not be stable (which may be detrimental to physical systems).

The discussion so far is concentrated on single-input/single-output (SISO) nonlinear systems. In a multi-input/multi-output (MIMO) systems, each output should be taken separately into consideration and in order to get the relative degree of a MIMO system we should sum up the relative degrees of each individual output to find the total relative degree of the system.

3.3 Nonlinear Coordinate Transformation for Fully Linearized System

In order to form a fully linearized system pick up the original state vector x and transform it into a new state vector z through a coordinate transformation by choosing:-

$$z_1 = h(x) = L_f^{1-1} h(x) \tag{3.7}$$

After that we can write

$$\dot{z}_1 = \frac{\partial h(x)}{\partial x} \dot{x}$$

But we have ($\dot{x} = f(x) + g(x)\, u$) so substituting in the above equation we get:-

$$\dot{z}_1 = \frac{\partial h(x)}{\partial x} \big(f(x) + g(x)\, u\big)$$

$$\dot{z}_1 = \frac{\partial h(x)}{\partial x} f(x) + \frac{\partial h(x)}{\partial x} g(x)\, u$$

$$\dot{z}_1 = L_f h(x) + L_g L_f^{1-1} h(x) u \tag{3.8}$$

As we know$L_g L_f^{1-1} h(x) = 0$, so, the above can be written as shown below:-

$$\dot{z}_1 = L_f^{2-1} h(x) = z_2$$

Therefore

$$\dot{z}_1 = z_2 = L_f^{2-1} h(x)$$

$$\dot{z}_2 = z_3 = L_f^{3-1} h(x)$$

.

.

$$\dot{z}_{n-1} = z_n = L_f^{n-1} h(x)$$

$$\dot{z}_n = V_{ctrl} = L_f^n h\big(\phi^{-1}(z)\big) + L_g L_f^{n-1} h(\phi^{-1}(z))\, u \tag{3.9}$$

Now our fully linearized system with z- coordinates can be written as shown below:

$$\dot{z} = Az + BV_{ctrl} \tag{3.10}$$

Where

$$A = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \\ 0 & 0 & 0 & \cdots & 0 \end{bmatrix}$$

$$B = [0 \quad 0 \quad \dots \quad 1]^T$$

And V_{ctrl} is the control input for our linearized system. This input will be driven by the linear control system designed using equation no. (3.10) as a plant.

3.4 Control System Steady State and Transient State Response

In order to do a time response analysis and design a controller for any system we should know a basic terms which are illustrated below that terms help us to analyses our control system and its behavior. In addition, system behavior could be tested by applying standard signals as an input, these signals such as unit step, ramp and other signals but here in our research used a unit step.

Applying a unit step signal will help us to have detail information on our plant behavior and also, analyze certain characteristics of the closed loop control system using results from linear system analysis. Thus, we will first review the fundamental concepts such as *Transient and Steady State Responses of a Control System*.

Transient response characteristics can be classified as delay time, rise time, peak time, settling time and maximum percent overshoot as shown in figure (3.1). Steady state response is best viewed by analyzing the steady state error. One can see the respective definitions below. The definitions are given according to the standard second order system model:

$$\frac{Y(s)}{u(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{3.11}$$

Delay Time (t_d): It is the time required by the system response to reach (50%) of the final value for the first time.

Rise Time (t_r): There are two definitions for the rise time according the value of (ζ) $is\ damping\ ratio$:-

1-The first case is when the systems are under-damped or the value of $\zeta < 1$, In this case, rise time is defined as the time required by the response to reach from (0) to (100%) value of final value first time.

2-The second case is when the systems are over-damped or the value of $\zeta > 1$, In this case rise time is the time required by the system response to reach from (10%) value to(90%) value of final value.

Peak Time (t_p): The time required by the system response to reach the maximum value for the first time.

Settling Time (t_s): The time required by the response to reach a band within the specified range of about (2% to 5%) of its final value for the first time.

Maximum Percent Overshoot (M_p): It can be defined as the percentage of the deviation of the response from steady state value at the peak time (highest value of the response).

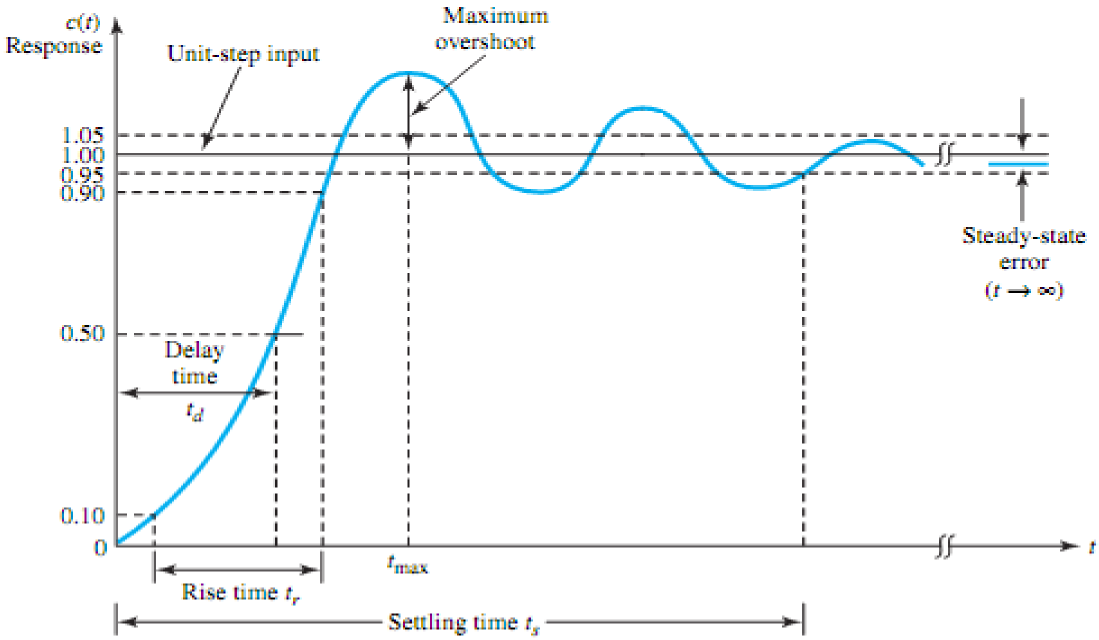


Figure (3.1) transient response characteristics for second order systems

Steady State Error: It is the difference between the actual output and the desired output as time goes to infinity.

3.5.1 Controller Design

As mention [32] not less than 95% of the control loops are of Proportional + Integral + Derivative (PID) type, a considerable number of loops utilize proportional + integral (PI) subtype.

PID controllers may be found in all areas where an automatic control action is needed [32]. Regardless of being PID or another type, controllers are often implemented in the feedback form shown in Figure 3-2.

First of all, we should understand the operation and the construction of PID controller and how can we use it in a system to get the desired output and after that choose the suitable type of controller to achieve our goals.

But as explain in [46] proportional-integral-derivative (PID) involves the risk of overshoots in some cases and also if have a high order equation in transfer function denominator we should use novel of (PID) PDD2 to eliminate the effect of integrators.

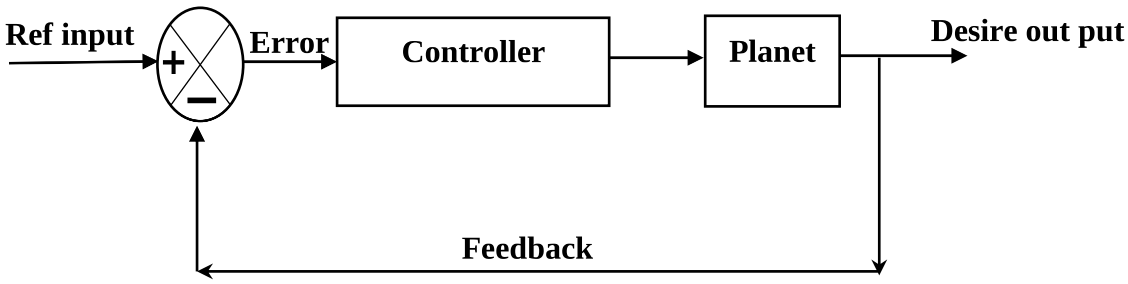


Figure 3.2 Controller operation

3.5.2 Details of the PID Controller

A general PID controller with three gain parameters can be shown by the following transfer function:-

$$Kp + \frac{KI}{S} + Kd\,S = \frac{Kd\,S^2 + Kp\,S + KI}{S}$$

The gains are:

Kp= Proportional gain KI = Integral gain Kd = Derivative gain

From figure (3.1). The error represents, the difference between the reference value (input) and the corresponding desired output .This error signal will change to give the desirable output according to the controller constants (Kp ,KI and Kd).

And each constant has an effect on controller performance and also system behavior. So, in the next section will see this effects on controller characteristics.

3.5.3 Controller Characteristics

- A proportional action due to (Kp) minimize the effect of rise time and minimize, but never remove the steady state error.
- An integral action due to (Ki) will remove the effect of the steady state error, but might elongate the duration of the transient response.
- A derivative action due to (Kd) will increase system stability but decrease the overshoot and enhance the response of the system.

The effect of each parameter of controller (Kp, Kd, and Ki) on the closed loop response can be summarized in the following table (3-1):-

Table 3-1 controller constant characteristics

Close Loop Response	**Rise time**	**Overshoot**	**Settling time**	**Steady State Error**
Kd	Slight Change	Decrease	Decrease	Slight Change
Kp	Decrease	Increase	Slight Change	Decrease
Ki	Decrease	Increase	Increase	Removed

Note that these correlations may not be exactly accurate, because Kp, Ki, and Kd are dependent of each other. In fact, changing one of these variables can change the effect of the other two. For this reason, the table should only be used as a reference when one is determining the values for Ki, Kp and Kd.

So far, the work and components of the controller were clarified but the use of the required type of controller depend on the nature of the plant, the design requirements and stability.

3.5.4 Derivative Effect on PID controller

Although derivatives are not desired in controlling certain plants (because it is amplifies higher frequency components) but in some cases may need to utilize it to cancel the effect of high order integrative action in transfer function of the plant.

Some nonlinear models when transformed into a fully linearized model will may be in the form of integrators. Where integrators are equivalent to a low pass filter. Therefore will add a high pass filters which represent the derivative part in controller. This solution is taken in order to reach point of equilibrium which are represented by band-limited derivative

These implementation can cause a lot of differences in the output signal. In order to cancel the effect of overshoot in the output. So that, high pass filter is essential with high order equation in denominator of transfer function. This filtering method most commonly adopted with MATLAB implementation. To be more specific, this done by substitute the transfer function of high pass filter in the plant transfer function which is:

$$\text{High pass filter} = \left(\frac{Ns}{S + N}\right)$$

CHAPTER FOUR

GENERATOR MODELING AND DESIGN

4.1 Introduction

In the previous chapters, we have discussed the main principles of nonlinear control theory and some concepts and technique for designing feedback linearization aided PD controller for nonlinear control systems.

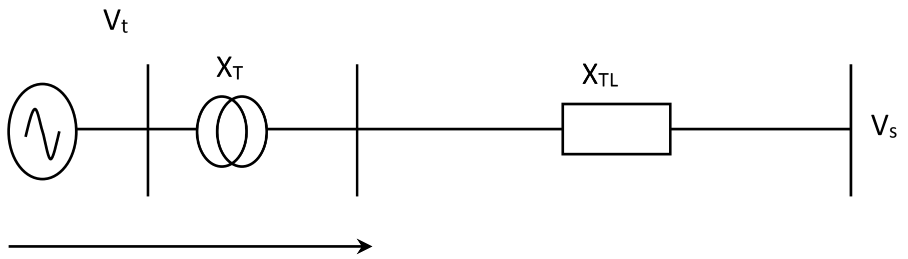
The main topic of the this chapter is to join the theory of power system dynamics and control techniques, so as to open a new discipline and to design a novel controller (PDD2) to enhance the stability of large-grid power system. To achieve this goal, at first we must link the design techniques of nonlinear control with the dynamics of the power system. Here in this chapter will present a mathematical model of a power system which includes synchronous generators, transformer, transmission line and infinite bus bar.

It is very important from beginning to have a good understanding and comprehension of the objects under consideration, in order to represent them with mathematical models as accurately as possible. Then we can do our analysis of this model.

So, we will introduce respectively, the rotor dynamics equations, the field winding's electro-magnetic equations of a synchronous generator, power equations, and equations of the steam valve governors [36]

4.2 **Synchronous Generator Model Connect To Infinite Bus**

In this section will present a mathematical model for synchronous generator (G) where it connected though the power transformer (T) and transmission line with impedanace (X_{TL}) to infinite bus (Vs) as shown in figure (4-1). This model described in detail in [36].



Figure(4-1)A one machine infinite bus power system

Vt--terminal voltage Vs--infinite bus voltage

X_t--reactance of the transformer X_{TL}--Reactance of transmission line

This model involves the load angle (δ in radian), which is the angular difference between the generator induced voltage E_q vector and the generator terminal voltage Vt vector as shown in Figure (4-2).

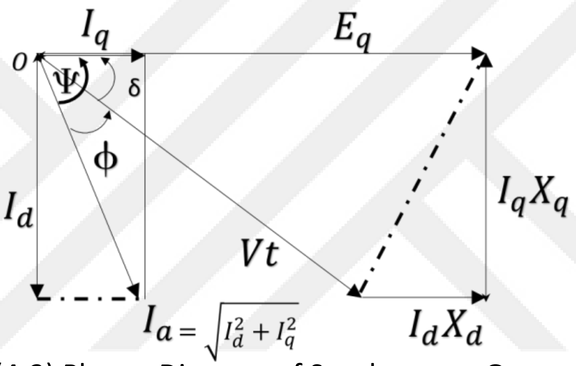


Figure (4-2) Phasor Diagram of Synchronous Generator

Load angle will be the controlled variable in the first part of the controller design work. The same model shows the relation of the angular velocity of the rotor (ω rad/sec), transient voltage of the q-axis $\grave{E}_q$and the mechanical power supplied by the prime mover (steam turbine etc.) to generator (P_m) with terminal voltage and load angle. As mentioned before, the full derivation of the model is available in [36] but here will take only the model equations and simplify them into a more generic form as done in [37].The main equation that represent our system is:-

$$\dot{\delta} = \omega - \omega_o \quad (4.1)$$

$$\dot{\omega} = -\frac{D}{M}(\omega - \omega_o) + \frac{\omega_o}{M}P_m - \frac{\omega_o\,\acute{E}_q V_s}{M\,\acute{X}_{ds}}\sin(\delta) \quad (4.2)$$

$$\dot{\acute{E}}_q = -\frac{1}{\acute{T}_d}\acute{E}_q + \frac{X_d - \grave{X}_d}{T_{do}\acute{X}_{ds}}V_s\cos(\delta) + \frac{1}{T_{do}}\,u_f \quad (4.3)$$

$$\dot{P_m} = \frac{1}{T_s}(-P_m + P_{mo}) + \frac{1}{T_s}\,u_p \quad (4.4)$$

Where “equation no. (4.1), (4.2) represents mechanical and (4.3), (4.4) represents electrical subsystems of the generator respectively". The parameters of equation no. (4.1) – (4.4) are shown in Table 4-1.

Table 4.1- values and definition for parameters in synchronous generator model [39].

Parameter	Definition	Value
ω_o	System speed	$2\pi f_o$ here$\omega_o = 1$
M	Inertia coefficient of generator	7.6
P_{mo}	Initial mechanical power input from the turbine	1
P_m	Mechanical power input from the prime mover	
D	Damping constant	3
V_s	Infinite bus voltage	1.5
X_d	Generator synchronous reactance of the d–axis	0.9
X_q	Generator synchronous reactance of the q–axis	0.6
$\grave{X}_d$	Generator transient reactance of the d–axis	0.36
X_{TL}	Reactance of transmission line	0.36
X_T	Reactance of transformer	0.12
T_{d_o}	The field short circuit time constant	5
$\acute{T}_d$	Transient field short circuit time constant	5
T_s	Equivalent time constant of the steam turbine	5
$\acute{X}_{ds}$	$=\grave{X}_d + X_{TL} + X_T$	0.84
X_{qs}	$=X_q + X_{TL} + X_T$	1.08
I_d	Generator Current in d-axis	$\frac{E_q^{`} - V_s \cos\delta}{\acute{X}_{ds}}$
I_q	Generator Current in q-axis	$\frac{V_s \ sin\delta}{X_{qs}}$
V_d	Generator terminal voltage d-axis	$X_q I_q$
V_q	Generator terminal voltage q-axis	$E_q^{`} - I_d \grave{x}_d$
V_t	Generator terminal voltage	$\sqrt[2]{V_d^2 + V_q^2}$

Table 4.1- values and definition for parameters in synchronous generator model [39].

Parameter	Definition	Value
E_q	Internal voltage of q-axis(no load)	$E_q = \acute{E}_q + (X_d - \grave{X}_d)I_d$
ω	Generator rotor speed	
u_f	Generator field circuit voltage	
u_p	Electrical control signal to the steam pressure valve	

In order to manipulate our model equations efficiently and convert the model to more general and compact form as mentioned in [38] we can rewrite the previous equation as shown below:-

$$\dot{X}1 = X2 \tag{4.5}$$

$$\dot{X}2 = aX4 - bX2 - cX3\sin(X1) \tag{4.6}$$

$$\dot{X}3 = -p1X3 + p2\cos(X1) + u1 \tag{4.7}$$

$$\dot{X}4 = -fX4 + h + u2 \tag{4.8}$$

Where, the conversion details are shown in Table 4.2.

Table -4.2- State variables of simplified form of synchronous generator [39].

No.	Parameter	Symbol	Definition
1	$X1$	$=\delta$	Load angle
2	$X2$	$=\omega - \omega_o$	the deference between the generator speed and system speed
3	$X3$	$= \acute{E}_q$	Transient internal voltage of q-axis
4	$X4$	$= P_m$	mechanical power input from the prime mover

h=$\frac{P_{mo}}{T_s}$, $u1=\frac{1}{T_{do}}\ u_f$, $u2=\frac{1}{T_s}\ u_p$, $a=\frac{\omega_o}{M}$

$b=\frac{D}{M}$, $c=\frac{\omega_o\, V_s}{M\, \acute{X}_{ds}}$, $p1=-\frac{1}{\acute{T_d}}$, p2=$\frac{X_d-\grave{X}_d}{T_{do}\acute{X}_{ds}}$

So the state space representation for nonlinear synchronous generator model will be as show below:-

$$\begin{bmatrix}\dot{x}1\\ \dot{x}2\\ \dot{x}3\\ \dot{x}4\end{bmatrix}=\begin{bmatrix}x2\\ ax4-bx2-cx3sinx1\\ -P1x3+P2\cos x1\\ -fx4+h\end{bmatrix}+\begin{bmatrix}0\\0\\1\\1\end{bmatrix}u$$

4.3 Load Angle and Terminal voltage Control for Synchronous Generator

The generator always inclined to fall out of synchronism when connected to an electrical grid, so there must be a limit for the maximum power generated by the generator therefore, the generator can be loaded without falling out-of-synchronization of the grid. However we should hold the generator in synchronism especially in case of a perturbation. So, we have to limit the generator operating area and this done by limiting the excitation field and the load angle of synchronous generator (practical stability limit) [39, 40, and 41]. This procedure is a good technique to ensure stable operation for generator in the case of any disturbance in the power system grid, such as a short circuit etc. [42]. This objective can be done by find a control laws designed by input-output feedback linearization in order to control the generator model described above by the equations (4.5, 4.6, 4.7, and 4.8 respectively).

The generator model has two inputs, the first input for stabilize the load angle (δ=X_1) which is controlled by driving the electrical signal that control the steam pressure valve (u_2). After completing the load angle (δ) controller design, stabilize the terminal voltage (V_t) by manipulating the excitation field voltage (u_1) which is the second input in our model and it is well known from the basics of control theory that if the number of the inputs available equal to the controlled outputs the control system can be estimated and will be satisfactory.

As a result, the composition of excitation control system for synchronous generator with a controller of load angle will be added to the terminal voltage controller as we will see in next sections. The load angle and terminal voltage controllers are alternating the controlling on excitation current. To be more specific we cannot separate the controller of terminal voltage and work independently without load angle controller because they are coupled with each other [42].

At this point should mention the concept which is very important in our design at this point which is the relative degree of synchronous generator model. As discussed before, in Chapter 3, it is said that the number of differentiations of output at which the input appears first time was called as relative degree of a nonlinear system. When we consider the load angle (δ=X1) and differentiate it three times the steam power control signal (u2) appears first time. So one can say that, the load angle dynamics has a relative degree of three.

The terminal controller dynamics is based on the dynamics of the transient q-axis voltage (Eq or x3). So it should have a relative degree of one only. That can be proven very easily. As a result the total relative degree of the plant equals to four. This means that the plant is of full relative degree.

4.3.1 Load Angle Stability by Steam Valve Control

The method utilized in this research is the input-output feedback linearization that is explained in section (3.2) which is used to stabilize the load angle this method based on differentiate the output function (Y) of the system repeatedly until the input (u) appears and the times of differentiation of the output function (Y) until the input appear is relative degree as we said before so, the important thing in this approach based on the correct selection of the output.

In this case, the target is to stabilize the load angle (δ) that's mean the output (Y) will be equal the load angle (δ or x_1). Knowing that, the relative degree of the mechanical subsystem is equal to three ($x1 - u2$ relation) we will differentiate it three times to obtain input ($u2$). Here, the field excitation voltage ($u1$) is assumed as an external input and will be generated by the terminal voltage controller:-

The output Y= δ

And we have $X1 = \delta$ as shown in table-1-so and start differentiate the output,

$Y = \delta = X1$

$\dot{Y} = \dot{X}1 = X2$

$\ddot{Y} = \dot{X}2 = aX4 - bX2 - cX3\sin(X1)$

$\dddot{Y} = \ddot{X}2 = a\dot{X}4 - b\dot{X}2 - \left[cX3\,\dot{X}1\cos(X1) + c\dot{X}3\sin(X1)\right]$

$\dddot{Y} = \ddot{X}2 = a\dot{X}4 - b\dot{X}2 - \; cX3\,\dot{X}1\cos(X1) - c\dot{X}3\sin(X1)$ (4.9)

But we have the following equations:-

$\dot{X}4 = -fX4 + h + u2$ (4.8) and

$\dot{X}1 = X2$ (4.5)

Substitute both of them [equation no. (4.8) and no. (4.5)] in equation no. (4.9) we get the following equation:-

$$\dddot{Y} = \ddot{X}2 = -\mathrm{a}fX4 + \mathrm{a}h - b\dot{X}2 - \; cX3\,X2\cos(X1) - c\dot{X}3\sin(X1) + au2$$

(4.10)

Now, substitute equation no. (4.7) in equation no. (4.10) to check if the input (u2) appears or not:-

$$\dddot{Y} = \ddot{X}2 = -\mathrm{a}\,fX4 + \mathrm{a}\,h - b\dot{X}2 - \; cX3\,X2\cos(X1) - c\sin(X1)\,[-pX3 + p2\cos(X1) + u1] \; + au2$$

$\dddot{Y} = \ddot{X}2 = -\mathrm{a}\,fX4 + \mathrm{a}\,h - b\dot{X}2 - \; cX3\,X2\;\cos(X1) + pc\sin(X1)\,X3 -$
$p2\;c\sin(X1)\cos(X1) - \mathrm{c}\sin(X1)\,u1 + au2$ (4.11)

For the sake of simplicity, (4.11) could be rewritten again as follows:-

$$\ddot{Y} = \ddot{X}2 = \mathrm{f(X)} - \mathrm{c}\sin(X1)\, u1 + au2 \qquad (4.12)$$

Where

$$f(X) = -\mathrm{a}\, fX4 + \mathrm{a}\, h - b\dot{X}2 - \ cX3\, X2\cos(X1) + pc\sin(X1)\, X3 - p2\, c\sin(X1)\cos(X1)$$

Next step, we should do, is to estimate a control law according to the definition of feedback linearization (Chapter 3):-

$$\ddot{Y} = V_{ctrl} = \mathrm{f(X)} - \mathrm{c}\sin(X1)\, u1 + au2$$

$$\boldsymbol{u2} = \frac{\boldsymbol{V_{ctrl}} - \boldsymbol{f(X)} + \boldsymbol{c\, u1\, sin(X1)}}{\boldsymbol{a}}$$

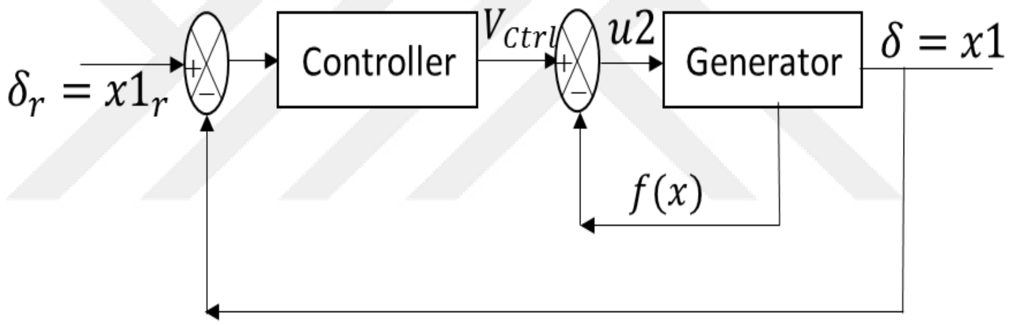


Figure (4-3) Block diagram for generator control law

And the system will become as shown in figure (4-3) after that we should transform the generator model into a linear and controllable system by define new state variable (Z). In order to form a fully linearized system and establish a transfer function for the generator model:-

$Z1 = Y$

$Z2 = \dot{Z}1 = \dot{Y}$

$Z3 = \ddot{Y} = \dot{Z}2$

$\dddot{Y} = \dot{Z}3$

From equations above we can find the state space representation for generator model as shown below:-

$$\begin{bmatrix}\dot{Z}1\\ \dot{Z}2\\ \dot{Z}3\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}Z1\\ Z2\\ Z3\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 1\end{bmatrix} V_{ctrl}$$

$$where\ V_{ctrl} = f(X) - \mathrm{c}\sin(X1)u1 + au2$$

From the linear control theory it is easy to find the transfer function from the above system. We have from the previous chapter:-

$$\dot{Z} = Az + BV_{ctrl}$$

$$Y = C\ Z$$

Take the Laplace transformation for both sides we get

$$sz(s) = A\ z(s) + B\ V_{ctrl}(s)$$

$$\frac{z(s)}{V_{ctrl}(s)} = (s - I)^{-1}B$$

But we have $y = [1 \quad 0 \quad 0]\ Z$ so

$$y(s) = Cz(s)$$

$$\frac{y(s)}{z(s)} = C$$

So, the equivalent transfer function for fully linearized model for synchronous generator will be:-

$$\frac{z(s)}{V_{ctrl}(s)} * \frac{y(s)}{z(s)} = C(sI - A)^{-1}B$$

$$\frac{y(s)}{V_{ctrl}(s)} = C(sI - A)^{-1}B = \frac{1}{s^3}$$

Where

$$A = \begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 0 & 0 & 0\end{bmatrix} \qquad and \qquad B = \begin{bmatrix}0\\ 0\\ 1\end{bmatrix} \qquad and \qquad C = [1 \quad 0 \quad 0]$$

Through the transfer function, we can guess the behavior of the system and rely on this behavior to decide which type of controller can we use?

In order to stabilize the load angle (δ) and we have 3 poles at the origin. This means that, the linear plant behaves as a triple integrator. To stabilize the system by closing a loop like shown in Figure 4-4, a double differentiation combined with a proportional term, hence a PDD2-controller, is needed in order to get enough phase lead to compensate for the three integrators. The transfer function of a PDD2-controller in the s-domain is given by [43]:

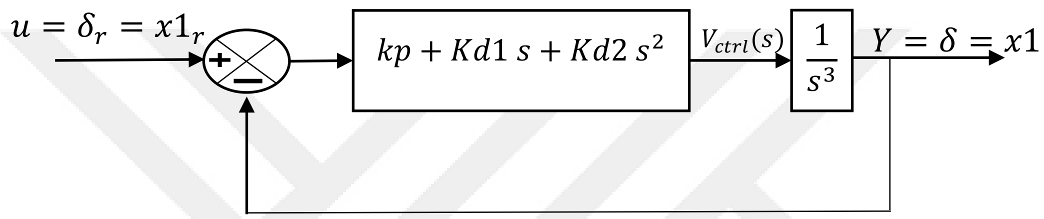


Figure (4-4) PDD2 controller with fully linearized generator model Block diagram

PDD2= $Kd2\ s^2 + Kd1\ s + Kp$ (4.13)

$$G(s) = (Kd2\ s^2 + Kd1\ s + Kp) * \frac{1}{s^3}$$

$$G(s) = \frac{Kd2\ s^2 + Kd1\ s + Kp}{s^3} \quad (4.14)$$

$$\frac{Y(s)}{u(s)} = \frac{G(s)}{1 + G(s)H(s)} \quad (4.15)$$

Substitute (4.13) into (4.14) to derive the transfer function:-

$$\frac{Y(s)}{u(s)} = \frac{\frac{Kd2\ s^2 + Kd1\ s + Kp}{s^3}}{1 + \frac{Kd2\ s^2 + Kd1\ s + Kp}{s^3}}$$

$$\frac{Y(s)}{u(s)} = \frac{Kd2s^2 + Kd1\ s + Kp}{s^3 + Kd2\ s^2 + Kd1\ s + Kp} \quad (4.16)$$

The denominator of equation no. (4.16) can be solved as shown in equation no. (4.17).

$$\frac{Y(s)}{u(s)} = \frac{Kd2\, s^2 + Kd1\, s + Kp}{(s+\propto)(s^2 + 2\zeta\omega_n\, s + \omega_n^2)} \qquad (4.17)$$

$$\frac{Y(s)}{u(s)} = \frac{\mathrm{Kd2\ s^2 + Kd1\ s + Kp}}{s^3 + (2\zeta\omega_n+\propto)s^2 + (\omega_n^2 + 2 \propto \zeta\omega_n)s+\propto \omega_n^2} \qquad (4.18)$$

By comparing equation no. (4.17) with equation no. (4.15) we can calculate a relation to find the values of Kd1, Kd2 and Kp as below:-

$$Kd1 = \omega_n^2 + 2 \propto \zeta\omega_n \qquad (4.19)$$

$$Kd2 = 2\zeta\omega_n+\propto \qquad (4.20)$$

$$Kp =\propto \omega_n^2 \qquad (4.21)$$

Then substitute Kd1, Kd2 and Kp into the numerator of equation no. (4.18) in order to find general form for transfer function for fully linearized synchronous generator and start tuning for PDD2 controller:-

$$\frac{Y(s)}{u(s)} = \frac{(2\zeta\omega_n+\propto)s^2 + (\omega_n^2 + 2 \propto \zeta\omega_n)s+\propto \omega_n^2}{s^3 + (2\zeta\omega_n+\propto)s^2 + (\omega_n^2 + 2 \propto \zeta\omega_n)s+\propto \omega_n^2} \qquad (4.22)$$

4.3.1.1 Load Angle Controller Implementation

Because of the effect of noise and also, derivative needs prediction for future inputs to tell its value. Therefore, for these reasons the derivative block in MATLAB is not equivalent to the ideal s-domain derivative.

The derivative block output at the present time is (u[t]-u[t-dt])/dt where "dt" in MATLAB is the last time step taken by the ODE (Ordinary Differential Equation) solver. When using variable-step solver this is only faintly related to "h(s) = s". This is why the simulated results do not match the closed-loop transfer function results Thus, using a plain derivative is not recommended. MATLAB implements a special solution which is described below.

MATLAB performs an approximate derivative of the form "s/ (1+b*s)" via a high-pass filter, where "$b = \frac{1}{N}$" is small if we compared it with the dominant time constant of the system. This not only remove time-domain conflict, but also ensure the implementation of PID controller [36]. For the previous reasons we will utilize two different techniques in the implementation of our controller and compare them which is:-

1-*Derivative Approximation Via High-Pass Filter*:-

This technique based on implementing the action of derivative inside the equation of our (PDD2) controller and this done by substitute each ($s = \frac{s}{1+bs} = \frac{s}{1+\frac{s}{N}} = \frac{Ns}{s+N}$) as shown below:-

We have PDD2=$Kd2\ s^2 + Kd1\ s + Kp$ from equation (4.13)

$$PDD2 = Kd2\left(\frac{Ns}{S+N}\right)^2 + Kd1\left(\frac{Ns}{S+N}\right) + Kp$$

$$PDD2 = \frac{Kp(s+N)^2 + Kd1Ns(s+N) + Kd2N^2s^2}{(s+N)^2}$$

$$PDD2 = \frac{Kp(s^2 + 2Ns + N^2) + Kd1Ns^2 + Kd1N^2s + Kd2N^2s^2}{s^2 + 2Ns + N^2}$$

$$PDD2 = \frac{Kps^2 + 2NKps + KpN^2 + Kd1Ns^2 + Kd1N^2s + Kd2N^2s^2}{s^2 + 2Ns + N^2}$$

$$PDD2 = \frac{(Kp + Kd1N + Kd2N^2)s^2 + (2NKp + Kd1N^2)s + KpN^2}{s^2 + 2Ns + N^2}$$

If we choose N=100 as discussed in [44] we get:-

$$PDD2 = \frac{(Kp+100Kd1+10000Kd2)s^2+(200Kp+10000Kd1)s+10000Kp}{s^2+200s+10000} \qquad (4.23)$$

And the circuit will be as shown in figure (4-5)

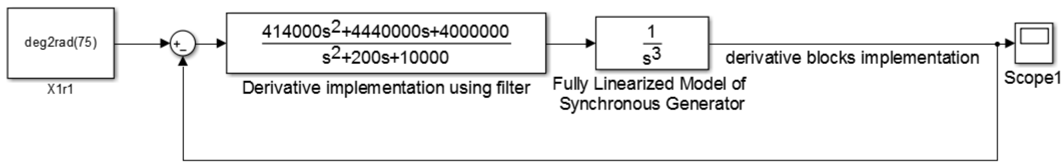


Figure (4-5) PDD2 using derivative implementation via high pass filter

2-*Using Derivative Blocks*:-

In this technique we can assembling the (PDD2) controller by the derivative block in MATLAB as shown in figure below:-

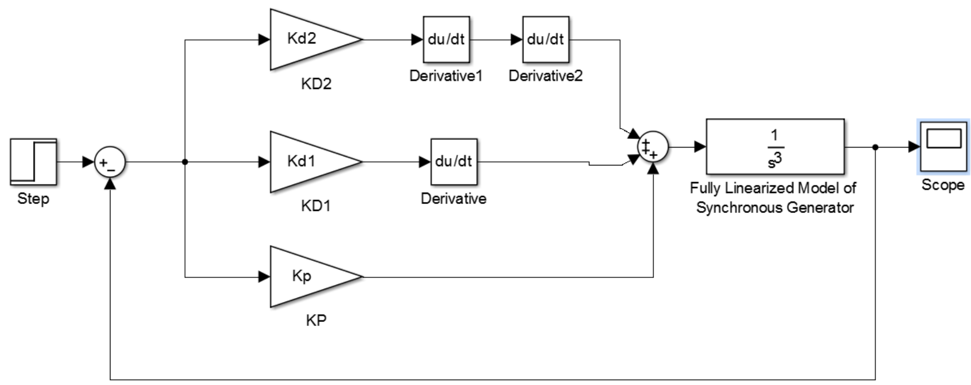


Figure (4-6) PDD2 assembling using derivative blocks

And in chapter five will compare between the two techniques and see the responses of both of them with selected values of Kd1, Kd2 and Kp.

4.3.1.2 PDD2 Parameter Tuning (Kd1, Kd2 and Kp)

The closed loop transfer function of (PDD2) controller with fully linearized synchronous generator model equation no. (4.17) has three distinct roots one pair of complex conjugate ($s = -\zeta\omega_n \mp \omega_n\sqrt{\zeta^2 - 1}$) and the other one is distinct real root ($s = -\propto$) as shown below:-

$$\frac{Y(s)}{u(s)} = \frac{Kd2\ s^2 + Kd1\ s + Kp}{(s+\propto)\left(s + \zeta\omega_n + \omega_n\sqrt{\zeta^2 - 1}\right)\left(s + \zeta\omega_n - \omega_n\sqrt{\zeta^2 - 1}\right)} \tag{4.24}$$

The values of these three pole will governing the response of plant transfer function especially when it has a dominant pole so, the values of controller constants (Kd1, Kd2 and Kp) will completely rely on the value of ($\zeta\omega_n$ and $\propto$) as explained in chapter three.

In this case the check for the dominant pole compare "α" with "$\zeta\omega_n$ " because of ($\zeta\omega_n$) represent the real part of the complex conjugate root so, will compare the real parts of the roots in order to obtain dominance of poles because the real part compute how fast the response effect and decreases[37].

In the next chapter will pick some values for ($\zeta\omega_n$ and $\propto$) and estimate controller constants (Kd1, Kd2 and Kp) then estimate the responses for each value according to the following equations:-

$$Kd1 = \omega_n^2 + 2 \propto \zeta\omega_n$$

$$Kd2 = 2\zeta\omega_n + \propto$$

$$Kp = \propto \omega_n^2$$

4.3.2 Control of Terminal Voltage by Changing Generator Excitation Field

As we did before and through the technique utilized in this research input-output feedback linearization explained in previous chapter we will use it again in order to stabilize the terminal voltage (V_t) by changing the generator excitation field (u1). However, to find a relation between the output and input of the plant and based on input-output feedback linearization principles should differentiate the output function

(Y) of the system repeatedly until the input (u) appears and the times of differentiation of the output function (Y) until the input appear is our system relative degree as mention before.

So, the main goal is stabilize the terminal voltage (V_t) that's mean the output (Y) will be equal the terminal voltage (V_t) which is equal to ($\sqrt[2]{V_d^2 + V_q^2}$ where V_d is generator terminal voltage in d-axis and V_q is generator terminal voltage in q-axis) then differentiate it repeatedly until the input ($u1$) appears (where u1 is $\frac{1}{T_{do}}\ u_f$ and u_f is generator field circuit voltage and T_{do} is field short circuit time constant) as shown below.

All of the above can be done when ($u2$) continues connected to the system where ($u2$) is the electrical control signal governing the steam pressure valve which is responsible to stabilize the load angle (δ) as explain in previous section this makes our system is multi input multi output system (MIMO) because we cannot decouple or separate the load angle (δ) controller and terminal voltage controller on each other and will discuss this issue in the next section but now will design a suitable controller for terminal voltage (V_t) as shown :-

As said before Y= V_t

From table (4.1) we have:-

$$Y = v_t = \sqrt[2]{V_d^2 + V_q^2} \qquad (4.25)$$

Where (v_t is the terminal voltage)

To find a relation between the output and input of the plant and system relative degree we have to differentiate the output (Y) until the input (u1) appears:-

$$\dot{Y} = \dot{v_t} = \frac{V_q\dot{V_q} + V_d\dot{V_d}}{\sqrt[2]{V_d^2 + V_q^2}} \qquad (4.26)$$

We should estimate $\dot{V_d}$and $\dot{V_q}$so:-

$$V_d = X_q I_q \qquad (4.27)$$

$$\dot{V}_d = X_q \dot{I}_q \qquad (4.28)$$

$$I_q = \frac{V_s \ sin(\delta)}{X_T + X_{TL} + X_q}$$

$$I_q = \frac{V_s \ sin(\delta)}{X_{qs}}$$

Since $\delta = x1 \quad and \quad \dot{X}1 = X2$ so we have

$$\dot{I}_q = \frac{V_s \dot{x1} cos(x1)}{X_{qs}}$$

$$\dot{I}_q = \frac{V_s \ x2 \ cos(x1)}{X_{qs}} \qquad (4.29)$$

Substitute equation no. (4.28) in equation no. (4.27) we get

$$\dot{V}_d = \frac{V_s X_q \ x2 \ cos(x1)}{X_{qs}} \qquad (4.30)$$

The next step is to estimate $\dot{V}q$:-

When we have a loaded generator V_q equal:-

$$V_q = E_q^{`} - I_d x_d^{`} \qquad (4.31)$$

$$\dot{V}_q = \dot{E}_q^{`} - \dot{I}_d x_d^{`} \qquad (4.32)$$

But from table (4.1) we have

$$I_d = \frac{E_q^{`} - V_s \cos(\delta)}{x_d^{`} + x_{TL} + x_T} \qquad (4.33)$$

Andsince $\grave{E}_q = x3 \qquad \delta = x1$ then

$$I_d = \frac{x3 - V_s \cos(x1)}{X_{ds}^{`}}$$

$$\dot{I}_d = \frac{\dot{x}3 + V_s \dot{x}1 \ sin(x1)}{X_{ds}^{`}}$$

$$\dot{I}_d = \frac{\dot{x}3 + V_s \ x2 \ sin(x1)}{X_{ds}^{`}} \qquad (4.34)$$

Substitute equation no. (4.33) in equation no. (4.31) we get

$$\dot{V}_q = \dot{\grave{E}}_q - \frac{\dot{x}3 + V_s \; x2 \; sin(x1)}{\grave{X}_{ds}} \grave{x}_d$$

And as we said $\grave{E}_q = x3$ so:-

$$\dot{V}_q = \dot{x}3 - \frac{\dot{x}3 + V_s \; x2 \; sin(x1)}{\grave{X}_{ds}} \grave{x}_d$$

$$\dot{V}_q = \dot{x}3 - \frac{\dot{x}3\grave{x}_d}{\grave{X}_{ds}} - \frac{\grave{x}_d}{\grave{X}_{ds}} V_s \; x2 \; sin(x1)$$

$$\dot{V}_q = \left[1 - \frac{\grave{x}_d}{\grave{X}_{ds}}\right] \dot{x}3 - \frac{\grave{x}_d}{\grave{X}_{ds}} [V_s \; x2 \; sin(x1)]$$

$$\dot{V}_q = \left[1 - \frac{\grave{x}_d}{\grave{X}_{ds}}\right] \dot{x}3 - \frac{\grave{x}_d}{\grave{X}_{ds}} [V_s \; x2 \; sin(x1)] \qquad (4.35)$$

Substitute equation no. (4.35) and equation no. (4.30) in equation no. (4.26) we get:-

$$\dot{Y} = \dot{v}_t = \frac{\left[1 - \frac{\grave{x}_d}{\grave{X}_{ds}}\right] \dot{x}3V_q + \frac{\grave{x}_d V_q}{\grave{X}_{ds}} [V_s \; x2 \; sin(x1)] + \frac{V_d X_q}{X_{qs}} [V_s \; x2 \; cos(x1)]}{\sqrt[2]{V_d^2 + V_q^2}} = V_{ctrl}$$

$$\left[1 - \frac{\grave{x}_d}{\grave{X}_{ds}}\right] \dot{x}3 \; V_q + \frac{\grave{x}_d V_q}{\grave{X}_{ds}} [V_s \; x2 \; sin(x1)] + \frac{V_d X_q}{X_{qs}} [V_s \; x2 \; cos(x1)] = V_{ctrl} * \sqrt[2]{V_d^2 + V_q^2}$$

$$\left[1 - \frac{\grave{x}_d}{\grave{X}_{ds}}\right] \dot{x}3 \;\; V_q = V_{ctrl} * \sqrt[2]{V_d^2 + V_q^2} - \frac{\grave{x}_d V_q}{\grave{X}_{ds}} [V_s \; x2 \; sin(x1)] - \frac{V_d X_q}{X_{qs}} [V_s \; x2 \; cos(x1)]$$

Separate $\dot{x}3$ from above equation:-

$$\dot{x}3 = \frac{(V_{ctrl}) * \sqrt[2]{V_d^2 + V_q^2} - \frac{\grave{x}_d V_q}{\grave{X}_{ds}} [V_s \; \mathrm{x2cos} \; x1] - \frac{V_d X_q}{X_{qs}} [V_s \; x2cosx1]}{V_q \left[1 - \frac{\grave{x}_d}{\grave{X}_{ds}}\right]} \qquad (4.36)$$

But we have (4.8) which is:-

$$\dot{X}3 = -p1X3 + p2\cos(X1) + u1$$

Substitute it in equation no. (4.36) we get:-

$$-p1X3 + p2\cos(X1) + u1 = \frac{(V_{ctrl}) * \sqrt[2]{V_d^2 + V_q^2} - \frac{\grave{x_d} V_q}{\grave{X_{ds}}}[V_s\, x2\, sin(x1)] - \frac{V_d X_q}{X_{qs}}[V_s\, x2\, cos(x1)]}{V_q\left[1 - \frac{\grave{x_d}}{\grave{X_{ds}}}\right]}$$

$$u1 = \frac{(V_{ctrl}) * \sqrt[2]{V_d^2 + V_q^2} - \frac{\grave{x_d} V_q}{\grave{X_{ds}}}[V_s\, \mathrm{x}2\, sin(x1)] - \frac{V_d X_q}{X_{qs}}[V_s\, \mathrm{x}2\, cos(x1)]}{V_q\left[1 - \frac{\grave{x_d}}{\grave{X_{ds}}}\right]} + p1X3 - p2\cos(X1)$$

$$u1 = \frac{(V_{ctrl}) * \sqrt[2]{V_d^2 + V_q^2} - V_s\, \mathrm{x}2\left[\frac{\grave{x_d} V_q}{\grave{X_{ds}}} sin(x1) + \frac{V_d X_q}{X_{qs}} cos(x1)\right]}{V_q\left[1 - \frac{\grave{x_d}}{\grave{X_{ds}}}\right]} + p1\, X3 - p2\cos(X1) \qquad (4.37)$$

If we look for the last equation no (4.37) will see that the input ($u1$) appear after one time differentiation of the output (Y) which is the terminal voltage (V_t) and the relative degree according to the definition for (V_t) and ($u1$) is equal to one. As a result we established a relation between output (V_t) and input ($u1$) as obtained above.

So, the overall closed loop is a multi-input multi-output system (MIMO). However the both controllers (Load angle and terminal voltage controller) will work together in order to stabilize the plant and put the terminal voltage (Vt) and the load angle (δ) of the synchronous generator at a fixed value.

In this case the relative degree should be calculated for whole system. In other word the relative degree of synchronous generator model is equal to sum of relative degree of load angle controller and relative degree of terminal voltage controller which is equal to four and this equal to the number of our dynamics governing the generator operation So, the model is a full relative degree and because of these reason there is no remaining dynamics.

From previous estimation we have established a relation between input and output for the synchronous generator model connected to infinite bus after one time of differentiating for the output. So, the system is 1st relative degree and it is too easily to establish the linearized equivalent plant which is equal to$\left(\frac{1}{s}\right)$.

Thus the equivalent linearized system to control the terminal voltage of synchronous generator is:-

$$\frac{\mathrm{Y(s)}}{\mathrm{V_{ctrl}(s)}} = \frac{1}{\mathrm{s}}$$

One can consider the block diagram shown in Figure 4-6 for control schemes. As we have only a single integrator here, we can simply use a (P controller):

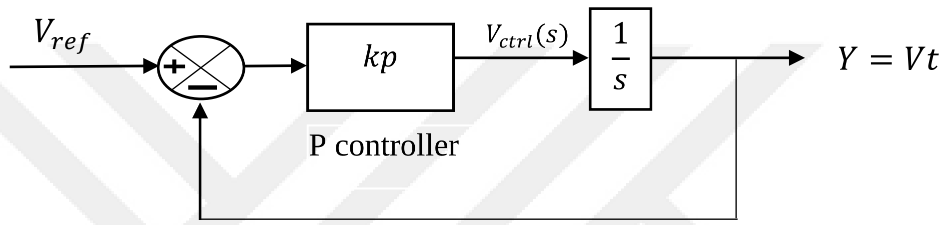


Figure (4.7) Terminal voltage controller for linearized generator model

From figure (4.7) we can find easily the closed loop according to equation (4.15) for full linearized system which control the terminal voltage:-

$$\frac{Y(s)}{u(s)} = \frac{G(s)}{1 + G(s)H(s)} = \frac{\frac{Kp}{s}}{1 + \frac{Kp}{s}}$$

$$\frac{Y(s)}{u(s)} = \frac{s}{s + Kp} \tag{4.38}$$

From equation (4.38) we can see that the close loop transfer function for fully linearized system has one pole on the left side in s-domain so the system is always stable.

CHAPTER FIVE

NUMERICAL APPLICATION AND SIMULATION

5.1 Introduction

In this chapter will focus on the implementation and simulation of the theoretical approach which are developed and presented in chapter four and how we could use MATLAB functions in that implementation to establish a satisfactory result.

Furthermore, a discussion of the selected values for controller constants Kd1, Kd2 and Kp (load angle controller) and the selection of Kp for terminal voltage controller and controller tuning rely on the value of damping ratio (ζ) and the real pole for the plant (α).

Hence, in the first case when we stabilize the load angle, we will use two techniques to implement the PDD2 controller as presented in previous chapter. The first one was using derivative Blocks in order to assemble the (PDD2) controller and the second technique was using the equivalent transfer function for controller to implement a band-limited derivative (high-pass model) which is driven in chapter four. After that we make a comparison between these techniques with respect to the same values of damping ratio (ζ) and the real pole (α).

5.2 MATLAB Function and Derivative Blocks

To start assembling nonlinear synchronous generator model and its controllers, one will need to simulate its operation using Simulink so, we should understand the definition of MATLAB functions which is defined in appendix (A) in order to describe the nonlinear parts in synchronous generator model. In addition to the limitations of the derivative block which will be used in that implementation and try to overcome this limitation. Derivative blocks has a limitation as describe in [45] which is that In real applications, and due to high frequency noise amplification this block should be avoided to use wherever possible .

5.3 Synchronous Generator Model Simulation Using Simulink

5.3.1 Parameters

The following simplified model will be selected to be implemented in MATLAB Simulink: -

$$\dot{X}1 = X2 \quad (5.1)$$

$$\dot{X}2 = aX4 - bX2 - cX3\sin(X1) \quad (5.2)$$

$$\dot{X}3 = -p1X3 + p2\cos(X1) + u1 \quad (5.3)$$

$$\dot{X}4 = -fX4 + h + u2 \quad (5.4)$$

Where

$h=\frac{P_{mo}}{T_s}$, $u1=\frac{1}{T_{do}} u_f$, $u2=\frac{1}{T_s} u_p$, $a = \frac{\omega_o}{M}$

$b = \frac{D}{M}$, $c = \frac{\omega_o V_s}{M \acute{X}_{ds}}$, $p1 = -\frac{1}{T\acute{}_d}$, $p2=\frac{X_d-\grave{X}_d}{T_{do}\acute{X}_{ds}}$

Table -5.2- values used in simplified form of synchronous generator

Generator Constant			
X1	0	m	7.6
X2	3	pm	1
X3	0	d	3
X4		Vs	1.5
a	0	xd	0.9
b	0.394737	xq	0.36
c	0	x'd	0.36
u1	1	Xs	0.12
p	0.2	Xt	5
p2	0.9	T'd	5
f	0.2	Ts	5
h	0.2	X'ds	0.84
Wo	1	Xqs	1.08

Table -5.1- values and definition for parameters in synchronous generator model [39]

Parameter	Definition	Value
D	Damping constant	3
V_s	Infinite bus voltage	1.5
X_d	Generator synchronous reactance of the d–axis	0.9
X_q	Generator synchronous reactance of the q–axis	0.6
$\grave{X}_d$	Generator transient reactance of the d–axis	0.36
X_{TL}	Reactance of transmission line	0.36
X_T	Reactance of transformer	0.12
T_{d_o}	The field short circuit time constant	5
$\acute{T}_d$	Transient field short circuit time constant	5
T_s	Equivalent time constant of the steam turbine	5
$\acute{X}_{ds}$	$=\grave{X}_d + X_{TL} + X_T$	0.84
X_{qs}	$=X_q + X_{TL} + X_T$	1.08
ω_o	System speed	$2\pi f_o$ here $\omega_o = 1$
M	Inertia coefficient of generator	7.6
P_{mo}	Initial mechanical power input from the turbine	1
P_m	Mechanical power input from the prime mover	

5.3.2 Load Angle Stabilizing Implementation Using Simulink

5.3.2.1 Implementation of Load Angle Stabilizing Controller for Fully Linearized Model

After the full linearized model for synchronous generator has been derived in chapter four we study the effect of pole locations with respect to origin of $(jw - axis)$ on the closed loop response and the difference between the use of derivative blocks and implementation of derivative using high pass filter.

We will choose three groups of values, for each group will study the effect of pole location with respect to three values of damping ratio (ζ) (0.1, 0.5 and 0.9) in order to study the influence of the variation of damping ration (ζ) on each group.

Therefore, the first group of values will be two complex conjugate poles near the ($jw - axis$) and a third real pull out from ($jw - axis$) and see the effect of damping ratio on each values.

In the second group all three poles are near each other on left side of ($jw - axis$) and change the value of damping ratio (ζ) and study the effect on response of the model

The third group keep the real pole (α) near origin ($jw - axis$) and try to pull out the complex conjugate poles away from the origin ($jw - axis$) and with the same three values of damping ratio (ζ) which is (0.1, 0.5 and 0.9).

To do so, using the MATLAB code in appendix (A) to evaluate the unit step response for each group of values and estimate the controller constant (Kd1, Kd2 and Kp) for each value. After that use the estimated constants firstly with derivative blocks controller with variation of damping ratio, natural frequency and real pole location (ζ, ω_n and $\propto$) as shown table (5-2):-

And repeat the MATLAB code from appendix (A) on each case in three groups of values so, In group one the first three cases where the real pole (α) go far from the origin ($jw - axis$) and damping ration (ζ) change (0.1, 0.5, 0.9) the response will be as shown in figure (5-2):-

Table (5-2) selected values for case study (1,2 and 3)

Case NO	∝	ζ	ωn	Kd2	Kd1	Kp
1	5	0.1	5	6	30	125
2	10	0.5	5	15	75	250
3	15	0.9	5	24	160	375

Case NO	pole1	pole2	pole3
1	-5	-0.5+4.975i	-0.5-4.975i
2	-10	-2.5+4.33i	-2.5-4.33i
3	-15	-4.5+2.18i	-4.5-2.18i

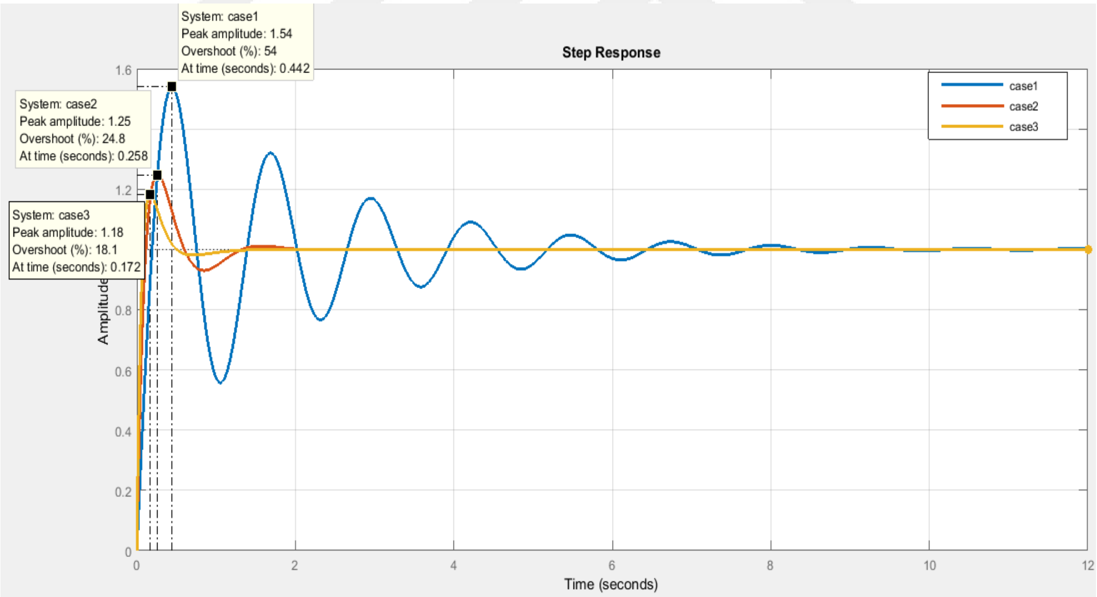


Figure (5-2) responses for case (1, 2 and 3) with (∝) go far from origin and change of ζ

In the second groups of values the three cases will show in table (5-3) where the three poles near each other and only the damping ratio (ζ) will change (0.1, 0.5, 0.9). Then will calculate the values of (Kd2, Kd1 and Kp) and substitute it in MATLAB code in appendix (A) and estimate the responses for each case as shown in figure(5-3) :-

Table (5-3) selected values for case study (4,5 and 6)

Case NO	∝	z	ωn	Kd2	Kd1	Kp
4	5	0.1	10	7	110	500
5	5	0.5	10	15	150	500
6	5	0.9	10	23	190	500

Case NO	pole1	pole2	pole3
4	-5	-1+9.95i	-1-9.95i
5	-5	-5+8.66i	-5-8.66i
6	-5	-9+4.359i	-9-4.359i

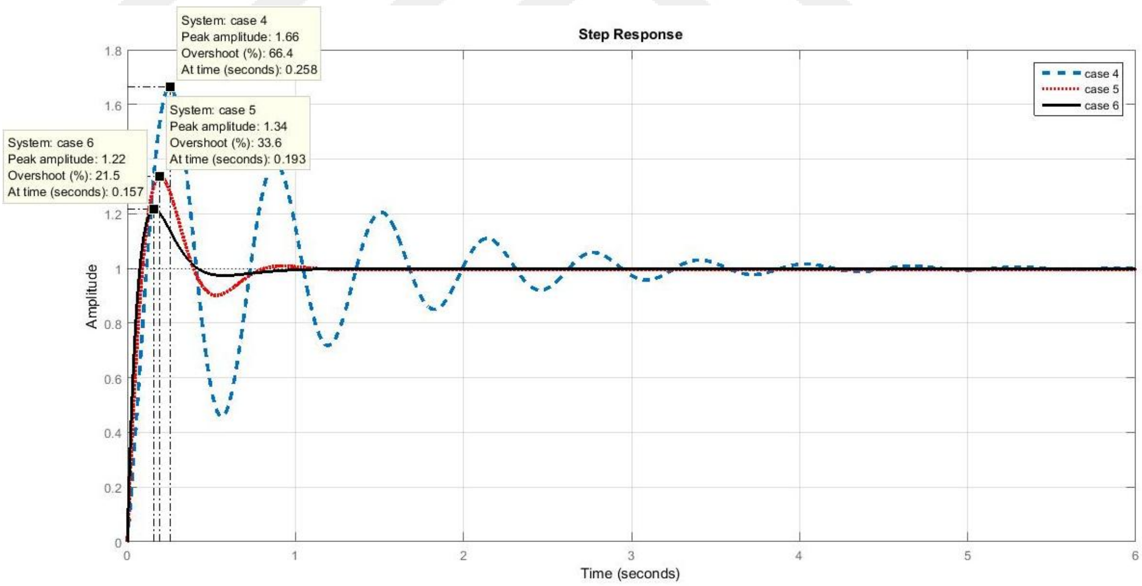


Figure (5-3) responses for case (4, 5 and 6) with all poles near each other and change of ζ

The third group of values three cases shown in table (5-4) where the complex poles goes far from the origin and keep the real pole (α) near the origin (jw-axis) and the damping ratio (ζ) will change (0.1 , 0.5 and 0.9) and after that calculate the values of controller constant (Kd2, Kd1 and Kp) and substitute it MATLAB code in appendix (A) and estimate the responses for each case as shown in figure (5-4):-

Table (5-4) selected values for case study (7,8 and 9)

Case NO	∝	z	ω_n	Kd2	Kd1	Kp
7	1	0.1	10	3	102	100
8	1	0.5	15	16	240	225
9	1	0.9	20	37	436	400

Case NO	pole1	pole2	pole3
7	-1	-0.999+9.95i	-1-9.95i
8	-1	-7.5+12.99i	-7.5-12.99i
9	-1	-18+8.718i	-18-8.718i

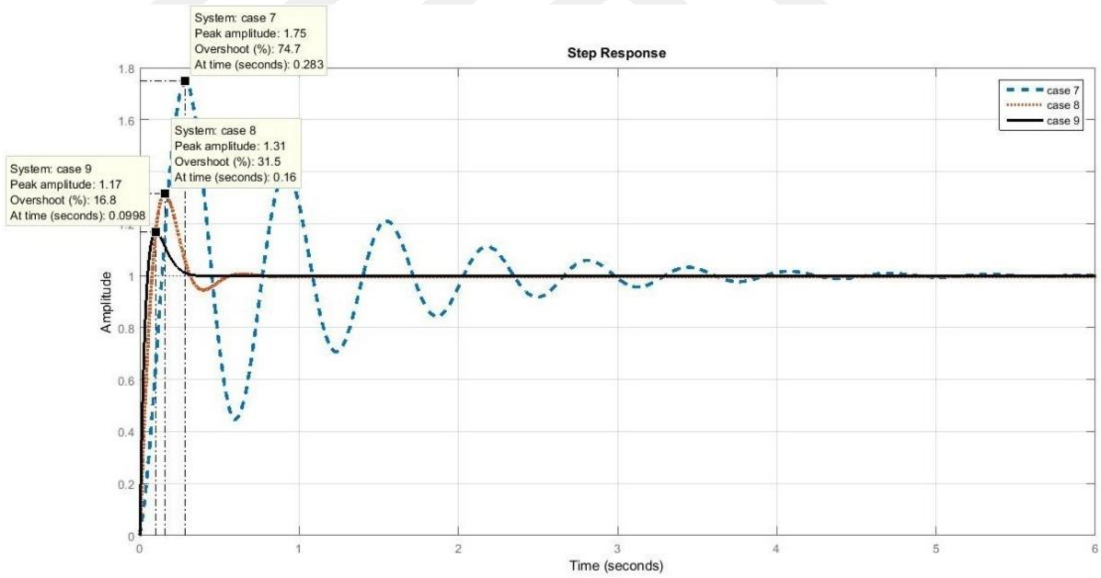


Figure (5-4) responses for case (7, 8 and 9) with complex pole go far from origin and change of ζ

From above three groups of values we can see the effect of damping ration (ζ) clearly in reducing the oscillation of the response when increase it to (0.9) and make the system more stable. From the previous three groups of cases and in order to select the best parameters or values for controller that gives best results and best responses.

We can select the following cases from each group:-

1-(Case 3) from group one,

2-(Case 6) from group two

3- (Case 9) from group three.

Then in order to compare between them we should plot them together as shown in figure (5-5) to select the best case which give us better controller constants (Kd2, Kd1 and Kp) . So, far we can implement these values in Simulink circuits to show the influence of MATLAB derivative blocks and derivative blocks implementation on fully linearized generator model. So, the circuit will be connected as shown in figure (5-6):-

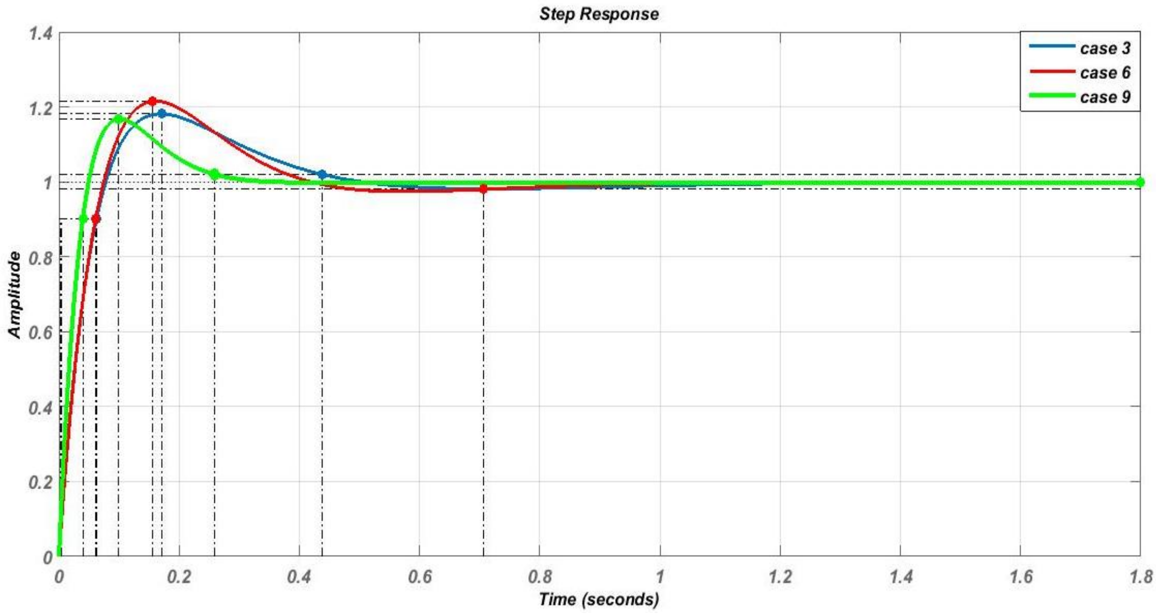


Figure (5-5) responses comparison for case (3, 6 and 9)

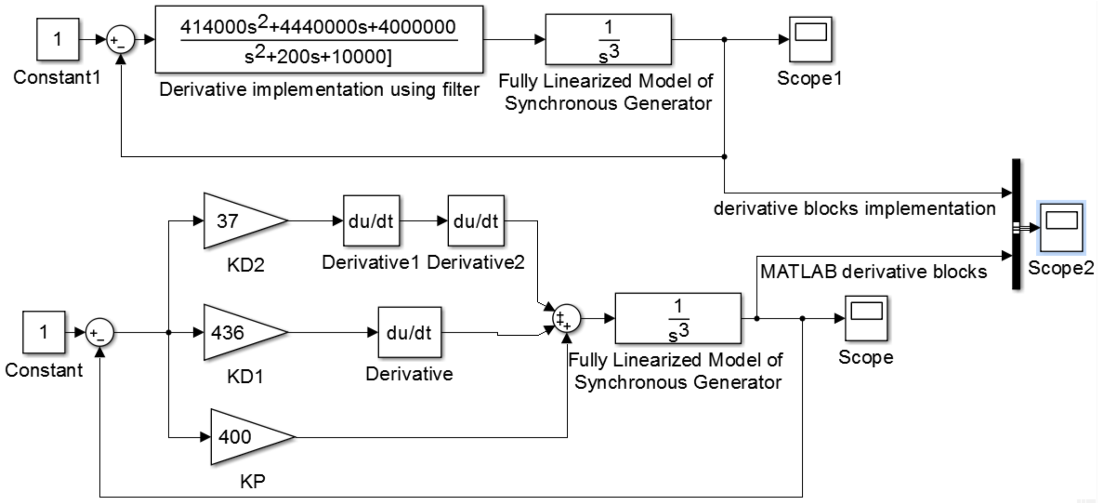


Figure (5-6) MATLAB Derivative blocks and the implementation of derivative blocks circuit with fully linearized model case 9

After connecting the circuit as shown in figure (5-6) and then estimate the responses for both technique (derivative blocks and derivative implementation) as shown in figure (5-7) below:-

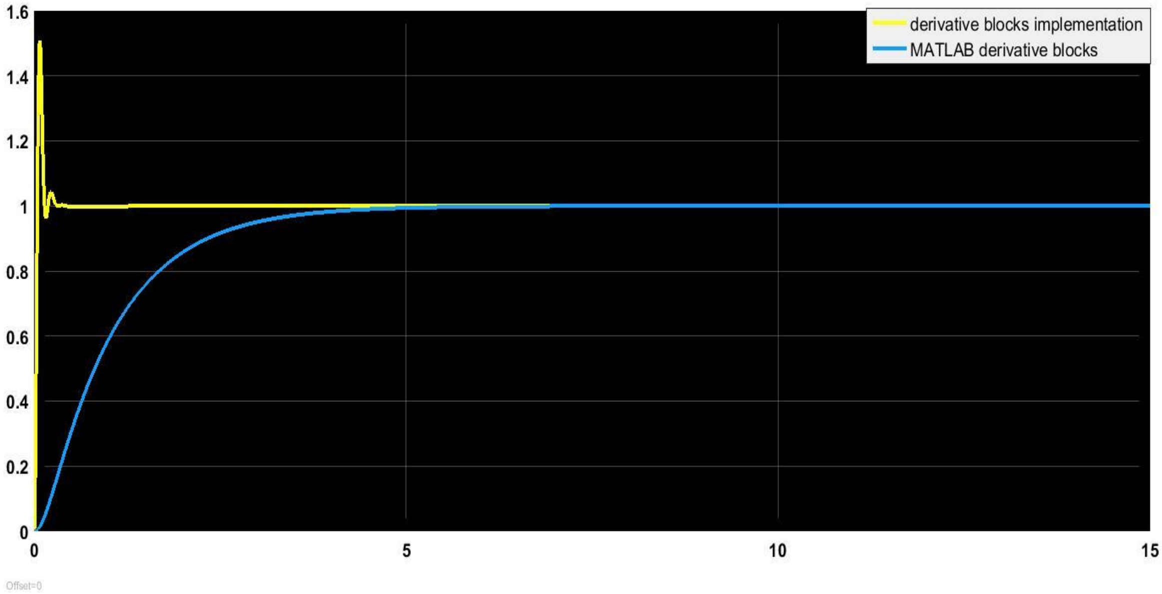


Figure (5-7) the difference between the MATLAB derivative Block and implementation of derivative case 9

Now, from figure (5-7) we can see the difference between MATLAB derivative blocks and implementation of derivative blocks using high pass filter. The influence of MATLAB derivative makes the system response slow. On the other hand, the implementation of derivatives give us a high over shoot reached to (50%) and fast response. Therefore, we use a filter equal to ($\frac{1}{0.5s+1}$) connected to the input of the system to overcome this problem and get good performance.

Now, according to following equation:-

$$PDD2 = \frac{(Kp + Kd1N + Kd2N^2)s^2 + (2NKp + Kd1N^2)s + KpN^2}{s^2 + 2Ns + N^2}$$

Will estimate the equivalent implementation for each above nine cases as shown in table (5-5) for N=100:-

Table 5.5- transfer function numerator coefficients for N=100 which is equivalent to MATLAB derivative blocks parameters for previous nine cases

case no	S^ 2	S	KpN^2
1	63125	325000	1250000
2	157750	800000	2500000
3	256375	1675000	3750000
4	81500	1200000	5000000
5	165500	1600000	5000000
6	249500	2000000	5000000
7	40300	1040000	1000000
8	184225	2445000	2250000
9	414000	4440000	4000000

Thus, it is obviously clear that the implementation of derivative using high pass filter is the best technique therefore, this technique will be adopted in our controller design. This decision has been taken rely on the following reasons. The first reason is that it makes the system more stable, and secondly makes the system reach to steady state faster than the other method and eliminate the effect of high overshoot by adding filter in the input of the system.

5.3.2.2 Implementation of Load Angle stabilizing Controller for Nonlinear Model

Here in this section we have two objective the first one is to show a comparison between the nonlinear model and fully linearized model of synchronous generator which is obtained using input-output feedback linearization method for both controller representations (MATLAB derivative blocks and implementation of derivative) to study the influence of nonlinear parts in model dynamics on whole system after elimination for these parts from model dynamics and ensure that the linearized model which is estimated using input-output feedback linearization method is equivalent to nonlinear model.

The second objective is to choose which representation for controller is the best the MATLAB derivative blocks or implementation of derivative using high pass filter? These controller representation will be used to stabilize the load angle (δ) then will study the effect of poles position with respect to (jw-axis) and (ζ) on controller operation and response.

To start with first objective will select parameters in case (3) from the previous section rely on good response where in theses issue the (α) is pull out from the origin with (ζ) equal to (0.9) then connect the circuit as shown in figure (5-8).

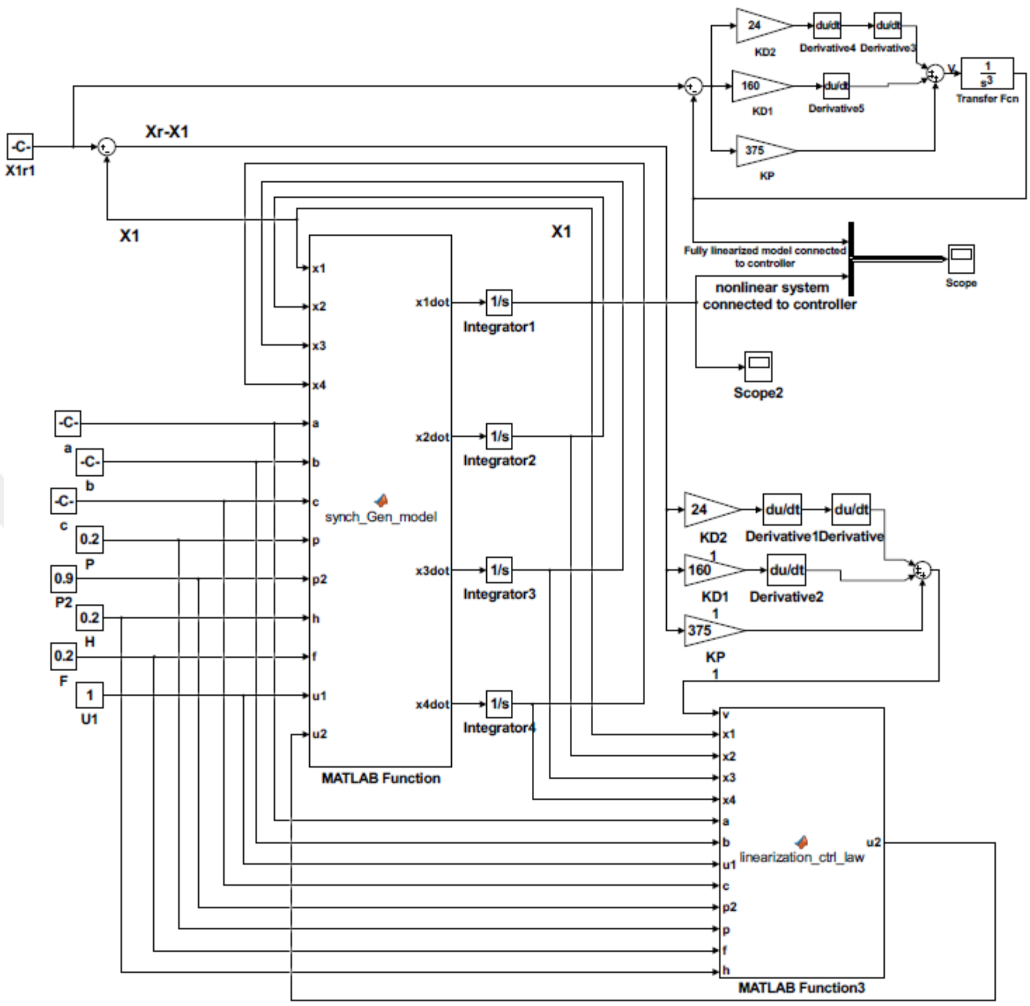


Figure (5-8) case 3 comparison between nonlinear system and full linearized model using derivative blocks

In this circuit will use MATLAB function block in order to add nonlinear elements in system equations and the control law which is estimated in chapter four using input output feedback linearization and the controller will represented firstly by MATLAB derivative blocks representation then compare between fully linearized model and nonlinear model for synchronous generator.

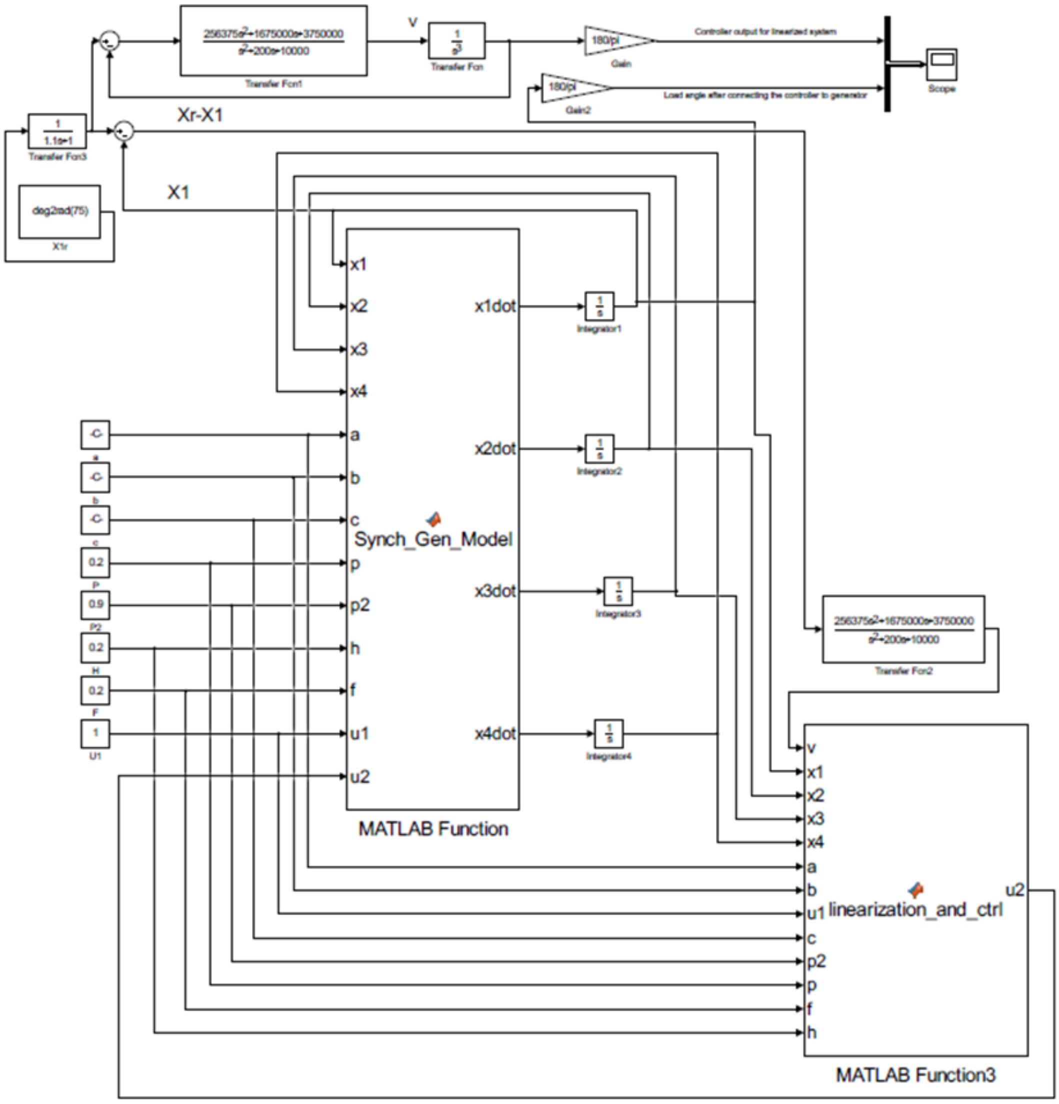


Figure (5-9) case 3 compare between nonlinear system and full linearized model by implementing the derivative

Then repeat this step and represent the controller by derivative implementation using high pass filter as shown (5-9) then compare between the results to study the system behavior after linearization in both representation.

Now, from figure (5-10) and figure (5-11) which are the responses obtained from circuit in figures (5-8) and (5-9) respectively we can conclude that the fully linearized system is equivalent and identical to nonlinear system and the nonlinearity parts and the type of representation for controller of using derivative blocks or implementing of the derivative has no effect on the performance of system.

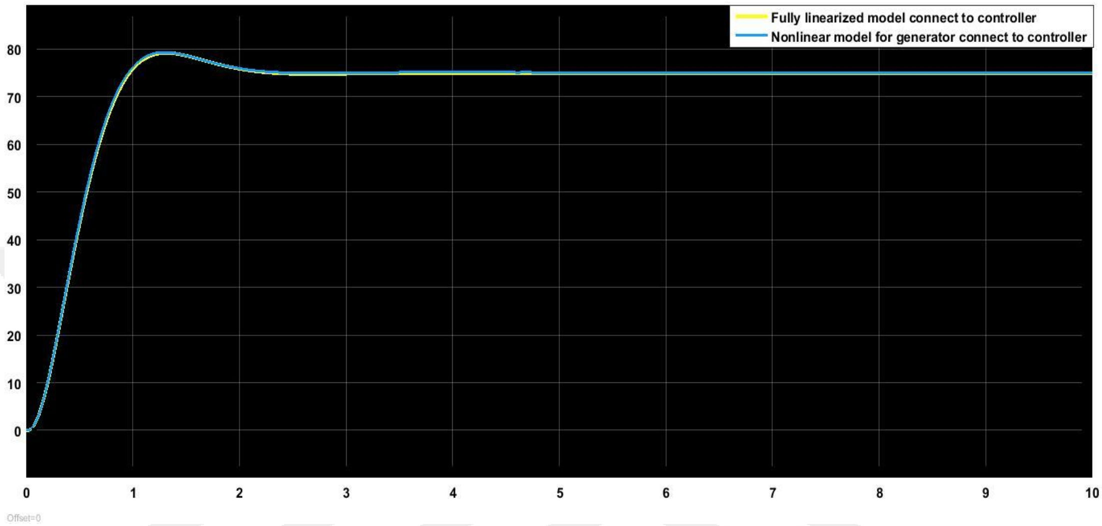


Figure (5-10) difference between the nonlinear and linear model using derivative blocks in Simulink (δ=75°)

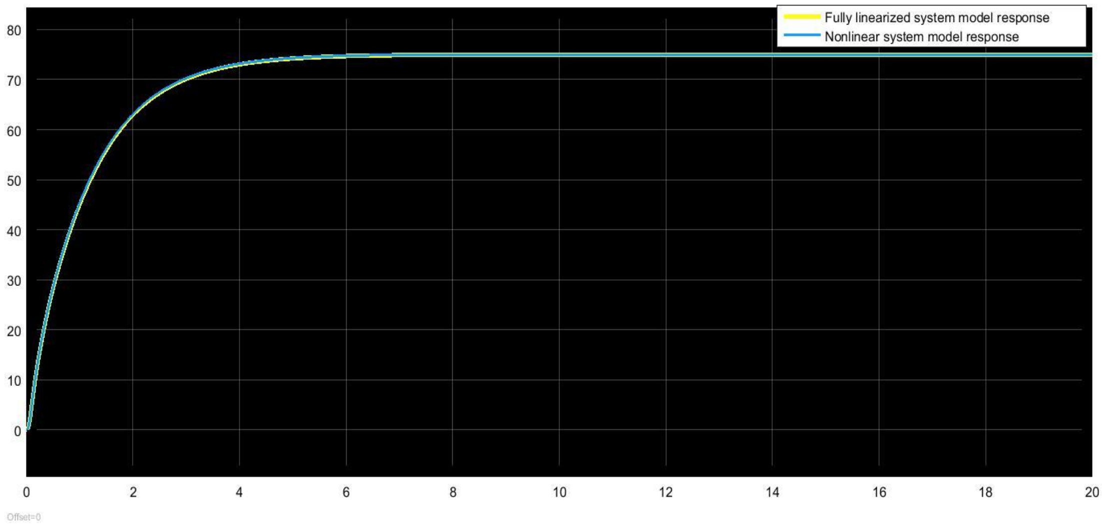


Figure (5-11) difference between the nonlinear and linear model using derivative implementation in Simulink (values of case 3)

Thus, in order to compare the value of controller constants according to poles position and (ζ) in the next section will use the implementation of derivative using high pass filter because MATLAB derivative blocks as mention in [45] should be avoided wherever possible especially in real application (nonlinear models) because of high frequency noise amplification as we said before.

5.3.2.3 Poles Location Effects in S-domain On Load Angle (δ) Controller Constants

In this section will study the effect of system poles locations on nonlinear system behavior and see the responses for three case with damping ration (ζ=0.9) these values and parameter for case (3, 6, and 9) where case three is real pol near the origin, case 6 all three pole near each other and case nine the real pole is far from the origin as we said before as shown in table (5-6):-

Table 5-6 Controller constants and system poles for nonlinear system synchronous generator

Case NO	**∝**	**ζ**	**ωn**	Kd2	Kd1	Kp
3	15	0.9	5	24	160	375
Case NO	Pole1		Pole 2		Pole 3	
3	-15		-4.5+2.1795i		-4.5-2.1795i	
Case NO	**∝**	**ζ**	**ωn**	Kd2	Kd1	Kp
6	5	0.9	10	23	190	500
Case NO	Pole1		Pole 2		Pole 3	
6	-5		-9+4.359i		-9-4.359i	
Case NO	**∝**	**ζ**	**ωn**	Kd2	Kd1	Kp
9	1	0.9	20	37	436	400
Case NO	Pole1		Pole 2		Pole 3	
9	-1		-18+8.718i		-18-8.718i	

One can now find the responses for the above values using the controller design in Figure (5-9) which utilizes the derivative implementation using high pass filter and see the influence of real pole (α) on system behavior as shown in figure (5-12).

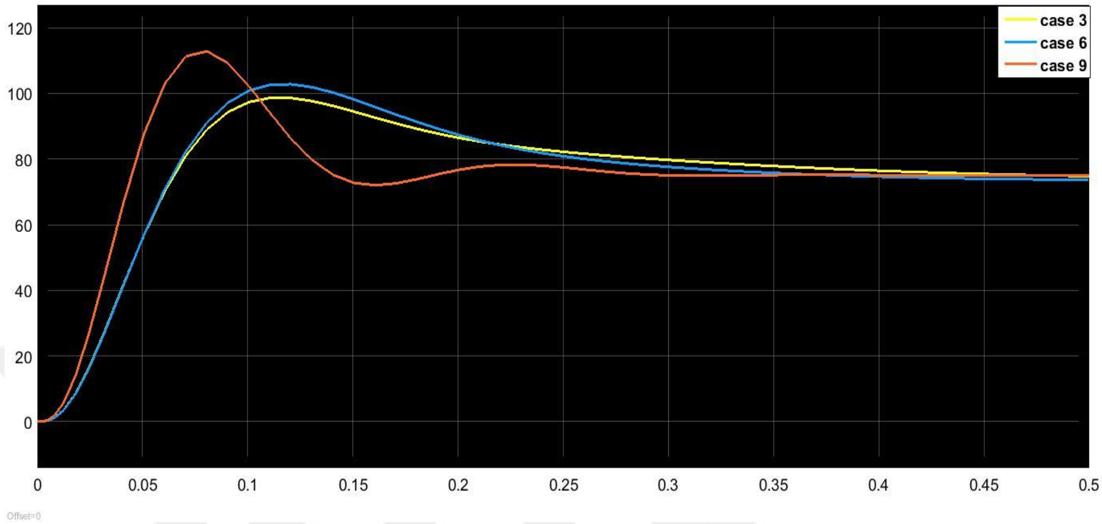


Figure (5-12) case 3, 6 and 9 poles position for load angle (δ=75°) and (ζ=0.9)

The system model has three poles two of which are complex poles and the third pole is (α) which is always real pole. It is clear from figure (5-14) that case (3) gives the best response with lowest oscillation so, we will select these values in our load angle controller for the next step when connect the both controller for load angle (δ) and terminal voltage to nonlinear system model.

5.3.3 Terminal Voltage (Vt) Controller Implementation

In this section will implement the linearized model obtained in previous chapter to control the terminal voltage (Vt) which is equivalent to first order system after applying input-output feedback linearization technique on terminal voltage equation as explain in detail in chapter four therefore, it is enough to use only proportional controller (P) to control such linearized system . Where used only (P) from (PID) controller block and use (Kp= 1.02)

In this case it is important to mention that we cannot separate the controller for terminal voltage and the load angle controller because the load angle and terminal voltage (Vt) are coupled with each other where the reference terminal voltage (desired voltage) equal to unity (Vref=1) so, the system here will be MIMO system and the controller will connected as shown is figure (5-13) and use parameter of case (3) for load angle controller constants (KP,Kd1, and Kd2)which is used in previous section and the value for (Kp) used in terminal value is equal to(1.02):-

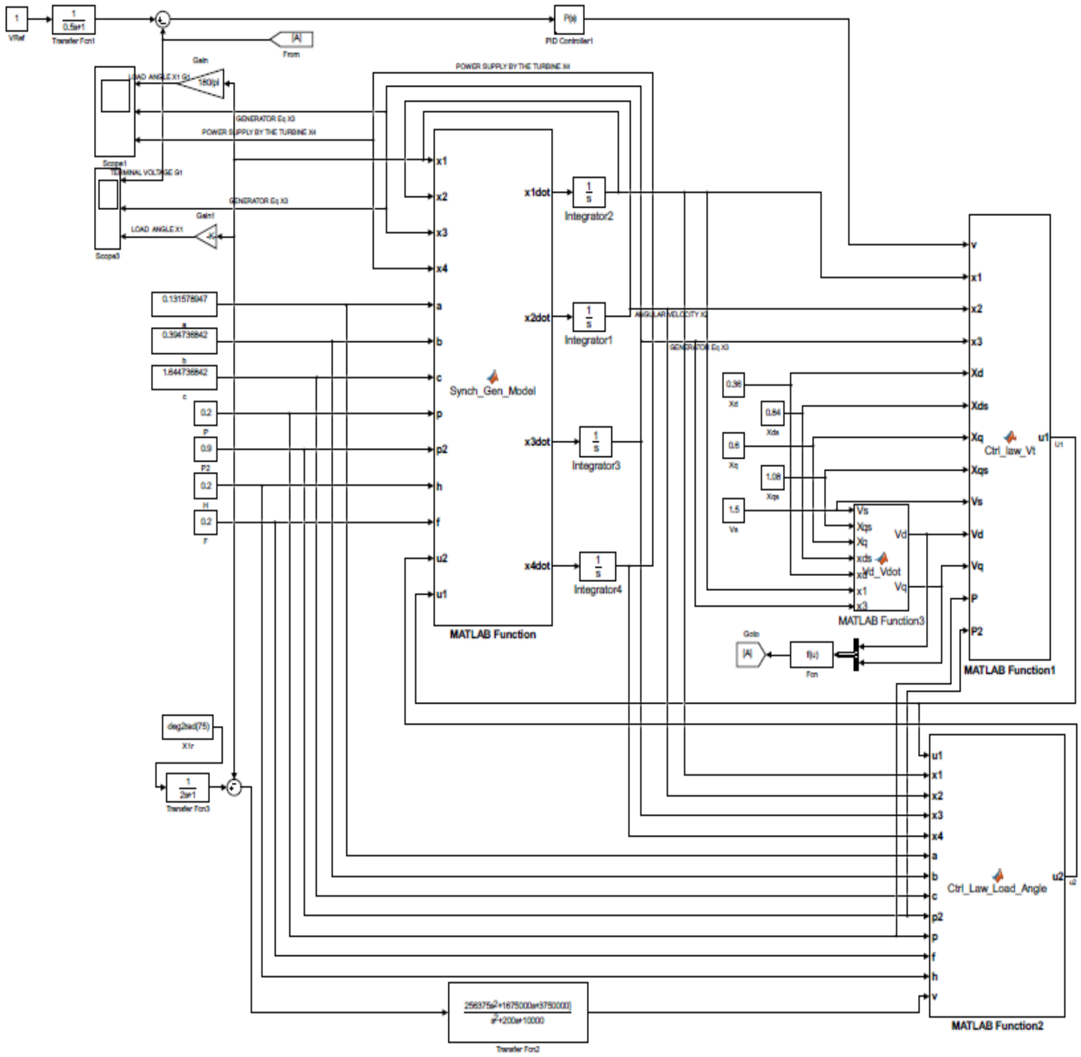


Figure (5-13) load angle and terminal voltage controller connected to nonlinear system

Then we get the result shown in figure (5-14) and figure (5-15) and all result obtained here is for load angle (δ) equal to (75°) and reference terminal voltage equal to (1)

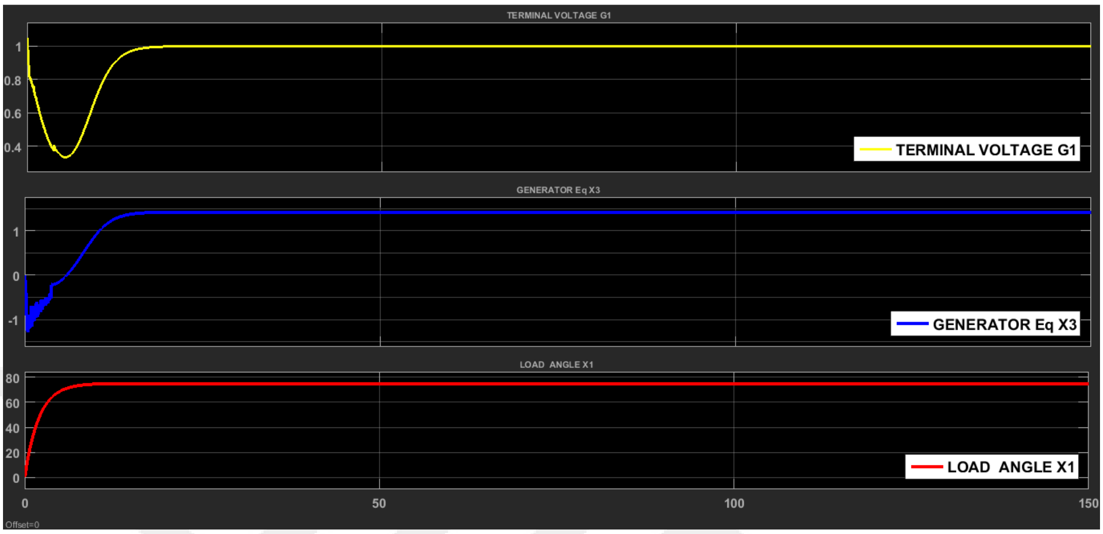


Figure (5-14) load angle (δ=75º), generated voltage Eq and terminal voltage

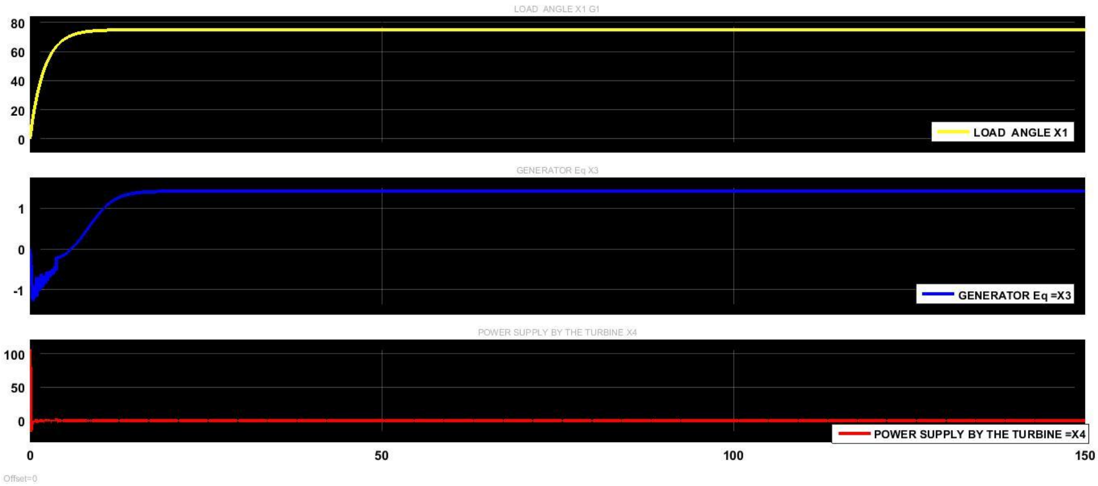


Figure (5-15) load angle (δ=75º), generated voltage Eq. and power supply by turbine

CHAPTER SIX

CONCLUSIONS AND SUGGESTION FOR FUTURE WORK

6.1 Conclusion

In this work, we did a coordinate transformation for our nonlinear synchronous generator equations this yield to define a new inputs where the nonlinearities in new coordinates are fully masked. This formation produced in linearization which are suitable and valid for huge class of operating points of the plant than Jacobian linearization. So, the feedback linearization is applied to our power system in a form of input –output feedback linearization which is performed as the output is a linear of new control input. After that, offered two stages accompany to each other aiming at the control of synchronous generators. The first stage is a theoretical study of synchronous generator controller design and the second one is the simulation of that study using Simulink in MATLAB. Here the designs generate control laws that drive steam valve and field excitation inputs of the whole plant. The control approach which is used to implement these controller based on input-output feedback linearization theory. Where the theory was applied through two stages:-

The first stage assumes the terminal voltage is fixed and manipulate the electrical signal to the steam valve controller in order to control the synchronous generator load angle. The second stage designs a controller for terminal voltage to establish a fixed level of output voltage by manipulating the excitation field voltage.

The stages are finalized by connecting both controllers (for load angle and terminal voltage) to the full nonlinear system model of our synchronous generator the mechanical and electrical subsystems are coupled (Load angle and terminal voltage) and cannot be separated.

The simulation results didn't give unexpected values or behavior for both controllers after the transients where all results converged to the desired values for both load angle and terminal voltages. In addition, the issue of implementing a derivative is resolved using band limited derivatives in form of high pass filters which does not yield any problems.

Where the load angle controller needs a different type of a PID controller which is of double derivative plus proportional (PDD2) type, because we get three poles in the origin after the model have been linearized. Of course, the controller constants was carefully chosen. These constants (Kp, Kd1 and Kd_2) are chosen according to the transient response requirements such as maximum overshoot, settling time and damping ratio. Decreasing the overshoot is a primary goal and the best case is also presented and obtained from the graphs in previous chapter. We found that the overshoot depend on the value of the damping ratio (ζ). So, regardless of poles position with respect to origin so, when increase the damping ratio (ζ) to (0.9) the overshoot is decrease and when the damping ratio decrease (ζ) to (0.1) the overshoot increase.

Finally, it is expected that the designs with high value of damping ratio (ζ) equal to (0.9) will work in realistic environment without any problems for electrical grid and system discrepancy. And these controllers can be used in practice in synchronous generator which is connect to huge electrical grid where the regulation for this generator can be done automatically.

6.2 Suggestion for Future Work

Here in this section will present the suggestions for the future work which are possible to be applied on the simulation did on synchronous generator model and its controllers. These proposed suggestion as follows:-

1. Multi generator control that is mean more than one generator can be studied and added with respect to the power flow between them. And estimate new model dynamics for that system and design symmetrical controller for each generator using one of control theories.
2. Do a robustness test for nonlinear controllers which are designed by this research. This robustness tests done by adding all expected electrical faults such as (earth fault single line to ground fault and three line fault) and also,

mechanical faults such as rotor air gap eccentricity, rotor and stator vibration characteristics stator poles faults…etc.

3. Try to apply other control theory in order to linearize the synchronous generator model and after that use of the artificial inelegance technique such as neural networks or genetic algorithm for controller tuning to reach the optimum values for controllers constants and compare the results obtained.
4. Due to large control input (field voltage)steam turbine signal one may need to perform additional work to achieve physical acceptable levels this may be done by a limiter but it lead to high frequency chattering thus the controller design should be revisited an optimization step might be a solution.

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Appendix A

Code

when $\propto$=1 and z=0.25 and wn=1

```
sys = tf([13 34 40],[1 0 0 0]);

closedloop=feedback(sys,1);

subplot(2,1,1);grid;

step(closedloop);grid;

subplot(2,1,2);grid

impulse(closedloop)
```