A Dissertation on

"SIMULATION OF TRANSIENT IN NUCLEAR POWER PLANT UNDER DISTURBANCE CONDITION"

Submitted in the partial fulfillment of the requirements of the degree of

MASTER OF TECHNOLOGY

In

NUCLEAR SCIENCE & ENGINEERING

By

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CERTIFICATE

This is to certify that the MAJOR Project-I (AP-811) report entitled **"SIMULATION OF TRANSIENT IN NUCLEAR POWER PLANT UNDER DISTURBANCE CONDITION"** *is a bonafide work done by* **AMAN GUPTA** *bearing Roll No* **(2K14/NSE/04)**, *a student of Delhi Technological University, in partial fulfilment of the requirements for the award of Degree in Master of Technology in* "**Nuclear Science & Engineering**". As per the declaration of the student this work has not been submitted for the award of any other degree or diploma.

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Candidate Declaration

I, hereby declare that the work which is being presented in this thesis entitled "**SIMULATION OF TRANSIENT IN NUCLEAR POWER PLANT UNDER DISTURBANCE CONDITION**" is my own work carried out under the guidance of Dr. N. K. Puri, Assistant Professor, Department of Applied Physics, Delhi Technological University, New Delhi.

I further declare that the matter embodied in this thesis has not been submitted for the award of any other degree or diploma.

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Acknowledgement

I would like to take this opportunity to acknowledge and extend my heartfelt gratitude to Asst. Professor **Dr. NITIN KUMAR PURI** for his vital encouragement and support which has made the completion of my project possible. His knowledge of the subject and his innovative ideas has been a great resource and inspiration. It was because of his constant guidance that I was able to complete this work.

It was the fundamentals that he taught me that enabled me to understand the problems that I faced during my project. He always had time to spare for me and guide me through the right path. He was the one who taught me to have a research oriented approach to my learning. He always inspired me to be well updated in anything that I am learning.

I would also like to thank teachers of our institute for providing me there valuable support to carry my project.

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ABSTRACT

It is well known fact that the fission products inside the reactor constitute a potential source of radiation hazard. Any abnormality in normal operating conditions of the nuclear power plant can lead to severe radioactive accident in the plant. One of such situation may occur when there is transient flowing in the system connecting nuclear power plant to the grid or load center. In case transient become high, this can led to immediate shutdown of reactor. If there is any malfunction of component in shutdown procedure of the reactor, then it can led to the severe accident with all radioactive material spread in the environment. So to prevent such condition, it is necessary that the behavior of the nuclear power plant under transient condition is studied. In this work we are going to do the same, which is to develop the model of nuclear power plant and then to simulate the effect of disturbance in the system so that the transient flowing in the system due to disturbance can be studied. This helps us to understand the behavior of the system.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

In present situation nuclear energy seems to be very promising source of energy. Especially, in present scenario where the demand for energy is increasing day by day. But, like other sources of energy it also has some serious drawback, which can go against it. The major problem associated with nuclear power plant is involvement of the radioactive material and hence, the safety of the nuclear power plant is primary concern. It is well known fact that the fission products inside the reactor constitute a potential source of radiation hazard. Any abnormality in normal operating conditions of the nuclear power plant can lead to severe radioactive accident in the plant. Hence proper safety features are needed to ensure that the integrity of the fuel is maintained throughout the operating cycle with negligible release of radioactive materials.

One of such situation may occur when there is transient flowing in the system connecting nuclear power plant to the grid or load center. Reason that transient are such dangerous because it flows for wide range of frequency and has value 4 to 5 times the normal operating value of the system. In case transient become very high and crosses permissible level of the system, this can result in immediate shutdown of reactor as the alternator is already tripped and is out of the system and hence, energy generated in the fuel pellets is no longer used for power generation. If there is any malfunction of component in shutdown procedure of the reactor, then it can led to the severe accident with all radioactive material spread in the environment.

So to prevent such condition, it is necessary that the behavior of the nuclear power plant under transient condition is studied. So that, its stability and safety is maintained, and we get the improved design of the nuclear power plant. In this work we are going to do the same, which is to develop the model of nuclear power plant and then to simulate the effect of disturbance in the system so that the transient flowing in the system due to disturbance can be studied. This helps us to understand the behavior of the system.

Using same nuclear power plant model we will verify that the power generated by the reactor mainly depends upon neutron population in a reactor. More the number of neutrons in the reactor more the fission reaction taking place inside it and greater is the energy generated. Thus, to control the power generated by the reactor, the neutron population or multiplication factor ‘k’ must be controlled. Complete modeling of nuclear power plant and its simulation work is done on MATLAB software using its SIMULINK tool.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In recent times way the energy is generated is taken a huge step ahead and many new energy sources has come into the picture. Most of them are renewable in nature and has wide scope of energy generation. Some of these are solar, wind, marine, geothermal and many others. But form past few decades the energy source that has emerged as suitable alternative to thermal power plant is nuclear energy or nuclear power plant. Nuclear energy can termed as renewable energy source as very small amount of nuclear fuel gives very huge amount of energy and thus, provides us inexhaustible kind of energy source.

Therefore, major portion of this work is concentrated on nuclear power plant and to start with there is some brief introduction regarding its material, fuel, working and most important safety aspect of nuclear power plant.

2.2 NUCLEAR POWER PLANT

Nuclear power plant is a facility in which electricity is generated from the heat released by a nuclear reaction. This reaction is called nuclear fission, in this a heavy nucleus split into small nuclei along with some neutron and large amount of energy is also released.

The release of energy in the nuclear fission reaction may be illustrated by considering the fission of a U^{235} atom, which splits up into barium and krypton atoms and releases three more neutrons for further fission of other U^{235} atoms and thus chain reaction is sustained.

$$U^{235} + n \rightarrow Ba^{141} + Kr^{92} + 3n$$

If we consider the mass of the components in above reaction we could conclude that the components on the right-hand side of the equation weighed 0.091% less than those on the left-hand side of the equation. Thus, during the reaction, approximately 0.1% of the original mass is converted into energy. Conversion of mass into energy is in accordance with Einstein's equation of

$$E = mc^2$$

where,

E = energy released (J)

m = loss of mass (kg)

c = speed of light (m/s)

The energy released appears as kinetic energy of the fission products and neutrons, which then collide with surrounding atoms and increases their thermal energy and thus, released heat can be utilized for power generation.

2.3 NUCLEAR REACTOR

Nuclear reactor is most important part of nuclear power plant. It is a system that contains and controls sustained nuclear chain reactions of fissile material with the consequent release of energy. Before discussing about different types of reactor used for power generation, it would be helpful if we review some important parts and components of a typical reactor.

2.3.1 FUEL

The fuel elements are embodied inside reactor structure this region is called reactor core. Generally, the most basic fuel used in typical reactor is uranium. The fuel may have various physical forms such as metal, or an alloy or a compound such as the oxide UO_2 or carbide UC of fissile material. Usually, the pellets of the fuel are arranged in tubes to form fuel rods. The rods are arranged into fuel assemblies inside the reactor core.

2.3.2 MODERATOR

In nuclear fission reaction we get free neutron as one of the products, initial they are of very high kinetic energy. At this energy level they have low probability of carrying out other fission reaction. So, they have to be slowed down to thermal energy range so that absorption cross-section of the material increases considerable. Thus, moderation is the process of the reduction initial high kinetic energy free neutron to thermal energy range. These initial high energy neutrons are called fast neutron because of their high speed.

The reduction in energy is accompanied with the reduction of neutron speed. Thus, it is also known as neutron slow down. Since energy is conserved, reduction of the neutron kinetic energy takes place by transfer of energy to other material.

A moderator is a medium that reduces the energy of fast neutrons, and turning them into thermal neutrons capable of sustaining a nuclear chain reaction involving uranium-235 or a similar fissile nuclide as a reactor fuel. The nuclei with low mass number are most effective for the purpose of moderator. Therefore, moderator is always low mass number material. Water, heavy water, graphite are often used as moderator. Occasionally, beryllium and beryllium oxide is used as moderator but it is very costly.

2.3.3COOLANT

It is main working fluid that is used to remove the heat generated from the fuel elements inside the reactor. In many reactors, this heat is then used in a steam generator or boiler to raise the steam. This type of cooling system is called two stage cooling system. In first stage heat is transferred from fuel elements to coolant and in second stage heat in coolant is used to generate the steam. This type of configuration is used in pressurized water reactor (PWR). While in single stage cooling system the steam is generated directly in the reactor core and then it is passed through the turbine that drives the electrical generator. This is commonly used in boiling-water reactor (BWR).

Some important properties that all coolant must have are high specific heat and high rate of heat transfer so that the heat generated inside the reactor is removed effectively, good nuclear properties as it does not absorb any neutron and remain inactive in high radioactive region, cost and availability it should cheap and easily available in plenty, compatibility it must be compatible with reactor cooling circuit and does not have any corrosive action with reactor structure, ease of pumping because coolant with low viscosity require much less pumping power to circulate them around the reactor circuit than required for high viscosity coolant.

The material used as coolant in nuclear reactor are water, heavy water, liquid sodium and molten salts these are liquid coolants the gaseous coolant are steam, helium and carbon dioxide. In case water or heavy water used as coolant in reactor then it also serve the propose of moderator inside the reactor.

2.3.4 CONTROL RODS

It is most important part of the reactor control system. Form the above nuclear fission reaction we have seen that every single neutron that causes fission produces three neutron in return which again causes further fission and produces more neutron. Thus, the number of free neutron increase exponentially and therefore heat generated inside the rector also increases in same proportion. Therefore to control the generated heat in the reactor we required some control device to control the chain reaction of the reactor that ensure safety of nuclear power plant.

Control rod is a device containing material having a high neutron absorption cross section that is used to govern the rate of fission reaction in nuclear reactor by absorbing excess neutrons. These are movable in nature which provides more flexibility in controlling the reactor. As they absorb neutron, any movement of control rod affect the neutron population inside the reactor. On withdrawal of the rods the neutron population increases while insertion of it decreases neutron population. Thus, reactor can be start, shut down or output power can be changed by appropriate motion of control rods. Control rod are adjusted to keep the reactor critical and to be operated at specific power level according to the requirement.

Materials that can be used as control rods are boron, cadmium, indium, silver and hafnium. Of these boron has high neutron absorption cross section and hence is most widely used control rod material.

2.4 TYPES OF REACTOR

There different types of nuclear power reactor that are used today for power generation around the world. These reactors have different configuration in terms of material used as fuel, coolant, moderator and control rod material. Reactor may also differ in terms of operating temperature and pressure of various components of the reactor. Typical types of reactor are shown below in tabular form.

Table 2.1 - Types of reactor

REACTOR TYPE	FUEL	COOLANT	MODERATOR
Boiling water reactor (BWR)	Enriched uranium dioxide (UO_2)	Water	Water
Pressurized water reactor (PWR)	Enriched uranium dioxide (UO_2)	Water	Water
Pressurized heavy water reactor (PHWR)	Natural uranium dioxide (UO_2)	Heavy water	Heavy water
Light water graphite reactors	Enriched uranium dioxide (UO_2)	Pressurized water	Graphite
Gas cooled reactor	Natural or enriched uranium dioxide (UO_2)	Carbon dioxide (CO_2)	Graphite
Fast neutron reactor	plutonium dioxide (PuO_2) and uranium dioxide (UO_2)	Molten sodium	None

From above classification we see that all reactors have different combination for fuel, coolant and moderator. However, they can also be classified on the basis of different parameters such as purpose of reactor. Generally, nuclear reactors serve three purposes. Firstly, civilian reactors are used to generate energy for electricity, secondly military reactors that are used to create materials to be used in nuclear weapons, and lastly research reactors that are used to develop weapons or energy production technology, for training purposes, for nuclear physics experimentation, and for producing radio-isotopes for medicine and research fields.

Out of all these reactors we have chosen pressurized water reactor (PWR) for our simulation work because it is the most common types of commercial reactor used in our country.

2.5 PRESSURIZED WATER REACTOR

This is the most common type reactor used with over 230 in use for power generation and several hundred more employed for naval propulsion. From above table it can be seen that it uses ordinary water as both coolant and moderator. Principal of this reactor is that the coolant circuit containing ordinary water is pressurized to prevent boiling of it even at very high temperature. These types of reactor involve two stage heat transfer system from reactor to turbine. In this hot pressurized liquid water as a coolant from the primary circuit is used to generate steam in secondary circuit at lower pressure. Steam is generated in the boiler and is fed directly to the steam turbine that is coupled to the generator.

Light water enters the reactor core at the temperature about 290 ^{0}C or 550 ^{0}F. The water passes down to bottom of the core of fuel assembly and then flows up the core between the fuel elements collecting the energy generated in the fuel pellets. Heated light water exits the reactor core through a series of pipes at temperature of about 350 ^{0}C or 630 ^{0}F. The coolant light water is maintained at high pressure of about 15 MPa or 150 bars, at such high pressure water will not boil and remain in liquid state. The light water coolant also acts as the moderator for the reactor. Neutrons absorbed by the light water makes the enrichment of uranium necessary. The fuel used is approximately is 3 % to 4 % enriched compared to natural uranium.

Since coolant water does not boil in the reactor, hence the steam for the turbine must be produce external outside the reactor. For this purpose steam generator or boiler is used, it is kind of heat exchanger with pressurized light water from the reactor on the hot side. The heat is transferred from the hot pressurized water to comparatively cooler water on the other side. This generates the steam that is used for turbine to rotate.

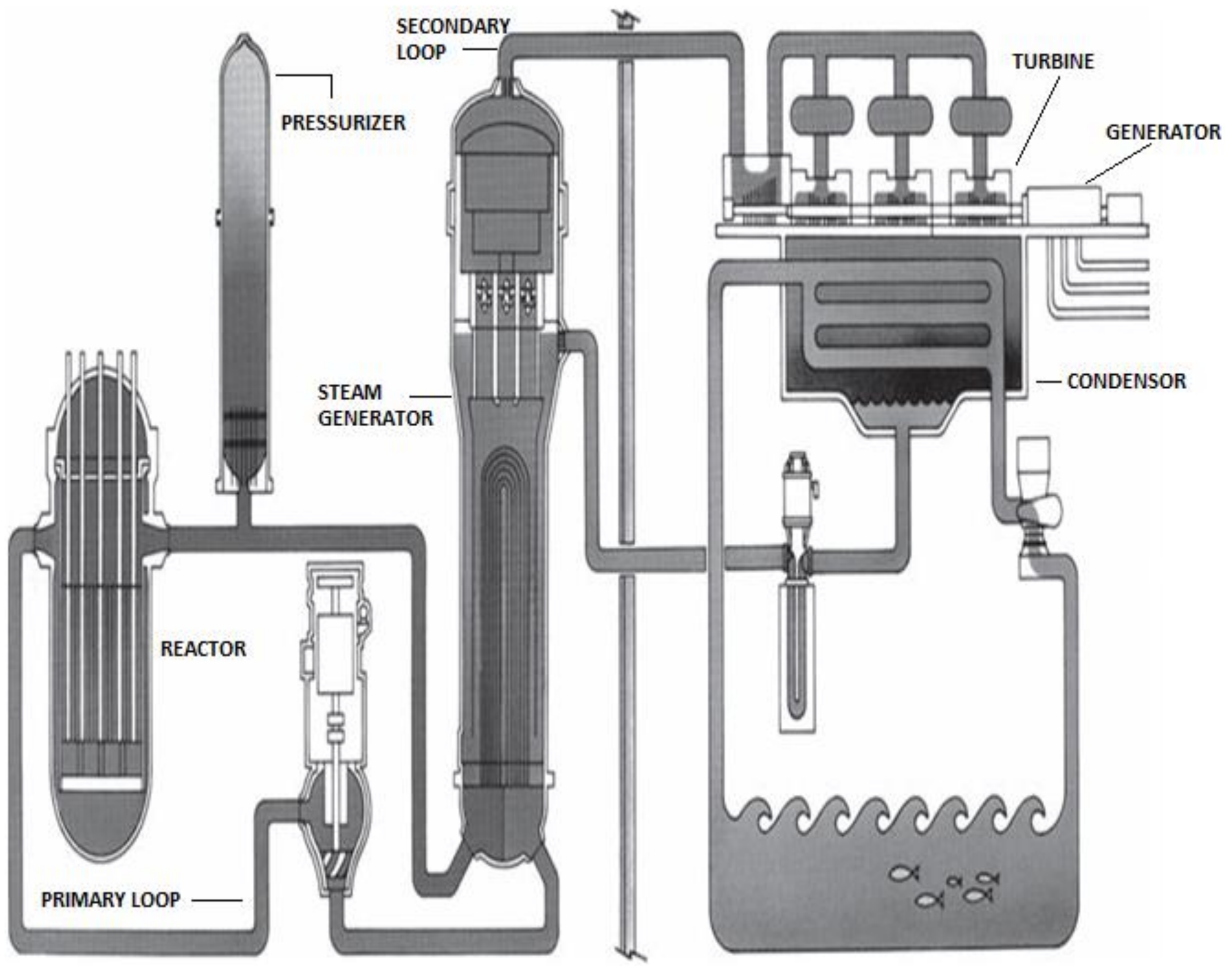

Figure 1.1 - Schematic diagram of the light water-moderated and water-cooled pressurized water reactor (PWR)

The steam that goes to turbine is at approximately 320 ^{0}C or 610 ^{0}F 7 MPa or 70 bars. It passes from the steam generator into the turbine where heat energy of the steam is used to rotate the turbine. Inside the turbine steam expands and both temperature and pressure of the steam decreases. From the turbine low pressure steam moves to condenser, where it condensate into water and is then returned to the steam generator for reuse as steam and same process flows continuously. Pressurized water reactor (PWR) typically has two, three, or four such steam generating loops per reactor vessel.

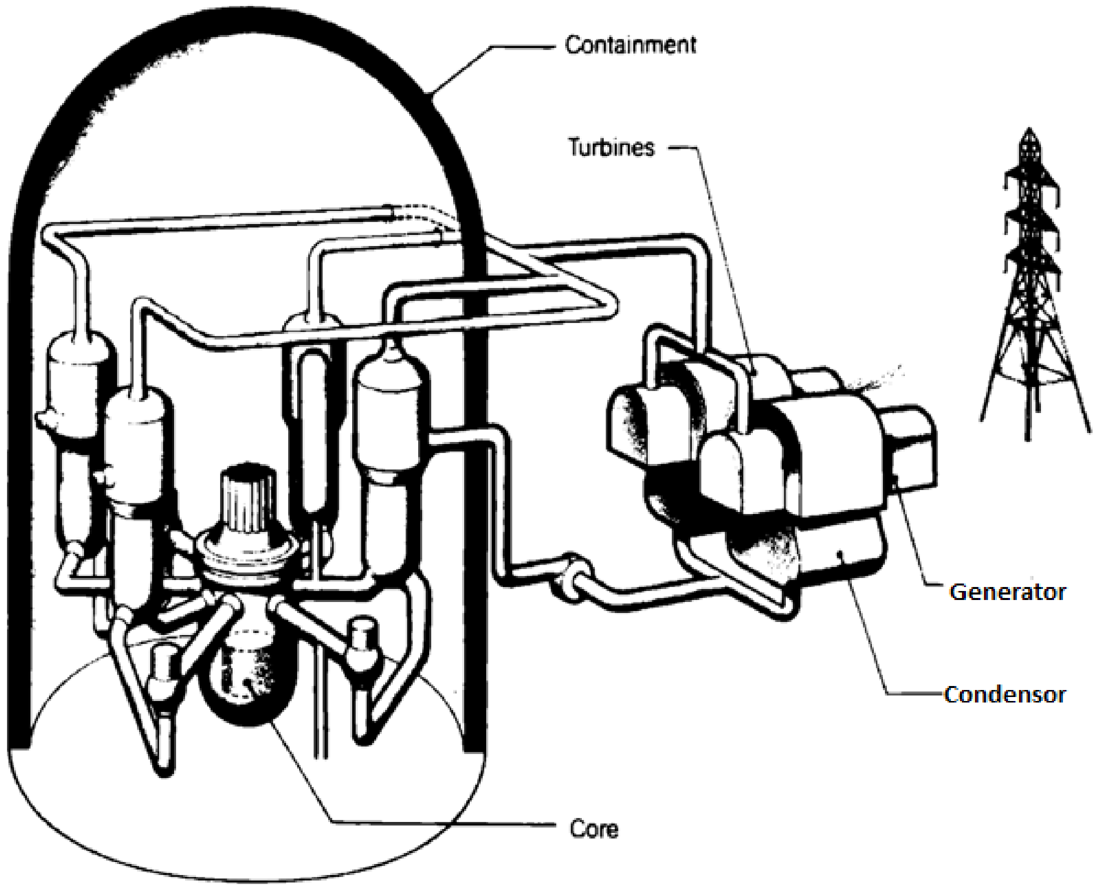

Figure 1.2 – Four loop pressurized water reactor (PWR) with turbine and generator

As the heat energy of steam rotates the turbine, the generator coupled to it also rotates. This causes the copper conductor to cut the magnetic field inside the generator and to produce the electrical energy. This generated power can be transmitted to any part of the country though transmission lines and can be used for any purposes. Thus, we get clean, reliable and sustainable source of energy for long term utilization.

Now coming to the reactor fuel assembly, the fuel elements in a pressurized water reactor (PWR) are in the form of uranium oxide (UO_2) pellets mounted in a 4m long tube made of a zirconium alloy called zircaloy. That prevents the radioactive fission product to escape the fuel pellets. This stops the mixing and reaction of radioactive fission by product with the fuel assembly surroundings. If zircloy tube were not used then there may be the case that radioactive fission product can get into primary coolant circuit which make the light water radioactive. This could have been harmful adverse effect on the structural properties of the reactor and it cooling circuit. But, due to use of zircloy such situation is omitted.

Although the steam cycle efficiency of a pressurized water reactor (PWR) is low nearly to 35% to 40%, but its capital cost is considerably less than that of other reactors. This is possible because of great reduction in core size of the reactor, which is made possible by the enormous increase of volumetric power density and core rating. This can be seen from the table given below.

Table 2.2 - Volumetric Power Densities for Various Reactor Systems

Reactor	Thermal power (MW)	Core diameter (m)	Core height (m)	Core volume (m)	Avg. vol power density (MW/m^3)	Avg. fuel rating (MW/ton)
BWR	3800	5.01	3.81	75	51	24.6
PWR	3800	3.6	3.81	40	95	38.8
PHWR	3425	7.74	5.94	280	12.2	26.4
Light water graphite reactor	1875	17.37	9.14	2166	0.865	3.15
Gas cooled reactor	1500	9.1	8.3	540	2.78	11

From the table we can see that average volume power density is highest for the pressurized water reactor (PWR), it is approximately double than its second highest counterpart that is boiling water reactor (BWR). Its overall core volume is lowest among the all other reactors which makes its building and initial capital cost much lower than any other reactor. Average fuel rating shows that power generated per ton of fuel, this is also highest for the PWR. Thus, for fixed amount of fuel in all reactor the power generated by the PWR is highest than all other counterparts reactor and because of the high rate of heat generated per unit mass of fuel (fuel rating) the response of a pressurized water reactor (PWR) to changes in operating conditions is much more rapid than that of any other reactor. Hence, we can understand the reason of its popularity and why the PWR constitute the major portion of all existing reactor in world.

2.6 SAFETY ASPECT OF NUCLEAR POWER PLANT

From above discussion we can conclude that the nuclear power plant has various advantages such as

- Lower emission of green house gases
- Reliability
- Efficient
- Continuous operation
- Easy transportation of fuel
- Longer life span

From above all advantages one can say that it is very promising source of energy in present scenario where the demand for energy is increasing day by day. But, like other sources of energy it also has some serious drawback, which goes against it. Some of the disadvantages are

- Production of radioactive waste
- Lack of technology for waste disposal
- Leakage of radioactive material
- Energy generated in the reactor core even after shutdown

Thus from above we conclude that the major problem associated with nuclear power plant is involvement of the radioactive material and hence, the safety of the nuclear power plant is primary concern. It is well known fact that the fission products inside the reactor constitute a potential source of radiation hazard. Any abnormality in normal operating conditions of the nuclear power plant can lead to severe radioactive accident in the plant. Hence proper safety features are needed to ensure that the integrity of the fuel is maintained throughout the operating cycle with negligible release of radioactive materials. This involves limitations on power level and temperature of the core, and requirement of cooling of reactor core under all conditions.

In spite of all the safety measure, many incidents occurred in the past 50-year period though very few of them resulted in injury or death to plant operators or the general public. These incidents has helped the designers of nuclear power stations do assess the risks and consequences of the adopted for design of the nuclear power plant. It also led the designers to focus on the risks outside the premises of the nuclear power plant. As any small technically fault in any component related to nuclear power plant can be a threat resulting into devastating consequences.

If we have to establish nuclear energy as the primary source of energy in the longer term, despite the potential dangers involved, it is essential that the each accident serves as a research opportunity for the designers for upgrading the future design with better safety management to make the nuclear power stations safer. For nuclear power plant it is essential that the entire possible scenario related to nuclear power plant is studied so that behavior of the power plant can be understand and proper safety features can be added to the existing system. One of such situation may occur when there is transient flowing in the system connecting nuclear power plant to the grid or load center.

Even if a system operates in the steady state condition for most of its time, but it must be capable of withstanding the over voltage and over current stresses generated during transient conditions in the system. It is crucial to understanding the transient behavior of the system, which helps us to eliminate the flaw in current power plant and its system design. This also allows us to improve our future design so that it can deliver a reliable and high quality power. The transient phenomena in the systems is generated by the disturbances due to switching operations, faults in the system, lightning strikes and partial discharges from defective power equipment, etc. These transient involve a frequency range from d.c. to several MHz. Transients result in over voltages, over currents, distorted waveforms or all three of them in single event. This depends on the system configuration in which transient flows.

Reason that transient are such dangerous because it flows for wide range of frequency and has value 4 to 5 times the normal operating value of the system. In case transient become very high and crosses permissible level of the system then under the protective measure of the system generator is tripped or disconnected through automatic relay operation. As generator is tripped it goes out of the system and stop generating the power, this has to be followed by immediate shutdown of reactor as the energy generated in the fuel pellets is no longer used for power generation. And if there is any malfunctioning of any component in shutdown procedure of the reactor, then it can led to the severe accident with all radioactive material spread in the environment.

So to prevent such condition, it is necessary that the behavior of the system under transient condition is studied. So, that the system's stability and safety is maintained, and we get the improved design of the nuclear power plant. In this work we are going to do the same, which is to develop the model of nuclear power plant and then to simulate the effect of disturbance in the system so that the transient flowing in the system due to disturbance can be studied. This helps us to understand the behavior of the system. Complete simulation work is done on MATLAB software using its SIMULINK tool. In next chapter we will studied about the model in detail.

CHAPTER 3

SIMULATION WORK

3.1 BLOCK DIAGRAM OF PWR POWER PLANT

Before developing the simulation model, we should know the basic block diagram of the pwr power plant. It has main components are

- Pressurized water reactor (PWR)
- Steam generator
- Steam turbine
- Alternator or electric generator
- Steam condenser
- Feedback controller

These are the some essential components of the pressurized water reactor power plant. There are some secondary components also such as coolant circuit pump, condenser pumps, heat exchanger and etc. The basic block diagram of the pressurized water reactor power plant is shown below.

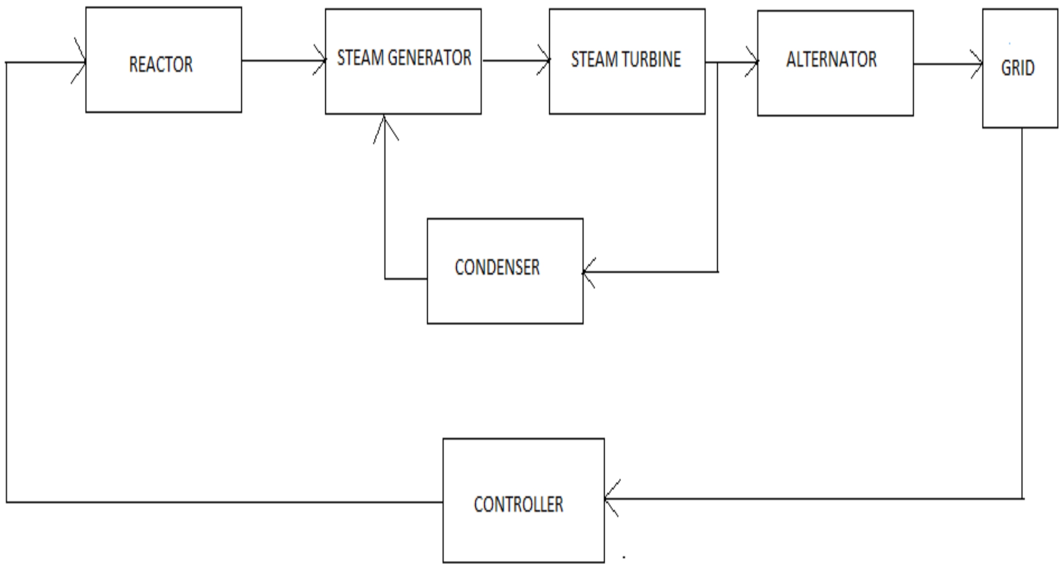

Figure 3.1 – Block diagram of PWR power plant

The above block diagram shows the basic operation of the pressurized water reactor (PWR) power plant. The basic working principal of pressurized water reactor (PWR) power plant is that the reactor coolant circuit containing ordinary water is pressurized to prevent boiling of it even at very high temperature. It involves two stage heat transfer system from reactor to turbine. In this hot pressurized liquid water as a coolant from the primary circuit is used to generate steam in secondary circuit at lower pressure. Steam is generated in the boiler and is fed directly to the steam turbine that is coupled to the generator.

Light water enters the reactor core at the temperature about 290 ^{0}C or 550 ^{0}F. The water passes down to bottom of the core of fuel assembly and then flows up the core between the fuel elements collecting the energy generated in the fuel pellets. Heated light water exits the reactor core through a series of pipes at temperature of about 350 ^{0}C or 630 ^{0}F. The coolant light water is maintained at high pressure of about 15 MPa or 150 bars, at such high pressure water will not boil and remain in liquid state. The light water coolant also acts as the moderator for the reactor. Neutrons absorbed by the light water makes the enrichment of uranium necessary. The fuel used is approximately is 3 % to 4 % enriched compared to natural uranium.

Since coolant water does not boil in the reactor, hence the steam for the turbine must be produce external outside the reactor. For this purpose steam generator or boiler is used, it is kind of heat exchanger with pressurized light water from the reactor on the hot side. The heat is transferred from the hot pressurized water to comparatively cooler water on the other side. This generates the steam that is used for turbine to rotate.

The steam that goes to turbine is at approximately 320 ^{0}C or 610 ^{0}F 7 MPa or 70 bars. It passes from the steam generator into the turbine where heat energy of the steam is used to rotate the turbine. Inside the turbine steam expands and both temperature and pressure of the steam decreases. From the turbine low pressure steam moves to condenser, where it condensate into water and is then returned to the steam generator for reuse as steam and same process flows continuously.

As the heat energy of steam rotates the turbine, the generator coupled to it also rotates. This causes the copper conductor to cut the magnetic field inside the generator and to produce the electrical energy. This generated power is given to the grid, from there it can be transmitted to any part of the country though transmission lines. Thus, we get clean, reliable and sustainable source of energy for long term utilization.

3.2 PRESSURIZED WATER REACTOR (PWR) BLOCK

Out of these components, pressurized water reactor is most important part of the power plant. It is a system that contains and controls sustained nuclear chain reactions of fissile material with the consequent release of energy. To simulate the reactor block various important process are consider that govern the reactor behavior. These are

- Criticality of the reactor
- Fission neutron

All these three process are very important to simulate the behavior of the reactor, and we will go through each of them one by one.

3.3 CRITICALITY OF REACTOR

When the nucleus of an unstable atom splits into two parts a considerable amount of energy is released this process is called nuclear fission. A splitting of nucleus take place when a neutron collides with a heavy nucleus causing it to split into small nuclei called the fission products. This reaction is accompanied with the release of huge amount of energy and more neutrons are generated. These additional neutrons, cause further fission of other heavy nucleus and cause them to split in lighter elements and thus chain reaction is sustained.

Nuclear fission is a process mainly driven by neutron population in a reactor. More the number of neutrons in the reactor more the fission reaction taking place inside it and greater is the energy generated. Thus, it can be said that to control the rate of the fission reaction inside reactor, the neutron population must be controlled. We have already seen that neutron induced fission reaction produces extra neutron as one of its product which carry forward fission reaction in the next generation and so on chain reaction is maintained. Nuclear energy can be harnessed in sustainable manner through fission chain reaction. Such chain reaction can be characterized in terms of multiplication factor ‘k’.

Multiplication factor ‘k’ can be defined as the ratio of number of fission neutron in one generation to the number of fission neutron in the preceding generation. In terms of equation

$$k = \frac{\text{number of fission neutron in one genration}}{\text{fission neutron in the preceding generation}}$$

If ‘k’ is greater than 1 then number of fission neutron increase from one generation to next generation. The energy released in this case increases with time, and the system or the reactor inside which it takes place is called supercritical.

If ‘k’ is less than 1, then the number of neutrons decrease with time from one generation to next generation and the energy releasing from the reaction goes on decreeing with time. Finally, chain reaction dies out and reactor is shut down. This type of system is called subcritical.

If ‘k’ is equal to 1, then the chain reaction proceed at constant rate as the number of neutron in different generation are same and energy is released at steady level. Such type of system is called critical system.

Table 3.1 – Criticality of reactor

k = 1	Critical	Steady release of energy
k < 1	Subcritical	Chain reaction dies out
k > 1	Supercritical	Chain reaction become uncontrolled

In reactor the energy released is controlled by the varying value of ‘k’. To increase the power generated by the reactor the value of ‘k’ is increased to value greater than unity and power generated by the reactor is increased. On reaching the desired power level, the value of 'k' is again reduced is to 1 to maintain the criticality and hence the specific power level is maintained by the reactor. To reduce the power or shutdown the reactor, the value of 'k' is reduced to value less than 1 to make the reactor subcritical. Thus the output power of reactor is reduced.

To simulate the effect of multiplication factor 'k' in the reactor model, we have use the gain block of MATLAB in simulink. The gain block parameter is used as multiplication factor 'k' and its variation can be seen in the behavior of reactor system simulation.

3.4 FISSION NEUTRON

Neutrons that are released in fission reaction are known as fission neutron. Most of them are released within 10^{-14} s after the fission reaction are called prompt neutron, they constitute the 99% of the fission neutron. Rest of the 1% neutron is called delayed neutron which are released long after the fission event. To simulate the effect of the fission neutron in reactor block we will use equation describe below.

Let the average number of neutron (prompt and delayed) released per fission be 'υ', and 'η' be the average number of neutron emitted per neutron absorbed by the mixture of fissile and non-fissile nuclides. The value of η can be obtained through equation given below.

$$\eta = \frac{1}{\Sigma_a} \sum_i \upsilon(i)\, \Sigma_f(i)$$

Where $\upsilon(i)$ and Σ_f are the value of υ and fission cross-section for i^{th} nuclide respectively. Σ_a is cross-section of the mixture of fissile and non-fissile nuclides. The above equation is in discrete form, to obtain equation in continuous form the summation is replaced by integration. Hence, the modified form of equation is

$$\eta = \frac{1}{\Sigma_a} \int \upsilon(i) \Sigma_f(i) di$$

Above equation can be easily modeled in MATLAB as we have the corresponding block of integration in s-domain. This block can be used to simulate the effect of fission neutron in reactor system. The s-domain integration block is cascaded with gain block used for multiplication factor 'k' as both of them are related to each other. Multiplication factor 'k' is the ratio of number of fission neutron in one generation to the number of fission neutron in the preceding generation while 'η' is the average number of neutron emitted per neutron absorbed. Thus, by simulating both these effect we get the closest approximate behavior of the reactor and hence, we can develop the simulation block for reactor. By varying the value of multiplication factor 'k' we can see the corresponding change in power level that is generated by the reactor in the simulation work.

3.5 GENERATOR BLOCK

Transient in the systems are generated mainly because of the disturbances due to faults occurrence in the system. A fault in a system is any failure that interferes with the normal operation of the system. Most of the faults is caused because of lighting strokes on high-voltage transmission lines. As a result a very high transient flows in the system that greatly exceeds the rated voltage of the line. There are 4 types of fault that occurs in the power system.

Table 3.2 – Types of fault

Type of fault	Abbreviation	Type
Single line to ground	LG	Unsymmetrical
Line to line	LL	Unsymmetrical
Double line to ground	LLG	Unsymmetrical
Symmetrical three phase	LLL	Symmetrical

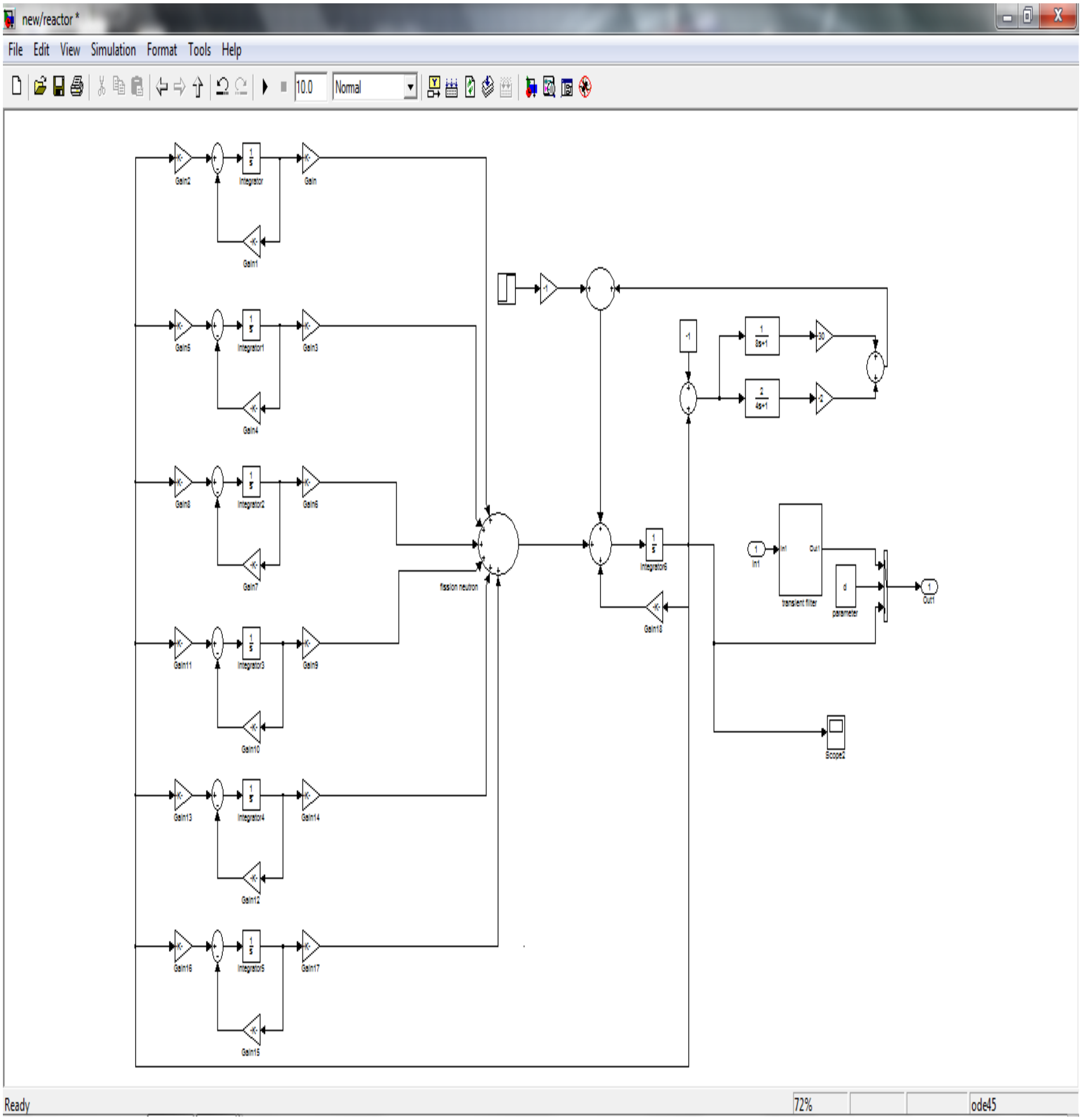

Figure 3.2 – Simulation model of reactor

Except for the three phase fault, all other faults are unsymmetrical in nature. These unsymmetrical faults results in an unbalanced system. The easiest method to analyze system operation under faults condition is through the use of symmetrical components method. In symmetrical component analysis the unbalanced system is decompose into three sequence of balanced networks. These three sequence networks are the positive sequence, negative sequence and zero sequence network. They are three sets of symmetrical balanced phasors. For all the four faults stated above specific sequence networks comes into picture out the three sequence networks that is the positive sequence, negative sequence and zero sequence network. This is represented in the table given below.

3.3 - Sequence network for different types of fault

Type of fault	**Abbreviation**	**Sequence network**
Single line to ground	LG	Positive, negative and zero sequence networks
Line to line	LL	Positive and negative sequence networks
Double line to ground	LLG	Positive, negative and zero sequence networks
Symmetrical three phase	LLL	Positive sequence network

From the above table we can see that zero sequence network are only used when there is ground involved in the fault such as single line to ground fault (LG) and double line to ground fault (LLG). Negative sequence network are used for all unsymmetrical fault that is LG, LL, LLG faults. Whereas positive sequence network are used for all the faults LG, LL, LLG and LLL faults. Thus to simulate the alternator block of PWR power plant we will use the positive sequence impedance because irrespective of the type of fault in the system transient can be simulated using positive sequence impedance as it accounts for all the fault occurring in the system.

In this case for the alternator block we will use the positive sequence impedance of alternator and transform it into s-domain to get corresponding transfer function for alternator block. This transformation in s-domain is done using Laplace Transform technique for the electrical circuit elements. Moreover, for each electrical component block in this simulation we will use same method to derive the transfer function of that respective block. That is, taking the positive sequence impedance of the each block and transforms it into respective s-domain form using Laplace Transform technique to get corresponding transfer function.

3.6 CONTROLLER

Controller compares the actual value of the output with the desired value of the power plant output and determines the deviation. This produces a control signal that reduces the deviation to zero. The manner in which controller produces the control signal is called the control action. For this simulation of transient in pwr power plant we have use proportional integral (PI) controllers.

For a controller with proportional control action the relationship between the controller output u(t) and the error signal e(t) is

$$u(t) = K_p\, e(t)$$

Using Laplace transform

$$K_P = \frac{U(s)}{E(s)}$$

Kp is termed the proportional gain.

Proportional controller is essentially an amplifier with an adjustable gain block.

For a controller with integral action, the value of the controller output u(t) is changed at a rate proportional to the error signal e(t).

$$K_i\, e(t) = \frac{du(t)}{dt}$$

Or,

$$u(t) = K_i \int_0^t e(t)\, dt$$

K_i is an adjustable constant

Transfer function of the integral controller is

$$\frac{K_i}{s} = \frac{U(s)}{E(s)}$$

In this simulation we use proportional integral (PI) controllers which combine the action of both proportional plus integral controller. The controlling action of a proportional integral controller is given by

$$u(t) = K_p\, e(t) + \frac{K_p}{T_i} \int_0^t e(t)\, dt$$

Transfer function of the PI controller is

$$\frac{U(s)}{E(s)} = K_p \left(1 + \frac{1}{T_i s}\right)$$

T_i is called the *integral* time of the controller.

3.7 INTER-CONNECTED POWER PLANT

All the power plants are inter-connected with each other. This inter-connected system so formed is called the grid. It is preferable to have inter-connected the systems because they are very important and have various advantages.

1. It improves the overall stability - Systems that are inter-connected have greater reserve power than a system working alone. Moreover, large system is able to withstand a large disturbance more efficiently and hence, it is inherently more stable.
2. Continuity of Service - If a power plant goes out of supply or if it has been shut down for repair work then the load of that generator is shared by the other power plant inter-connected in the system and the continuity of supply is maintained by the virtue of inter-connected power plant system.
3. More economical - When several power plants of different capacity is inter-connected, then the load can be shared among the various power plants so that the overall operating cost is minimized.

Because of these advantages the power plant are inter-connected but on the other hand, due to inter-connection of power plant the disturbance or transient that appears on one power plant does affect the others power plant connected in the system. Thus, it is necessary that the pwr power plant used in simulation must be connected with some other power plant also. This serves the two purposes. Firstly, it will bring the simulation model more closely to the real world inter-connected system of power plant. Secondly, this will help us to understand the behavior transient more broadly, as we can compare the effect of transient in different power plant and can also derive the conclusion regarding safety of pwr power plant on comparing it with other power plant used in simulation.

The other power plant connected with the pwr power plant is hydro power plant because it also serves as the base load power plant as it is done by pwr power plant and other reason is that the other conventional power plant that is thermal power plant is much similar to pwr power plant except that the boiler is replaced by a nuclear reactor. Moreover, hydro power plant is completely different from the pwr plant as it uses the energy of flowing water to generate power. Thus, hydro power plant is chosen as second power plant in this simulation work.

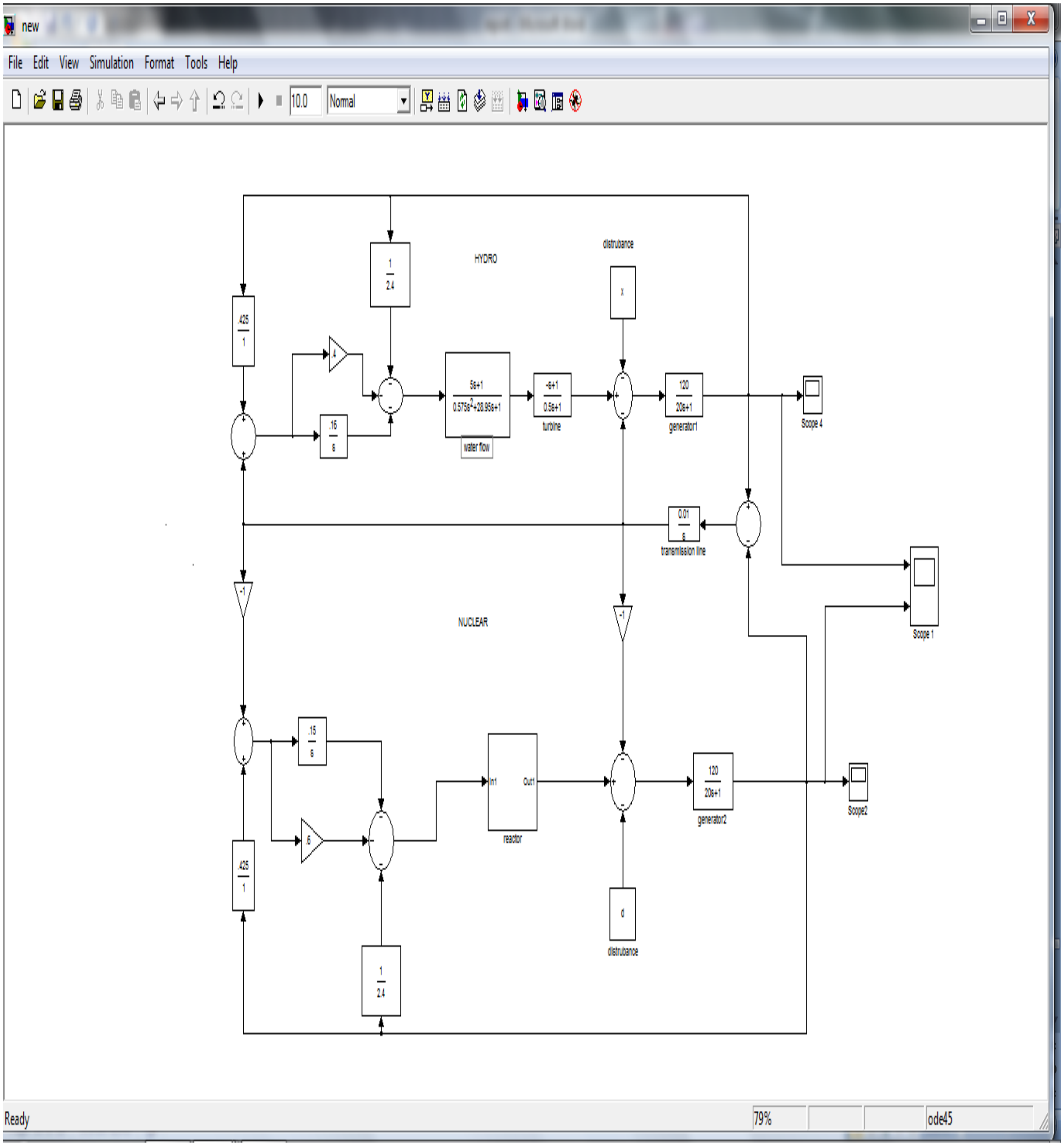

Figure 3.3 – Simulation model of PWR Power Plant inter-connected with Hydro Power Plant

CHAPTER 4

SIMULATION

4.1 SIMULATION STEPS

From the block diagram we can see that the ‘x’ is the variable given for the disturbance inserted in hydro power plant and ‘d’ is for disturbance inserted in pwr power plant. Value to the variable ‘x & d’ can assigned in the MATLAB command window and then after running the simulation we can see its effect as transient in the system from the graph for the different components. We can compare the transient that appears for the different value the disturbance inserted in the system.

There are two parts of this simulation

1. The normal operation of pwr power plant, which involves the variation in the power generated by the pwr power plant as the multiplication factor ‘k’ is varied
2. Behavior of the system under transient condition when disturbance is inserted in the simulation model. In this part there are cases in which disturbance inserted in simulation is varied and its behavior on both the power plant is studied.

4.2 NORMAL OPERATION OF PWR POWER PLANT

Under this part there are mainly three cases

1. $k = 1$ Critical
2. $k < 1$ Subcritical
3. $k > 1$ Supercritical

These cases are taken one by one below

- Case 1 – For k = 1 (critical system)

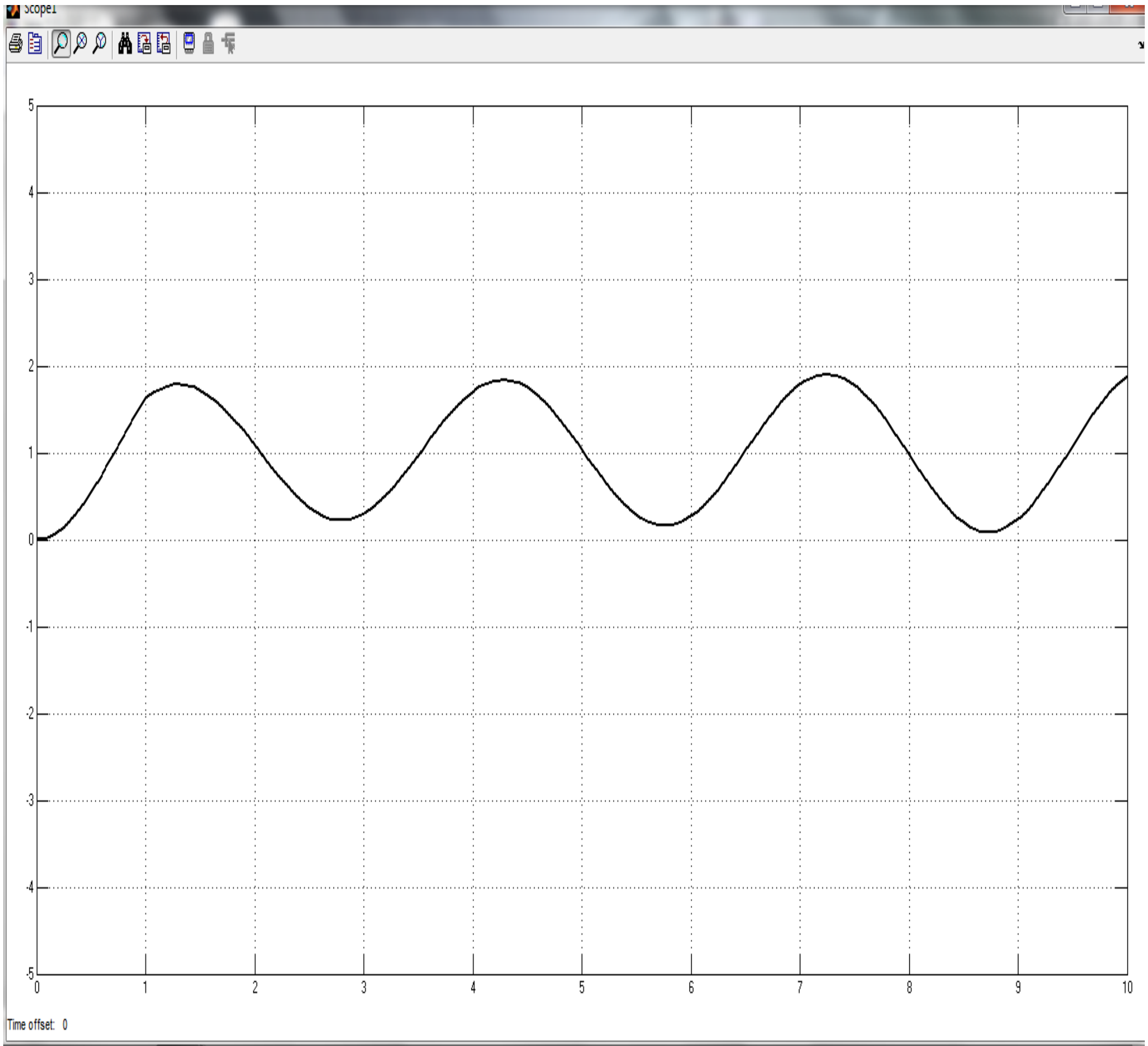

Figure 4.1 – Simulation graph for power generated by PWR at k = 1

Form this graph we clearly see that for criticality condition that is, k = 1 the power is generated by pwr at constant rate.

- Case 2 - For k < 1 (subcritical system),

  k = 0.7

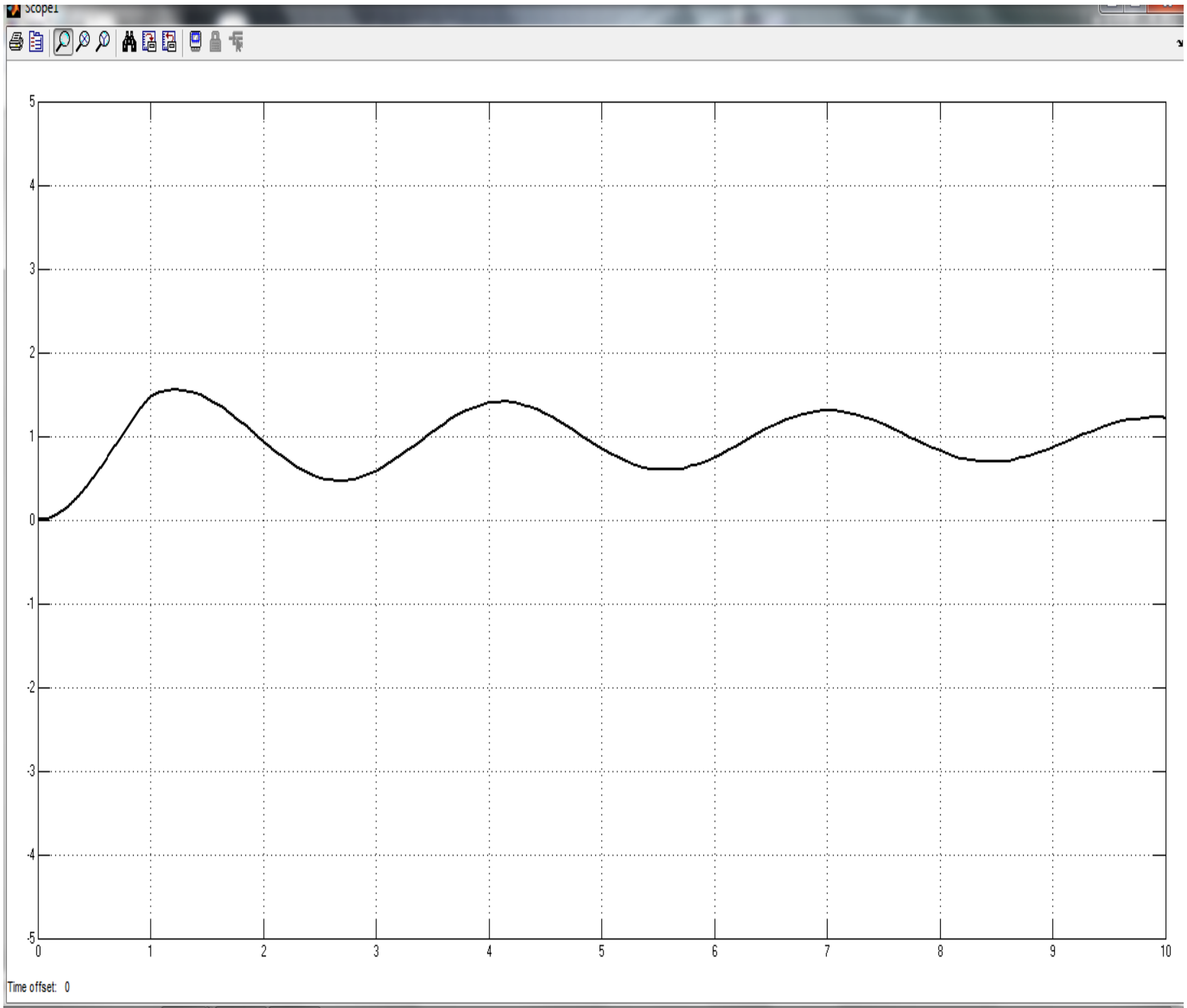

Figure 4.2 – Simulation graph for power generated by PWR at k < 1 (k = 0.7)

Form the above graph it is clearly that for sub-criticality condition that is, k < 1 the power is generated by pwr goes on decreasing with time and if this pattern continues this will ultimately led to reactor shut down.

- Case 3 - For k > 1 (supercritical system),

  k = 1.2

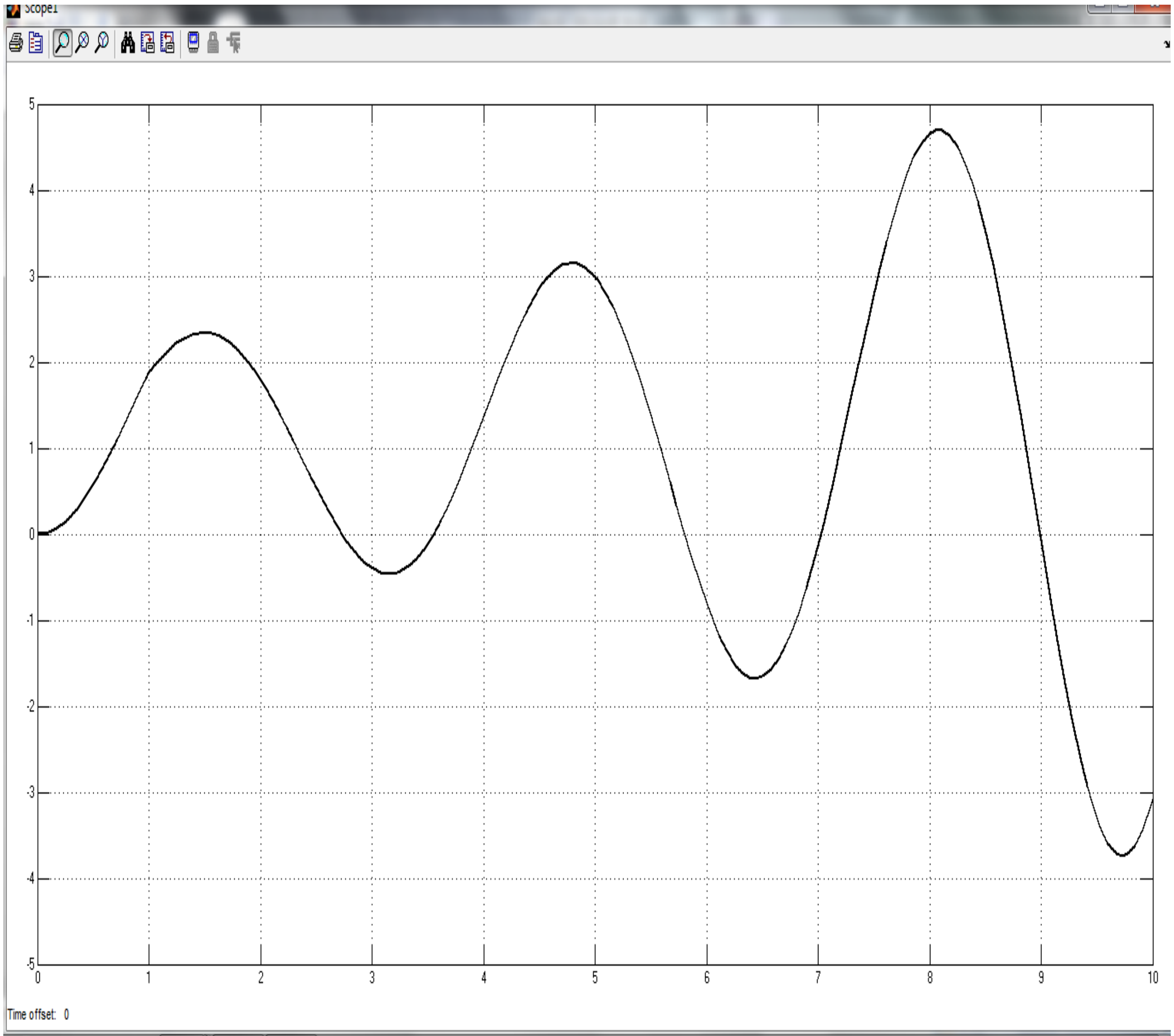

Figure 4.3 – Simulation graph for power generated by PWR at k > 1 (k = 1.2)

Form the above graph it is clearly that for super-criticality condition that is, k > 1 the power is generated by pwr increases rapidly with time.

4.3 CONCLUSION

From the above three graph it is clearly visible that how the multiplication factor ‘k’ controls the power generated by the reactor.

- For k =1; the power is generated at constant rate.
- For k < 1; power generated decreases with time.
- For k > 1; power generated increases with time.

Thus, it is evident that the power generated by the reactor mainly depends upon neutron population in a reactor. More the number of neutrons in the reactor more the fission reaction taking place inside it and greater is the energy generated. Thus, to control the power generated by the reactor, the neutron population or multiplication factor ‘k’ must be controlled.

4.4 SYSTEM UNDER DISTRUBANCE

Under this part of simulation we will study the effect of disturbance inserted in the system and studied how the transient flow in the system. We will also see that what is the effect on the power plant is when disturbance is inserted in other power plant. We will vary the value of disturbance inserted and see the difference in the behavior of the transient. We will take each case one by one.

In the model ‘x’ is the variable given for the disturbance inserted in hydro power plant and ‘d’ is for disturbance inserted in pwr power plant. For the graph given in this section, upper graph is for hydro power plant while the lower one is for pwr power plant.

- Case 1 - disturbance for both the plant is zero.

  x = 0 ; d = 0

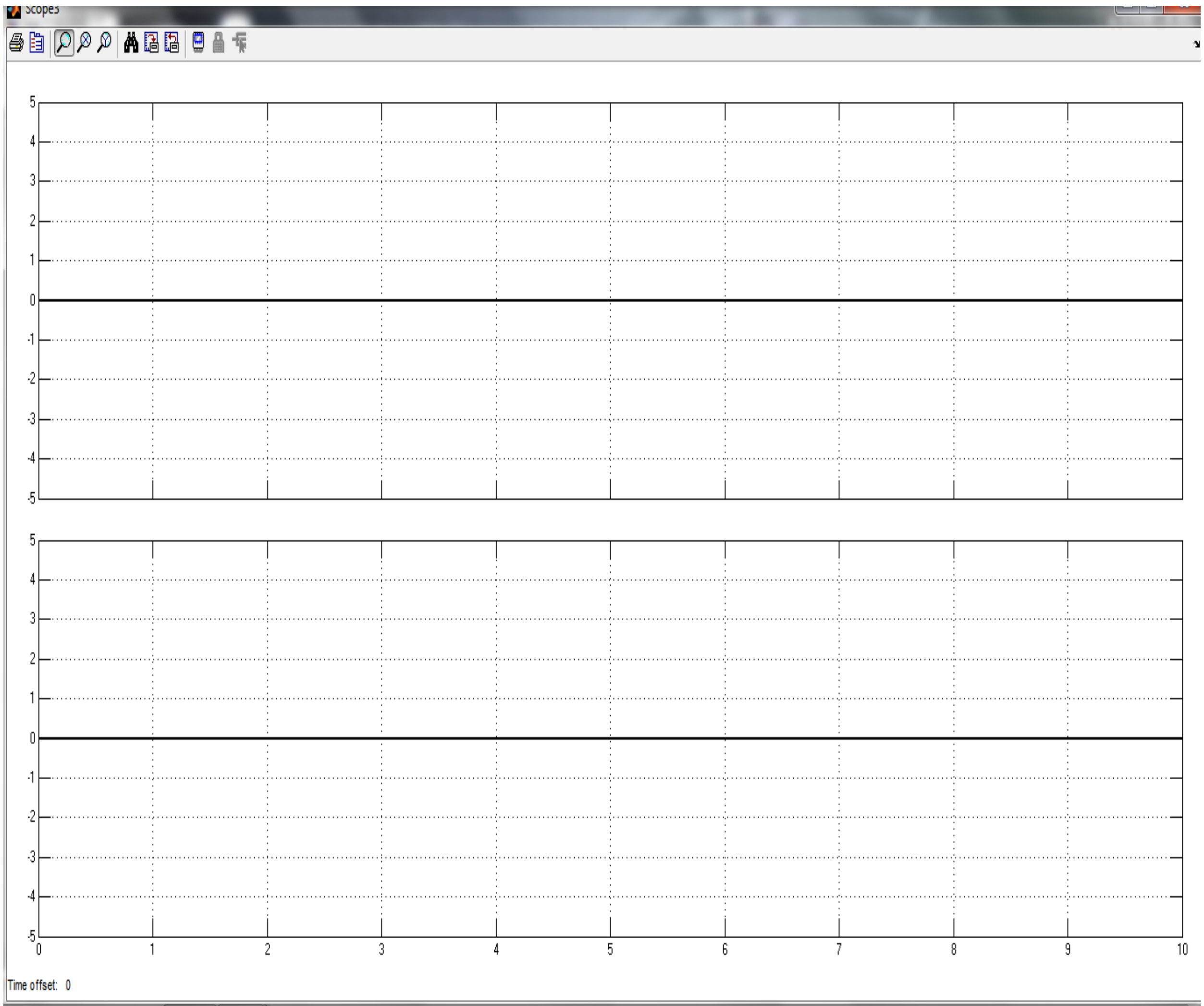

Figure 4.4 – Simulation result of transient response for x = d =0

As the disturbance for both the power plant is zero, we can see that the response of the system is ideal and no transient is generated in either of the power plant. Thus, the system behavior is ideal.

- Case 2 – disturbance for hydro power plant is 10% and for pwr power plant is zero.

  x = 0.1; d = 0

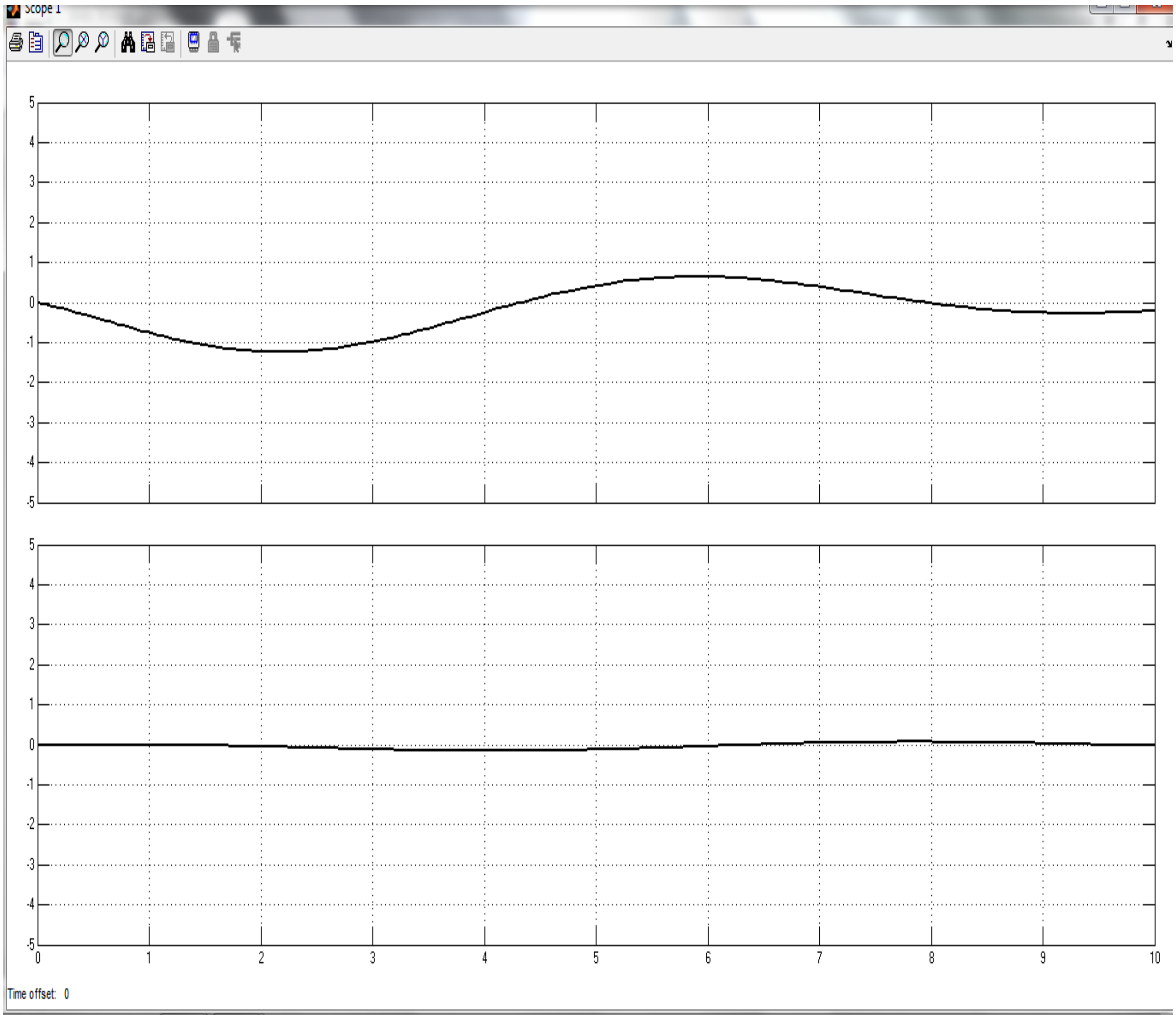

Figure 4.5 – Simulation result of transient response for x =0.1; d =0

In this case we have inserted disturbance only in hydro power plant and transient is generated for both the power plants. From the graph for hydro plant we can see that transient generated is high but it tends to die out with the time. For pwr power plant we see that the magnitude of transient generated is very less and it also dies out with time. On compare the transient response of both the power plants we can verify that the transient generated for pwr power plant is of lower magnitude and dies out faster than other, when disturbance is inserted in other power plants.

- Case 3 - disturbance for hydro power plant is zero and for pwr power plant is 10%.

  x = 0; d = 0.1

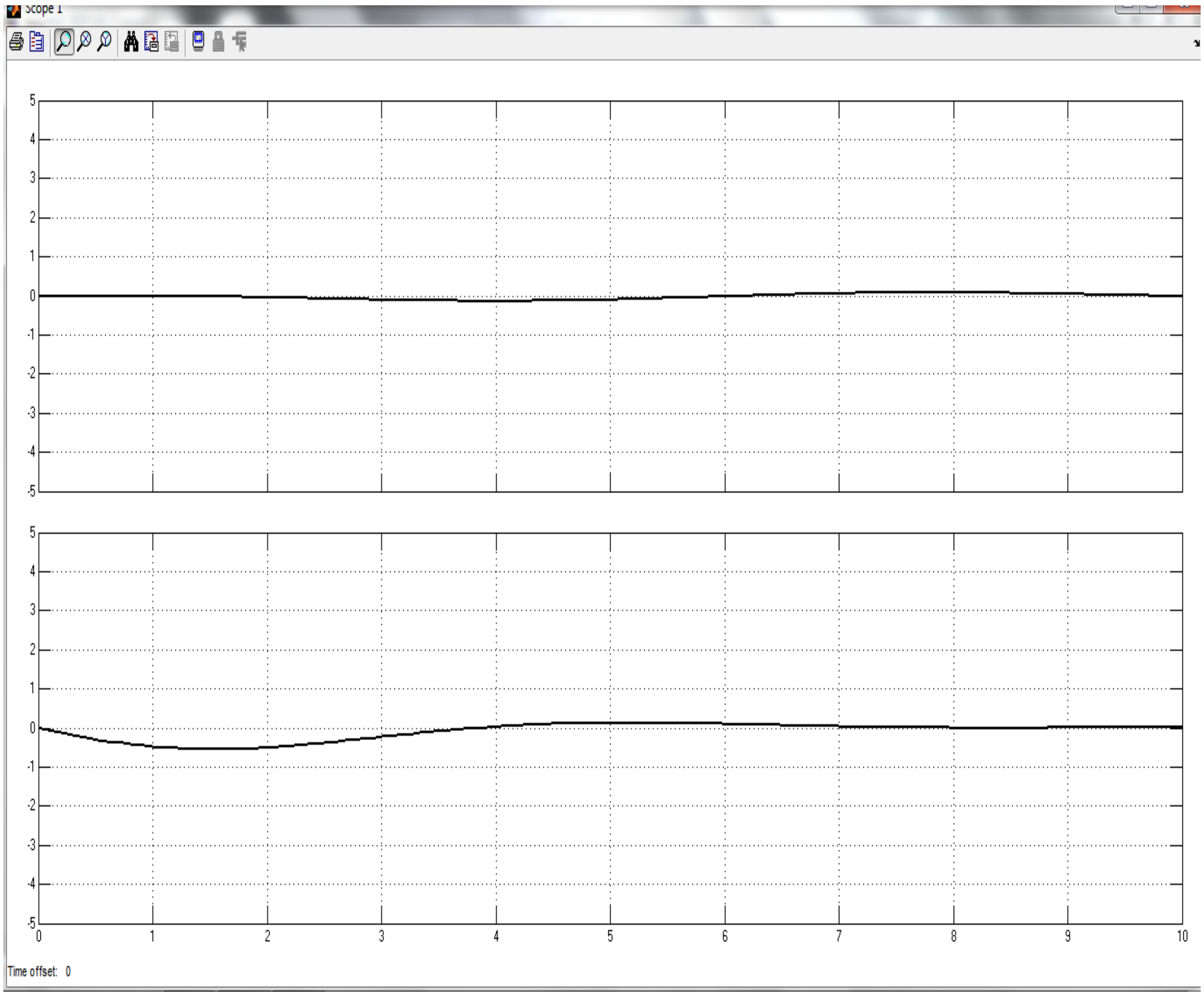

Figure 4.6 – Simulation result of transient response for x =0; d =0.1

In this case we have inserted disturbance only in pwr power plant and transient is generated for both the plants. From the graph for pwr power plant we can see that transient generated is high but not as high as for hydro in pervious case, here also transient dies out faster with the time. For hydro plant we see that the magnitude of transient generated is very less and it also dies out with time. On compare the transient response of both the power plants we can see that transient generated for pwr power plant is of little higher magnitude than of hydro power plant. On comparing case 2 & 3 we can see that for same disturbance the transient generated in pwr power plant is of lower magnitude and dies out faster than that of hydro power plant.

- Case 4 – disturbance for both power plant is 10%

  x = 0.1; d = 0.1

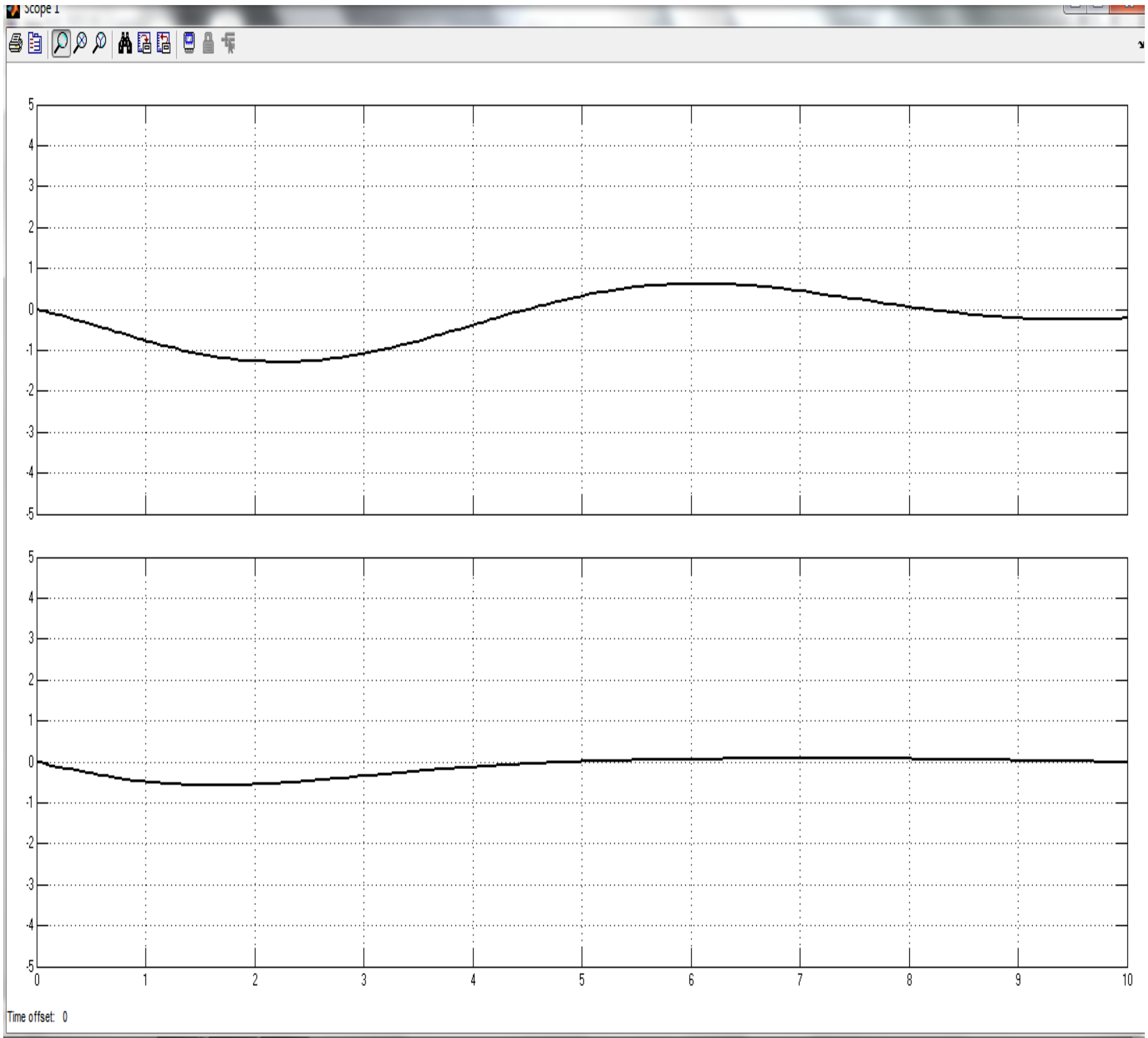

Figure 4.7 – Simulation result of transient response for x =0.1; d =0.1

In this case we have inserted disturbance in both power plant and transient is also generated for both the power plants. From the graph for hydro power plant we can see that transient generated is high but it tends to die out with the time. For pwr power plant we see that the magnitude of transient generated is less and it also dies out with time. On compare the transient response of both the power plants we conclude that the transient generated for nuclear power plant is of lower magnitude, and dies out faster than other plants.

- Case 5 - disturbance for both power plant is 20%

  x = 0.2; d = 0.2

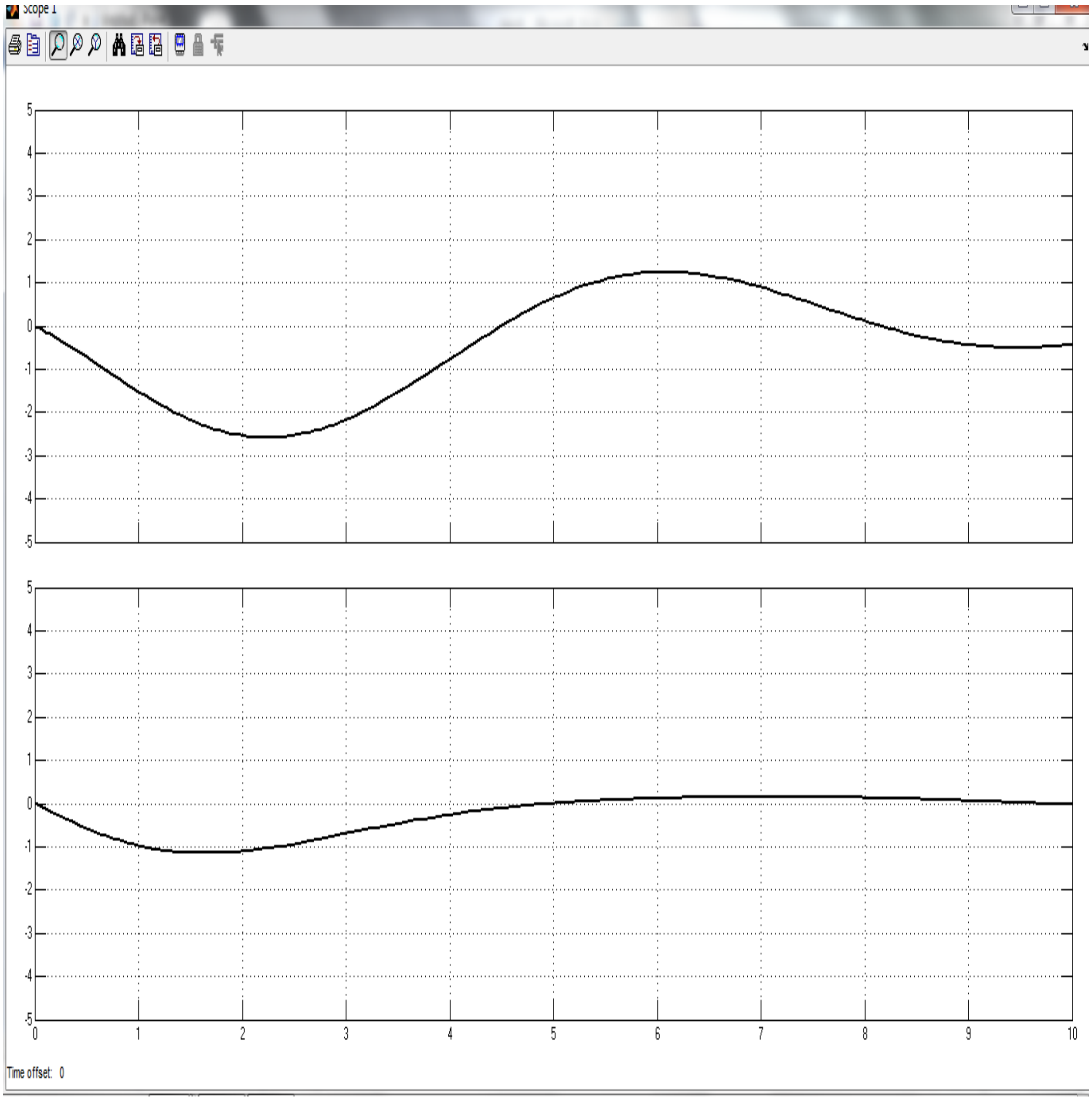

Figure 4.8 – Simulation result of transient response for x =0.2; d =0.2

In this case we have inserted disturbance in both power plant of higher magnitude and transient is also generated of higher magnitude for both the plants. From the graph we can see that for hydro power plant transient generated is much high and dies out less slowly with time.

For pwr power plant we see that the magnitude of transient generated is less and dies out faster compared to hydro. We can also conclude that as the magnitude of the disturbance is increased the transient generated in the power plant is also increased and it dies out slowly with time.

4.5 CONCULSION

Table 4.1 – First peak value of the transient for different distrubances

	x=0; d=0	**x=0.1; d=0**	**x=0; d=0.1**	**x=0.1; d=0.1**	**x=0.2; d=0.2**
PWR Power Plant	0	-0.15	-0.55	-0.575	-1.15
Hydro Power Plant	0	-1.235	-0.175	-1.3	-2.6

From the above table we can conclude that for this part of simulation the transient generated for pwr power plant is less severe than the hydro power plant and for the former transient die out much faster than the latter. The main reason for the difference in behavior is that the power control in pwr power plant much more rapid than other power plant. Whereas, for hydro power plant it takes some time for power control as the adjustment of flow of water to the turbine takes time which is slower in response. Thus, we can say that pwr power plant is much more reliable and stable than other power plant.

Thus, we can conclude that as pwr reactor response is much faster and instantaneous therefore the transient generated for this plant is less severe and dies out faster than hydro power plant. Therefore, under transient condition pwr power plant is much safer than other power plant in the system.

CHAPTER 5

RESULT

5.1 RESULT

Form the above simulation we can derive two conclusions, first is for the normal operation of the PWR power plant, while the later one is for the behavior of the PWR power plant under transient effect when it is inter-connected with the other power plant in the grid.

From the first part of the simulation it is evident that the power generated by the reactor mainly depends upon neutron population in a reactor. More the number of neutrons in the reactor more the fission reaction taking place inside it and greater is the energy generated. Thus, to control the power generated by the reactor, the neutron population or multiplication factor 'k' must be controlled.

From the second part of the simulation it is clear that the transient generated for pwr power plant is less severe than the hydro power plant and for the former transient die out much faster than the later. The main reason for the difference in behavior is that the power control in pwr power plant much more rapid than any other power plant. Whereas, for hydro power plant it takes some time for power control as the adjustment of flow of water to the turbine takes time which is much slower in response. Thus, we can say that pwr power plant is much more reliable and stable than other power plant.

Thus, we can conclude that as pwr reactor response is much faster and instantaneous therefore the transient generated for this plant is less severe and dies out faster than hydro power plant. Therefore, under transient condition pwr power plant is much safer than other power plant in the system.

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