ANALYSIS OF GRID INTERCONNECTION PROBLEMS OF SHP PLANTS

A DISSERTATION

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

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in

ALTERNATE HYDRO ENERGY SYSTEMS

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this dissertation, entitled, **"ANALYSIS OF GRID INTERCONNECTION PROBLEMS OF SHP PLANTS"** in partial fulfilment of the requirement of the award of the degree of **"Master of Technology"** in **"Alternate Hydro Energy Systems",** Submitted In Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee is an authentic record of my own work carried out during the period from July 2010 to June 2011 under the supervision of **Shri S. N. Singh,** Senior Scientific Officer, Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee and **Dr. D. K. Khatod,** Assistant Professor, Alternate Hydro Energy Centre, Indian Institute of Technology Roorkee.

I have not submitted the matter embodied in this dissertation for award of any other degree.

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ABSTRACT

Electricity grid interconnections have played a key role in the history of electric power systems. The greatest benefits of interconnection are usually derived from synchronous AC operation, but this can also entail greater reliability risks. An alternative energy supply to assist the main power stations in future is expected from renewable energy sources based on distributed generation like Small hydropower power plant (SHP). SHP capacity has experienced tremendous growth in the past decade due to its environmental benefits, technological advances and government incentives.

This dissertation report describes the grid interconnection elements, problems associated with grid interconnection and SHP station operation during grid connected mode, Modelling and Simulation of grid connected SHP, modelling of synchronous generator, Excitation systems, Hydro turbine and governor. This report includes five different type models which is run in the MATLAB software. These models are synchronous generator connected with light load, Synchronous generator in grid connected mode, Synchronous generator in grid connected mode during Fault, Two synchronous generator connected with grid and Synchronous generator in grid connected mode during suddenly load change. The simulated systems consist of synchronous generator of 325kVA, 415V, 3 phase, 50 Hz. After running the each model in MATLAB software observing the waveforms of Rotor speed, Excitation voltage, stator current, stator voltage, load current and load voltage. Analysing this waveform and able to observe the steady state time, transient duration, effect on waveforms at different condition and include recommendation in this content synchronization technique, frequency control of grid and Fault control of grid and micro grid.

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NOMENCLATURE

The notations used in this report are listed below:

For Synchronous Generator

J	Constant of inertia in $Kg\text{-}m^2$
T_m	Mechanical torque in N-m
T_e	Electromagnetic torque in N-m
δ	Power angle in rad
ω_o	Speed of operation in rad/s
$\Delta\omega$	Speed variation with respect to speed of operation in rad/s
V	Voltage in V
i	Current in A
R	Resistance in Ω
L	Inductance in H
Ø	Magnetic flux linkage in weber
R_s	Stator resistance in Ω
Ll_s	Leakage inductance in H
Lm_d	Magnetizing inductance of d-axis in H
Lm_q	Magnetizing inductance of q-axis in H
R_f'	Field resistance in Ω
L_{lfd}'	Field leakage inductance in H
R_{kd}'	Damper resistance of d-axis in Ω
L_{lkd}'	Damper leakage inductance of d-axis in H
R_{kq}'	Damper resistance of q-axis in Ω
L_{lkq}'	Damper leakage inductance of d-axis in H
R_{kq2}'	Damper resistance of q-axis (Only if round rotor) in Ω
L_{lkq2}'	Damper leakage inductance of d-axis (Only if round rotor) in H
F	Friction factor in N-m-s
P	Number of pole pairs
Tf	Friction torque in N-m
V_f	Field voltage in V

Ns	Synchronous speed in rpm
f	Frequency in Hz

For Excitation Systems

V_{ref}	Desired value of stator terminal voltage in pu
V_d	Terminal voltage of V_d in pu
V_q	Terminal voltage of V_q in pu
Vf	Field voltage for the synchronous machine in pu
Ka	Gain of regulator in Sec
Ta	Time constant of regulator in Sec
K_e	Gain of excitor in Sec
T_e	Time constant of Excitor in Sec
T_b	Time constant of lead- lag compensator in Sec
K_f	Gain of damping filter
T_f	Time constant of damping filter in Sec

For Turbine and Governor

P_{ref}	Reference mechanical power in pu
ω_{ref}	Reference speed in pu
ω_e	Mechanical actual speed in pu
p_{eo}	Machine actual electrical power in pu
$d\omega$	Speed deviation in pu
Pm	Mechanical power in pu
g_{ate}	Gate Opening in pu
K_a	Gain of servo-motor in Sec
T_a	Time constant of servo-motor in Sec
K_p	Proportional gain constant
K_i	Integral gain constant
K_d	Derivative gain constant
T_w	Water Starting time in Sec

CHAPTER 1

INTRODUCTION

1.1 GENERAL

With the large- scale interconnection of power system, the control and operation among geographically distributed, structurally heterogeneous and autonomous power systems becomes increasingly complicated. The key responsibility of the interconnected system is to control and maintain frequency and voltage of power system. Most of Small hydropower plants (SHPs) are connected to utility grid, hence it becomes very important to analyse the problems associated with grid interconnection of SHP plants.

1.2 SMALL HYDRO POWER PLANTS

SHP is the installation for the production of hydro-electricity up to 25 MW in a power plant in which individual unit capacity should exceed 5MW.

SHP schemes can be broadly categorized in the following types as follows:

i. Run-off River Schemes
ii. Dam Toe based Schemes
iii. Canal Based Schemes

1.2.1 Run-off River Schemes

Run-off River hydropower schemes are those, in which water is diverted towards power house, as it comes in the stream. Practically, water is not stored during flood periods as well as during low electricity demand periods, hence water is wasted. Seasonal changes in river flow and weather conditions affect the plants output. After power generation water is again discharged back to the stream. Generally, these are preferred for high head and low discharge SHP schemes.

1.2.2 Dam Toe based Schemes

The main feature of Dam Toe Based Power Plant scheme is a dam across the river which creates a storage reservoir. This stored water may be used for power generation, irrigation, water supply and flood control. Power generation is done through a power station which is located at the toe of the dam. The water is taken to the power house through a penstock embedded in the dam. Used water from the power house is sent to the main stream.

1.2.3 Canal Based Schemes

Canal based small hydropower scheme is planned to generate power by utilizing the fall in the canal. These schemes may be planned in the canal itself or in the bye pass channel. These involve SHP schemes with low head and high discharge. These schemes are associated with advantages such as low gestation period, simple layout, no submergence and rehabilitation problems and practically no environmental problems.

1.3 GENERATOR USED IN SMALL HYDRO POWER PLANTS

1.3.1 Synchronous Generator

A Synchronous machine is an AC machine in which the rotor moves at a constant speed which depends on the supply frequency and the number of poles as follows

$$N_s = \frac{120f}{P} \tag{1.1}$$

Where, N_s = Synchronous speed in rpm.

f= frequency of the generated voltage in Hz

P= No of poles

The real power that it produces is controlled by the governor of its prime mover. The reactive power that it produces is controlled by the level of excitation of its field. A synchronous machine requires more complex control than does an induction machine, both to synchronize it with the Grid and control its field excitation. It also requires special protective equipment to isolate it from the Grid under fault conditions. Significant advantages are its ability to provide power during Grid outages and allow the SHP owner to control the power factor at the facility by adjusting the dc field current [1].

1.3.2 Asynchronous Generator

An asynchronous machine also known as induction machine will work as a generator when it is driven at a speed slightly higher than the corresponding synchronous speed. If its speed drops below the synchronous speed, it will absorb power from the Grid. The real power it produces is controlled by the governor of the prime mover. The conventional induction machine always absorbs reactive power. It cannot control voltage or power factor [1].

1.4 OPERATION MODE OF SMALL HYDRO POWER PLANTS

Small hydro power plants can be operated in two different modes as given below

i. Isolated mode

ii. Grid Connected mode

1.4.1 Isolated Mode

Isolated power supply systems using Mini/Micro/SHPS are emerging as technically reliable and economical option for power supply to remote and isolated places. For electrification of such areas, grid extension would be either extremely costly or practically impossible. In this case, renewable energy such as micro/mini/small hydropower plant working in isolated mode would be least cost alternative.

For such systems following provisions in generating equipment are essential:

i. Adequate fly-wheel affect should be provided for full load rejection, speed rise should be less than 35%.

ii. Excitation system for generator should have provision of voltage control. In case of Micro hydels, manual excitation control with excitation limit can be considered.

iii. Electronic load controller; Induction Generator controller can be used for maintaining constant frequency/voltage. Figs. 1.1&1.2 show the typical connection scheme for isolated operation of SHPs [2].

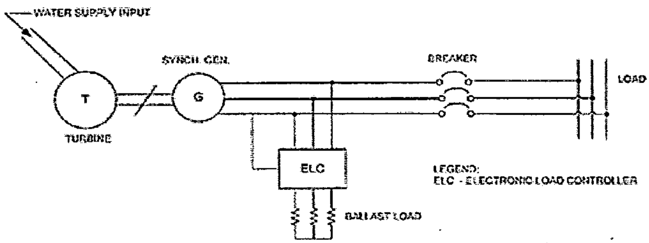


Fig. 1.1: Synchronous generator in isolated mode

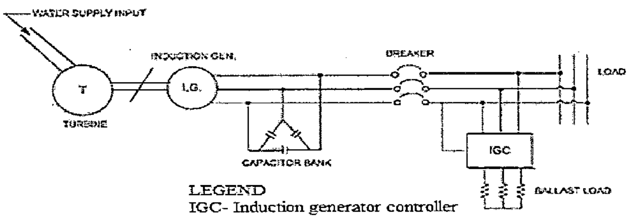


Fig. 1.2: Induction generator in isolated mode

1.4.2 Grid Connected mode

In case of grid connected mode, governor is used for maintaining the balance between mechanical power & electrical power. Figs. 1.3 and 1.4 show the connection schemes of SHPs in grid connected mode.

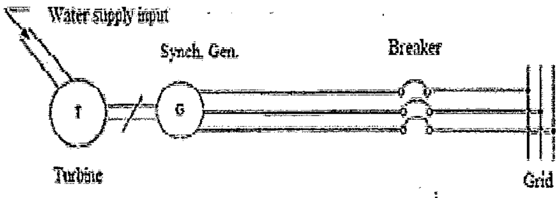


Fig. 1.3: Synchronous generator in grid connected mode

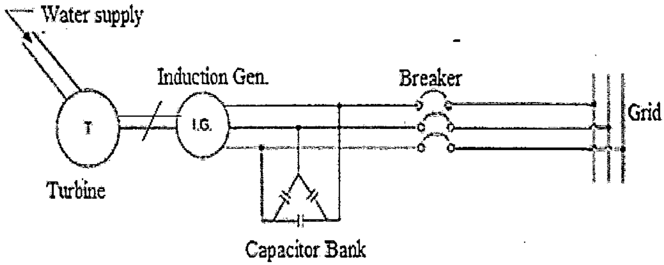


Fig. 1.4: Induction generator in grid connected mode

In the case of induction generator, requirement of capacitor bank is optional. The grid-connected SHPs can further be classified into following two categories:

a. Power plants with local load

These power plants will regularly operate in parallel with connected grid, but supply the requirements of localized industrial or other facility. The power plant and load together may be considered of electrical energy either as a net importer of electrical energy to grid or as a net exporter of electrical energy from grid.

b. Power plants with Out local load

These power plants are typically connected to grid through a dedicated line. Typically, there will be no other customer load between the grid substation and power plant. The generators of these power plants will always operate in parallel with the grid [2-8].

1.5 GRID INTERCONNECTION OF THE SHP PLANTS

A connection of several generating station in parallel to create a power pool is called interconnected grid system. Grid system consists of transmission and distribution system, transformer, protection equipment etc. Different regions have different amounts of hydro potentials for power generation as well as different demand patterns. Some areas may have deficient hydro capacity to serve the load while other areas may have significant amounts of spare hydro capacity after serving the load. In this condition enhanced interconnections and trade within and among different regions can significantly improve the load factor, lower the overall costs of power production and diversify sources of power supply. Stronger grids may also open up new avenues of competition among private SHP owners further limiting power costs to industry and consumers.

Following are the main requirements of grid interconnection of SHP plants are:

i. To ensure the safety of the SHP plants operating in parallel with Grid
ii. To facilitate the safety of large industrial consumer, and general public.
iii. To maintain a high standard of power quality.
iv. To coordinate of maintenance schedules.

1.5.1 Technical Aspects of Grid Interconnection Of SHP

There are number of technical rationales for grid interconnections, many of which have economic components as well. Technical rationales for grid interconnection include:

i. Improvement of reliability and pooling reserves: The amount of reserve capacity that must be kept by individual networks to ensure reliable operation when supplies are short can be reduced by sharing reserves within an interconnected network.
ii. Reduced investment in generating capacity: Individual system can reduce their generating capacity requirement or postpone the need to add new capacity, if they are able to share the generating resources of an interconnected system.
iii. Improvement of load factor and load diversity: Systems operate most economically when the level of power demand is steady over time, as opposed to having high peaks.

Poor load factors (the ratio of average to peak power demand) mean that utilities must construct generation capacity to meet peak requirements, but this capacity sits idle much of the time. Systems can improve poor load factors by interconnecting to other systems with different types of loads, or loads with different daily or seasonal patterns that complement their own.

iv. Diversity of generation mix and supply security: Interconnections between systems that use different technologies and/or fuels to generate electricity provide greater security in the event that one kind of generation becomes limited (e.g., hydroelectricity in a year with little rainfall). Historically, this complementarily has been a strong incentive for interconnection between hydro-dominated systems and thermal-dominated systems. A larger and more diverse generation mix also implies more diversity in the types of forced outages that occur.

v. Economic exchange: Interconnection allows the dispatch of the least costly generating units within the interconnected area providing an overall cost savings that can be divided among the component systems. Alternatively, it allows inexpensive power from one system to be sold to systems with more expensive power.

vi. Environmental dispatch and new plant siting: Interconnections can allow generating units with lower environmental impacts to be used more and units with higher impacts to be used less. In areas where environmental and land use constraints limit the siting of power plants interconnections can allow new plant construction in less sensitive areas.

vii. Coordination of maintenance schedules: Interconnections permit planned outages of generating and transmission facilities for maintenance to be coordinated so that overall cost and reliability for the interconnected network is optimized.

1.5.2 Grid interconnection elements

A listing of the basic elements of an interconnection system is provided below.

1.5.2.1 Transmission Lines

Transmission lines are of two basic varieties: overhead lines and underground (or undersea) cables. Overhead lines are more common and less expensive than cables. The main design consideration for overhead lines is the choice of conductor type and size so as to minimize impedance (and the associated losses), minimize cost, and minimize the weight that must be carried by support structures. Conductor cross-sections are typically measured in square centimeters (cm^2) in the metric system. The capacity of a conductor to carry current without exceeding thermal limits is called its ampacity, measured in kA for large conductors. Although copper is a better conductor, it has been overtaken in recent years by aluminum, which is lighter, cheaper, and in abundant supply. The most common overhead conductors for high-capacity, long-distance transmission is stranded aluminum wire reinforced with steel, aluminum conductor steel reinforced (ACSR), Other design considerations for overhead lines are the type of transmission towers and insulators used, and the configuration of conductors on the support structures, which affects the reactance of the conductors and the strength of electromagnetic fields (EMFs) around the lines.

Underground cables are used where overhead conductors are inappropriate due to environmental or land use considerations such as in high-density urban areas or ecologically sensitive areas. Cables are insulated and are typically routed through underground conduits, and often require cooling systems to dissipate heat. Cables may use copper instead of aluminum, balancing the greater cost of copper against its superior conductivity and lower resistive heating. Undersea cables are usually made of copper, and may be surrounded by oil or an oil-soaked medium, then encased in insulating material to protect from corrosion. Undersea cables often have a coaxial structure, which has an inherently high capacitive reactance; therefore undersea cables are usually DC, which is not affected by reactance.

1.5.2.2 Support Structures

There are many possible types of support structures for overhead transmission lines. In developed countries, transmission lines are supported on structures made of steel lattice and tubular steel. Steel lattice has the highest strength to weight ratio, and is the easiest to assemble in areas that are difficult to access. Where aesthetics are an important factor, however, other materials are often used. The main function of support structures is to keep the conductors away from contacting trees or other objects, including people and animals; thus the structures must be tall enough to do so. Also taller structures minimize ground-level EMFs. Because overhead transmission lines are not insulated, they are typically suspended from towers on strings of ceramic insulators, which are designed to prevent flashover, or the leakage of current from the conductors to the tower, which would present a lethal prospect to anyone touching the tower. AC transmission towers are usually designed to carry three conductors: the three phases of AC power systems. Towers that hold these in an equilateral triangle shape (called a "delta") keep the mutual reactances of the three phases balanced. Non-delta configurations often require that conductors to be transposed or switch to be placed, at regular intervals along the transmission path. Some towers carry more than one circuit with three phases per circuit.

1.5.2.3 Transformers and Substations

Transformers are static electric devices that consist of a set of windings that transfer power by electromagnetic induction between circuits, usually with changed voltage and current but at the same frequency. An isolation transformer may contain an electrostatic shield between the primary and secondary windings to reduce unwanted electrical noise [4]. Therefore Transformers are used to change voltage levels in AC circuits, allowing transmission at high voltages to minimize resistive losses and distribution at low voltages at the customer end for safety. The essential element of a transformer consists of two coils wrapped around an iron core. An alternating current in one coil produces a changing electromagnetic field that induces a current in the other. The voltages on either side are in the same ratio as the number of turns on each coil. Transformers step up the voltage from generator to transmission system, and other transformers step it down, often in several stages, from transmission to sub-transmission to primary distribution to secondary distribution, and finally to the end-user voltage such as 415 V, At the distribution level. Transformers often have taps that can be used to change the turns ratio this allows operators to maintain customer voltage levels when system voltages change. Modern transformers are extremely efficient, typically greater than 99% but even small losses can produce a significant amount of heat which must be dissipated to prevent damage to the equipment. Large transformers are cooled by circulating oil which also functions as an electrical insulator.

Large transformers are housed in substations where sections of a transmission and distribution system operating at different voltages are joined. Larger substations have a manned control room, while smaller substations often operate automatically. In addition to transformers, important substation equipment includes switch-gear, circuit breakers and other protective equipment and capacitor banks used to provide reactive power support.

1.5.2.4 Protection Systems

When SHP plants are integrated into the Grid, it is important to provide sufficient protection for SHP. Grid operators are concerend about the dynamic security and integrity of Grid and safety of line crews with which SHP units are interconnected. Relays and Switchgear normally provide protection to Grid and SHP plants. Protective relaying devices interpret input conditions in a prescribed manner and after specified conditions are met they respond by operating switchgear or by alarm to protect the SHP.

Table 1.1: Relay functions [1]

Function and IEEE standard device number	Description
Sync-check (25)	Synchronizing or synchronism-check relay. A synchronizing device that produces an output that causes closure at zero phase angle difference between two circuits. It may or may not include voltage and speed control. A sync-check relay permits the paralleling of two circuits that are within prescribed limits of voltage magnitude, phase angle, and frequency.
Under/overvoltage (27/59)	A device that operates when its input voltage is less than a predetermined value (27). A device that operates when its input voltage exceeds a predetermined value (59).
Directional power (32)	A device that operates on a predetermined value of power flow in a given direction.
Negative phase sequence current (46)	A device in a polyphase circuit that functions upon a predetermined value of polyphase current in the desired phase sequence, when the negative phase-sequence current exceeds a preset value.
Negative phase sequence voltage (47)	A device in a polyphase circuit that functions upon a predetermined value of polyphase voltage in the desired phase sequence, when the negative phase-sequence voltage exceeds a preset value.
Neutral under/overvoltage (27G/59G)	A device, installed to specifically detect the voltage on the neutral of a three-phase system relative to system ground, that operates when its input voltage is less than a predetermined value (27). A device that operates when its input voltage exceeds a predetermined value (59).
Directional overcurrent (67)	A device that functions at a desired value of ac overcurrent flowing in a pre-determined direction.
Instantaneous phase overcurrent (50)	A device that operates with no intentional or coordinated time delay when the current exceeds a preset value.
Neutral overcurrent (50/51 N)	A device that operates with coordinated time delay when the current exceeds a preset value.
Voltage-restrained overcurrent (51V)	An overcurrent relay that changes its sensitivity based on varying voltage levels.
Undercurrent or under power (37)	A device that functions when the current or power flow decreases below a predetermined value.
Under/overfrequency (81 U/O)	A device that responds to the frequency of an electrical quantity and operates when the frequency exceeds or is less than a predetermined value.
Transformer differential (87T)	A device that operates on a percentage, phase angle, or other quantitative difference of two or more currents or other electric quantities.

Relays ensure that SHP equipment operates normally and ceases to energize the grid during faults or other abnormal conditions. Protective relays may be electromechanical, solid-state, or multifunction. In some cases, protective functions may be integrated with the SHP control or systems controls. Protective relays typical in SHP interconnection systems are shown in Table 1.1. Depending on the size of the SHP unit and the number of phases, some of those protective relays might be needed [1].

1.5.2.5 Dispatch, Monitoring and Control Systems

Systems dispatchers are responsible for operating the Grid such that sufficient resources are available to serve the connected load with acceptable voltages. To accomplish this, the dispatchers often require specific information from the SHP units [1].

Traditionally, monitoring and control have been conducted semi-manually with a heavy reliance on telephone communications with plant operators and field personnel. Nowadays, these activities are automated. Supervisory control and data acquisition (SCADA) systems combine remote sensing of system conditions with remote control over operations. For example, control center SCADA systems control key generators through automatic generator control (AGC), and can change the topology of the transmission and distribution network by remotely opening or closing circuit breakers. This monitoring and control is enabled by dedicated phone systems (often fiber-optic based), microwave radio, and/or power line carrier signals.

1.6 OBJECTIVE OF THE DISSERTATION WORK

The objective of this dissertation is to analyze the problems associated with grid interconnection of SHP plats. To connect the SHP plants with grid, it is essential to ensure that operational limits of frequency, voltage and phase angle within the range. In this work attempts has been made to simulate different operating condition of grid connected SHP plants.

1.7 ORGANIZATION OF THESIS

The following is the organization of this dissertation report.

Chapter 1 presents the purpose of grid interconnection of SHP along with associated Technical Aspects.

In Chapter 2, Literature review on grid interconnection problems associated with SHP has been presented.

Chapter 3 presents the detailed descriptions of grid interconnection problems associated with SHPs. This chapter also suggests some recommendations to mitigate the problems arising due to grid interconnection of SHPs.

In Chapter 4, Modelling and simulation of different components of SHP like synchronous generator, hydro turbine and governor and Excitation systems has been presented under different operating conditions.

In Chapter 5, Conclusion of dissertation work and future scope of work have been presented.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a review of research activities related with grid interconnection problems associated with SHP and other renewable energy resources based on distributed generation (DG).

Ortjohann et al. [9] presented a hierarchy control strategy of (DG) systems. They concluded the key responsibility of the interconnected system as controlling and maintaining frequency and voltage of the power system. For this purpose, they proposed a strategy to bring and manage many mini-grids to operate in parallel. The load sharing, power dispatch, frequency control and voltage control have been automatically managed by the proposed strategy. With the help of simulation results, they showed improved power supply system due to fast response, adaptability, flexibility and efficiency of their strategy. With this proposed strategy, they suggested to interconnect mini-grids with each other and existing conventional power systems to form huge smart power systems.

Skolthanarat et al. [10] presented a design, modeling, and control of grid interconnection for a wind farm with round-rotor synchronous generators. They suggested grid interface multi-level inverter with H-bridge converters to improve the power quality of the utility grid. The fast transient response of the real and reactive power control was achieved by the feedback control in synchronous rotating reference frame. Stability of the integrated subsystems was also analyzed with the nyquist criteria and classical control theory. By the Simulation results with PSCAD in normal operations and short circuit fault operations were also illustrated.

Weichao et al. [11] examined the effects due to large incremental generation in-feed to the power grid including impacts on the system stability level and constraint on power transfer limit. They showed that generator switching device could be used to improve the overall operational performance and confirmed by a case study on the North-west China Grid. They suggested the existing power grid as unable to accommodate large incremental generation expansion, as it may result undesirable effects on system stability and power flow congestion in the power grid. Therefore, they concluded that the output level of new generation unit must to be trimmed down. Case studies on two scenarios were discussed to show that the proposed measures could significantly improve the system stability, reduce the capacity shortfall level and improve the generation unit utilization efficiency.

Barsali et al. [12] presented technical-economical simulations of a deregulated electricity market for the setting of power flow limits in the interconnection lines. In this, they introduced a check by an Independent System Operator for scheduling power flows within the operating limits of the transmission grid. These operating limits of the transmission grid are generally fixed to ensure a given level of security in the power system. Nowadays the problem is simply solved by verifying that after a line has gone out of service, the remaining lines are able to transport the power flowing in the faulty line. They proposed different approach based on probabilistic assumptions. The methodology developed under this approach was based on the consideration that the total costs for the customers must be minimized. They also showed concluded that how the setting of interconnection limits would affect the amount of Expected Undelivered Energy (EUE).

Mittal et al. [13] presented the interconnection issues of variable speed permanent magnet synchronous generator (PMSG) connected to grid as per prevailing grid standards during healthy and fault conditions. The variable speed operation of PMSG has been demonstrated while feeding the real power to the grid keeping DC link voltage constant. Further, the fault ride-through capability of PMSG has been demonstrated using MATLAB Simulink based simulations. The inverter was controlled so as to meet IEEE standard 1547 requirements for connection of distributed generation to the local grid. The simulated result validated the topology.

Yun-Hyun Kim et al. [14] conducted a research on a fast and robust phase locked loop (PLL) of Molten carbonate fuel cells (MCFC) power conditioning system (PCS) under Unbalanced Grid Voltages. They presented that grid-interconnection system a fast robust and precise phase angle detector was most important to the active power control and grid synchronization. The phase angle could easily be estimated by synchronous PLL system. This PLL Strategy detected positive sequence voltage quickly and accurately. Simulation and Experimental results were presented to verify this strategy under different kind of voltage dips.

Chen et al. [15] performed the Grid Computing (GC) application for distributed heterogeneous power systems. According to them, the large-scale interconnection of power systems, the control and operation among geographically distributed, structurally heterogeneous and autonomous power systems becomes increasingly complicated. They concluded that GC is a novel technology for integration and management of computing resources from multiple administrative domains applied to a common task, especially for problems which are computational-intensive or/and data-intensive.

Rodriguez et al. [16] presented that the increasing penetration of distributed power generation into the power system would lead to a continuous evolution of grid interconnection requirements. They expected active power control to play an important role both during grid faults (low-voltage ride-through capability and controlled current injection) as well as in normal conditions (reserve function and frequency regulation) and they proposed a flexible active power control based on a fast current controller and a reconfigurable reference current selector. Several strategies to select the current reference were studied and compared using experimental results obtained during an unsymmetrical voltage fault. They found the developed flexible active power controller capable of adapting itself to the fault situation and reconfigurable in case the grid requirements change. They proved that, during unbalance conditions, it would be possible to obtain zero active and reactive power oscillations only by accepting highly distorted currents. It has been also proven that the distribution power generation system (DPGS) could be a very flexible power producer able to work in constant current, constant active power, or constant reactive power modes depending on the grid fault type and the utility network necessity.

Adhikary et al. [17] presented a soft connection between two micro-hydro units forming a mini- grid system. They described the operation and the design of the induction generator controller (IGC), used for the power balancing at varying consumers load as required for standalone micro-hydro generators and the synchronizer unit, used for the Mini-grid interconnection. Three phase induction motors have been used as single phase generators by using C-2C capacitor configuration for supplying single phase resistive load. They proposed a simple soft connection scheme based on classical Zero Crossing Detector. Operation and experimental tests of IGC based Mini-grid system with soft connection has also been presented. Through the results, it has been shown that the proposed model is feasible for rural electrification schemes.

Blaabjerg et al. [18] presented a research work on overview of control and grid Synchronization. Due to the increasing number of Distributed power generation systems (DPGS) connected to the utility network, they raised the issue of new and stricter standards in respect to power quality, safe running, and islanding protection. They also suggested that improvement in the control of distributed generation systems to meet the requirements for grid interconnection. They gave an overview of the structures for the DPGS based on fuel cell, photovoltaic, and wind turbines. In addition, control structures of the grid-side converter were presented; and the possibility of compensation for low-order harmonics was also discussed.

Shi-Hua et al. [19] introduced the basic concept of power grid crises management and the basic principle of small-disturbance theory to analyze the damping character of Jiangsu power grid and adopted prony theory to prove the above calculated result. Then they discussed the effect of PSS device to raise the damping property of power system. This study has theoretical and practical significance to guarantee the security and stability of power grid.

Zhu et al. [20] presented the research work on the improvement of the cost and reliability of utility-tied PWM inverter. They investigated an ac voltage sensorless grid synchronization control, applicable for either in grid- parallel inverter mode or in boost PFC rectifier mode. Based on d-q coordinate and standard two-loop vector control structure, the sensorless technique utilizes an ac line voltage estimator and an angle-searching algorithm, which adjusts a reference phase angle online and keeps the inverter synchronized with the grid. Initially lab experiments demonstrated a fast convergence in tracking the ac line phase angle and a stable control of the inverter current and power flow in the either direction. They found this method feasible to meet some core requirements such as grid synchronization, harmonic and dc current limits fault protection and anti-islanding.

Chang et al. [21] addressed an important issue of interconnecting distributed power generators with the electric grid. The issues were discussed in the context of distributed power generation (DPG) interconnection standards. Common requirements for typical distributed power generation interconnections were described in three categories general specifications, and requirements, safety and protection requirements, and power quality requirements based on interconnection standards.

Li et al. [22] studied problems based on transient thermal circuit equation and modified thermal limits, which was involved in mathematical model of optimal power flow (OPF) about available transfer capacity (ATC). The weakest lines were found applying modal analysis, then they estimated whether the transmitting capacity was conditioned by the temperature variation of the lines by using constraints of temperature substitute for the thermal limits of the weakest lines. They constructed a new model which was in order to overcome conservatism of judgement by current capacity, and the latent transmitting capacity will be fully excavated. Then, increased the conductor allowable temperature from 70°C that specified by the present specifications to 80°C, a great number of both foreign and domestic test data showed that it would make great profit in the long run.

Rajeshwari et al. [23] suggested the power quality problem as an issue due to the increase in sensitive load, proliferation of non-linear loads and switching devices and increasing awareness of the implications of poor power quality. They suggested to frames standards and guidelines for power quality norms for grid interfacing of wind farms to facilitate improving power quality and operational efficiency of wind farms.

Saha et al. [24] presented modelling and simulation of micro turbine (MT) to analyze its load following performance as distributed energy resources (DER) with general as well as critical priority loads. The system comprises a synchronous generator and a MT coupled to it. Simulations were carried out in islanded and grid connected mode of the systems to observe its behaviour when supplying customers variable loads. They also presented modelling and simulation of microturbine with a speed control system of the MT-synchronous generator to keep the speed constant with load variation. The load following characteristics was observed and validated for this MT-synchronous generator model in Matlab-Simulink environment with power system block sets. This is applicable with combined heat power (CHP) generators both with general fuel as well as bio-fuels. The use of bio-fuels is very much promising for generating green power preventing green house gas emissions for fighting against global warming. But it may take some time to be in the market place for its commercial use.

Timbus et al [25] suggested that if distributed power generation systems (DPGS) based on renewable energy resources are not properly controlled, their connection to the utility network could generate problems on the grid side. Therefore, considerations about power generation, safe running and grid synchronization must be done before connecting these systems to the utility network. They mainly discussed the grid synchronization issues of distributed systems. An overview of the synchronization methods as well as their major characteristics was given. They discussed to optimize the synchronization methods when running on distorted grid conditions. Simulation and experimental results were used to evaluate the behaviour of synchronization methods under different kind of grid disturbances such as voltage dips, harmonics and notches.

Singh et al [26] presented a research work on interfacing renewable energy resources (RES) with distribution systems utilizing power electronic converters. They presented a novel control strategy for achieving maximum benefits from these grid-interfacing inverters when installed in 3-phase 4-wire distribution systems. The inverter was controlled to perform as a multi-function device by incorporating active power filter functionality. The suggested that inverter could be utilized as power converter to inject power generated from RES to the grid and shunt APF to compensate current unbalance, load current harmonics, load reactive power demand and load neutral current. All of these functions may be accomplished either individually or simultaneously. This approach thus eliminated the need for additional power at PCC. Extensive Matlab/Simulink simulation as well as the DSP based experimental results have validated the proposed approach and showed that the grid-interfacing inverter could be utilized as multi-function device.

Daconti et al. [27] mentioned the main constraints that limit the transmission system power transfer capability, along with the existing method to alleviate these constraints. They also discussed the main feasibility issues to be addressed during uprating/upgrading solution. Aspects of effectiveness required technical analysis and usual methods for transmission line voltage and thermal uprating were presented. Finally, the dynamic thermal rate monitoring was emphasized as a good thermal uprating solution and its commercially available technologies were presented.

CHAPTER 3

GRID INTERCONNECTION OF SHP: PROBLEMS AND RECOMMENDATIONS

This chapter deals with grid interconnection problems associated with SHPs. This chapter also suggests some recommendations to mitigate the problems arising due to grid interconnection of SHPs.

3.1 GRID INTERCONNECTION PROBLEMS

One way of thinking about the technical problems of ac interconnections is to group them into those associated with the transmission interconnection itself, and those associated with operating the larger interconnected system. Thermal limits, stability limits, and voltage regulation are the main constraints on transmission line operation. Other transmission problems include loop and parallel path flows, and available transfer capacity. System-wide problems include frequency regulation, power quality, the coordination of planning and operations, political and institutional cooperation.

There are following points to be addressed adequately during grid interconnection

i. Thermal limits

ii. Stability limits

iii. Frequency variation

iv. Voltage regulation

v. Synchronization

vi. Power quality

vii. Grid fault

viii. Available transmission capacity (ATC)

ix. Surge Voltage

3.1.1 Thermal limits

The capacity of transmission lines, transformers, and other equipment is determined by temperature limits. If these limits are exceeded, the equipment can be damaged or destroyed. Equipment ratings have traditionally been conservative, and operators have stayed well below the rated limits, but increased power trading in liberalized markets has created pressure for higher utilization. Instead of a single thermal limit, dynamic ratings are now often used. For example, transmission lines can carry more current when heat is effectively dissipated, and thus will have a higher rating on cold, windy days without direct sunlight.

When transmission lines heat up, the metal expands and the line sags. If the sag becomes too great, lines can come into contact with surrounding objects, causing a fault. Excess sag can also cause the metal to lose tensile strength due to annealing, after which it will not shrink back to its original length. Important transmission lines are often monitored by a device called a "sagometer", which measures the amount of sag, making system operators aware of dangerous sag conditions. Thermal limits of a transmission line, distribution line are not a function of line length. Thus for a given line design, a line 1 km long and one 500 km long typically have the same thermal limit. Thermal limits usually determine the maximum power flow for lines less than 50 miles in length.

3.1.2 Stability limits

The stability limit of a transmission line is the maximum amount of power that can be transmitted for which the system will remain synchronized if a disturbance occurs. The power flow through a transmission line is governed by the following relation:

$$P = V_R \times V_s \times \sin\delta / X \qquad (3.1)$$

All other factors being equal, the power transmitted from the sending side to the receiving side increases as the difference in power angle between the two points, called δ (delta), approaches towards 90°, and decreases as it approaches towards 0°. However, the feedback mechanism that keeps generators in synchronism and returns them to synchronous operation if they are disturbed becomes more tenuous as δ approaches 90°. The stability limit represents the value of the power angle that allows the highest power transfer while maintaining stability; a typical maximum value of is δ around 45°.

In general, stability limits are more important than thermal limits for long transmission lines, while thermal limits are more important for shorter lines.

3.1.3 Frequency variation

The frequency deviation of a power system shall be limited to a specified modest range at the distribution level. For system operating at a nominal frequency of 50 Hz, the allowed frequency deviations are in the range of 48.5 Hz to 51.5 Hz i.e ± 3%. Impact of frequency variation is that at low frequencies the VAR output of power factor correction capacitors reduces thereby affecting the power factor. Also operation at low frequencies increases the flux in transformer thus pushing them near saturation and these results in increased VAR consumption and increased losses. A change in grid frequency beyond the safe limit can damage the equipment like generation, Transmission and various grid equipment. It could degrade the quality of the power being delivered to end users. It could also result in the collapse of the power systems itself (by triggering protective system action).

3.1.4 Voltage regulation

Voltage regulation describes the process and equipment to maintain voltage within acceptable limits. The primary objective of grid voltage regulation is to provide each customer connected to the grid with voltage that conforms to the design limitations of the customer's utilization equipment. Almost all utilization equipment is designed for use at a definite terminal voltage: the nameplate voltage rating. The voltage drops from the source to the utilization devices make it economically impractical to provide all customers with a constant voltage that corresponds to the nameplate voltage of their utilization devices. Thus, a compromise is necessary between the allowable deviation from utilization equipment nameplate voltage supplied by the power system and the deviation above and below the nameplate voltage at which satisfactory equipment performance can be obtained [1]. The voltage limits at the point of common coupling (PCC), where SHP is connected with a grid are specified. This is a stringent requirement that narrowly defines normal operating conditions at the PCC. The grid is to be designed and operated so that the service voltage at each PCC is within the limits of range. Utilization equipment is to be designed and rated to give fully satisfactory performance when the voltage at its terminals is within range of a utilization voltage limits. The voltage supplied to each customer at the PCC is an important measure of service quality. A satisfactory voltage level is required to operate lights, equipment, and appliances properly. Utilities generally maintain system voltages within 5-10 percent of nominal values in order to avoid the risk of voltage collapse, which can lead to a major interruption of service. Power system voltages are primarily governed by reactive power flows. Voltage along a transmission link are a function of the physical length of the circuit, the impedance per unit length, and the flow of power, the higher the current and the greater the reactance, the larger the voltage drops (if the reactance is predominantly inductive) or gain (if capacitive). Voltage collapse can be triggered when reactive demand is high and systems are operating near their stability limits, and then undergo a disturbance that triggers a quick downward spiral. To maintain voltages along long AC transmission lines, reactive compensation of various kinds can be employed, such as series and shunt capacitors, and shunt reactors. Devices called tap-changing transformers in the local distribution system are used to ensure that customer voltages are maintained even when system voltages change substantially. Factors involved in determining voltage drop on a grid include the primary voltage at which the electric power systems is operating, the number, size, and type of conductors, the length of the lines, the size and power factor of the various loads; and the location of loads on the grid. Multiple voltage-regulating devices are commonly used on grid, and it is necessary to coordinate the timing of the automatic voltage-regulating devices to prevent hunting (i.e., the regulating devices constantly adjusting the voltage in an attempt to reach the desired target voltage). The voltage-regulating devices commonly used on grid cannot respond instantaneously to maintain a constant regulated voltage output. When multiple voltage-regulating devices are used, the voltage-regulating devices closest to the source substation operate with the least time delay, and the voltage-regulating devices farther from the source substation have increased time delays. In the design of the grid system, the number, size, type, and control settings of these regulating devices are chosen based on known operating ranges of power flow and short-circuit duty.

SHP can affect the grid voltage two ways-

i. If power from a SHP device is injected into the power systems, it will offset load current and thus reduce the voltage drop on the grid systems. Just the existence of a SHP can completely offset the local electric power systems load, and the offset of this load may result in a voltage rise because of the elimination of the "voltage drop".

ii. If the SHP device supplies reactive power (capacitive) into the power system or absorbs reactive power (inductive) from the power systems, it will affect the voltage drop on the grid. For a given load level, if a SHP device supplies reactive power (capacitive), the voltage drop on the grid will be reduced, if a SHP device absorbs reactive power (inductive), the voltage drop on the grid will be increased [1].

3.1.5 Synchronization

Synchronization is the act of matching, within allowable limits the voltage magnitude, phase angle, and frequency of a SHP with grid prior to closing the SHP paralleling device. To minimize the transients to both the SHP and the grid, it is important that all three quantities be closely matched across the paralleling device before closing it. For three-phase applications, SHP phase rotation is typically checked at the time of SHP installation, with the phases being connected to the switches such that the phase rotation will always be correct. Synchronization is only a major concern for synchronous generators which is generating a voltage prior to synchronize action with the grid. Induction generators may be driven just above the synchronous speed by the prime mover before closing the paralleling device [1].

Table 3.1: Synchronization parameter limits for interconnection to grid [1]

Aggregate unit of SHP units (kVA)	Frequency difference (Δf Hz)	Voltage difference (ΔV%)	Phase angle difference (ΔØ°)
0-500	0.3	10	20
>500-1500	0.2	5	15
>1500-1000	0.1	3	10

Table 3.1 gives synchronization parameter limits for interconnection to grid. Out of phase Synchronization between the SHP and the grid may result in overheating of the synchronous generator armature core ends and damage to the SHP equipment. When operating at a low SHP voltage, the SHP may experience potentially large reactive power flow into the its units immediately after synchronization. The grid may experience low voltage because of the large reactive flow from the grid into SHP units. When operating at a high SHP voltage, the SHP will experience potentially large reactive power flow out of its units immediately after synchronization. The grid may experience high voltage because of the large reactive flow into the grid from the SHP units.

3.1.6 Power quality

Power quality phenomena include all possible situations in which the waveforms of the supply voltage or load current deviate from the sinusoidal waveforms at rated frequency with amplitude corresponding to the rated rms value of all three phases of a three-phase systems. The wide range of power quality disturbances cover sudden and short-duration deviation e.g. impulsive and oscillatory transients, voltage dips (or sags), short interruption, as well as study-state deviation such as harmonics and flicker.

Harmonic in power systems have received increased attention in recent years with the widespread application of advanced solid state power switching device in a multipule of power electronic applications. The ac power systems has a substantial number of large harmonic generating device i.e. adjustable speed drives for motor control and switch mode power supplies used in a variety of office equipment such as PCs fax machine etc. These device draw nonsinusoidal load currents consisting primarily of lower order 5^{th},7^{th}, 11^{th} and 13^{th} harmonics that distort the system power quality. Some of the sources for harmonics are as below [28]:

From domestic load

i. TV receivers
ii. Fluorescent lamps
iii. Electronic devices

From industrial loads

i. Diode/Thyristor converters
ii. Electric furnaces
iii. Discharge lamps

Control devices

i. Static VAR compensators
ii. Transformers

With the widespread use of harmonic-generating devices, the control of harmonic current to maintain a high level of power quality is becoming increasingly important. Table 3.2 gives Maximum harmonic current distortion in percent of current.

Table 3.2: Maximum harmonic current distortion in percent of current [1]

Individual harmonic order	h<11	11≤h<17	17≤h<23	23≤h<35	35≤h	Total demand distortion
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

A few detrimental impact of harmonic over power systems devices can be listed as below.

i. In transformers, harmonic currents can cause over- heating forcing the devices to be derated to prevent damage [28]

ii. Many modern power electronics based devices require a clean supply current to determine proper firing angles. Harmonics may cause the device to function incorrectly or not at all.

iii. The presence of any harmonic currents cause lowering of power factor with equal power, which means higher currents, must be generated by the utility leading to an increase in line losses.

iv. Inductive interference with telecommunication lines.

v. Error in what-hour induction meters.

vi. Some harmonics are directly affected by the presence of voltage harmonics. For example capacitors are affected by the voltage harmonics because they induce harmonics currents to flow which may cause the device to exceed its kVA rating.

The harmonics distortion problems can be realized in three ways, namely harmonic voltage distortion, harmonic current distortion and interharmonic distortion. These are described as follows.

3.1.6.1 Harmonic voltage distortion

The voltage waveform is never exactly a single frequency sine wave. This phenomenon is called "harmonic voltage distortion" or simply "voltage distortion". The voltage waveform can be described as a sum of sine waves with frequency being multiple of the fundamental frequency. The nonfundamental components are called "harmonic distortion".

There are three major contributions to the harmonic voltage distortion [28]

i. The voltage generated by a synchronous machine in a SHP plant is not exactly sinusoidal due to small deviation from the ideal shape of the machine.

ii. The power system transporting electrical energy from the power plants to the loads is not completely linear, although the deviation is small. Some components in the system draw nonsinusoidal current, even for a sinusoidal voltage. The classical example is the power transformer, where the nonlinearity is due to the saturation of the magnetic flux in the iron core of the power transformer. The amount of harmonic distortion originating in the power systems is normally small. The increasing use of power electronics for control of power flow and voltage carries the risk of increasing the amount of harmonic distortion originating in the power system. The same technology also offers the possibility of removing a large part of the harmonic distortion originating elsewhere in the system or in the load.

iii. The main cause harmonic voltage distortion is non linear loads. A growing part of the load is fed through power electronics converters drawing a nonsinusoidal current. The harmonic current components cause harmonic voltage components, and thus a nonsinusoidal voltage in the system.

3.1.6.2 Harmonic current distribution

The complementary phenomenon of harmonic voltage distortion is harmonic current distortion. The first is a voltage quality phenomenon the later is a current quality phenomenon. As harmonic voltage distortion mainly due to nonsinusoidal load currents, harmonic voltage and current are strongly linked. Harmonic current distortion requires over-rating of series components like transformer and cables. As the series resistance increase with frequency, a distortion current will cause more losses than a sinusoidal current of the same rms value.

3.1.7 Grid fault

Grid has detected a fault and de-energizes circuit any other source on that circuit needs to also stop energizing it. Maximum faults are limited by restricting substation transformer size, impedance or both installing bus or circuit reactors or inserting reactance or resistance in the transformer neutral. Minimum fault magnitude is largely dependent on fault resistance, which cannot be controlled. These low-magnitude faults are the most dangerous and difficult to detect. All detectable faults are cleared to minimize equipment damage, provide for public safety, and maintain overall reliability and power quality for all customers.

Clearing times for short circuits on grid vary widely and depend on the magnitude and type of protective equipment installed. In general, on most circuits, large current faults will be cleared in 0.1 s or less. Low-current faults frequently require clearing times of 5 s to 10 s or longer. Some very low level but potentially dangerous ground faults may not be cleared except by manual disconnection of the circuit. A supply systems is typically supplied through a circuit breaker or recloser located at the supply substation. It is divided into zones by fuses, recloses, or automatic sectionalizing devices that operate after counting current interruptions within a predefined time period. Most faults on the supply system are temporary in nature. That is, most faults are due to tree encroachment in an overhead distribution line, lightning, or other causes such that the source of the fault is gone after the initial operation of the protective devices. Therefore, automatic reclosing is usually employed on substation breakers or reclosers and on line reclosers, so the duration of an outage for most faults is limited to only a few seconds.

Following is the classification of different faults is [29]:

3.1.7.1 Unsymmetrical faults

The following are the symmetrical fault

i. Single phase to ground (L-G)

ii. Phase to phase (L-L)

iii. Two phases to ground (L-L-G)

iv. Phase to phase and third phase to ground

3.1.7.1 Symmetrical faults

The following are symmetrical fault

i. All three phases to ground (L-L-L-G)

ii. All three phases short- circuited (L-L-L)

Table 3.3 presents the most frequent short circuit faults in transmission systems and table 3.4 give an overview of different faults along with their causes.

Table 3.3 Most frequent Short-Circuit faults in power transmission circuits [29]

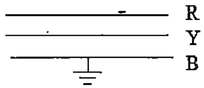
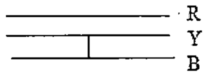
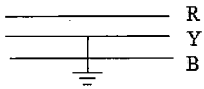
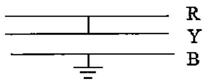
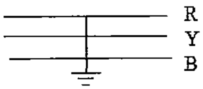
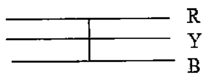
Type of short circuit fault	Representation	Percentage Occurrence
Single phase to ground (L-G)		70
Phase to phase (L-L)		15
Two phase to ground (L-L-G)		10
Phase to phase and third phase to ground		2 or 3
All the three phase to ground (L-L-L-G)		2 or 3
All the three phases shorted		2 or 3

Table 3.4 Major faults & their causes [29]

Type of fault	Cause
Insulation	Design of defects, Improper manufacturing, Improper installation and Aged or polluted insulation
Electrical	Lighting surges, Switching surges and Dynamic overvoltages
Mechanical	Animal contact, Tree contact, Vehicle Collision, Wind , Snow or ice, Contamination, Vandalism and major natural disasters
Thermal	Overcurrent and Overvoltage

Fault-current and fault-clearing issues related to the addition of SHP to the Grid may result in considerable impacts on the grid depending on the SHP size and type. If the SHP contributes fault current to the grid, the coordination of protective devices on the grid may be adversely affected and the fault current from the SHP may thermally overduty grid equipment and cause fault-interrupting equipment to experience fault current that exceeds equipment ratings. These are actually grid impact issues not strictly involved in the interconnection, but they should be carefully considered when adding the SHP to the grid and setting fault protective devices at the SHP.

The SHP system should be designed with adequate protection and control equipment including an interrupting device that will disconnect the SHP generator from grid if the grid experiences a fault. A failure of the SHP systems protection and control equipment including loss of control power should automatically open the disconnecting device to and thus disconnect the SHP system from the grid. The design of the SHP systems protection and control should consider the impact of the loss of control power and consideration should be given to automatically opening the disconnecting device. This will limit the possibility of disoperation of the SHP facility or damage to the SHP facility.

3.1.8 Available transmission capacity (ATC)

An important measure of transmission capacity is transmission transfer capability (TTC), which is the maximum power flow that a line can accommodate at any given time and still be able to survive the loss of a major generator or transmission link elsewhere in the system. Available transmission capacity (ATC) is the TTC of a line minus the amount of capacity already committed to other uses on that line. ATC is thus the measure of how much power can be safely transmitted over a transmission line at a given time while ensuring overall system reliability.

There are several types of transmission system problems that can determine the daily ATC limit. These problems include: [30]

3.1.8.1 Thermal limit

This is the maximum allowable flow in amps or MVA on a transmission line without exceeding the current carrying capability of the facility. Current rating may differ for short term and long term loading sequences and may vary with ambient temperature. A full AC load flow study or a fast DC load flow can detect thermal limit problems.

3.1.8.2 Low Voltage Limit

This is the lowest steady state voltage allowable at a transmission substation. This limit is generally set at 90% of nominal value for load serving substations but may be lower if the substation does not serve load. A full AC load flow study can detect low voltage limit problems.

3.1.8.3 Voltage Stability

The maximum allowable flow in amps or MVA on a line or across a transmission path such that loss of a transmission element due to a fault does not result in either a rapid voltage collapse or a slow voltage recovery. Only a complex stability study can detect a voltage stability limit problem.

3.1.8.4 Transient Stability limit

This is the maximum allowable flow in amps or MVA on a line or across a transmission path such that loss of a transmission element due to a fault does not result in generator instability. Only a complex stability study can detect a transient stability limit problem.

Determination of ATC always involves the determination of thermal limitations. Certain systems, such as tight urban networks, typically have only thermal problems. In such cases, it may be prudent to test only for thermal limitations. Other systems with lower load density, long transmission lines and remote generation are susceptible to all four types of problems. In such systems, testing usually includes low voltage stability or transient stability problems.

3.1.9 Surge Voltage

Transient surge voltages that occur in ac power circuits can be the cause of operational upset or product failure in industrial and residential systems and equipment. These problems have received increased attention in recent years because of the widespread application of complex semiconductor devices that are more sensitive to voltage surges than vacuum tubes, relays, and earlier generations of semiconductor devices. Logical and economical design of circuits to protect vulnerable electronic systems from upset or failure requires knowledge or estimates of the following: [1]

i. Transient voltage and current waveforms
ii. Frequency of occurrence of transients with various energy levels
iii. Particular environmental variations (such as amplitudes)
iv. Upset or failure thresholds of the particular equipment to be protected

3.2 RECOMMENDATION

Recommendation of grid interconnection problems of SHP plants is as follows.

3.2.1 Synchronization

Manual or automatic synchronization devices may be used for synchronization of the SHP with grid. Automatic synchronization is much preferred for the application because successful manual synchronization requires a highly skilled operator and unsuccessful synchronization can easily damage equipment on the grid and SHP itself. Generally, manual synchronization is not recommended.

Considerations in the design and operation of both types are discussed as follows.

i. Automatic synchronization: Many types of automatic synchronizers are available to replace part or all of the manual synchronizing functions. Sync-check relays, which are designed to check the grid voltage and the distributed generator voltage, close a contact when the two voltages are within certain length of time. The sync-check relays are the least costly and simplest to operate. The sync-check relays may also serve as signal devices for automatically closing the breaker at the PCC.

   Highly accurate and reliable automatic synchronization relays and electronic transducer combination packages are available with adjustable ranges to monitor and control the synchronism, frequency, phase or power factor and the voltage levels of the distributed generator. Dead bus relays can also be included in the combination packages to allow connection to a dead bus when the synchronization relay itself will not provide a signal to close the circuit breaker at the PCC.

ii. Manual synchronization: Manual synchronization equipment is rare and used only on smaller (i.e. less than 100 kW) distributed generator equipment or as a backup to an automatic system on larger units. Manual synchronization equipment or as a backup to an automatic systems on larger units. Manual synchronization equipment varies with distributed generator size but should include sync-check supervision to prevent closing outside of the accepted range. Guidance on equipment that may be used for manual synchronization is given in table 3.5 [1]

Table 3.5: Synchronizing guidance for manually paralleled SHP units

SHP size (kVA)	Voltage meters	Frequency meters	Phase angle		Sync scopes	Sync-check supervision
			Meter	Sync-lights		
0-10	2	0	0	2	0	Yes
>10-500	2	2	0	2	0	Yes
>500-1500	2	2	1	2	1	Yes
>1500-10000	2	2	1	2	1	Yes

Small single-phase systems (i.e. 10 kW or less) may be manually synchronized with grid with two voltmeters, two synchronization lights, and sync-check supervision. One voltmeter monitors grid voltage. The other monitors the distributed generator voltage.

Systems that are 10 kW or large may be manually synchronized with the grid with two voltmeters, two frequency meters, a synchroscope, and sync-check supervision. One voltmeter and one frequency meter monitor the grid voltage and frequency. The other voltmeter and frequency meter monitor the distributed generator voltage and the distributed generator voltage and frequency. A synchroscope pointer indicates the phase angle between the grid voltage and the distributed generator voltage. The straight-up, or 12:00, position indicates that the two voltages are in phase.

When a synchroscope is used, the connection between the grid and the distributed generator is made with the synchroscope rotating slowly in the clockwise direction and the pointer in about the 11:30 position. The rotation of the pointer shows that the frequencies of the grid and the distributed generator are not exactly the same. Synchronization with the pointer rotating slowly clockwise ensures the connection between the two units is made and there as a small outflow of power from the distributed generator.

3.2.2 Grid Frequency Control

Fig. 4.43 displays a simplified block diagram of the grid frequency control. This block diagram is only valid to obtain the mean value of grid frequency in the long term. The grid frequency control has the following variables: Electrical power (PE), frequency (F), Frequency set point (F SP) and Mechanical power (PM) of generators [31].

The grid frequency control has the following blocks: grid load, Grid spinning Masses, Distributed primary control loop, Secondary control loop and Tertiary control loop as shown in fig. 3.1

Grid load: It represents the total Electrical power (PE) of grid loads.

i. Grid spinning masses: It represents the rotating masses equation of the whole systems.
ii. Distributed primary control loop: For short times, from a few seconds to several minutes, the active turbine governors react for modifying turbines mechanical power according to correct frequency grid when a frequency deviation takes place.

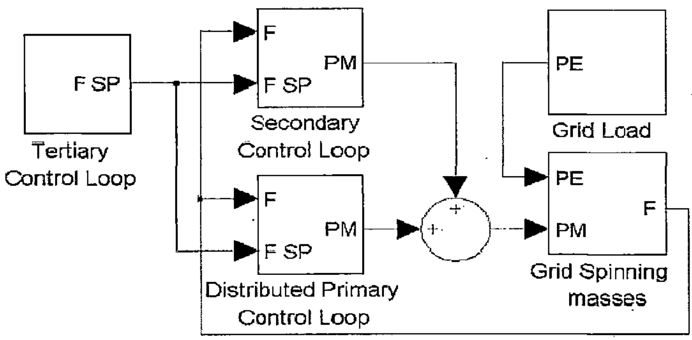


Fig. 3.1: Grid frequency control Simplified block diagram

All governors are proportional control (p type) for its controlled speed/frequency inputs. These p type controls are not able to cancel frequency error. Because of that, a small grid frequency error is still present after the action of governors. This kind of frequency control action is referenced as frequency primary control (FPC).

iii. Secondary control loop: For long times, several minutes time interval, another control systems reacts until obtaining a null frequency error. Only one system control of this kind must be active at the same time in the grid systems, since this control must be integral type control (I or P+I type). This kind of frequency control action is referenced hereinafter as frequency secondary control (FSC). Each turbine performing FPC recovers its initial spinning reserve when the FSP cancels the grid frequency error.

iv. Tertiary control loop: The grid dispatch centre manually changes the grid frequency set point hourly. This set point is introduced in all active governors for FPC and in the FSC. By this way, daily average grid frequency is equal to normal grid frequency. This kind of frequency control action is referenced as frequency tertiary control.

3.2.3 Fault control in Grid and Micro-Grid

Owing to the appearance of a negative sequence and amplitude drop in the grid voltages, the current magnitude that is delivered by the DPGS to the grid will rise considerably for the same amount of delivered power. Moreover, a negative-sequence current will appear, flowing uncontrollably through the power converter of the distribution system. In this sense, in (3.14), an approach based on a series inverter that is connected at the Point of common coupling (PCC) and controlled as current limiting impedance is proposed as a solution to limit the current rising inside the micro-grid. Additionally, in (3.15), it is argued that the switching of loads in micro-grids can cause relatively high transients in the voltage, and it is suggested that all power generation units should support the grid during such a disturbance in order to return to normal operating conditions. Moreover, the bandwidth of communication signals between the DPGS that is connected to the micro grid proves to be a big impediment for achieving proper implementation of such decentralized control. An improved solution, which bypasses this problem using variations in output impedance of each distributed system, is proposed in (3.16).

With respect to the negative-sequence current flowing through the grid-connected power converter, in (3.17) and (3.18), the implementation of a dual current controller, with one for the positive-sequence current and one for the negative-sequence current, has been discussed, and improved results are noticed when the negative-sequence current is also controlled. It should be noticed here that the complexity of the controller is doubled in this case, and an algorithm for detection of both positive-and negative-sequence components is necessary as can be observed in (3.19).

3.2.3.1 Current Control Strategies When Running on Grid Faults

Instantaneous active power p, which is delivered by a three-phase inverter to the grid, depends on the voltage vector in the PCC $\mathbf{v} = (v_a,v_b,v_c)$ and on the injected current vector in this point $\mathbf{i} = (i_a,i_b,i_c)$, such that [16]

$$p = v \cdot i \qquad (3.2)$$

Where • represents the dot product. Therefore, for a given voltage vector, there exist infinite current vectors, which are able to deliver exactly the same instantaneous active power to the grid. Hence it has been assumed that the energy source supplying power through the inverter exhibits slow dynamics, and hence, the active power reference will be considered a constant throughout each grid-voltage cycle. However, conclusions from this study are also valid for those cases in which the reference for the instantaneous active power could experience oscillations throughout a grid period, e.g., when active filtering functionality is implemented in the inverter.

Five different strategies for generating inverter reference currents in order to deliver to the grid active power p. In these strategies, it has been assumed that no reactive power should be injected to the grid ($q = 0$).

3.2.3.2 Instantaneous Active Reactive Control (IARC)

The most efficient set of currents delivering instantaneous active power P to the grid can be calculated as follows [16]

$$i_p = gv \qquad \text{with } g = p/|v|^2 \qquad (3.3)$$

Where |v| denotes the module of the three-phase voltage vector v, and g is the instantaneous conductance that is seen from the inverter output. In this situation, the grid converter is controlled to emulate a symmetric resistance on all three phases. The value of g is a constant in balanced sinusoidal conditions, but under grid faults, however, the negative-sequence component gives rise to oscillations at twice the fundamental frequency in |v|. Consequently, the injected currents will not keep their sinusoidal waveform, and high-order components will appear in their waveform. A current vector of (3.3) is instantaneously proportional to the voltage vector and therefore does not have any orthogonal component in relation to the grid voltage; hence, it gives rise to the injection of no reactive [16].

3.2.3.3 Instantaneously Controlled Positive-Sequence (ICPS)

The instantaneous active power that is associated with an unbalanced current $i = i^+ + i^-$, which is injected at the PCC of a three-phase unbalanced grid with $v = v^+ + v^-$, is given by

$$p = v \bullet i = v^+ i^+ + v^- i^- + v^+ i^- + v^- i^+ \qquad (3.4)$$

Where superscripts "+" and "-" denote the three-phase sinusoidal positive- negative-sequence signals, respectively. From (3.4), the positive-sequence current can be instantaneously controlled to deliver active power P by imposing the following constraints in the current reference calculation:

$$v \bullet i_p^+ = P \qquad (3.5a)$$

$$v \bullet i_p^- = 0 \qquad (3.5b)$$

Equation (3.6b) makes negative-sequence current components equal zero, whereas the positive-sequence current reference can be calculated from (3.6a) as follows:

$$i_p = i^+ + i^- = g^+ v^+ \qquad (3.6a)$$

$$g^+ = p/(|v+|^2 + v^+ \bullet v^-) \qquad (3.6b)$$

According to the p-q theory the instantaneous reactive power that is associated with the current vector of (3.6a) is given by

$$q = |v \times i_p^+| = |v^+ \times i_p^+| + |v^- \times i_p^+| \qquad (3.7)$$

Where the sign '×' denotes the cross product. It is possible to appreciate that the current reference that is calculated by means of (3.7) gives rise to oscillations at twice the fundamental utility frequency in the instantaneous reactive power that is injected to the grid.

It is worth noticing that positive- and negative – sequence components of the grid voltage should be perfectly characterized to implement this control strategy. Therefore, an algorithm that is capable of detecting the voltage- sequence components under unbalanced operating conditions should be added to the control system [16].

3.2.3.4 Positive-Negative-Sequence Compensation (PNSC)

Active power P can be delivered to the grid by injecting sinusoidal positive- and negative-sequence currents at the point of common coupling (PCC). To achieve this, the following constraints should be imposed in the current reference calculation [16].

$$v^+ . i_p^+ + v^- . i_p^- = P \qquad (3.8a)$$

$$v^+ . i_p^- + v^- . i_p^+ = 0. \qquad (3.8b)$$

From (3.8b), the negative-sequence reference current can be written as

$$i_p^- = - g^- v^- \quad , \text{where } g^- = (v^+ . i_p^+)/|v^+|^2 \qquad (3.9)$$

Substitution (3.9) in (3.8a) and simplifying, the positive- sequence reference current can be calculated by

$$i_p^{+} = g^{+} v^{+}, \quad \text{with} \quad g^{+} = p/\left(|v^{+}|^2 - |v^{-}|^2\right) \tag{3.10}$$

Adding (3.9) and (3.10), the final current reference becomes

$$i_p = i_p^{+} + i_p^{-} = g^{\pm}(v^{+} - v^{-}), \tag{3.11a}$$

$$g^{\pm} = p/\left(|v^{+}|^2 - |v^{-}|^2\right) \tag{3.11b}$$

Equation (3.11b) indicates that the injected current and voltage vectors have different directions. Consequently, the instantaneous reactive power that is delivered to the grid is not equal to zero but exhibits second order oscillations given by

$$q = |v \times i_p| = \left(|v^{+} \times i_p^{+}| + |v^{-} \times i_p^{-}|\right) + \left(|v^{+} \times i_p^{-}| + |v^{-} \times i_p^{+}|\right) \tag{3.12}$$

3.2.3.5 Average Active- Reactive control (AARC)

During unbalanced grid faults, current references that are obtained by means of the IARC strategy present high-order harmonics in their waveforms because instantaneous conductance g does not remain constant throughout grid period T. Since P has been assumed to be a constant, such harmonics come from the second-order component of $|v|^2$, being [19]

$$|v|^2 = |v^{+}|^2 + |v^{-}|^2 + 2|v^{+}||v^{-}|\cos(2wt + \varnothing^{+} - \varnothing^{-}) \tag{3.13}$$

High-order harmonics in the current references will be canceled if they are calculated by

$$i_p = G\, v, \text{ where } G = P/V_{\Sigma}^2 \tag{3.14}$$

Where V_{Σ} is the collective rms value of the grid voltage, and it is defined by

$$V_{\Sigma} = \sqrt{\frac{1}{T}\int_0^T |V|^2 dt} = \sqrt{\left(|v^{+}|^2 + |v^{-}|^2\right)} \tag{3.15}$$

In this case, instantaneous conductance is a constant under periodic conditions, namely, g = G. The current vector of (3.14) has the same direction as the grid-voltage vector, so it will not give rise to any reactive power. However, the instantaneous active power that is delivered to the unbalanced grid will not equal P, but it will be given by

$$P = i_p \cdot v = \left(|v|2/(V_{\Sigma}^2)\right) p = P^{+} + P^{-} \tag{3.16}$$

Substituting (3.13) and (3.15) in (3.16), it is easy to justify that the instantaneous active power that is delivered to the unbalanced grid consists of a mean value P that is accompanied by oscillations at twice the grid frequency. Since G is a constant, voltage and current waveforms will be monotonously proportional.

3.2.3.6 Balanced Positive- Sequence Control (BPSC)

When the quality of the currents that are injected in the grid plays a decisive role, they can be calculated as

$$i_p = G^+ v^+, \qquad \text{where } G^+ = P/|v^+|^2 \tag{3.17}$$

The current vector of (3.17) consists of a set of perfectly balanced positive-sequence sinusoidal waveforms. Under unbalanced operating conditions, the instantaneous active power that is delivered to the grid will differ from P because of the interaction between the positive-sequence injected current and the negative-sequence grid voltage, i.e.,

$$P = v \cdot i_p = v^+ \cdot i_p + v^- \cdot i_p \tag{3.18}$$

$$q = |v \times i_p| = |v^+ \times i_p| + |v^- \times i_p| \tag{3.19}$$

CHAPTER 4
MODELLING AND SIMULATION OF GRID CONNECTED SHP

4.1 INTRODUCTION

Small hydropower plants have received significant attention as a means of performance improvement of the electrical power systems by providing low cost energy with increased overall efficiency. A SHP station usually uses a fixed speed drive with mechanical regulation over the turbine water flow rate for controlling the active power generation. This chapter presents modelling and simulation of a SHP plant under different operating conditions [32].

4.2 MODELLING OF SHP

The SHP consists of three-phase synchronous generator system with excitation systems and Hydro Turbine with governor block. The mathematical modelling of different component of a grid connected SHP is given below.

4.2.1 MODELLING OF SYNCHRONOUS GENERATOR

The synchronous machine operates either as a generator or as a motor. The operating mode is dictated by the sign of the mechanical power (positive for generator mode and negative for motoring mode). The electrical part of the machine is represented by a sixth-order state space model. The model takes into account the dynamics of the stator, field and damper windings. The equivalent circuit of the model is represented in the rotor reference frame (d-q frame). Fig. 4.1 presents the equivalent circuit of a synchronous machine along d and q axes. The following equations are used to model the Synchronous generator [34-35].

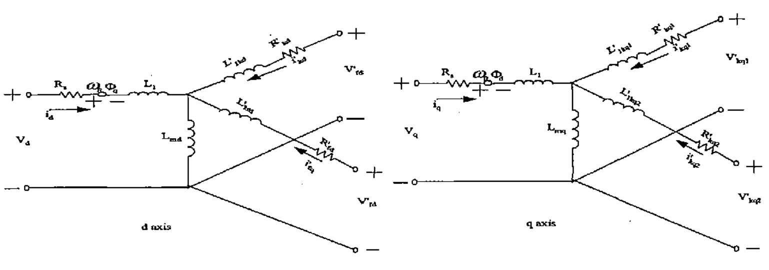


Fig. 4.1: Equivalent circuit of synchronous generator d axis and q axis

$$V_d = R_s i_d + \frac{d}{dt}\emptyset_d - \omega_R \emptyset_q \tag{4.1}$$

$$V_q = R_s i_q + \frac{d}{dt}\emptyset_q + \omega_R \emptyset_d \tag{4.2}$$

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt}\emptyset'_{fd} \tag{4.3}$$

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt}\emptyset'_{kd} \tag{4.4}$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d}{dt}\emptyset'_{kq1} \tag{4.5}$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d}{dt}\emptyset'_{kq2} \tag{4.6}$$

Where,

$$\emptyset_d = L_d\, i_d + L_{md}\,(i'_{fd} + i'_{kd}) \tag{4.7}$$

$$\emptyset_q = L_q\, i_q + L_{mq}(i'_{kq1} + i'_{kq2}) \tag{4.8}$$

$$\emptyset'_{fd} = L'_{fd}\, i'_{fd} + L_{md}\,(i_d + i'_{kd}) \tag{4.9}$$

$$\emptyset'_{kd} = L'_{kd}\, i'_{kd} + L_{md}\,(i_d + i'_{kd}) \tag{4.10}$$

$$\emptyset'_{kq1} = L'_{kq1}\, i'_{kq1} + L_{mq}\, i_q \tag{4.11}$$

$$\emptyset'_{kq2} = L'_{kq2}\, i'_{kq2} + L_{mq}\, i_q \tag{4.12}$$

Subscripts:

d, q: d and q axis quantity

r, s: Rotor and Stator quantity

l, m: Leakage and magnetizing inductance

f, k: Field and damper winding

R: Resistance

L_l: Leakage inductance

L_m: Magnetizing inductance

R'_{fd}: Field resistance

L'_{lfd}: Leakage inductance

R'_{kd} : Damper resistance

L'_{lkd}: Damper leakage inductance

All rotor parameters and electrical quantities are viewed from the stator and are identified by primed variables. The swing equation is described by [28]:

$$\Delta\omega(t) = \int \left[\frac{T_m - T_e}{2H}\right] dt - K_d\Delta\omega(t) \tag{4.13}$$

$$\omega(t) = \Delta\omega(t) + \omega_0 \tag{4.14}$$

Where, T_m: Mechanical torque

T_e: Electrical torque

4.2.2 Excitation Systems

The excitation system is an IEEE type I voltage regulator combined with an exciter. The basic elements that form the excitation system are the voltage regulator and the exciter. The exciter is represented by the following transfer function between the exciter voltage V_{fd} and regulators output E_f. Fig. 4.2 represents the block diagram of excitation systems [36]. Low pass filter is connected in series with positive sequence voltage. T_r is the time constant of the first-order systems that represents the stator terminal voltage transducer. Exciter block represents the first-order systems exciter. K_e is exciter gain and T_e is Exciter time constant. Lead Lag compensator is used to reduce the transient gain of first order systems. Damping block is used for derivative feedback of the first-order systems.

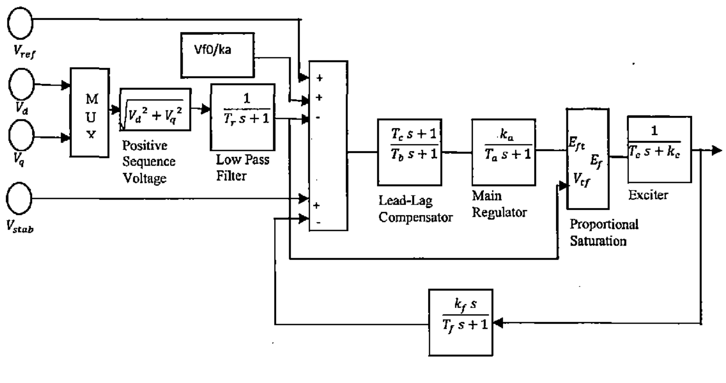


Fig. 4.2: Block diagram of excitation system

$$V_{fd} = \frac{E_f}{(K_e + sT_e)} \tag{4.15}$$

Where,

K_e represents exciter gain

T_e exciter time constant.

V_{ref} desired value of stator terminal voltage

V_d d axis component terminal voltage

V_q q axis component terminal voltage

V_f Field voltage of synchronous machine

T_b, T_c Lead lag Compensator time constant

T_f damping filter time constant

K_f damping filter gain

V_{f0} Initial field voltage

The block uses actual terminal voltage, desired value of terminal voltage and outputs appropriate field voltage to be applied to synchronous alternator. For simulation of synchronous generator the excitation is kept constant at 1.0 pu in this model of synchronous generator.

4.2.3 Hydro Turbine

This block represents a hydro turbine [34-35].

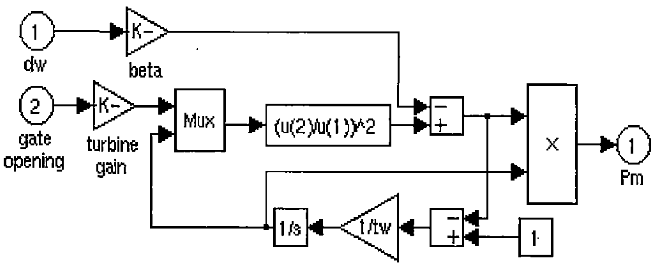


Fig. 4.3: Block-diagram representation of the hydraulic turbine

Where,

T_w water starting time

dw speed deviation

P_m Mechanical power of synchronous machine

4.2.4 Governor

.Fig. 4.5 represents the block diagram of governor.

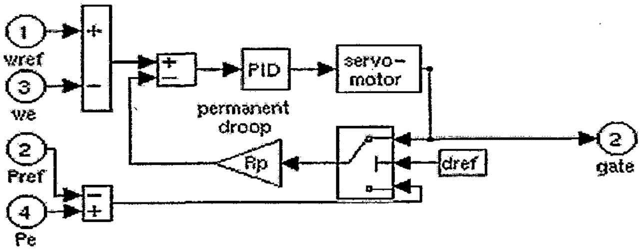


Fig. 4.4 Block-diagram representation of governor

Fig. 4.5 represents the block-diagram of gate servomotor.

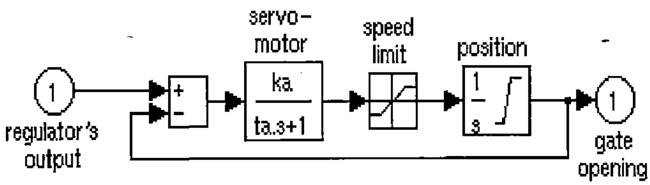


Fig. 4.5: Block-diagram representation of gate servomotor

4.3 SIMULATION OF SHP

The performance of SHP has been simulated under different conditions which are as below

4.3.1 SHP plant feeding local load

As shown in Fig. 4.6, SHP consists of a synchronous generator coupled with hydro-turbine feeding local load of 50 kW. For simulation of this system, different values of parameters taken are given in Table 4.1. For simulation purpose, first the synchronous machine is started at no load, then a local load of 50 kW is connected to SHP at t=0 sec.

Table 4.1: Values of different parameters for simulation purpose

Parameters	values
Servo motor gain, K_a	6.67
Servo motor time constant, T_a	0.007 s
Gate opening, g_{min}	0.01 pu
Gate opening, g_{max}	0.975 pu
Gate opening, V_{gmin}	-0.1 pu/s
Gate opening, V_{gmax}	0.1 pu/s
Permanent droop, R_p	0.05
Proportional gain, K_p	1.163
Integral gain, K_i	0.105
Derivative gain, K_d	0
Time constant T_d	0.01 s
Hydroulic turbine water starting time, T_w	1.00 s
Initial mechanical power, P_m	0.0996458 pu
Nominal power of generator, P	325 kVA
Line-to-line voltage of generator, V	415 V
Frequency, f	50 Hz
No of pole, P	4
Stator resistance, R_s	0.018281 pu
Stator leakage inductance, L_{ls}	0.06 pu
Stator magnetizing inductance of d-axis, L_{md}	2.46 pu
Stator magnetizing inductance of q-axis, L_{mq}	2.1 pu
Field resistance, R_f	0.007413 pu
Field leakage inductance, L_{lfd}	0.3133 pu
Damper resistance of d-axis,R_{kd}	0.2762 pu
Damper resistance of q-axis, L_{lkd}	1.901 pu
Inertia coefficent	0.1759
Regulator gain constant, K_a	350
Regulator time constant, T_a	0.0001 s
Low pass filter time constant, T_r	20e-6
Excitor constant, K_e	1.0
Excitor time constant, T_e	0.01 s

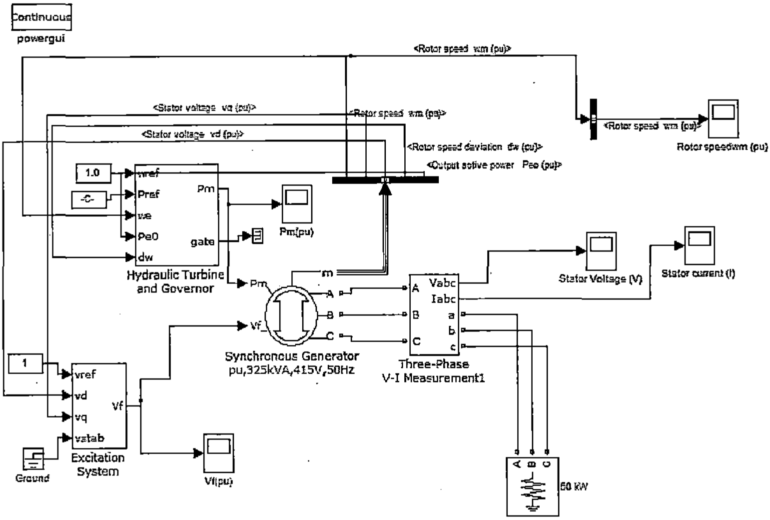


Fig.4.6: SHP plant feeding to local load

For this case, Rotor speed is shown in fig. 4.7. Rotor speed starts from 1.0 pu and oscillates due to inertia of machine and after 15 s, it reaches a steady state value of 0.995 pu. Excitation voltage starts with value 1.0 pu and rises upto 1.4 pu, after 15 s it reaches to a constant value of 1.09 pu. The excitation voltage is shown in Fig. 4.8. Three phase sinusoidal stator currents vs time waveforms are shown in Fig. 4.9. Three phase sinusoidal stator voltages vs time waveforms are shown in Fig. 4.10.

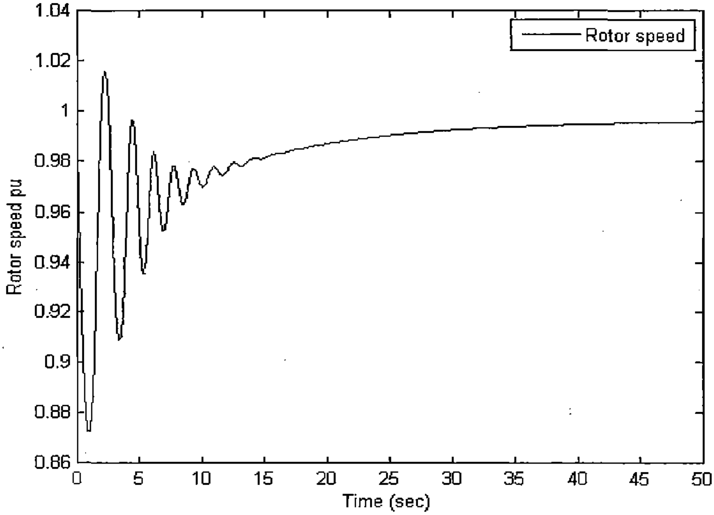


Fig 4.7: Waveform of Rotor speed vs Time

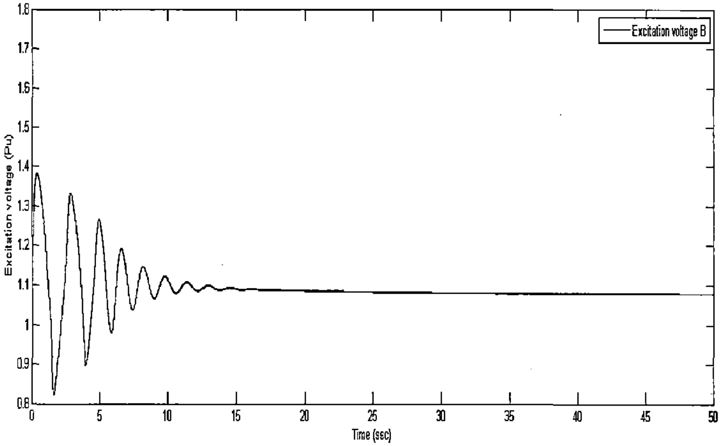


Fig 4.8: Waveform of Excitation voltage vs time

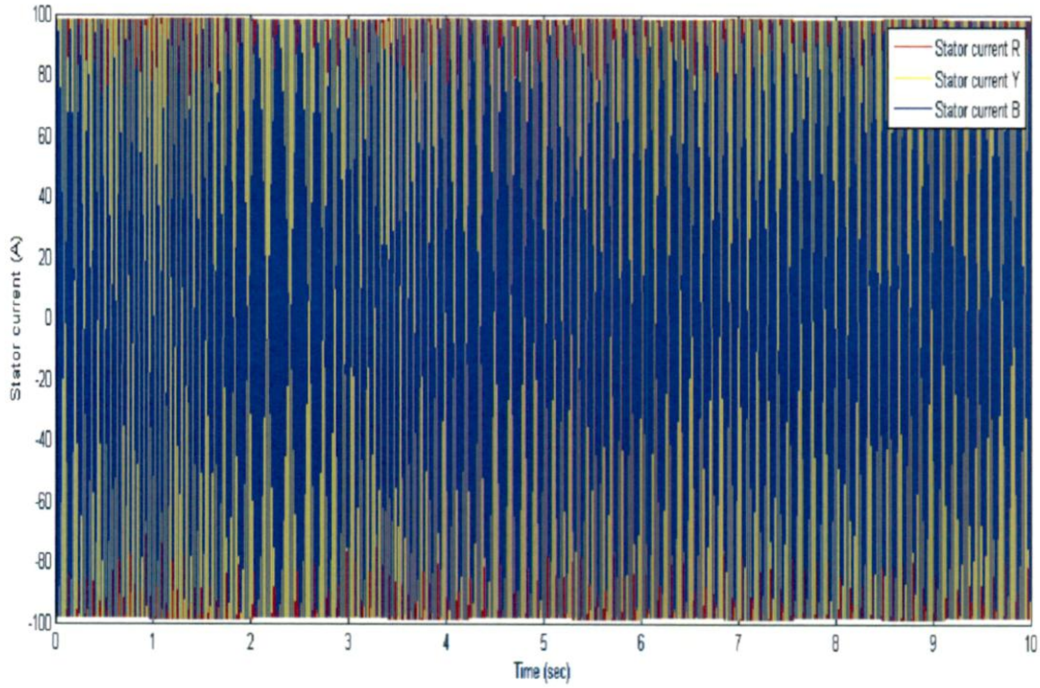


Fig 4.9: Waveform of Stator currents vs Time

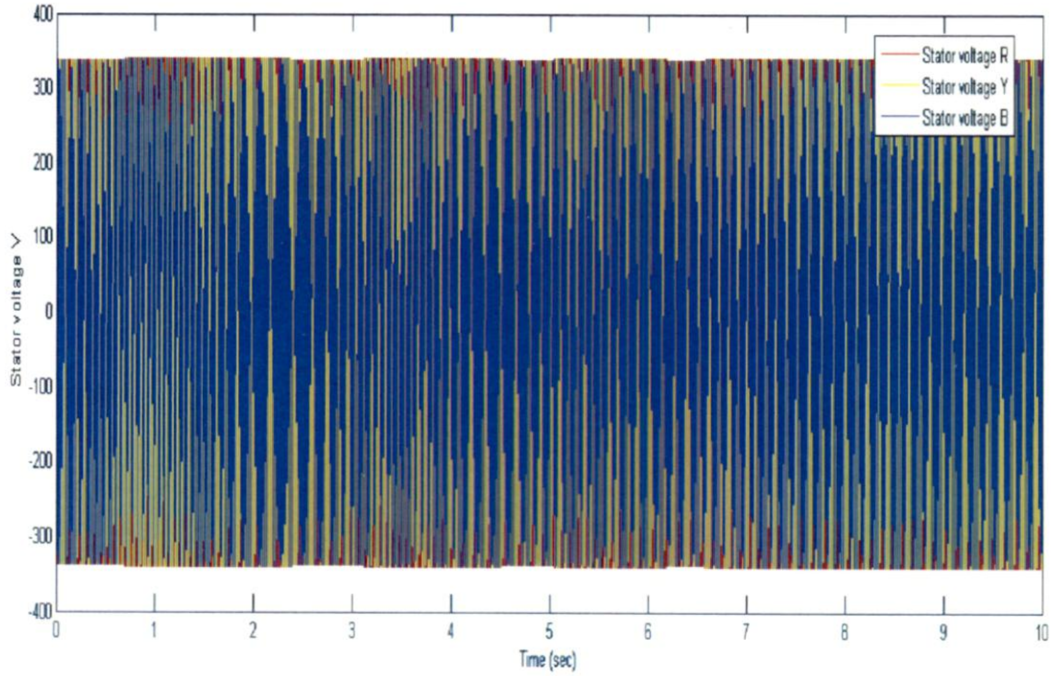


Fig 4.10: Waveform of Stator voltages vs Time

4.3.2 SHP plant in Grid connected mode

In this case, the SHP plant consists hydro-turbine coupled with synchronous generator and is connected to grid as shown in Fig. 4.11. For simulating this systems, same parameters of synchronous machine, excitation systems, turbine and governor have been used as given in Table 4.1. The different parameters of transformer are shown in Table 4.2. In this case, first SHP plant is started at no load condition, then it is connected with grid at t= 0.01 s.

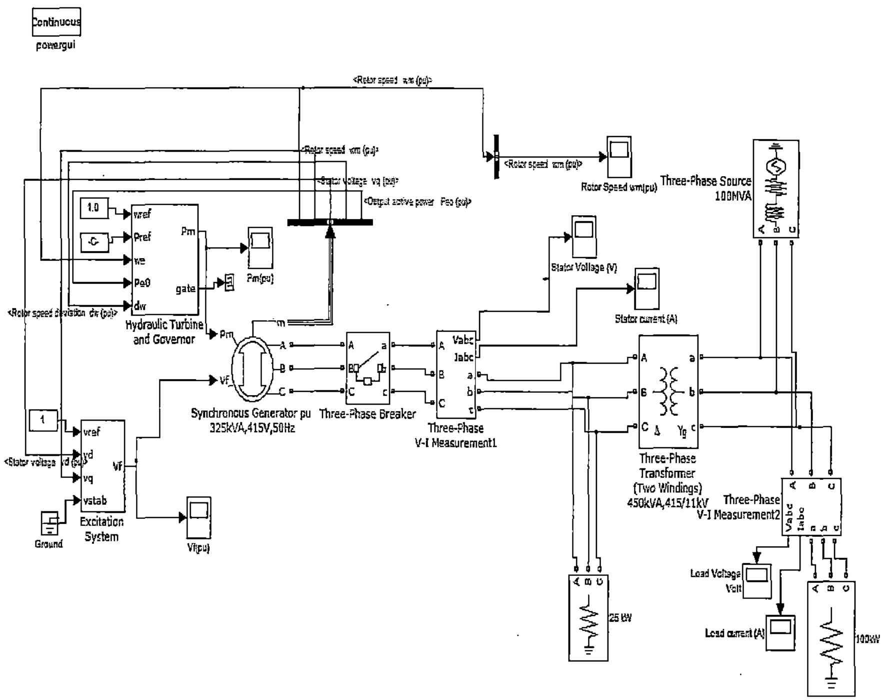


Fig. 4.11: Model of SHP plant in grid connected mode

Table 4.2: Values of transformer parameters for simulation purpose

Parameters	Values
Nominal power, P	450 kVA
frequency	50 Hz
Primary winding voltage, V1	415 V
Primary winding resistance, R1	0.002 pu
Primary winding inductance, L1	0.08 pu
Secondary winding voltage, V2	11 kV
Secondary winding resistance, R2	0.002 pu
Secondary winding inductance, L2	0.08 pu
Magnetization resistance, R_m	500 pu
Magnetization reactance, L_m	500 pu

For this case, Rotor speed is shown in fig. 4.12. Rotor speed starts from 0.94 pu and oscillates due to inertia of machine for 1 s after that it attains a steady state value of 1.0 pu as shown in fig. 4.12. Excitation voltage starts with very less value and rises upto 1.4 pu after 15 s, it comes to a constant value of 1.09 pu. The simulated graph is shown in fig. 4.13. Initially very high stator current is observed followed by closing of circuit breaker at 0.01 s and after 0.5 s, it comes to steady state value. Three phase sinusoidal stator currents waveforms are shown in fig. 4.14. Three phase sinusoidal stator voltages waveforms are shown in fig. 4.15. On grid side 100 kW load is connected at voltage level 11 kV. The load voltages vs time waveforms on 100 kW load sides are shown in fig. 4.16. Three phase sinusoidal load currents vs time waveforms on 100 kW load sides are shown in fig. 4.17.

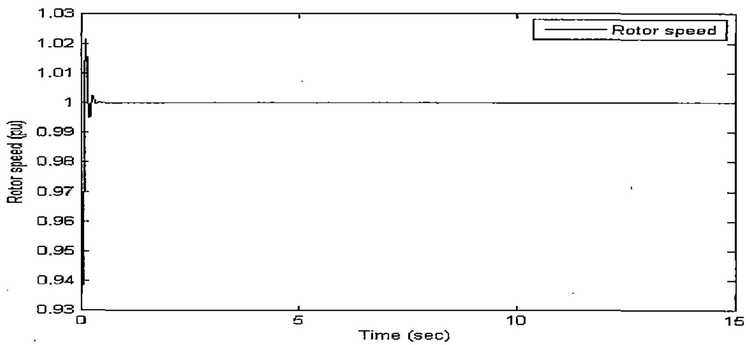


Fig.4.12: Waveform of Rotor speed vs Time

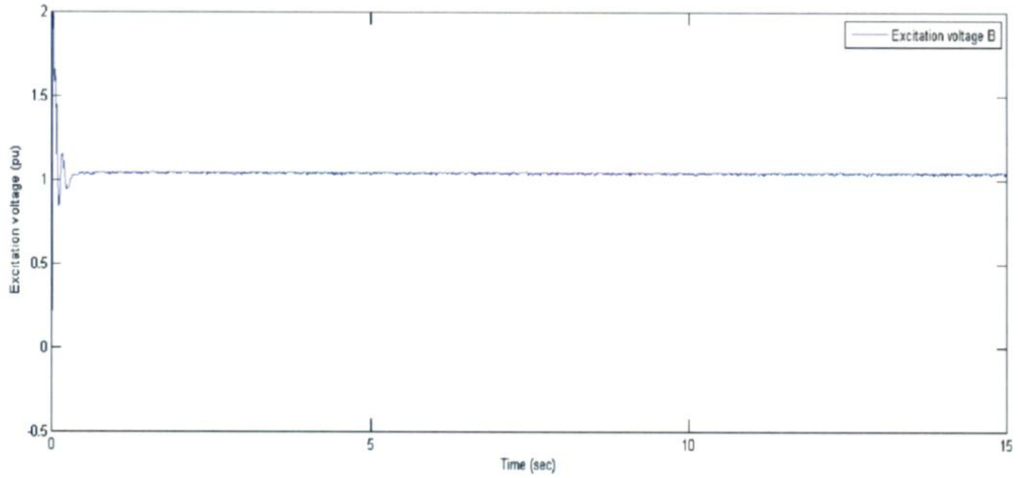


Fig.4.13: Waveform of excitation voltage vs Time

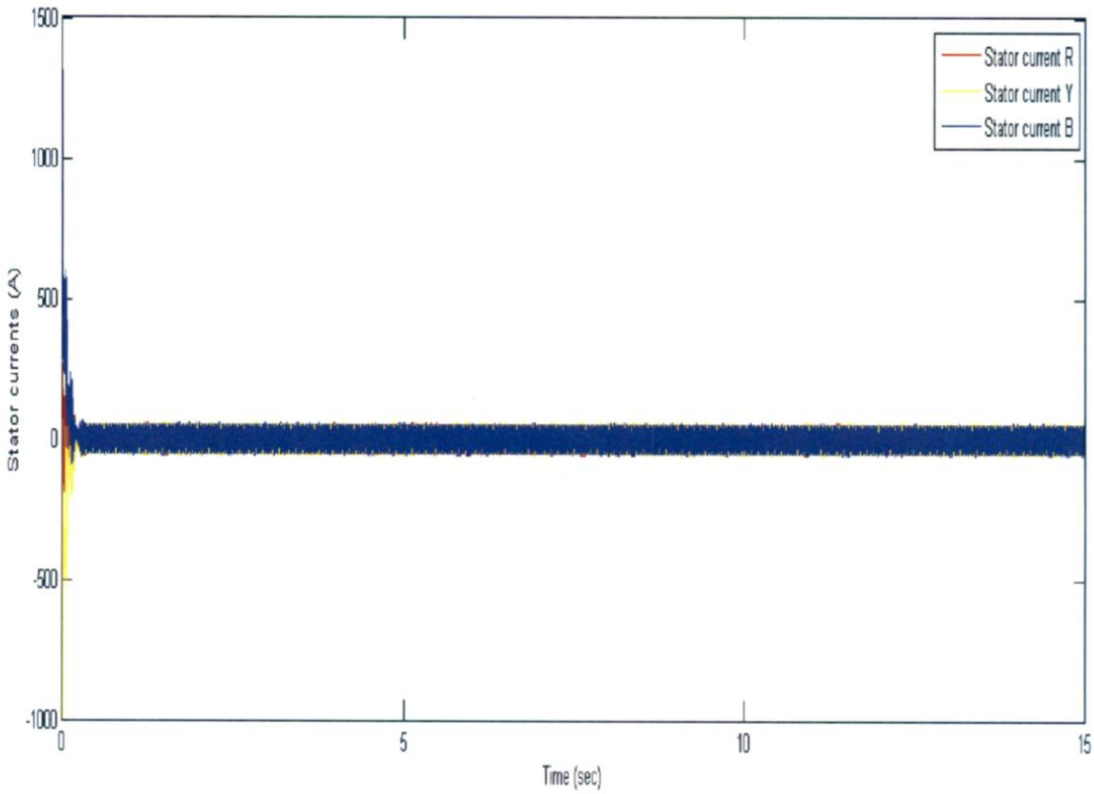


Fig. 4.14: Waveform of stator currents vs time

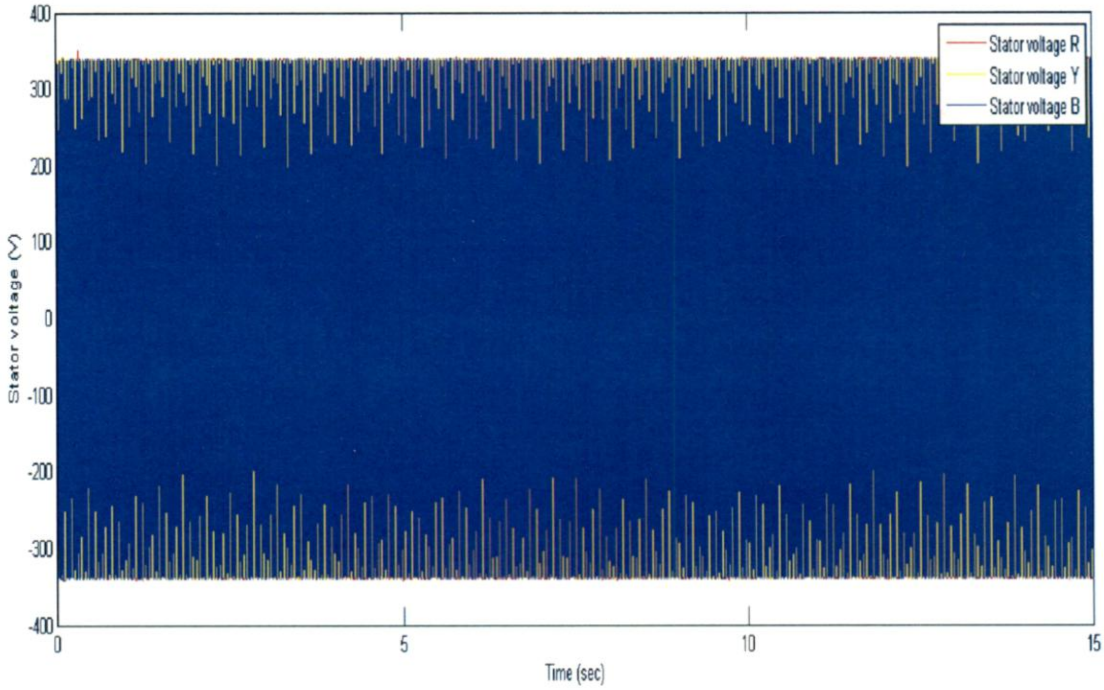


Fig. 4.15: Waveform of stator voltages vs time

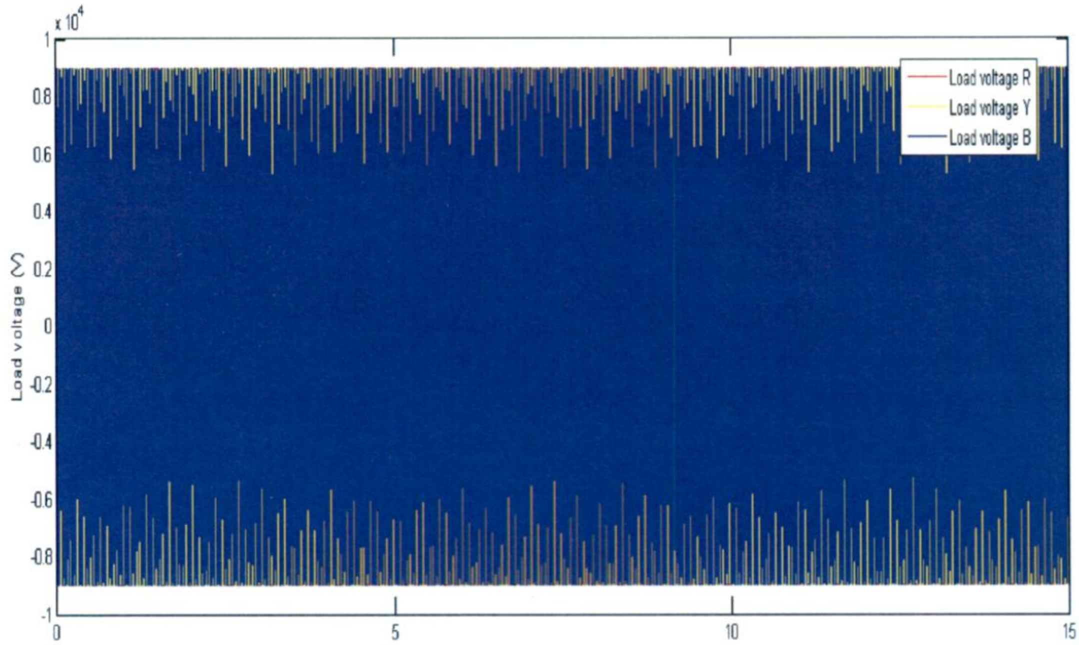


Fig. 4.16: Waveform of three phase load votages vs time

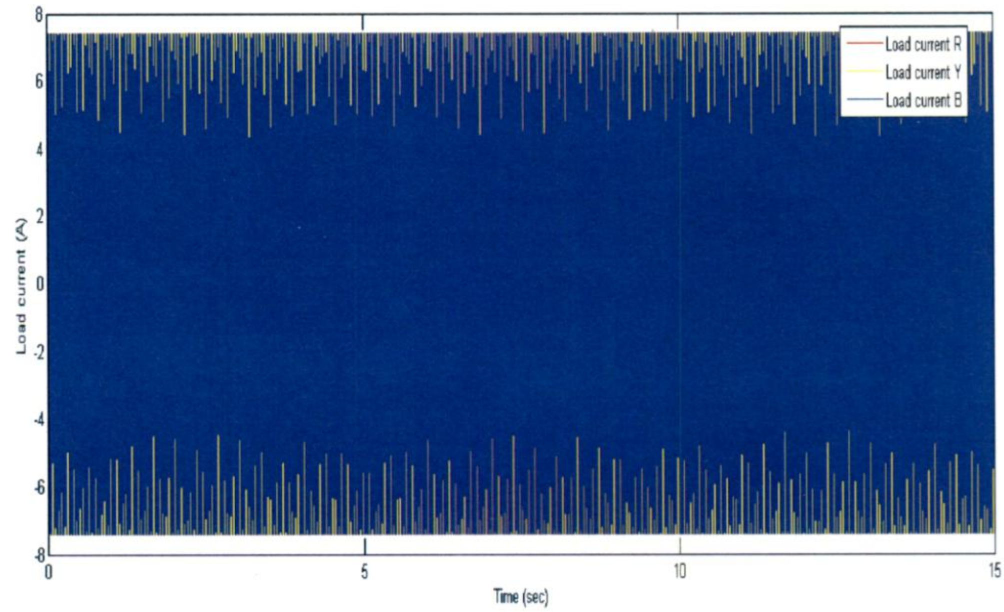
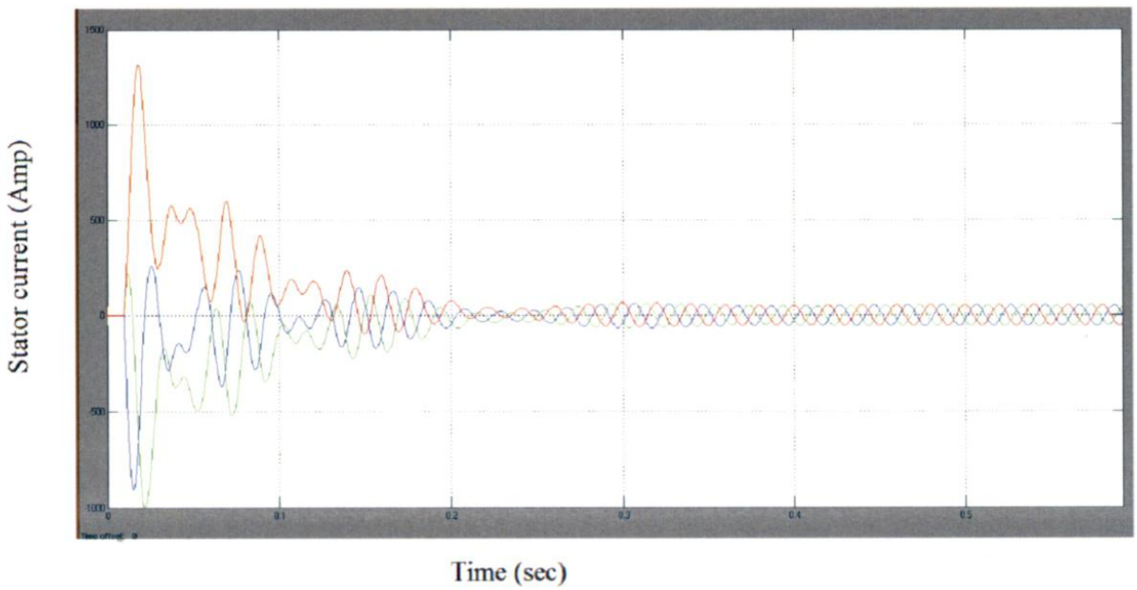


Fig.4.17: Waveform of three phase load currents vs time

In this case, model is run for 15 sec to achieve steady state condition. Closing time of circuit breaker is taken as 0.01 sec. The analysis of stator current waveform shows that during the switching action of circuit breaker for connecting the SHP to grid and starting of synchronous generator, transient current appears in all the three phases as shown in Fig. 4.18.



4.18 Waveform of transient stator currents vs time

4.3.3 Grid connected SHP plant during fault condition

In this case, the SHP plant consists hydro-turbine coupled with synchronous generator and is connected to as shown in Fig. 4.19. For simulating this systems different parameters of synchronous machine, excitation systems, turbine and governor are presented in Table 4.3. The different parameters of transformer are shown in Table 4.4. In this case, Initially SHP is starred at no load and than connected to the grid at t=0 s. There are two fault is created in this model, one fault is created on generator side at t= 6.0 s and another fault is created on grid side at t= 10.0 s.

Table 4.3: Values of different parameters for simulation purpose

Parameters	Values
Servo motor gain, K_a	3.33
Servo motor time constant, T_a	0.07 s
Gate opening, g_{min}	0.01 pu
Gate opening, g_{max}	0.975 pu
Gate opening, V_{gmin}	-0.1 pu/s
Gate opening, V_{gmax}	0.1 pu/s
Permanent droop, R_p	0.05
Proportional gain, K_p	1.163
Integral gain, K_i	0.105
Derivative gain, K_d	0
Time constant T_d	0.01 s
Hydroulic turbine water starting time, T_w	2.67 s
Initial mechanical power, P_m	1 pu
Nominal power of generator, P	325 kVA
Line-to-line voltage of generator, V	415 V
Frequency, f	50 Hz
No of pole, P	4
Stator resistance, R_s	0.0028544 pu
Field resistance, R_f	0.007413 pu
Field leakage inductance, L_{lfd}	0.3133 pu
Damper resistance of d-axis,R_{kd}	0.2762 pu
Damper resistance of q-axis, L_{lkd}	1.901 pu
Inertia coefficent	3.2
Regulator gain constant, K_a	300
Regulator time constant, T_a	0.001 s
Low pass filter time constant, T_r	20e-3
Excitor constant, K_e	0.001
Excitor time constant, T_e	0.1 s

Table 4.4: Values of transformer parameters for simulation purpose

Parameters	Values
Nominal power, P	3.0 MVA
frequency	50 Hz
Primary winding voltage, V1	415 V
Primary winding resistance, R1	0.027 pu
Primary winding inductance, L1	0.08 pu
Secondary winding voltage, V2	11 kV
Secondary winding resistance, R2	0.027 pu
Secondary winding inductance, L2	0.08 pu
Magnetization resistance, R_m	500 pu
Magnetization reactance, L_m	500 pu

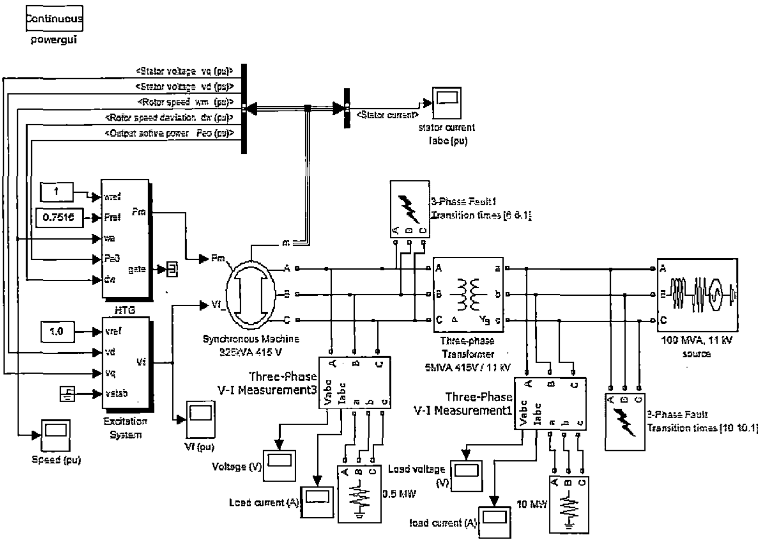


Fig. 4.19: Model of grid connected SHP plant during grid fault

For this case, Rotor speed is shown in fig. 4.20. Rotor speed starts from 1.0 pu and oscillates due to inertia of machine for 3.5 s after that it attains a steady state value of 1.0 pu, after fault on generator side at t=6 s it again oscillates for 1.5 s and attains steady state value of 1.0 pu. Due to fault on grid side at t= 10 s rotor speed oscillates for 2 s as shown in fig.

4.20. Excitation voltage starts around 6.0 pu and rises upto 10 pu, after 2 s it comes to a constant value of 2.2 pu. During faults excitation voltage rises upto 11.5 pu but it again attains steady state value after few cycle. The simulated graph is shown in fig. 4.21. Initially very high stator current is observed and after 2 s it attains steady state value. Due to fault created at t=6 s and t=10 s again high value of stator current and transient occures. Three phase sinusoidal stator currents waveforms are shown in fig. 4.22. Three phase sinusoidal load voltages waveforms are shown in fig. 4.23. Three phase sinusoidal load current waveforms are shown in fig. 4.24.

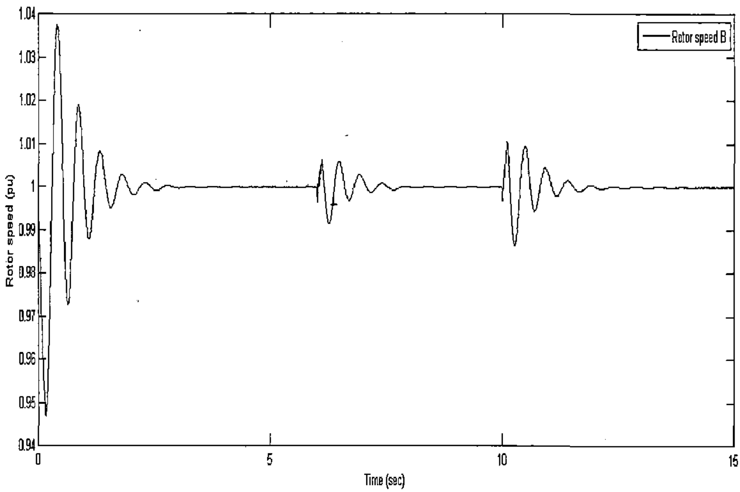


Fig. 4.20: Waveform of Rotor speed vs time

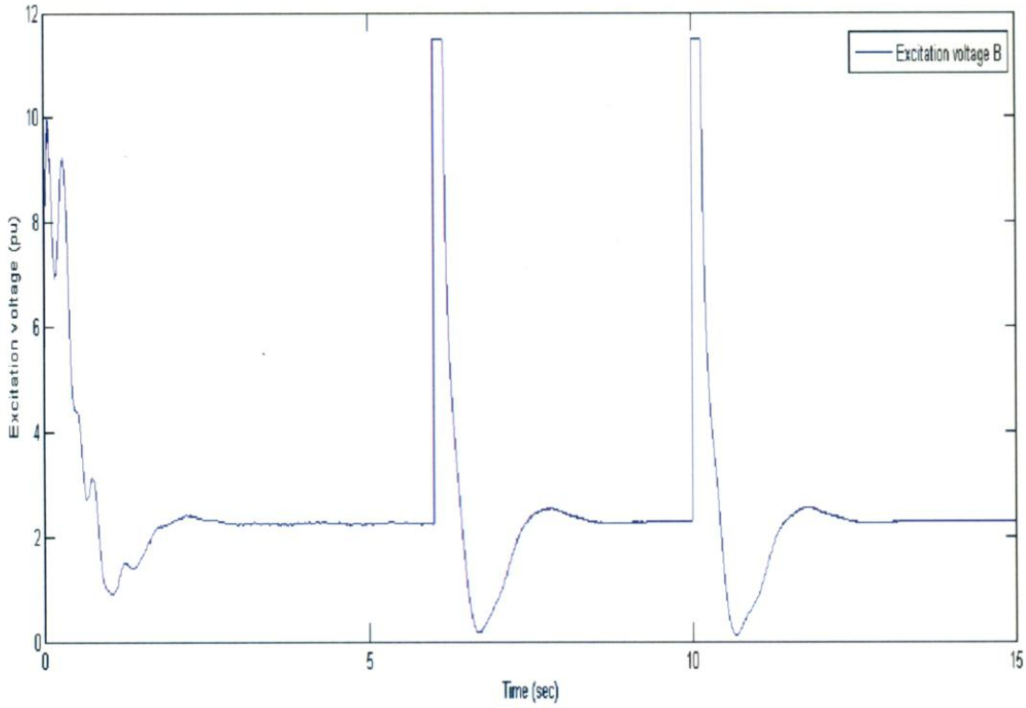


Fig. 4.21: Waveform of excitation voltage vs time

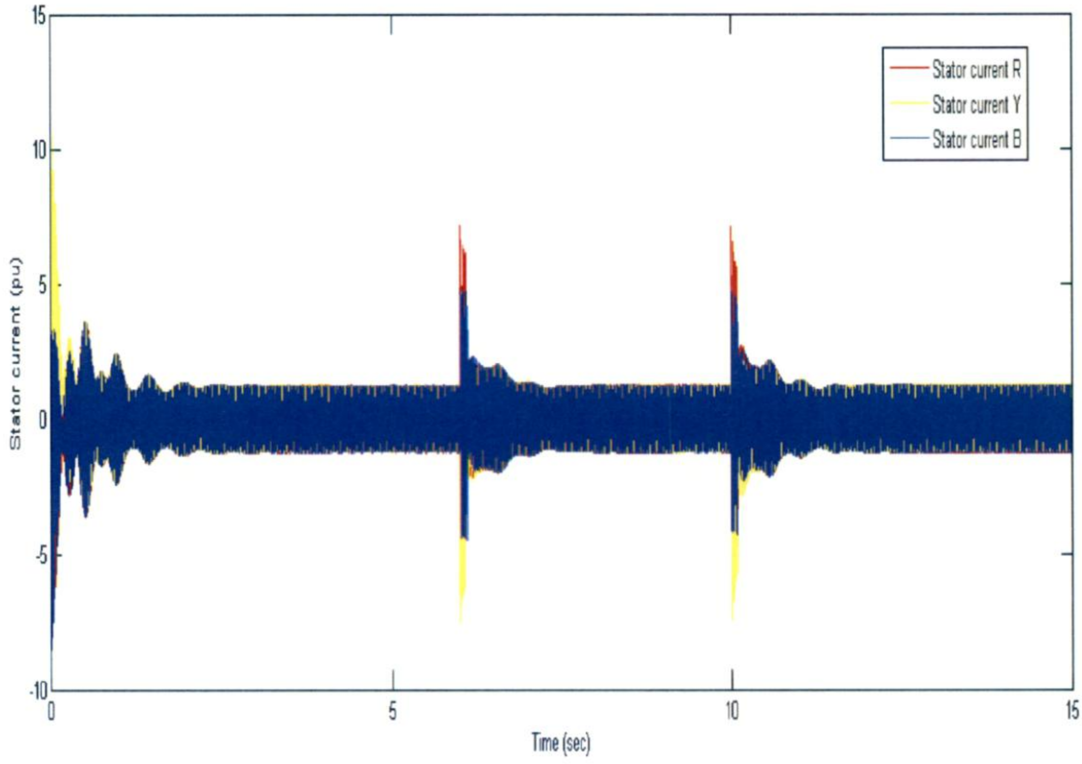


Fig. 4.22: Waveform of Stator currents vs time

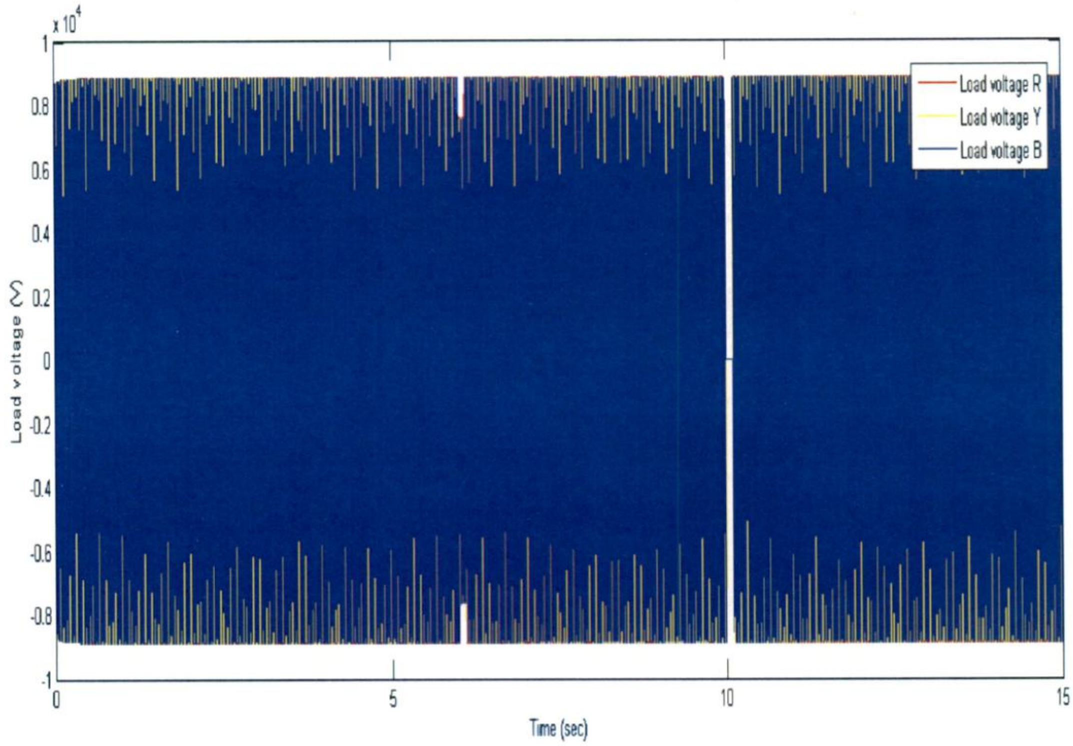


Fig.4.23: Waveform of load voltages vs time

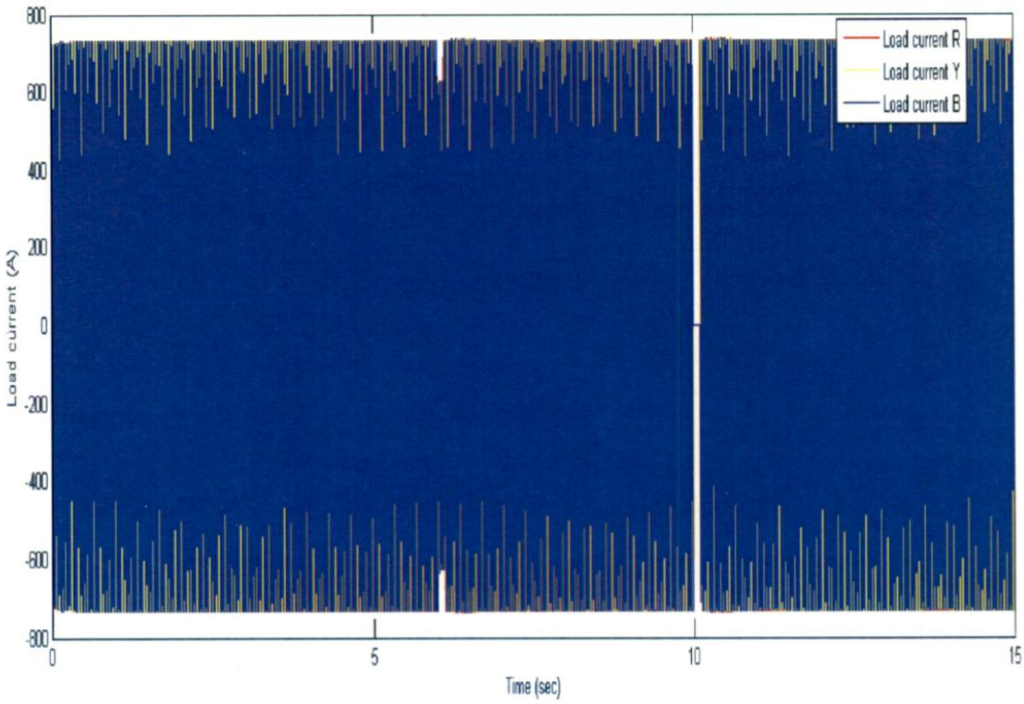
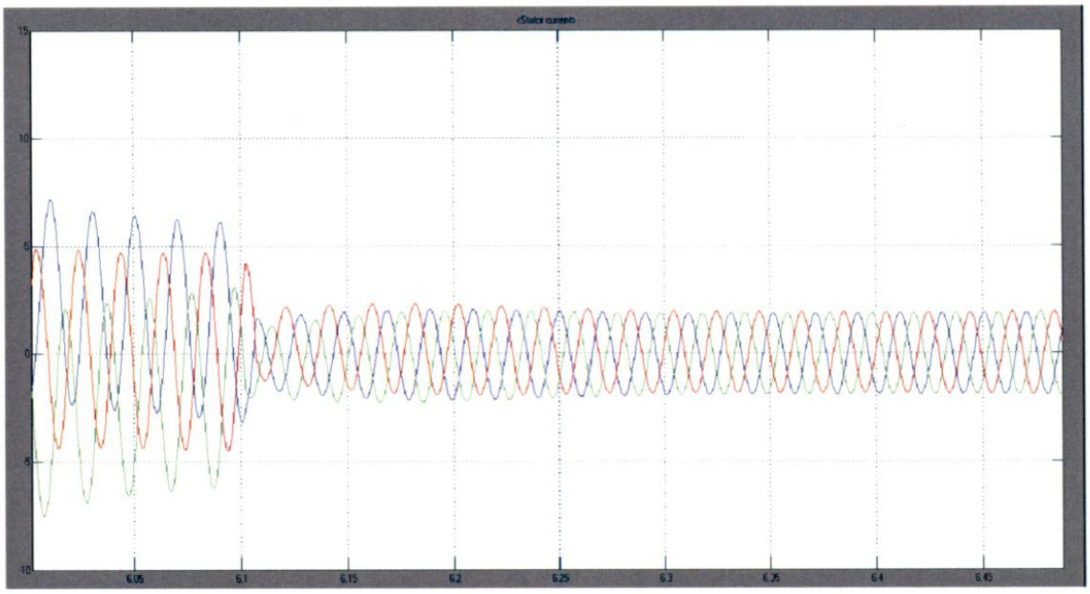


Fig. 4.24: Waveform of load currents vs time

First fault is simulated from t= 6.0 s to t=6.1 s and second fault is simulated from t=10.0 s to t=10.1 s. Due to fault, high transient current appears which is shown in Fig.4.25 and Fig. 4.26.

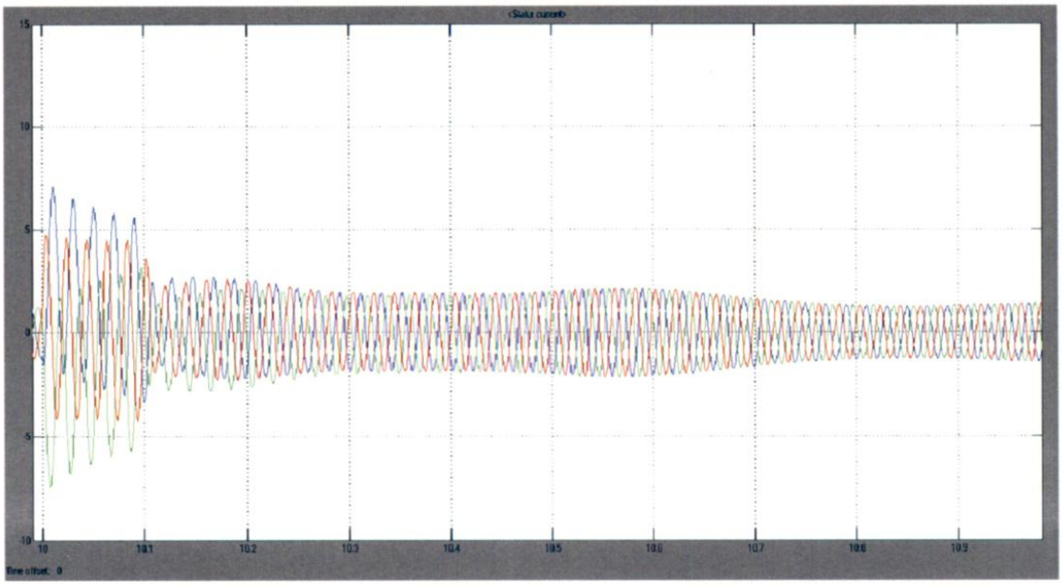
Stator current (A)



Time (sec)

Fig. 4.25: Waveform of transient stator currents vs time during first fault

Stator current (A)



Time (sec)

Fig. 4.26: Waveform of transient stator currents vs time during second fault

4.3.4 Two SHP plants Connected with Grid

In this case, two SHP plants consist hydro-turbine coupled with synchronous generator and are connected to the grid as shown in Fig. 4.27. For simulating this systems, same parameters of synchronous machine, excitation systems, turbine and governor have been used as given in Table 4.1. For simulation same parameters of both transforms have been used as shown in Table 4.2. In this case, Initialy both SHP 1 and SHP 2 are started at no load and then they are connected to the grid at t=0.01 s and t=0.1 s, respectively.

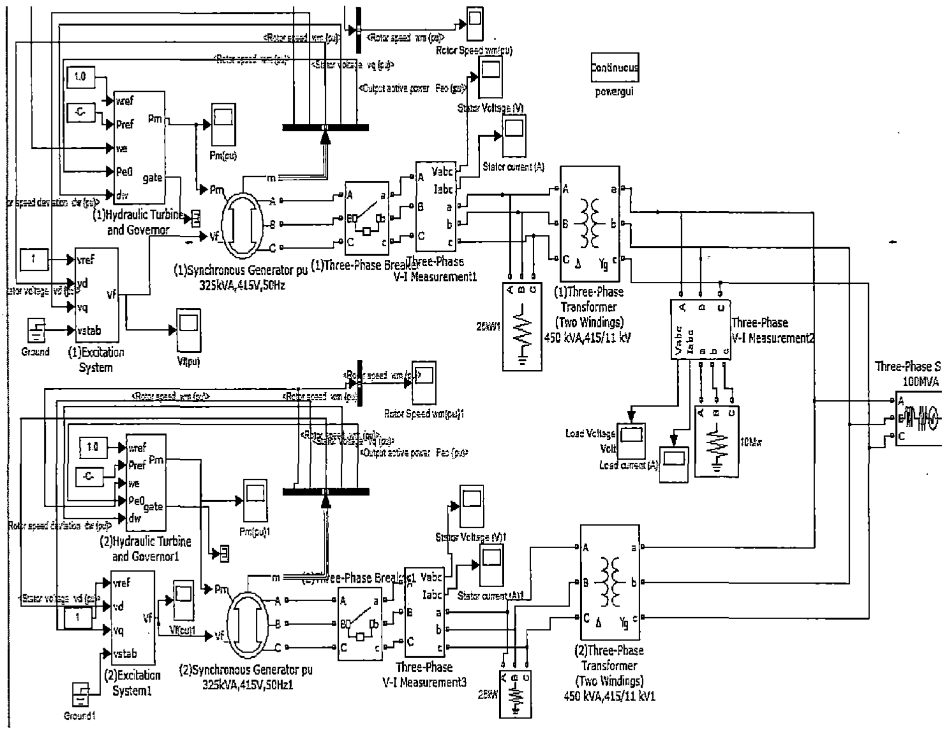


Fig.4.27: Model of two SHP plants connected with grid

For this case, Rotor speed of SHP 1 is shown in fig. 4.28. Rotor speed starts from 1.0 pu and oscillates due to inertia of machine for 0.8 s after that it attains a steady state value of 1.0 pu as shown in fig. 4.28. Initially very high stator current of SHP 1 is observed followed by closing of circuit breaker at t=0.01 s and after 0.2 s it attains steady state value. Three phase sinusoidal stator currents waveforms of SHP 1 are shown in fig. 4.29. Initially transient stator voltage is observed for SHP 1 as shown in fig.4.30. Three phase sinusoidal load voltages waveforms of SHP 1 are shown in fig. 4.31. Three phase sinusoidal load currents waveforms of SHP 1 are shown in fig. 4.32. Rotor speed of SHP 2 is shown in fig. 4.33. Rotor speed starts from 1.0 pu and oscillates due to inertia of machine for 0.8 s after that it attains a steady state value of 1.0 pu. Stator current of SHP 2 is shown in fig. 4.34. Stator current starts to flow after closing the circuit breaker at t=0.1 s, initially very high stator current is observed and after 0.2 s it attains steady state value. Three phase sinusoidal stator voltages waveforms of SHP 2 are shown in fig. 4.35.

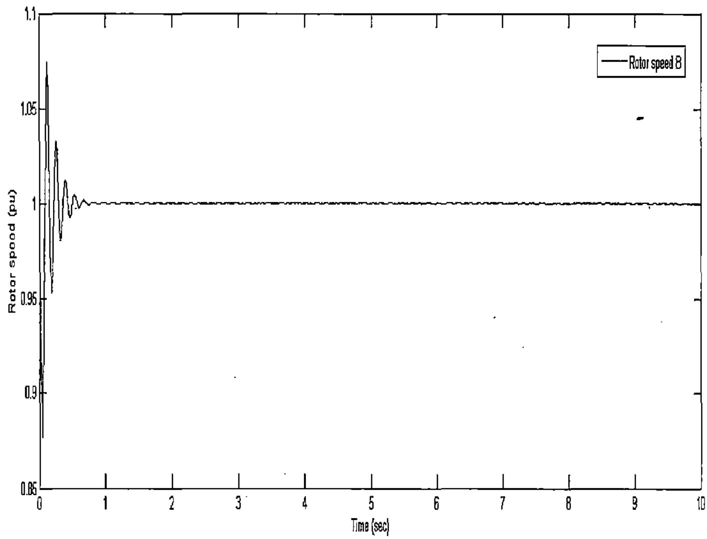


Fig. 4.28: Waveform of rotor speed vs time for SHP 1

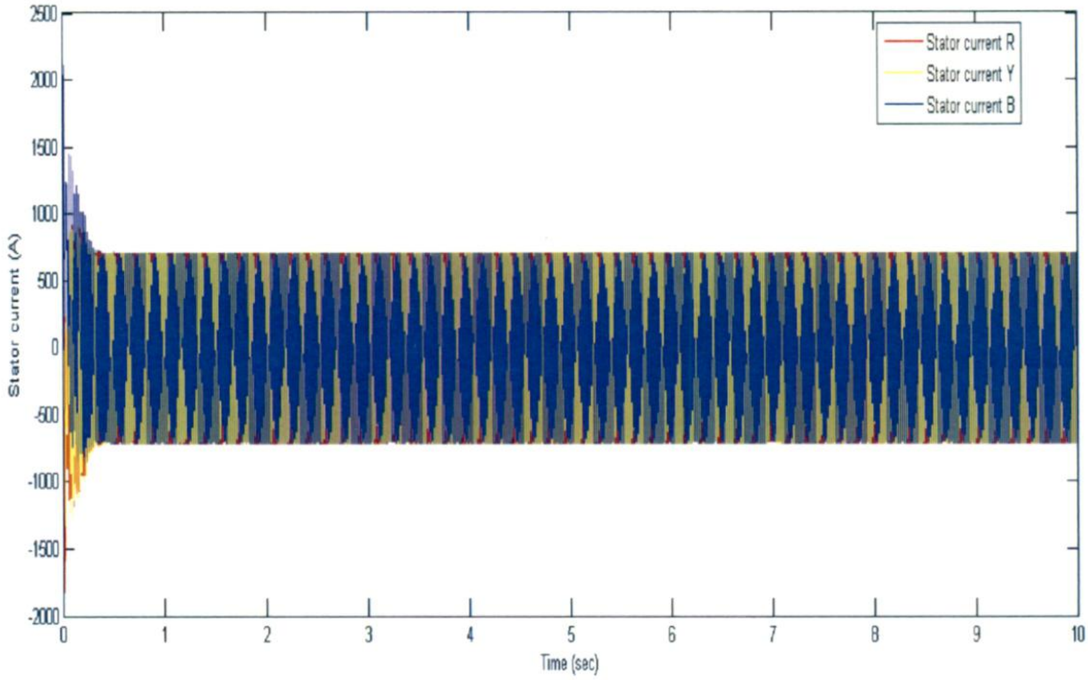


Fig.4.29: Waveform of stator currents vs time for SHP 1

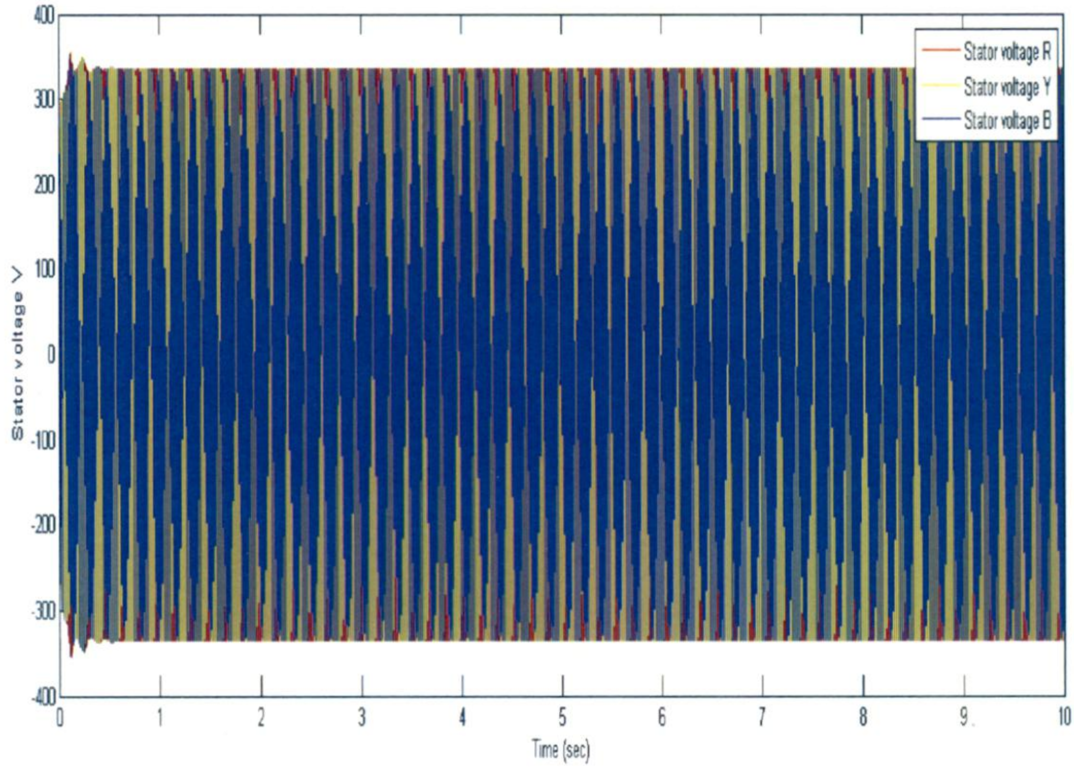


Fig.4.30: Waveform of stator voltages vs time for SHP 1

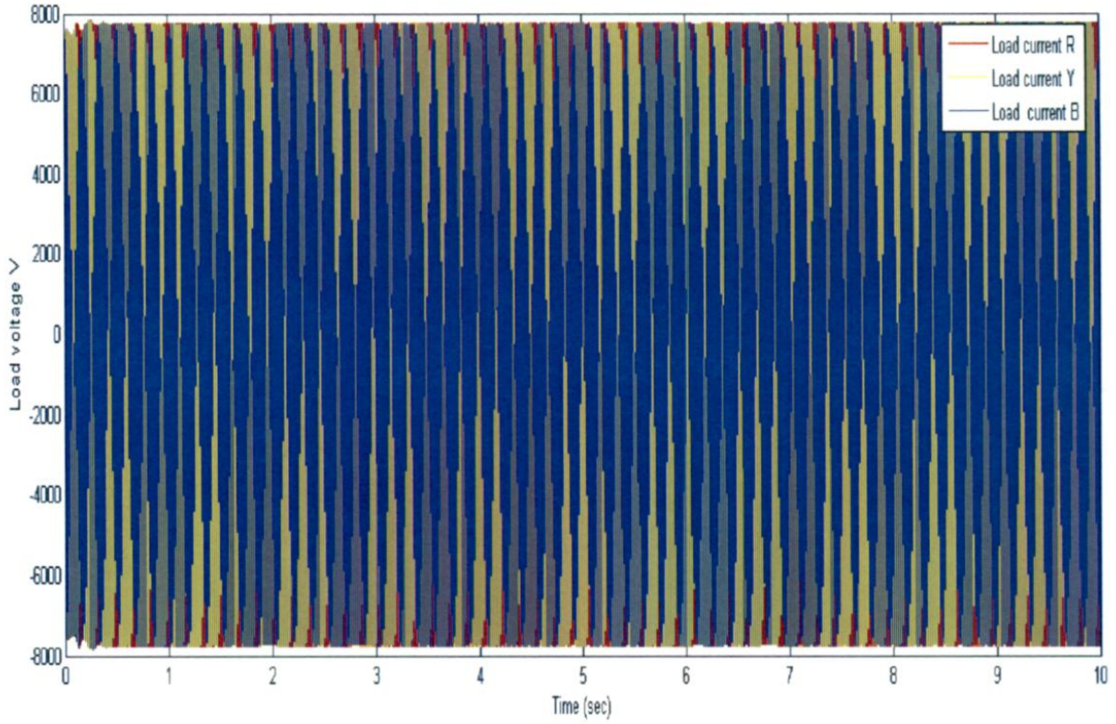


Fig.4.31: Waveform of load voltages vs time for SHP 1

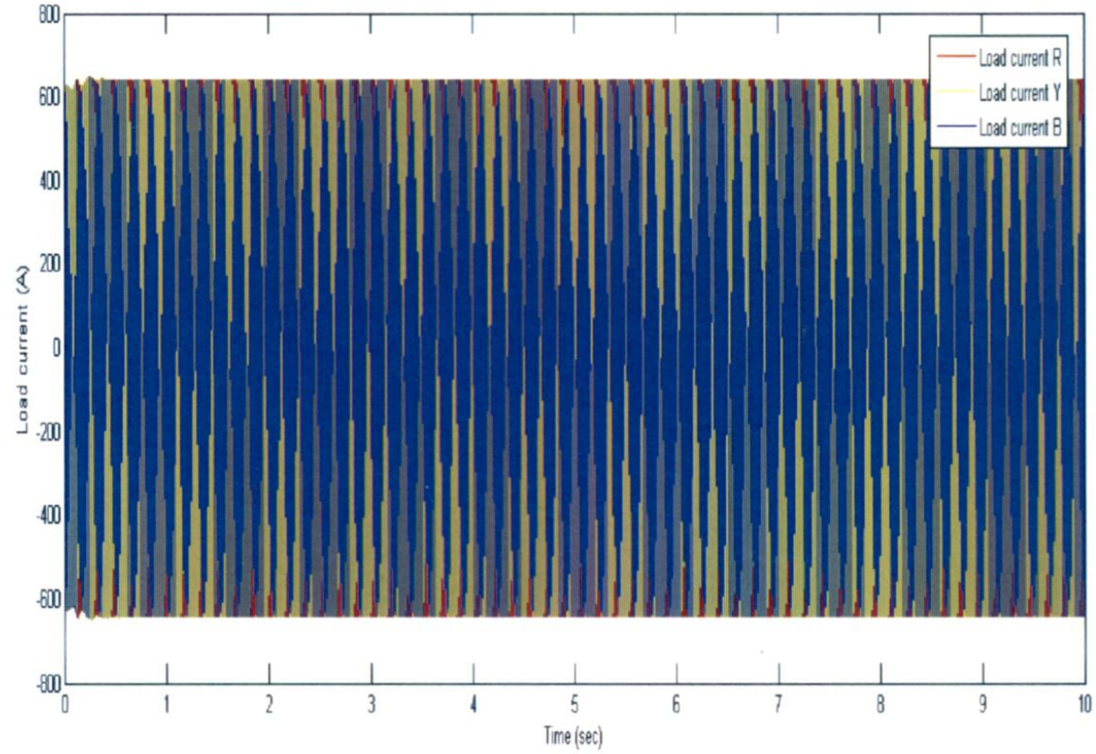


Fig.4.32: Waveform of load currents vs time for SHP 1

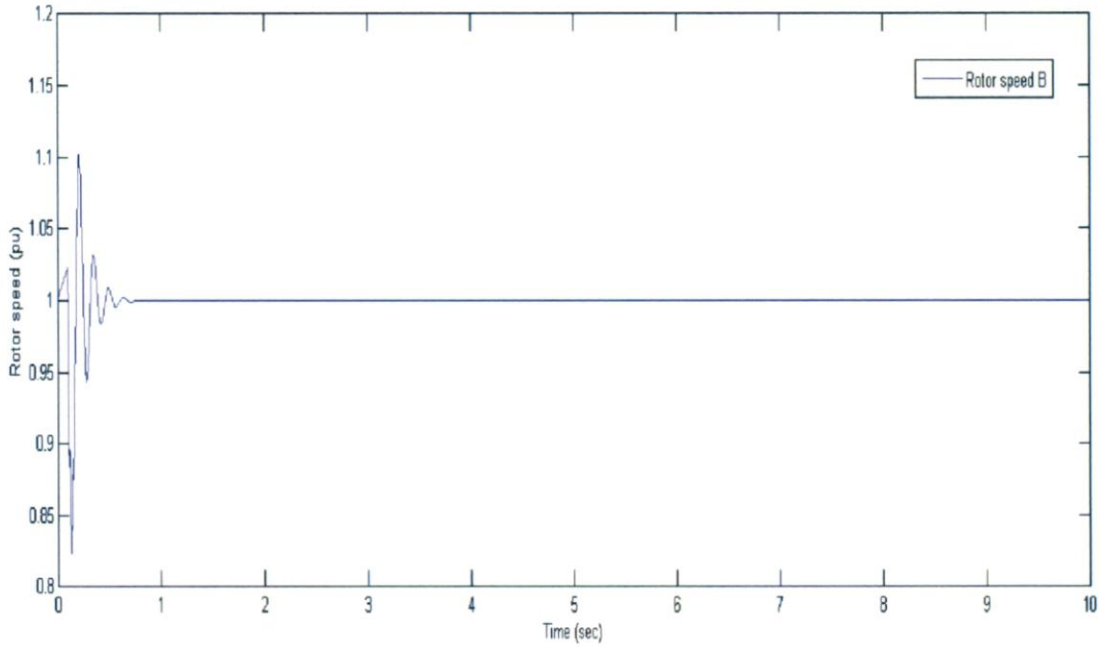


Fig.4.33: Waveform of rotor speed vs time for SHP 2

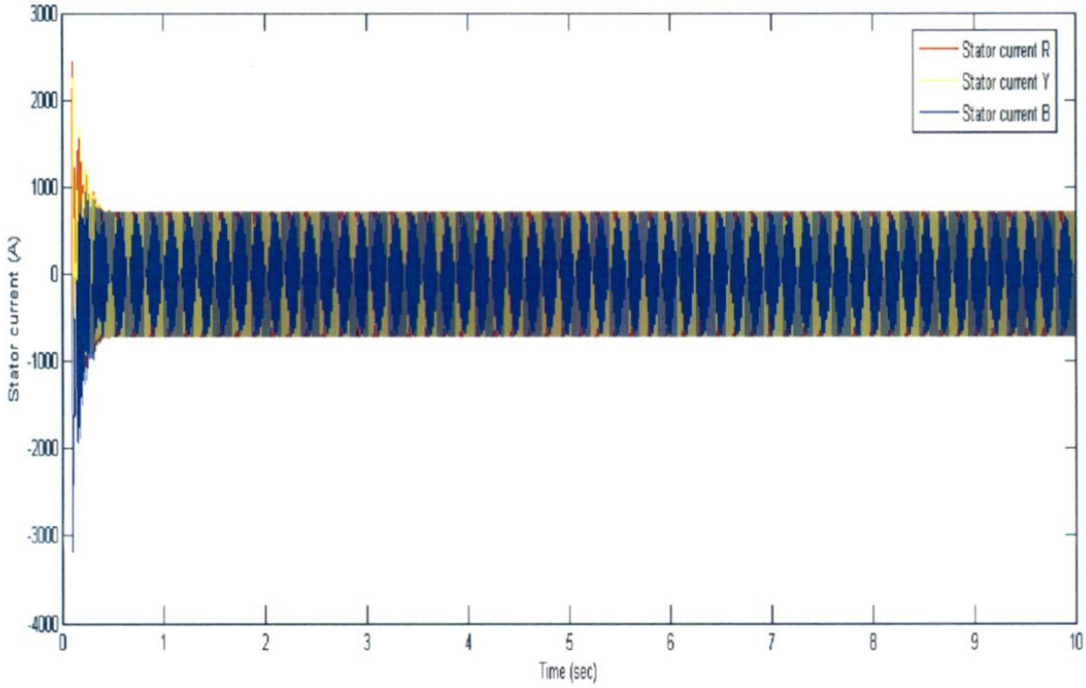


Fig.4.34: Waveform of stator currents vs time for SHP 2

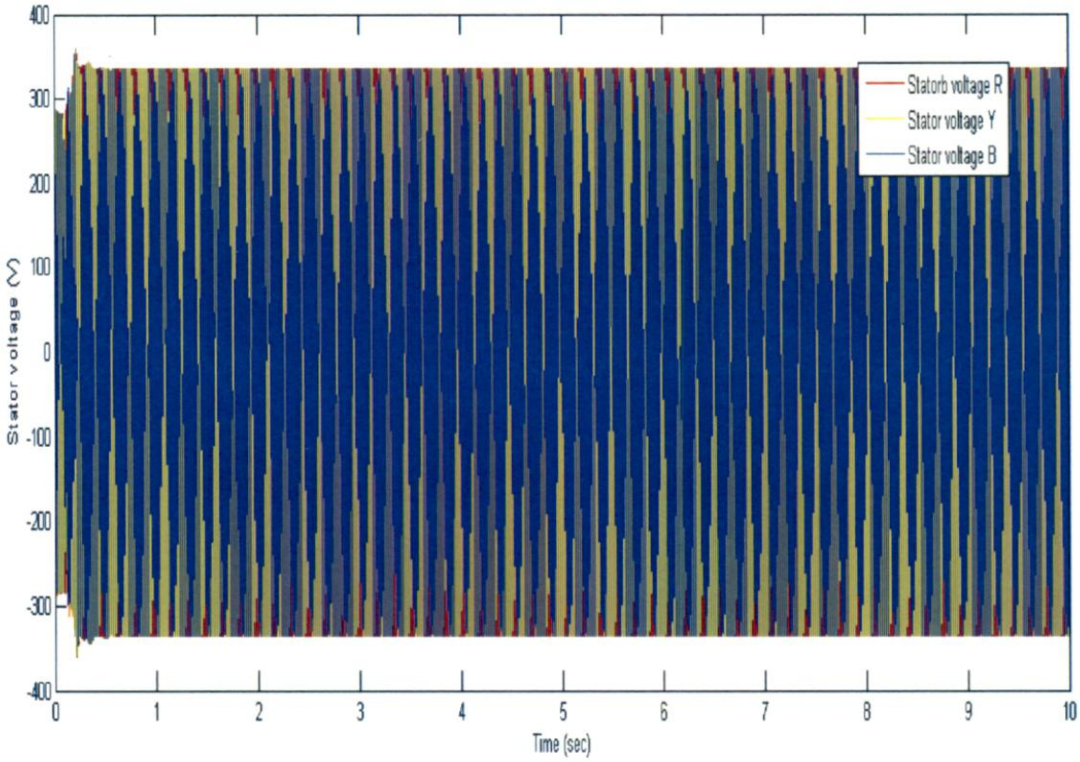


Fig.4.35: Waveform of stator voltages vs time for SHP 2

4.3.5 Grid Connnected SHP plant with Sudden load change

In this case, the SHP plant consists hydro-turbine coupled with synchronous generator and is connected to grid as shown in Fig. 4.36. For simulating this systems, same parameters of synchronous machine, excitation systems, turbine and governor have been used as given in Table 4.1. In this case, initially SHP plant is started at no load and it is connected to local load and grid at t=0.01 s. 50 km line is used to transmit the power. For distributing the power, distribution line of 4 km is connecting to the system. At t=4 s, 100 kW load is connected to the systems.

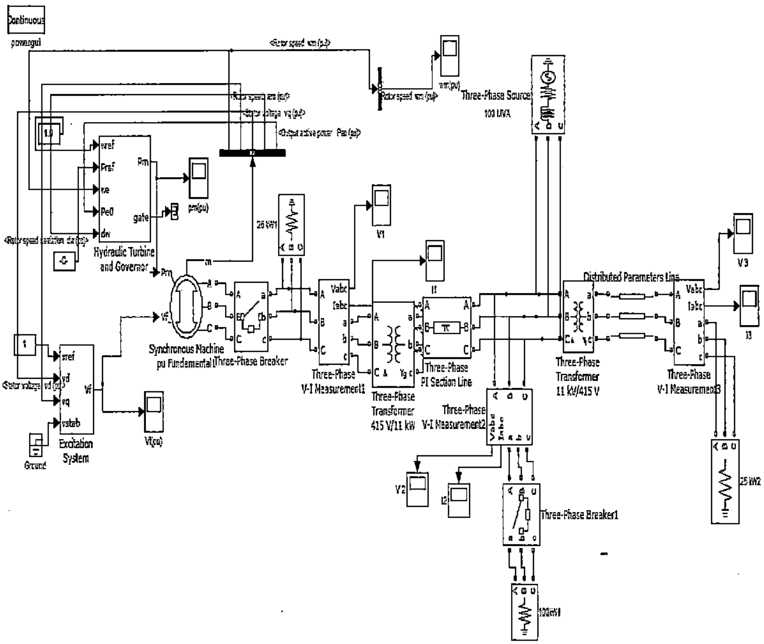


Fig. 4.36: Model of grid connected SHP plant during sudden load change

For this case, Rotor speed is shown in fig. 4.37. Rotor speed starts from 1.0 pu and oscillates for 0.5 s than it attains a steady state value of 1.0 pu. Due to sudden connection of load at t=4 s, dip in rotor speed is observed for that duration but it finally attains steady state value of 1.0 pu. Mechanical power is shown in fig. 4.38. Mechanical power starts from 0.0997 pu and oscillates for 1.2 s to attain a constant value. At t=4.0 s sudden load is changed on the systems therefore mechanical power again oscillates for few cycle. Excitation voltage starts at 1.0 pu and oscillates for 0.5 s, due to load change on system, excitation voltage rises on that time and again attains a steady state value 1.0 pu shown in fig. 4.39. Initially very high stator current is observed and after 0.2 s it attains steady state value. Three phase sinusoidal stator currents waveforms are shown in fig. 4.40. Three phase sinusoidal stator voltages waveforms are shown in fig. 4.41. Fig. 4.42 shows the three phase sinusoidal load curent waveforms of load 100 kW. Three phase sinusoidal load voltages waveforms are shown in fig. 4.43.

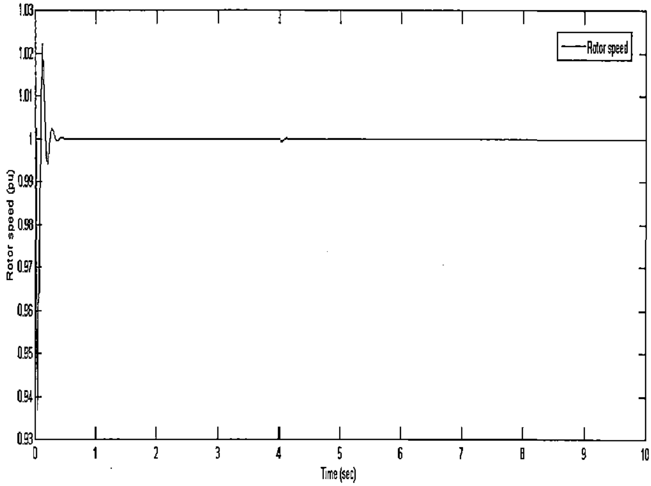


Fig.4.37: Waveform of rotor speed vs time

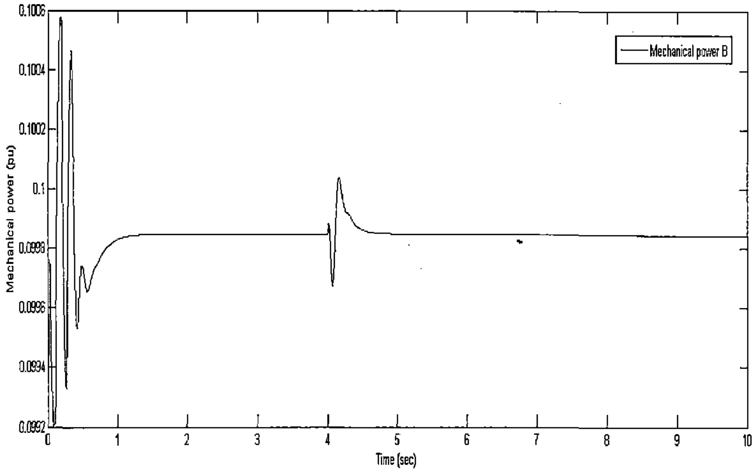


Fig. 4.38: Mechanical power vs time

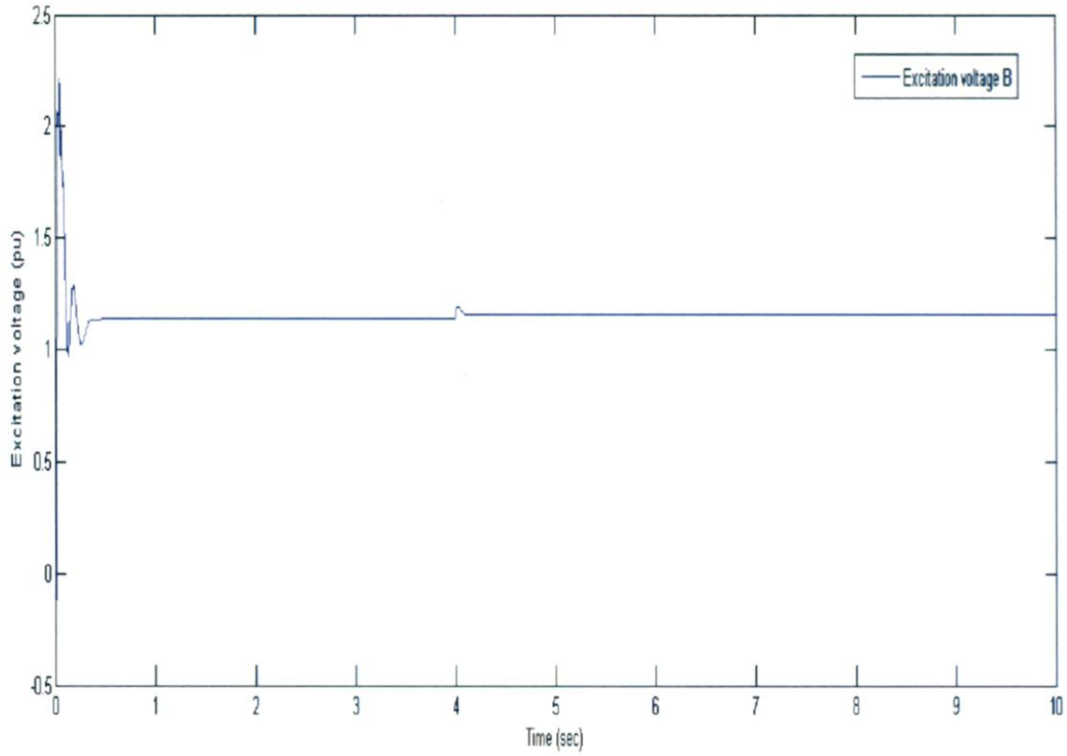


Fig. 4.39: Waveform of excitation voltages vs time

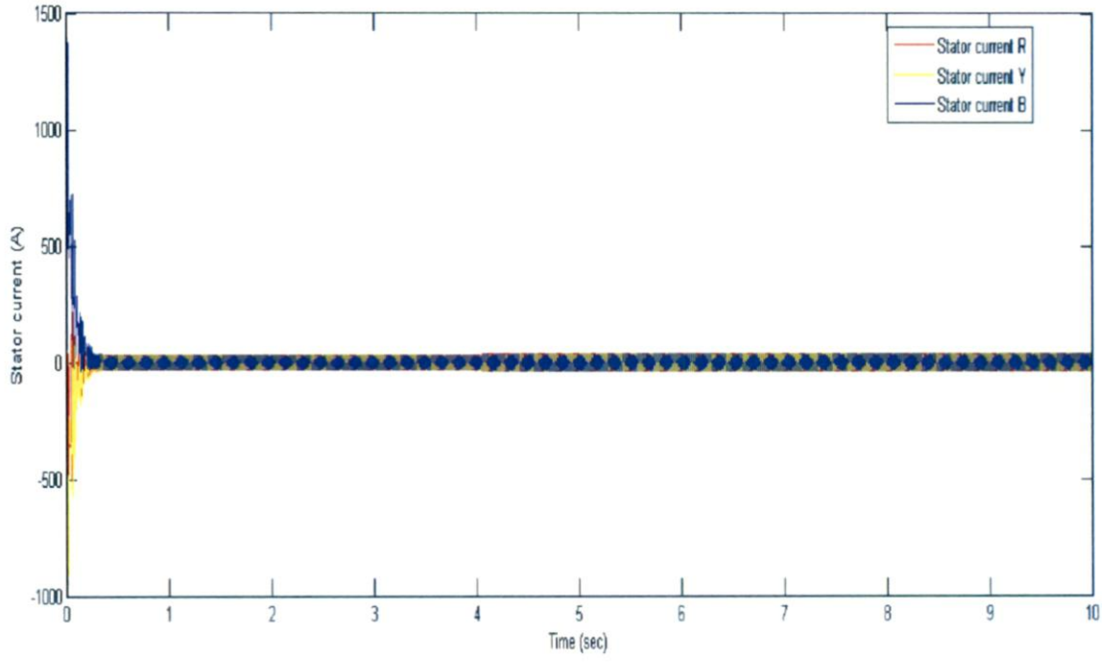


Fig.4.40: Waveform of stator currents vs time

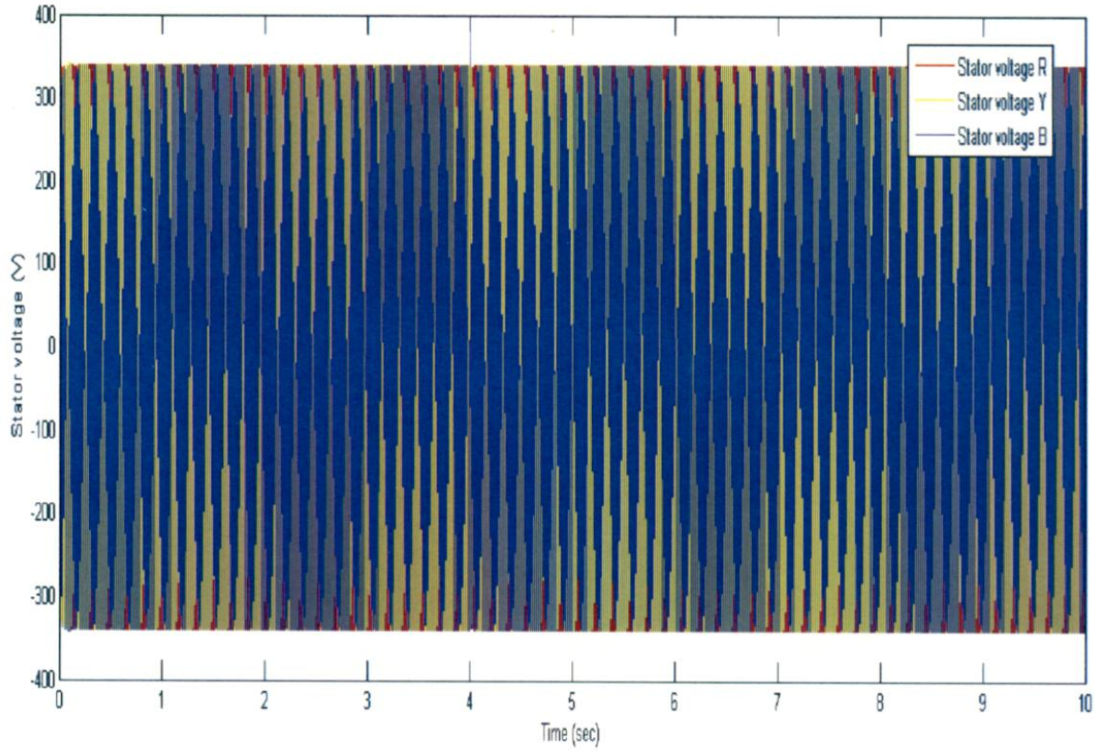


Fig. 4.41: Waveform of stator voltages vs time

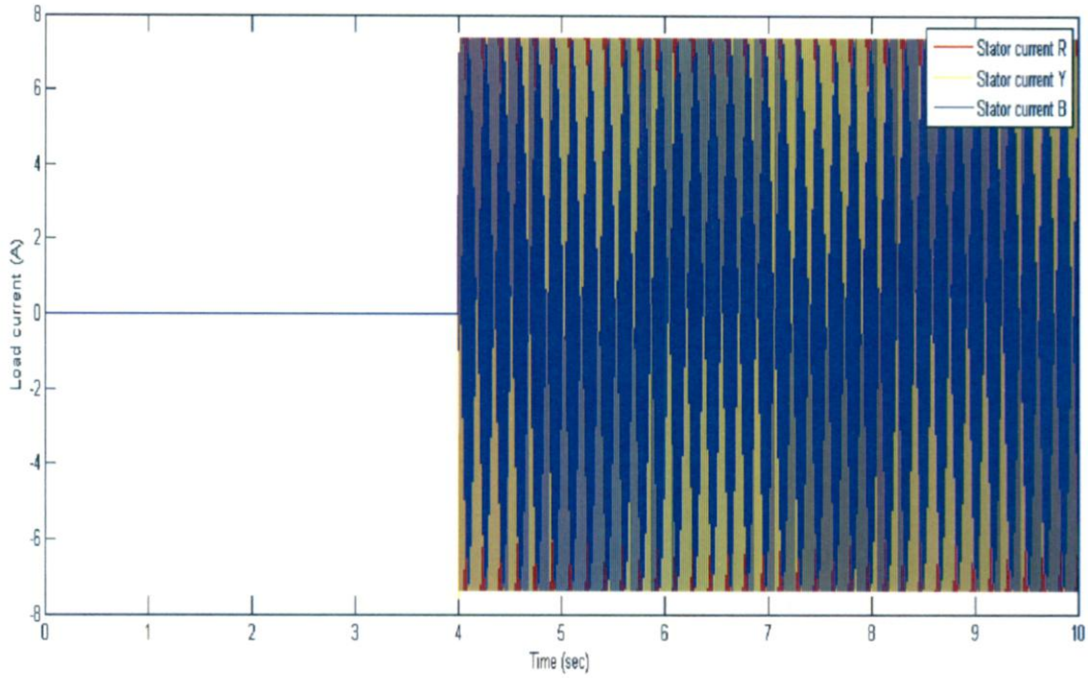


Fig. 4.42: Waveform of load currents vs time

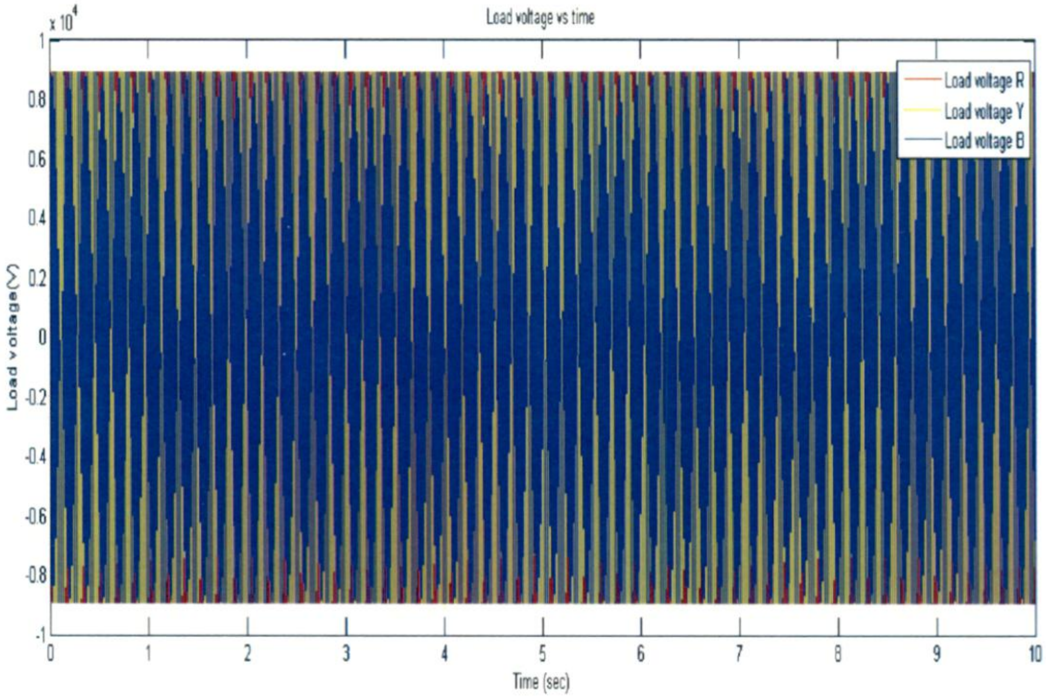


Fig. 4.43: Waveform of load voltages vs time

CHAPTER 5

CONCLUSION AND FUTURE SCOPE OF WORK

Small hydro power is a renewable, non- polluting and environmental friendly source of energy. It is perhaps the oldest renewable energy technique known to be the mankind for mechanical energy conversion as well as electricity generation. Small and mini hydel projects have the potential to provide energy in remote and hilly area.

5.1 CONCLUSION

This report presents detail description of problems associate with grid-interconnection of SHPs. The consideration of these problems is very important for safe and healthy operation of SHPs connected with grid. Hence, this report presents modelling and Simulation of grid connected SHP plant considering Synchronous generator, Excitation systems, Hydro-turbine and governor. The developed model has been simulated under different operating conditions under simulink/matlab environment. Based on the obtained results the following conclusions have been drawn:

i. Rotor speed initially oscillates for few cycles due to inertia of machine and it attains a constant speed 1.0 pu in steady state condition.
ii. Excitation voltage oscillates for few cycles initially and after few cycles it attains a constant value.
iii. Due to closing of circuit breaker and fault creation large transient current appears.
iv. Sudden change in load on the SHP effects rotor speed, Excitation voltage, Stator currents and mechanical power.
v. Due to fault creation on the grid side as well as on generator side, it directly effects the rotor speed, Excitation voltage, stator current, stator voltage, load current and load voltage.

5.2 FUTURE SCOPE OF WORK

The present work can be extended by considering the following points:

i. The simulation model may also be developed for induction generator as well as doubly fed induction generator to analyse the behaviour of grid connections.

ii. More than two SHP plants model connected to the grid can also be simulated.

iii. The developed simulation model can be extended to study the performance of SHP plant in isolated mode also.

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