HARDWARE IN LOOP SIMULATION OF A PV INTEGRATED DISTRIBUTION SYSTEM

A DISSERTATION

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

MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in Power System Engineering)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in this dissertation report entitled **"Hardware in Loop Simulation of a PV Integrated Distribution System"** submitted in partial fulfilment of the requirements for the award of the degree of **Master of Technology** in **Electrical Engineering,** with specialization in **Power System Engineering,** to the **Department of Electrical Engineering, Indian Institute of Technology Roorkee, India,** is an authentic record of my own work carried out under the guidance of **Dr. N. P. Padhy,** Professor and **Dr. P. Jena,** Assistant Professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee, India.

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

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ABSTRACT

Renewable energy sources are gaining interest now a day for its eco-friendly behaviour. Therefore most of the countries in the world have mandated that some portion of their utility must be from renewable sources. Solar power generation has also become more popular because of no limitation area for installation, no production of pollution. The rate of solar panel installation is increasing all over the world, so it is necessary to test the behaviour and properties of PV generation system when it is connected with the grid system and to study the problem which arises under different grid uncertainty condition.

The present dissertation analyses the PHIL testing of a PV power system simulated using RTDS. PHIL testing is a hybrid combination of pure physical test and pure software simulation test analysed together in a real time platform. In this work 13bus IEEE distribution test feeder has been simulated in Real Time Digital Simulator (RTDS), and an external hardware PV panel connects to the RTDS through Gigabit-transceiver analog input (GTAI) interface card. PHIL methodology used can be extended for development of in-house testing, emerging of distribution testing, simulation and virtual testing. It can be analysed to a PV power generation system for better efficiency and better operation during several condition of grid.

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LIST OF ABBREVIATIONS

ANERT	Agency for Non-conventional Energy and Rural Technology
CHIL	Control Hardware in Loop Simulation
DIM	Damping impedance method
DSP	Digital Signal Processing
GTAO	Gigabit-transceiver analog output
GTAI	Gigabit-transceiver analog input
GTDI	Gigabit-transceiver digital input
GTDO	Gigabit-transceiver digital output
HIL	Hardware in Loop Simulation
HuT	Hardware under Test / Device under Test
ITM	Ideal transformer model
JNNSM	Jawaharlal Nehru National Solar Mission
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
NAPCC	National Action Plan on Climate Change
PCD	Partial circuit duplication
PHIL	Power Hardware in Loop Simulation
PV	Photo voltaic
RTDS	Real Time Digital Simulator
RTS	Real Time Simulator
TFA	Time-variant First-order Approximation
TLM	Transmission line model
VSS	Virtual Simulated System

Chapter-1

INTRODUCTION

1.1 INTRODUCTION

The renewable energy sources are the best alternatives to fulfil today's increasing power demand and rapid demolishing of other fuel resources. They have been gaining interest in electrical field since last decade due to its eco-friendly characteristics. Reliable evolution of electrical systems involving renewable sources was started in 1980s. Worldwide many countries have mandated that some portion of their utilising electricity is from non-conventional energy sources and over 150 percentage of their renewable capacity have been expanded from 2009 to 2011[1]. In India the government has initiated "National Action Plan on Climate Change (NAPCC)", in which National Solar Mission, National mission for green India are included. "Agency for Non-conventional Energy and Rural Technology (ANERT), Kerala" is also a leading renewable energy organisation. Solar energy, wind energy, improved chulha , rural energy development etc. [2] are the main programmes of this organisation.

Among all non-conventional energy sources, solar energy sources have gained more interest for its special advantages like no pollution, no limitation area for installation, requirement of low maintenance as well as no moving parts. Therefore there is neither production of noise nor any dangers for birds. It has also another advantage that a personal solar panel can be installed on the roof top. But low energy efficiency and high initial cost have decreased its popularity. "Jawaharlal Nehru National Solar Mission (JNNSM)" started in 11 Jan 2010 to increase the importance of solar energy in the public [3]. It is the eighth key of NAPCC. The National Solar Mission is an important activity of the Government of India and State Governments to advance biologically feasible development while tending to India's energy security challenge. This contribution by India will compel the world to meet the difficulties of environmental changes. The Mission has set the focus of sending 20,000 MW of grid associated solar power by 2022 .This will lessen the expense of solar powered generation in the nation through (i) long term approach; (ii) large scale arrangement objectives; (iii) aggressive R&D; and (iv) household generation of basic raw materials, components & products, accordingly to accomplish grid tariff parity by 2022 [3]. Mission will make an empowering arrangement structure to accomplish this target and make India a worldwide pioneer in solar powered energy. Thar Desert has been set aside for photo voltaic power projects, enough to produce 700 GW to 2,100 GW. Till 2015-march, 3,744 MW solar power has been installed in India and it produce about 450 Terawatt-hour per year [2].

To improvise the energy conversion efficiency, reliability and reducing the installation cost of a PV power generation system, various tests analysis is necessary under different grid conditions [4]. All solar power generation systems have low voltage ratings hence these are connected in distribution network side. Therefore in this project work it is described a PV system connected to IEEE 13 bus distribution system and analyse its behaviour under various utility conditions. There are many methods has been implemented to represent a realistic grid connected PV model. One method is to model a hardware platform of whole system, while the test quality is important [5]. But a large distribution network in real hardware is not possible or we can't perform the test with our actual distribution network. Second option is to study the entire system with software simulation model. The main deficiency of this possibility is its dependency on power system component models, which affects the results [5]. In pure software simulation case the PV systems cannot realise under real weather conditions [6].

The third possibility is the combination of both physical and digital hybrid model which can solve the lack of these above two methods [7], called Hardware in Loop Simulation (HIL). HIL simulation is a different technique, where software models and hardware systems can put together into a single closed loop simulation [1]. This is achieved by using a real time simulator (RTS) that simulate the digital model and communicate between hardware and software parts through digital signal processing (DSP) interfaces in real time and in deterministic order [8]. In a HIL simulation, one part of the system for which exact model are not available can directly connected to the simulation and in other hand another part for which exact model are available can be simulated in nearly real time. This is possible because of computers with speed parallel processing capability [5]. This method has advantage of both pure software simulation and physical experiments.

Especially in the field of electrical systems, HIL divide in two parts. One is Control Hardware in Loop Simulation (CHIL) and another is Power Hardware in Loop Simulation (PHIL). In CHIL simulation only low range signals i.e. control signals of devices are directly fed or received to the simulations. But in PHIL simulation, large scale systems are to be simulated with the digital models. The piece of hardware which is to be tested is called Hardware under Test (HuT) [8]. There are several methodology and simulation tools which can be used to realise the PHIL tests. Among them the RTDS (Real Time Digital Simulator) is a better tool to perform complex simulations in near actual time with better speed. It uses RSCAD, a graphical user interface to simulate the software model with facility for data acquisition [9]. Contrary to CHIL where a controller is tested, PHIL involves analysing of a device which generates or absorbs power (e.g. a photovoltaic inverter or an induction motor). The signals between the Hardware Under Test (HuT) and the Real Time Simulator (RTS) are no longer at low signal in which Analog to Digital and Digital to Analog Converters are usually sufficient [10], therefore a special Power Interface is needed , called Power Amplifier.

1.2 ORGANIZATION OF THE REPORT

Chapter 1 shows the introduction to the requirement of non-conventional energy, importance of solar energy system connected with distribution grid, HIL testing and organization of the report.

Chapter 2 consists of review of literatures regarding PHIL testing and PV power generation system.

Chapter 3 gives the brief idea about solar power system and its necessary equipment for grid connection.

Chapter 4 present the detail of distribution system and IEEE 13 bus distribution network.

Chapter 5 describes the PHIL simulation technique and procedure to perform PHIL tests.

Chapter 6 presents the simulations and results obtained in this work as per the above methodology.

Chapter 7 shows the conclusion and future scope of work that can be done.

Chapter-2

LITRATURE REVIEW

In the world of increasing electrical demand the need of solar generation is also continuously increasing day to day life. To achieve the better solar power at better efficiency it should be tested under different grid condition before putting in action. So many more tests have been proposed and many algorithms have been developed to get better performance of the solar generation.

Hardware in loop tests of different electrical loads and sources are connected to the software grid modelling in RTS. Those tests were performed under various grid uncertainty conditions like voltage fluctuation, frequency fluctuation, unintentional islanding etc. to increase the efficiency of devices that are proposed in [1].

Chulsang Hwang et al. [4] have presented CHIL simulation tests of PV power generation taking various grid utility conditions. All the grid conditions are modelled in RTDS and showing its effect on the PV model as well as is converter system.

Mahdi Dargahi et al. [5] have demonstrated the different control method of PHIL simulation and the stabilization method to connecting an external device with RTDS. They also proposed new stability technique to connect a HuT for PHIL test with better accuracy and better stability.

Minwon Park and In- Keun [6] have proposed the constant re-enactment method of solar generation using RTDS. A hypothetical PV module in PSCAD under real atmosphere condition feed power to the electrical resistance load and tally the results with theoretical PV outputs.

Zhong Qing et al. [7] have proposed hardware in loop simulation of grid tied PV system. They have designed and simulated the control technique of the solar energy converters, MPPT algorithm and grid connected control of 520kwp solar panel system through RTDS with the help of external DSP interface.

Bogdan-Ionut Craciun et al. [8] have proposed in their paper, PHIL testing of some distributed generation systems utilising different interfacing algorithm. They have also proposed the effective interface method to connect a HuT with the real time simulator and to test them under some grid parameter variation.

F. S. AL-Ismail et al. [9] have proposed static synchronous compensator (STATCOM)-based damping stabilizers and executed to improve the damping at the low frequency. They have implemented PI controller internal voltage control of STATCOM using RTDS.

Panos Kotsampopoulos et al. [10] have implemented the power hardware-in-loop simulation testing to the distributed energy resources. They put mainly photovoltaic panel as DC micro grid connected to the distribution network.

High efficiency integrated buck boost converter with MPPT scheme [11] and fuzzy logic based multilevel inverter control [12] for PV power generation system simulated in MATLAB Simulink.

Sangsoo Park et al. [13] have described the sensor less MPPT technique for a PV generation system. The hardware implementation of DC-DC and DC-AC converter control scheme give the effective response with proposed new optimisation algorithm for sensor less MPPT method.

Eric de jong et al. [14] have presented the interface used and procedure of real time-power hardware-in-loop simulation test which is also utilised in distributed PV generation. They have also described that the real time simulation gives the possibilities of gaming simulation, virtual test, distributed testing and in-house test.

S. paran [15] have described in his paper the interface algorithm used for PHIL testing. He has proposed the various interface algorithm technique with their stability and accuracy issues.

C. A. Hill et al. [16] have implemented the buck-boost converter and MPPT for PV power generation and also designed the combination of fuel cell and PV panel which are connected in parallel. They have also put the MPPT to the DC-AC converter section.

Modelling of different kind of distributed generation system and its control strategy, has implemented in RTDS. Also W. Gao et al. [17] have proposed the operating scenarios of a standalone micro grid under load changing and under actual weather condition.

Mohamed A. Eltawil et al. [18] have described the solar photovoltaic technique and various aspects with connection to utility grid. They have also proposed the harmonics reduction in PV converter system for better operations.

Chapter-3

PHOTOVOLTAIC POWER GENERATION

3.1 INTRODUCTION

India has a good level of solar insolation and it receives the solar energy equals to 5000trillion kwh/yr. Depending on the site, the daily incident solar radiation ranges of 4 - 7 kwh/m^2. Over 2300 to 3200 hours of clear sunlight available for power generation per year. Fig 3.1 shows the solar radiation power density whole over the country and proportionally that much of solar energy can be produced. However, this colossal energy has not been collected to the full extent. To increase the solar power generation capacity, National Solar Mission has been announced. To meet the energy demands, most of countries also have adopted the energy strategies that advance the expansion of PV panel installations. Till now 1442.10 MWp of solar plants has been installed in India. It is also planned world's largest solar power plant of 4000 MWp in Rajasthan within three years.

Photovoltaic cell converts sun energy directly to electric power. The word photovoltaic comes from "photo" meaning light and "voltaic" which refers to production of electricity. Therefore, the photovoltaic process is "producing electricity directly from sunlight." Photo voltaic cells are comprised of crystalline silicon materials, that show a property, is known as the photovoltaic effect. In this effect the photon particles from sunlight fall on the PV panel. The silicon semiconductor material receives the photons and generates electron in N-type semiconductor and proton in P-type semiconductor. An electromotive force (emf) induces in the terminal electrodes of the solar panel, which drive a current through the external circuit when a load is connected between the electrode terminals. So the generated power of a solar cell is always DC.

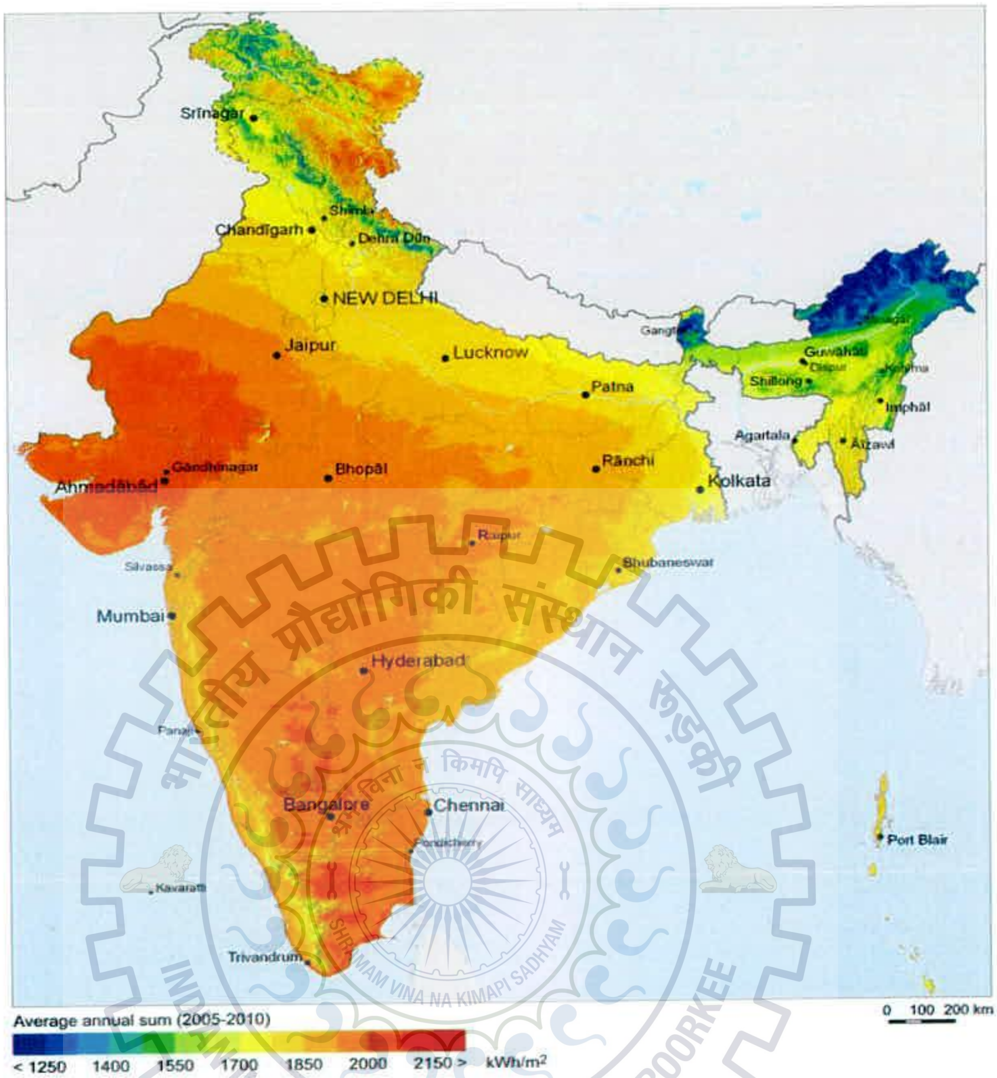

Fig 3.1 Solar resources map of India [3]

The solar power is measured in peak watt (Wp). The generation output of a solar cell depends on the ambient temperature and solar insolation. The rated power calculated of a PV module by taking the ambient temperature as 25^0C, solar radiation of $1000W/m^2$ and air mass of 1.5 [11]. As the PV array generates DC power, it needs to be converted from DC to AC for supplying power to utility grid or for use of home appliances. Therefore an inverter is necessary in solar power system. A maximum power point tracker (MPPT) can also be used to get the optimum power outputs. Besides that control switching, metering and protection devices are also needed. Some cases group of batteries are used to store the power for night use. The solar panels have high in cost which increase the capital cost of the whole system. Another disadvantage is requirement of large area for mounting PV cells. There are two type of PV generation system based on utility connections. (i) Standalone PV system and (ii) grid connected PV system.

3.1.1 STANDALONE PV SYSTEM

With a standalone PV system the solar cell is not associated with grid connection. It feeds power to the individual houses with battery storage facility. This storage battery store the charge during day time and the connected loads draw power from it at day time as well as night time. Most of people use grid connected PV system because of the cost of battery is high and they live in areas where public grid connection is available.

3.1.2 GRID CONNECTED PV SYSTEM

A grid connected PV system is that when the solar array produces more power than the power used by local connected loads, the extra power feeds to the connected grid. During night time the local loads can draw power from the utility grid. There is no storage facility for grid connected system.

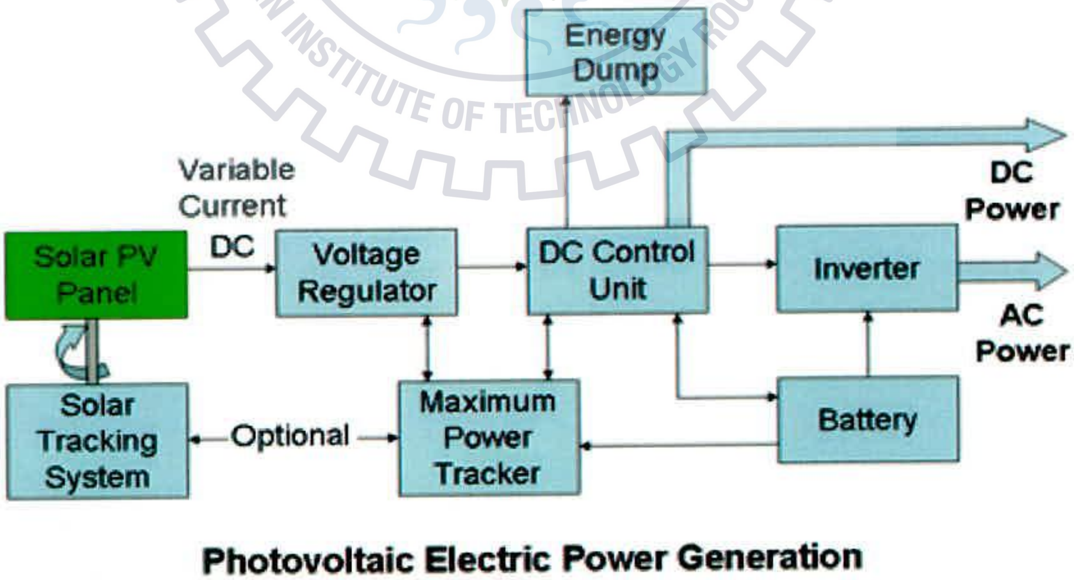

Fig 3.2 grid connected solar power system

3.2 PV ARRAY MODEL

The equivalent electrical circuit of photovoltaic cell is shown in fig 3.3

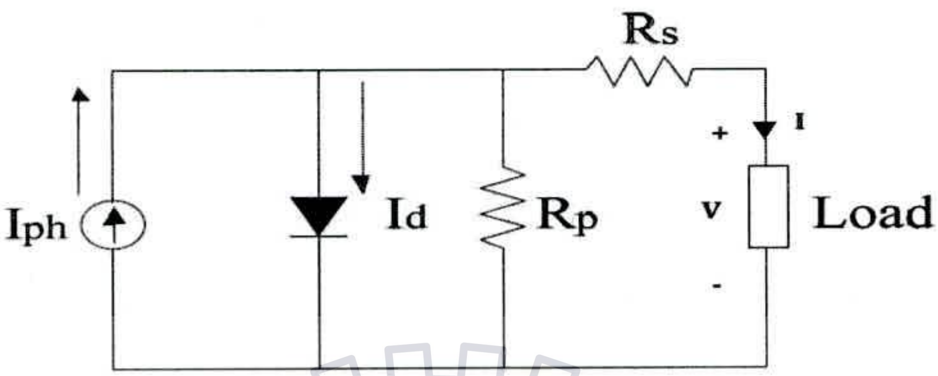

Fig 3.3 equivalent circuit diagram of PV cell [7]

The output current equation of photo voltaic cell can be obtained as a function of load voltage;

$$I = I_{ph} - I_d\left\{\exp\left[\frac{q(V+R_sI)}{AkT}\right] - 1\right\} - \frac{V+R_sI}{R_p} \quad (3.1)$$

Where, V & I are the solar cell output voltage and current. I_{ph} is the equivalent current injection determined by solar light intensity. I_d is the diode current. R_s & R_P are the series and shunt resistance. q Defines the electron charge. A is diode ideality factor. k is the Boltzman constant. T is the ambient temperature.

In actual practice PV array is the series and parallel combination of PV modules while PV module is combination of series and parallel PV cells [16]. When no. of solar cells connected the above equation modified as;

$$I = N_{pM}I_{scM} - \frac{N_{pM}I_{scM}}{\exp\left(\frac{qV_{ocM}}{N_SkT}\right)[exp\left(\frac{q(V_A+R_{SA}I_A)}{AkTN_SN_{SM}}\right)-1]} \quad (3.2)$$

Where, N_{pM} & N_{sM} are the no. of parallel and series PV modules respectively connected in the PV array. V_{ocM} & I_{scM} are open-circuit voltage and short-circuit current of solar array. R_{SA} is equivalent resistance of the entire PV array. V_A and I_A are the output voltage and current of PV array.

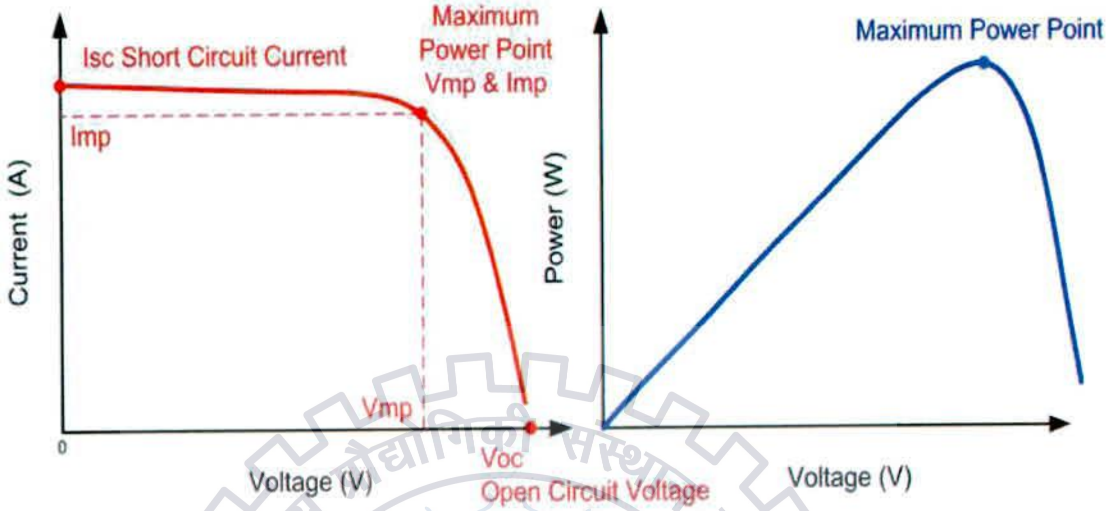

Fig 3.4 V-I characteristics and V-P characteristics of a solar cell

3.3 MAXIMUM POWER POINT TRACKER

Tracking the maximum power point of PV array is essential part of solar power system. This control method is to keep the output power maximum and send it to the grid for better efficiency. For this purpose a high frequency DC-DC boost converter is used. Different algorithm is used to operate the MPPT controller. Output of MPPT signal is fed to the gate signals of boost converter switches. DC-DC converter manages and controls the PV array to work at the MPP by changing the duty cycle of the converter switches [13]. The necessity of MPPT technology is a self-optimisation process which compares the present output power with the previous instant power calculated by its output voltage and current. There are many MPPT algorithm has been proposed for better optimising the output power.

3.3.1 PERTURB & OBSERVE

Perturb & Observe (P&O) is a simplest method which uses one sensor, i.e. the voltage sensor that senses the PV module voltages. It is easy to implement. Its cost is comparatively less. The MPPT continue to track in both directions even though it reaches the MPP by putting a wait function or a band limit of error to make it stable. However this method does not work satisfactorily when the solar insolation change rapidly due to continuous change of MPP. This leads the wrong MPP calculation.

3.3.2 INCREMENTAL CONDUCTANCE

Incremental conductance method uses two sensors i.e. voltage and current sensor. It defines at MPP the slope of the PV curve is zero.

$$(dP/dV)_{MPP}=d(VI)/dV \quad (3.3)$$

$$0=I+VdI/dV_{MPP} \quad (3.4)$$

$$dI/dV_{MPP} = - I/V \quad (3.5)$$

The equation 3.5 shows that when the incremental conductance is same as the PV array conductance then the MPP occurs. Complexity and cost both are comparatively less but more than the Perturb & Observe method. So these methods are widely used.

3.3.3 FRACTIONAL OPEN CIRCUIT VOLTAGE

Under varying solar irradiance and temperature levels, the curve operate at linear relationship between V_{MPP} and V_{OC} of the PV array, this tends to raise the fractional V_{OC} method.

$$V_{MPP} = k_1 V_{oc} \quad (3.6)$$

Where k1 is the proportionality constant which ranges between 0.71 to 0.78 and it depends on the PV array I-V curve. It usually has to be computed beforehand by empirically determining V_{MPP} and V_{OC} at different solar irradiance and temperature.

V_{MPP} can be calculated with V_{OC} measured by momentarily turnoff the power converter.

3.3.4 FRACTIONAL SHORT CIRCUIT CURRENT

Fractional I_{SC} calculated under changing atmospheric conditions, I_{MPP} shows linearly relation with the I_{SC} of a PV array.

$$I_{MPP} = k_2 I_{sc} \tag{3.7}$$

Where k_2 is also a proportionality constant related to the PV array. Its ranges vary from 0.78 and 0.92. Additional switch is connected to the converter to make periodically shorting of the PV array terminals to calculate I_{sc}.

3.3.5 FUZZY LOGIC CONTROL

Microcontrollers using fuzzy logic controller are best technique to MPPT. Fuzzy logic controller is working with uncertain inputs, not requiring a precise numerical model, and taking care of nonlinearity.

3.3.6 NEURAL NETWORK

Neural network technology senses V and I of the PV array to the microcontroller and adjust the MPP. This method is more efficient than others.

Incremental conductance method is less in cost and gives better result to track MPP. This method is used in this report.

3.4 POWER CONVERTERS

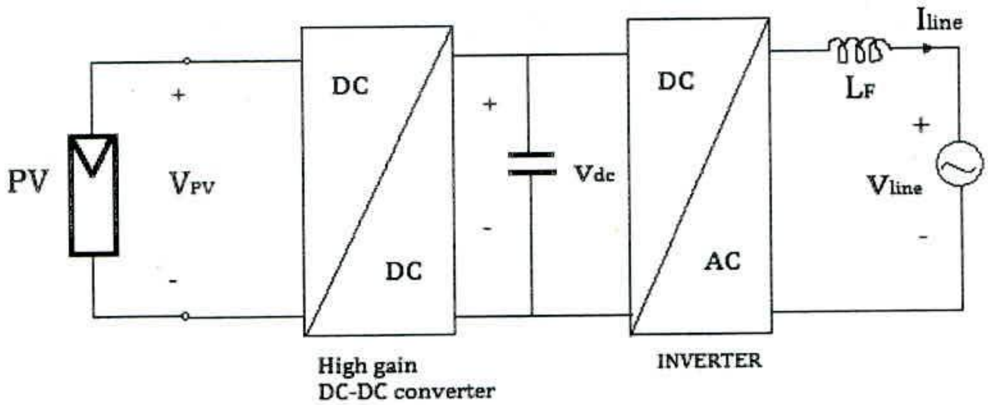

Fig 3.5 Connection of PV power converters

Fig 3.5 shows the various converters connected between the PV cell and the grid. For grid power transfer two sets of converters are used. A DC-DC converter set and a DC-AC inverter set.

3.4.1 DC-DC CONVERTER.

The first one converts the DC output power to control DC value, is a high gain DC-DC converter. The high frequency IGBT switches operate by taking gate signals from MPPT controller [17]. Each PV panel is connected to separate DC to DC converter for the purpose of maximum power point tracking. All the PV panels are then connected to the common DC link voltage V_{dc}. Use of isolated DC-DC converter allows independent grounding of PV panels.

3.4.2 DC-AC INVERTER

After converting DC to controlled DC the DC link voltage is fed to DC - AC inverter. A three phase output is obtained by this inverter. Inverter control signal is so designed that it gives a pure sine wave to the grid utility system. PWM technique is used to control the inverter valve.

Chapter-4

DISTRIBUTION SYSTEM

4.1 INTRODUCTION

Distribution system is a part of electrical network system which distributes the power to the consumer for utilisation. So its voltage range is low, about 230v to 11kv. But the current carrying capacity is comparatively high.

AC distribution is mainly classified into two types based on its voltage ratings. These are (i) Primary distribution and (ii) Secondary distribution. In primary distribution system the voltage level is comparatively high than general utilisation voltage. The voltage level depends upon the power that to be conveyed and the distance of the substation required to be fed. The most commonly used primary distribution voltages are 11kv, 6.6kv and 3.3 kv. Primary distribution system uses three wires; three phase system because of economic consideration. Primary distribution directly connected to the large loads like factories. In secondary distribution case the voltage rating is low i.e. 440v or 230v and it directly connected to each house loads. This distribution network supply power through three phase four wire system. Secondary distribution is connected between primary distribution system and the consumer's service mains through step-down transformer.

Further based on the scheme of connections distribution network is divided as (i) radial system, (ii) ring main system and (iii) inter connected system.

(i) In radial distribution system separate feeders radiate from a single substation. The power is fed at one end of the system. The end of the distributer nearest to feeding point is heavily loaded. Voltage variation occurs among the consumers. i.e. the consumer at the far end of the line subjected to the severe voltage drop. If any fault happens then all consumers suffer from power cut. This system has many disadvantages; still radial distribution system is mostly used as all the consumers are distributed far from the supply ends.

(ii) Ring main distribution system is modified version of radial system. In this system the primary sides of all distribution system forms a loop including substation connect to one point. Voltage fluctuations are less at the consumer end. System is more reliable during fault as power can be fed from any side.

(iii) Interconnected system is the advanced type of network, where ring main distribution system is formed but more than one supply points are connected to the loop. So no voltage fluctuation and no disturbance with faults at consumer side. But for this system there should be provision for more supply points, and then it works properly.

The distribution system network is necessary for reliable operation, proper voltage at the consumers and availability of proper power demand. In this project a 13 bus balanced radial distribution system simulation is used to represent the actual distribution network, where a PV distributed generation connect at its one bus.

4.2 IEEE 13BUS DISTRIBUTION SYSTEM

In order to represent the actual distribution system we take a standard IEEE 13 bus distribution system data and simulate it in the RSCAD software. The bus data and line data were taken from the IEEE standard given in the table in appendix-A. This distribution system voltage level is taken as 11kv at a frequency of 60 Hz. It is a balanced three phase three wire radial distribution system. Fig 4.1 shows the IEEE 13 bus network, where a PV power generation system is connected to one of its node. The solar panel is connected to the far end bus that is bus no. 10. Two transformer of rating 132/11kv, are connected in bus no.1 and bus no.6. They transfer the grid power to the distribution network.

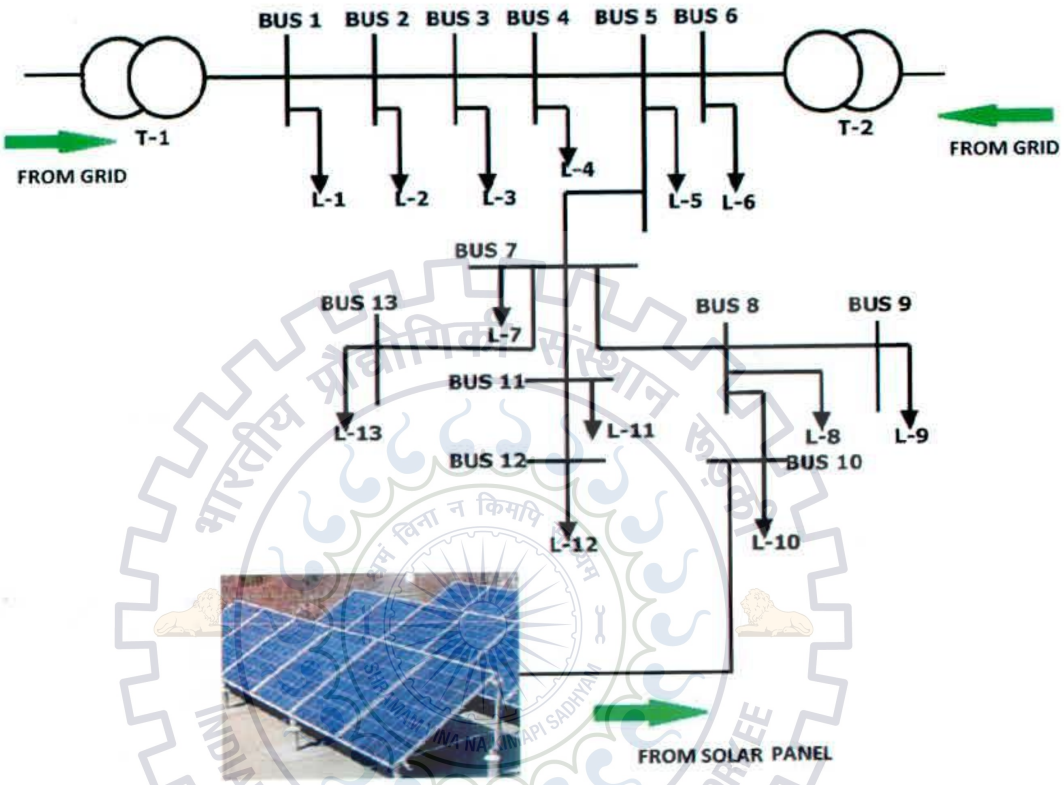

Fig 4.1 solar panel connected to an IEEE 13bus distribution system [18]

Chapter-5

POWER HARDWARE IN LOOP

5.1 INTRODUCTION

In the distribution network side voltage fluctuation, frequency variation, occurrence of fault is more common. When we put distributed generation systems in the networks, we must test properties of individual generating units in laboratory. The test includes provision of determining the active and reactive power during frequency and voltage variations, reactive power exchange control and protection setting, inter action to network during switching and behaviour on system disturbances. Because it is necessary to certify the unit before it is planted.

Traditionally two types of experiments were possible for medium and high power devices. i.e. Pure software simulation experiments or pure hardware experiments. But third possibility is the hybrid combination of the above two called Hardware in Loop Simulation (HIL) [8]. HIL simulation is the combination of hardware and software experiments performed together in a Real Time Simulator (RTS). Pure hardware model gives the better experimental result, but it is not always possible to experiment with a real platform. On the other hand, experiments can be performed in pure software simulation. But some components are not easy to model due to complexity of the systems and lack of component knowledge. So HIL simulation is introduced. Which system cannot be modelled in hardware that is put in software simulation and which model cannot be represented in software that is put in hardware model. In electrical system HIL simulation is divided into two categories.

5.1.1 CONTROL HARDWARE IN LOOP (CHIL)

CHIL tests the controller circuits of electrical systems. Digital to analog signals are exchange among the RTS and Device under Test (HuT). CHIL is used for the following applications.

- Power electronic control units for industrial use,
- Electric propulsion systems for electric vehicles,
- Generators of wind energy conversion systems,
- The assessment of aerospace industry controllers.

5.1.2 POWER HARDWARE IN LOOP (PHIL)

"PHIL simulation is a scenario where a simulation environment virtually exchanges power with real hardware, in contrast to the usual case in hardware-in-the-loop simulation, which involves only signal exchange." PHIL tests the electric power generators or absorber like PV generator and induction motor [14]. HIL is extended to the high level power between HuT and RTS. As it transfers high level power it requires a voltage and power interfaces. This power interface exchange low value signals of RTS to the high power of real test devices. Fig 5.1 shows the difference between CHIL and PHIL interface techniques. In PHIL interface system sensor is used to track the performance of HuT and a power amplifier is used to transfer power from RTS to HuT.

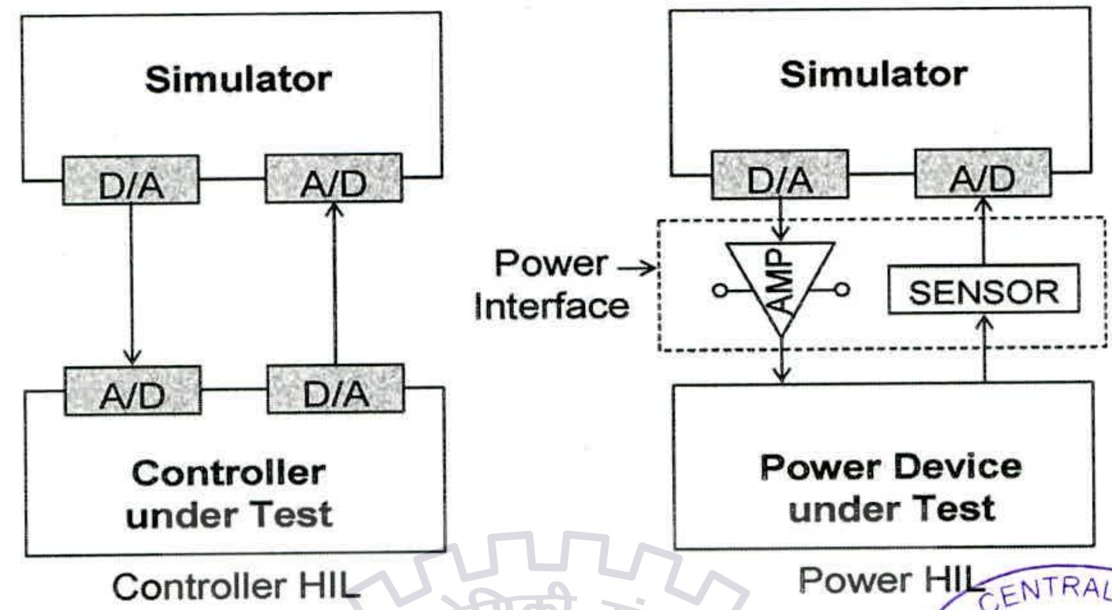

Fig 5.1 comparison of CHIL and PHIL simulation approach [14]

RTS is the main part of the Hardware in Loop which runs the virtual simulated model and gives an input output facility. As the works under real time, the RTS must be operated in real time or near to real time. Therefore the time step is small enough about 50ns to perform the simulation under dynamic conditions.

5.2 INTERFACE ISSUES

During the power exchange the error is introduced by the interface i.e. distortion and delay time may cause the instability problems. So interface algorithms have been developed to solve these issues. The interface algorithms define the connection between HuT and RTS. For a satisfactory PHIL test the following standards are required.

- High accuracy
- Low distortion
- Low phase lag
- High bandwidth

All these factors depend on the stability of the PHIL interface [5]. The sample time of RTS and the power interface should be match, otherwise the problems occurs at the higher voltage side.

5.3 POWER INTERFACES

It is allows the inter-connection between HuT and virtual simulated system. The sensor in the power interface may be mechanical type (tachometer, rotational speed detector) or electrical type (current or voltage sensor). The amplifier of the power interface can generate or absorb power by detecting the signals from RTS. So four-quadrant operation is required with a power source or power sink. Switch mode power amplifier or linear amplifier is used for this purpose. High frequency IGBT switches are composed in this amplifier to maintain accuracy as well as reducing the time delay. Power source or sink can be defined by connecting the power interface with the grid. For laboratory purposes a synchronous generator and induction motor load define the power sources and sinks respectively.

5.4 POWER INTERFACE METHODS

There are many interface method has been implemented, still there are instability problems present. Some interface method given as follows.

- The ideal transformer model (ITM) algorithm
- Time-variant First-order Approximation (TFA) algorithm
- Transmission line model (TLM) algorithm
- Partial circuit duplication (PCD) method
- Damping impedance method (DIM)

5.4.1 IDEAL TRANSFORMER METHOD (ITM) ALGORITHM

This interface algorithm (IA) technique is a voltage divider network, where one resistance represent the VSS and another represents the HuT. In figure 5.2(a) and (b), it is shown that the impedance refer to the hardware model is Z_L and the other part is a voltage source V_s and series Z_L refers to the virtual simulations. There are two type of ITM algorithm used i.e. either voltage-type ITM or current-type ITM. The traditional interface, suffers from inaccuracy and instability due to the time delay in D/A or A/D converter [15]. For convenience, let take the only error in a PHIL simulation is the lumped time delay Δt in the interface. The equivalent transfer functions loop of the ITM algorithm is;

$$G_{OL-VITM} = \frac{-Z_S}{Z_L} e^{-s\Delta t} \tag{5.1}$$

$$G_{OL-IITM} = \frac{-Z_L}{Z_S} e^{-s\Delta t} \tag{5.2}$$

The first equation is the voltage type ITM and second one is the current type ITM. The stability of this interface depends on the magnitude of Z_s/Z_L. This is a high accuracy algorithm and also it is easy to implement. The stability of this method depends on the ratio of equivalent impedances between simulation model and hardware model.

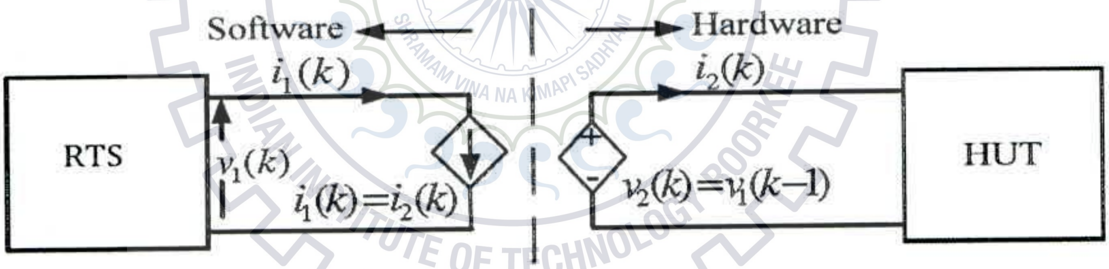

Fig 5.2(a) Voltage-type ITM method

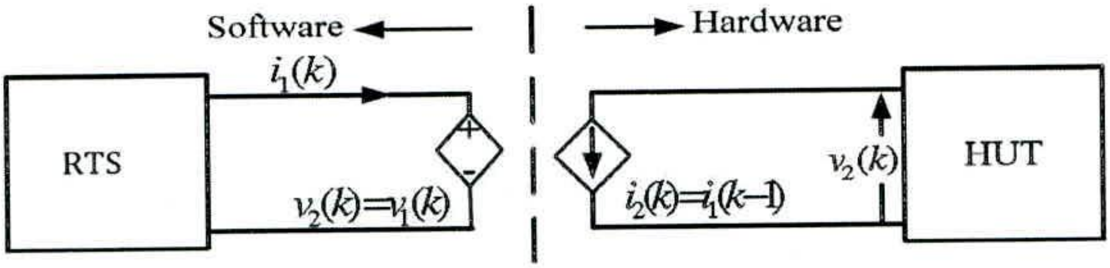

Fig 5.2(b) current-type ITM method

5.4.2 TIME VARIENT FAST-ORDER APPROXIMATION (TFA)

By using the time-variant first-order approximation (TFA) algorithm method the HuT can be modelled as a first order linear RLC system. Taking the previous simulation data by running the model, the coefficients of the HuT model can be obtained and updated. Compensations can be introduced in the simulator to correct the interface errors.

For example, let the HuT is a first order RL system. Then the equation is

$$\frac{di_2}{dt} = ai_2 + bi_2 \tag{5.3}$$

A trapezoidal approximation is used to discretize the equation; therefore value of i_2 can be found from the previous values of v_1 and i_2.

$$i_2(k) \approx \alpha v_1(k-1) + \beta i_2(k-1) = G_{eq}\, v_1(k) + i_{eq}(k) \tag{5.4}$$

Where α and β are the coefficients and determined by the following equations.

$$\begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} v_1(k-1) & i_2(k-1) \\ v_1(k-2) & i_2(k-2) \end{bmatrix}^{-1} \begin{bmatrix} i_2(k) \\ i_2(k-1) \end{bmatrix} \tag{5.5}$$

Figure 5.3 shows the *RL*-type TFA algorithm. Similar derivation can be realised for the *RC* type TFA. This method is more unstable than ITM. This method predicts the state variable of the hardware models. First order linear system can be interfaced in this method. This method has advantages of high bandwidth and auto error correction.

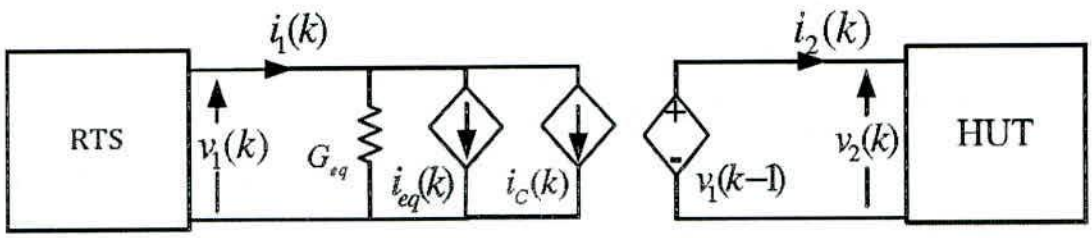

Fig 5.3 TFA interface method

5.4.3 TRANSMISSION LINE MODEL (TLM) ALGORITHM

The transmission line model (TLM) algorithm utilises linking capacitor or inductor to a TLM. This strategy is suitable for substantial decoupling of large systems for the simplification of parallel processing, because the transmission line can be further expressed in the Bergeron line model ("Norton or Thevenin resistive circuits from either side, only the past values at the other side can be seen"). This method is applied to connect digital and analog simulators for RTS. A Bergeron TLM replaces the linking capacitor *C* or inductor *L* by the equivalent $R_{lk;}$ given by;

$$R_{lk} = \frac{L}{\Delta t} \quad or \quad R_{lk} = \frac{\Delta t}{C} \tag{5.6}$$

Δt is the power interface time delay which is equal to the propagation time of the transmission line. The equivalent T.F. of this model is

$$G_{OL-TLM} = \frac{1-\alpha e^{-Z_s \Delta t}}{1+\alpha e^{-Z_s \Delta t}} \frac{Z_s}{Z_{lk}} \tag{5.7}$$

Where; $\alpha = \frac{Z_L - R_{lk}}{Z_L - R_{lk}}$

This algorithm is based on trapezoidal approximation so it is more stable. For high power application L and C need to be replaced by resistor. R_{lk} should change as the simulated model changes, because the linking component relate to R_{lk}. the delay time Δt in the interface could be reliant on the signal frequency or load condition. For a constant value of Δt the simulation accuracy will decrease. This method requires more maintenance and losses are comparatively high.

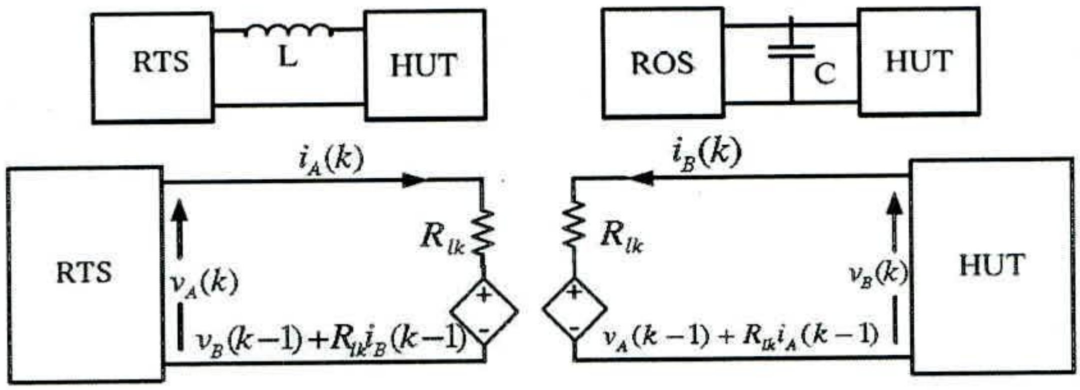

Fig 5.4 TLM interface method

5.4.4 PARTIAL CIRCUIT DUPLICATION (PCD) METHOD

The partial circuit duplication (PCD) method is based on the relaxation technique. It divides the whole circuit in sub circuits and use iteration method to solve. The linking component Z_{ab} is repeated in both RTS and HuT. The open loop transfer function is given by;

$$G_{OL-PCD} = \frac{Z_a Z_b}{(Z_a+Z_{ab})(Z_b+Z_{ab})}\, e^{-s\Delta t} \tag{5.8}$$

Z_a and Z_b are the equivalent impedances of the simulator and HuT respectively. This method is more stable than ITM method. It is possible to keep the open-loop transfer function below unity. Better accuracy can be obtained performing more no. of iterations. Accuracy of this method is low but large scale circuit system can be easily analysed.

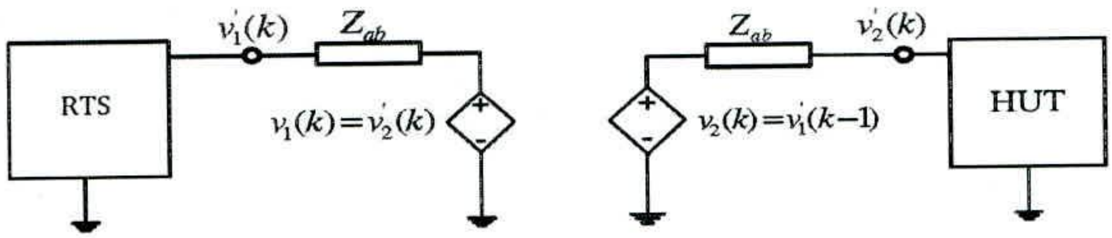

Fig 5.5 PCD interface method

5.4.4 DAMPING IMPEDANCE METHOD (DIM)

Damping impedance method is the joint method of ITM and PCD with additional adding of a Z* impedance in the circuit. When the Z* is zero, v* value is same as v_1 and it behaves as PCD method. When Z* is infinite, the simulation current is equals to i_1 and the DIM method becomes ITM method. The open loop transfer function is given by;

$$G_{OL-DIM} = \frac{Z_a(Z_b - Z^*)}{(Z_a + Z_{ab} + Z^*)(Z_b + Z_{ab})} e^{-s\Delta t} \tag{5.9}$$

The magnitude of T.F. can be observed by varying the value of Z*. When Z* is equals to Z_b the magnitude of T.F. becomes zero. The value of Z_b can determined from the RMS values of v_2^1 and i_2. This method is best suitable for PHIL testing. It gives better stability and better accuracy.

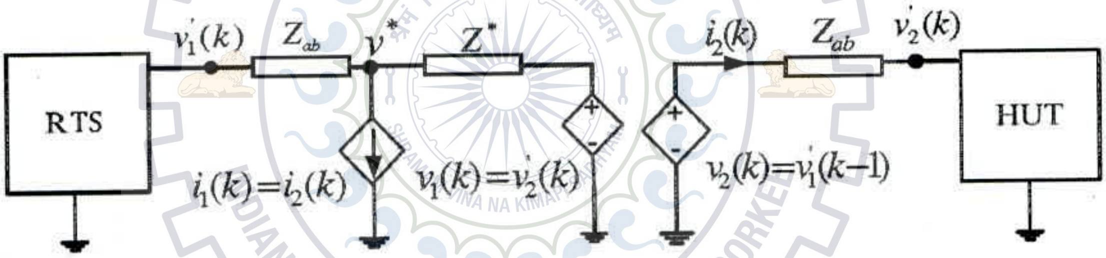

Fig 5.5 DIM interface method

Interface Algorithm	Accuracy	Stability	Ease for Implementation
ITM	***	*	***
TFA	***		
TLM	*	***	
PCD		***	**
DIM	***	**	**

Table 5.1 performance comparison of all Interface Algorithm

5.5 PROCEDURE FOR PHIL TEST

PHIL test gives better simulation result as the HuT and VSS are coupled closely. PHIL can be performed in various RTS, for example real time digital simulator (RTDS) and OPAL-RT. The real-time simulation is an evolution of "analogue Transient Network Analyzers and the Electromagnetic Transient Program." RTDS was developed in 1993 and use for HIL. OPAL-RT developed in 1997. RTDS has small time step so it gives better result during PHIL tests [14].

Fig 5.6 shows the laboratory setup for PHIL test. There are three main parts for PHIL testing. i.e. RTS, Power interface and the device which is to be tested. This device is not easy to simulate. RTS is the simulator where software simulation done through the graphical user interface. In RTDS simulator RSCAD software is used to simulate the virtual system. For OPAL-RT it is MATLAB Simulink. One can easily draw the system network to be simulated and compiled through this software. Necessary options are available in RSCAD for connecting hardware device to the simulator. Also the performance graphs and meter readings of the simulation as well as device are shown on computer screen. The power interface is the intermediate connecting device for HuT and RTS. Power interface scales up or scales down the power levels during action. There also provision for analog to digital conversion and vice versa. So that it can be connected digitally to the simulator as well as physically to the hardware devices. The power interface gives low level signals to the RTS through the RTS interface cards.

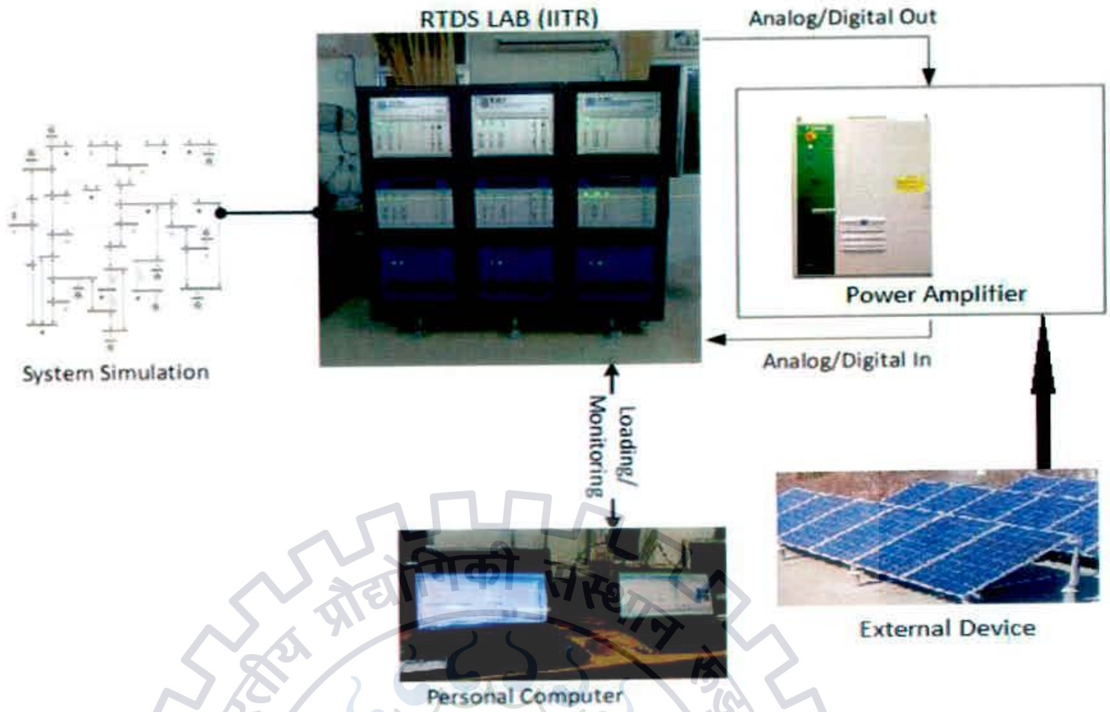

Fig 5.6 PHIL simulation setup

There are four no. of interface cards (GTAO, GTAI, GTDO and GTDI) available in the RTDS. Gigabit-transceiver analog output (GTAO) and Gigabit-transceiver analog input (GTAI) communicate to interface through analog signals; similarly Gigabit-transceiver digital output (GTDO) and Gigabit-transceiver digital input (GTDI) communicate through digital signals. Various loops are formed between RTS and external device through power amplifier.

Chapter-6

RESULTS AND DISCUSSIONS

6.1 BASIC CASE STUDY

The methodology discussed in the previous chapter has been applied to a small PV system of ratings 4V. The PV cell is connected to the RTDS for PHIL test without using of power interface. Without power interface the PV cell is directly connected through the GTAI interface card. A current limiter circuit is connected in series to limit the PV cell current, because the interface card has rating of 10 volt (max) and 25mA short circuit current. The voltage and current rating of PV cell are set to 4V and 10mA.

A 13bus radial distribution system is simulated in RSCAD taking the IEEE standard data. At bus no.10 the PV panel is connected. As the distribution network is ac system, it is required to convert the PV output DC to AC. For this purpose the DC-AC inverter is also simulated in RSCAD. Necessary instruments are required for grid connected solar power systems as they are virtually modelled in RSCAD. As the PV cell has lower power rating; its voltage and current ratings are scaled up for better HIL simulation results.

6.2 SIMULATION MODELS

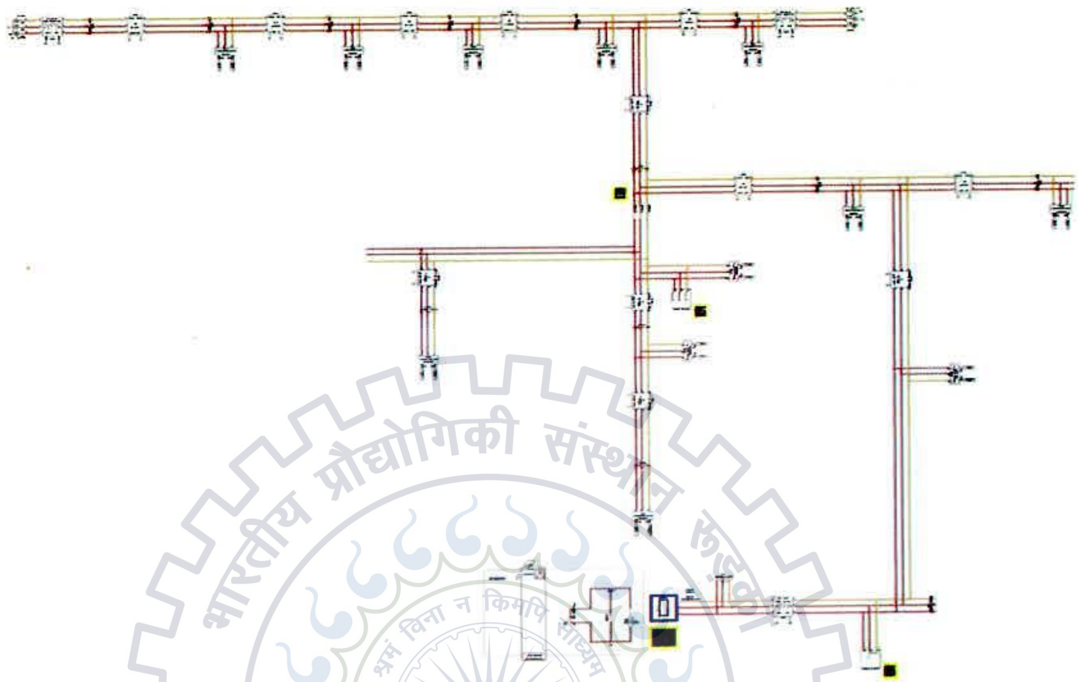

Fig 6.1 simulation model of PV generation system connected with 13bus distribution System

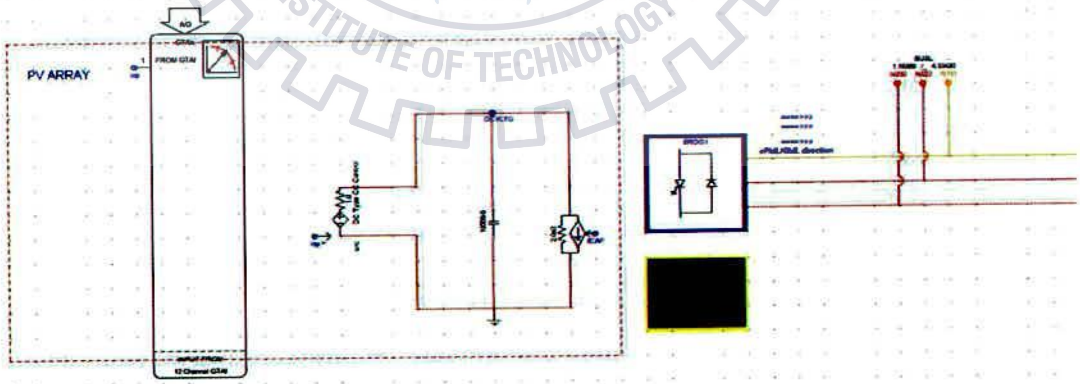

Fig 6.2 interfacing model to connect hardware PV model

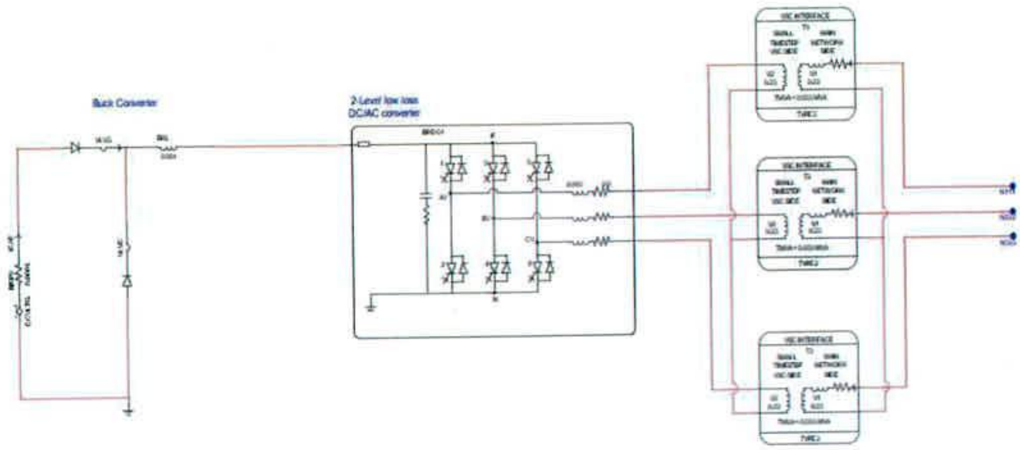

Fig 6.3 simulation model of DC-DC and DC-AC converter

6.3 SIMULATION RESULTS

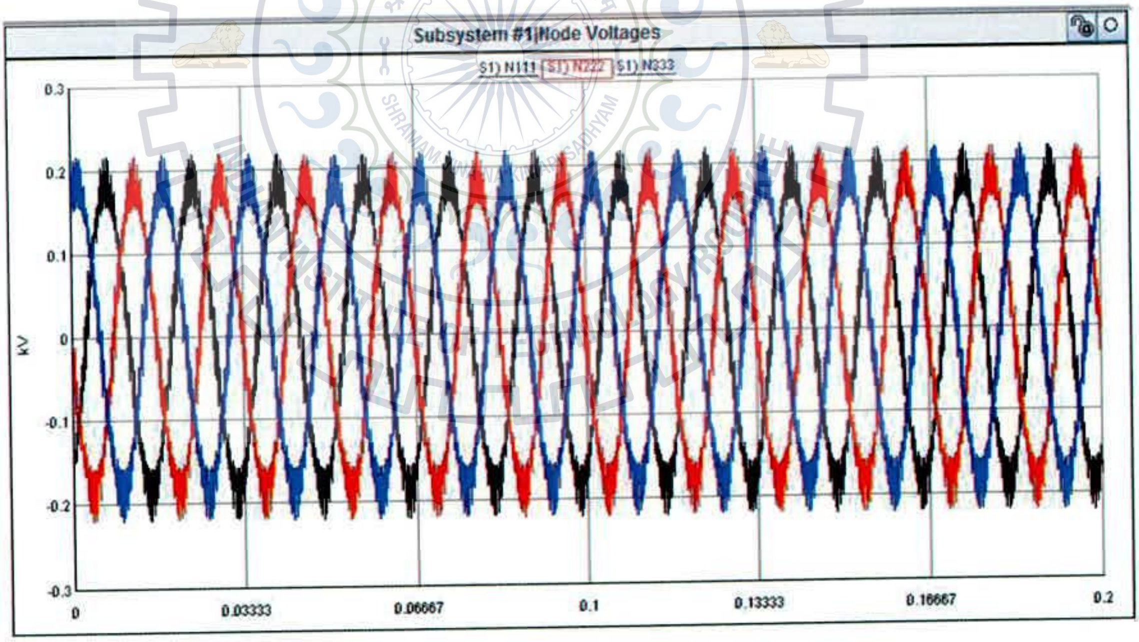

Fig 6.2 voltage waveform at inverter terminals for PV software simulation

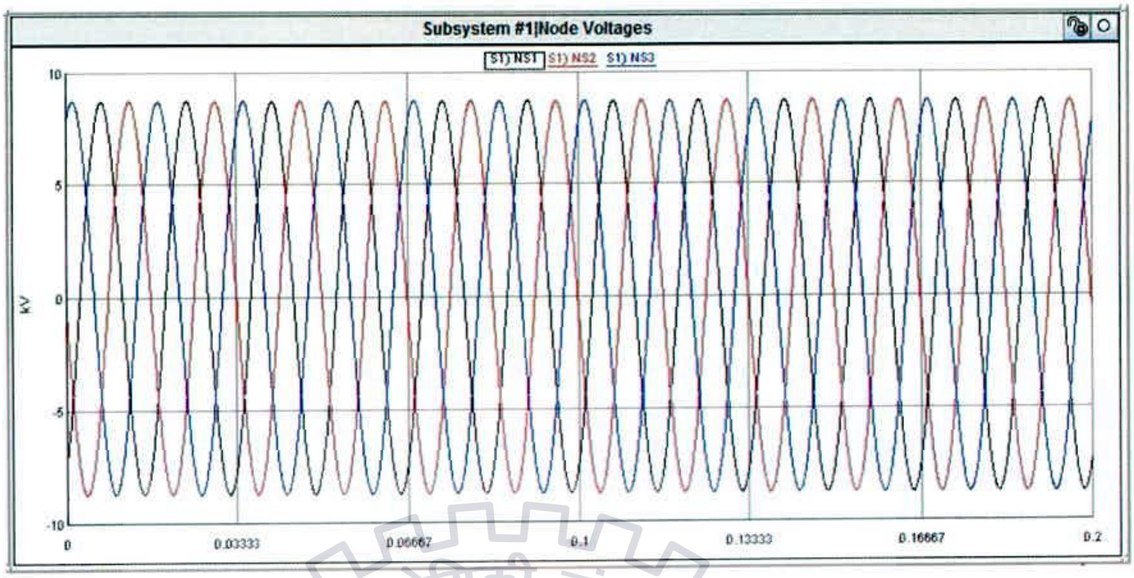

Fig 6.3 voltage waveform at node terminals of distribution system for PV software simulation

6.4 PHIL TEST RESULTS

Taking the hardware PV model we run the PHIL simulation and the voltages and power waveform is traced at different node of the distribution system. It is also analysed the waveform behaviour during grid uncertainty conditions.

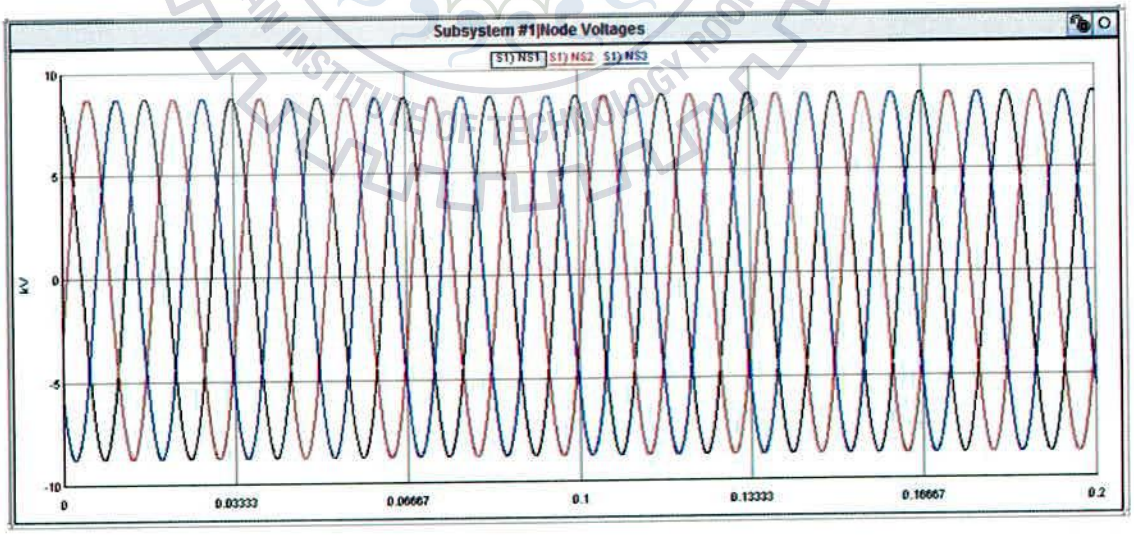

Fig 6.4 node voltage of distribution system for PV hardware simulation

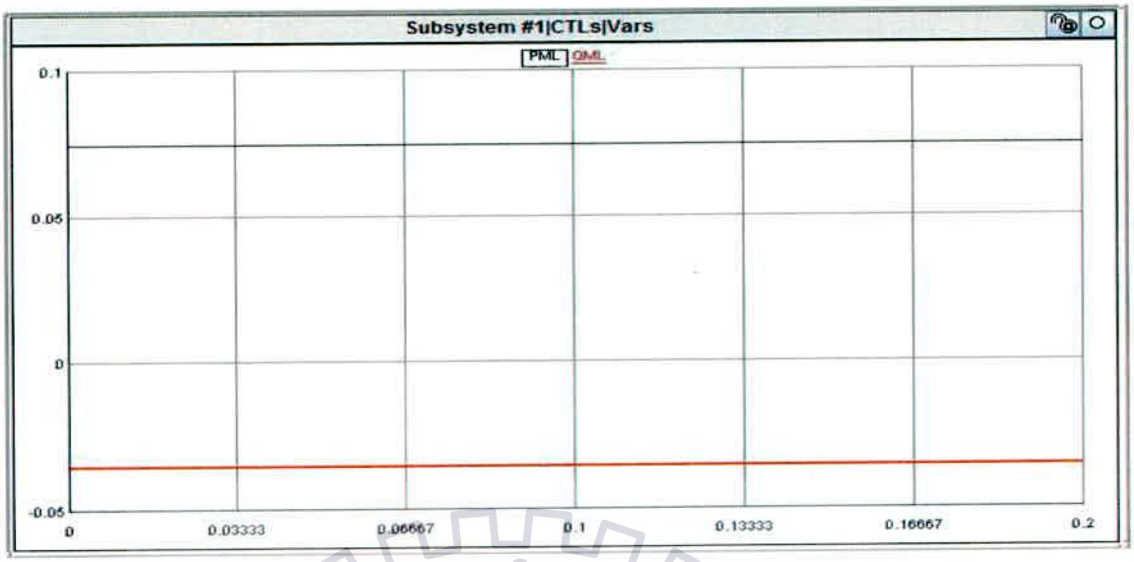

Fig 6.5 output power of PV cell in MW and reactive power in MVAR

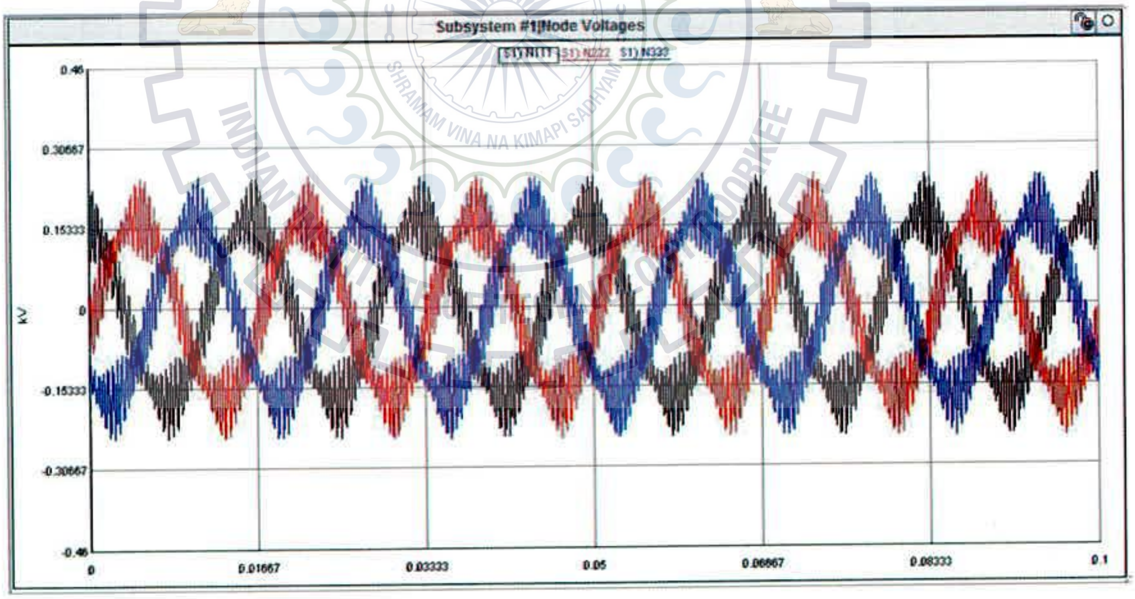

Fig 6.6 inverter output voltage waveform for PHIL test

6.4.1 EFFECT OF CHANGE IN LOAD

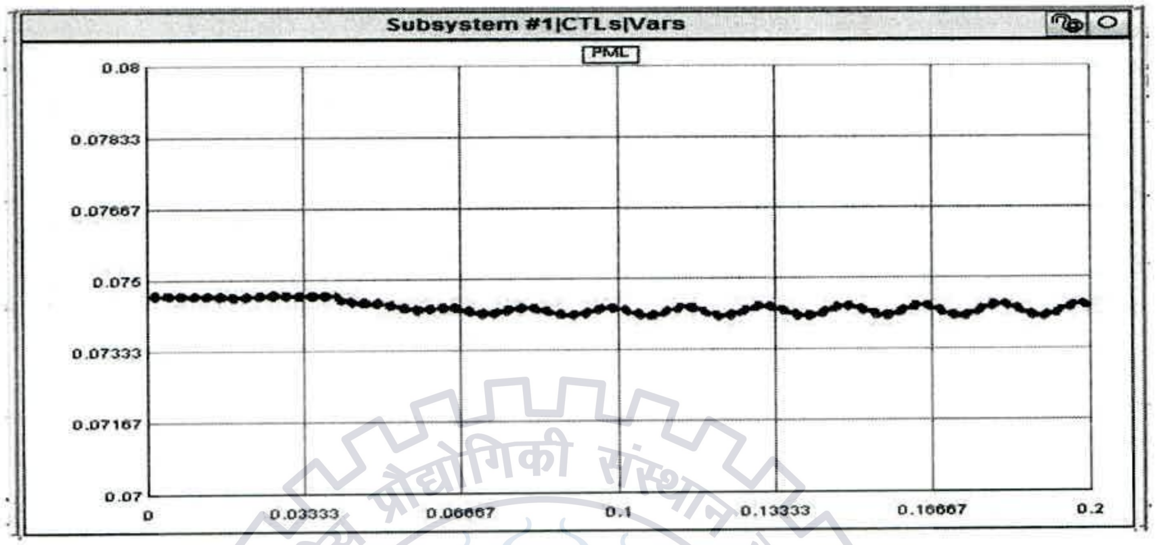

Fig 6.7 change of active power output of PV with decrease in load

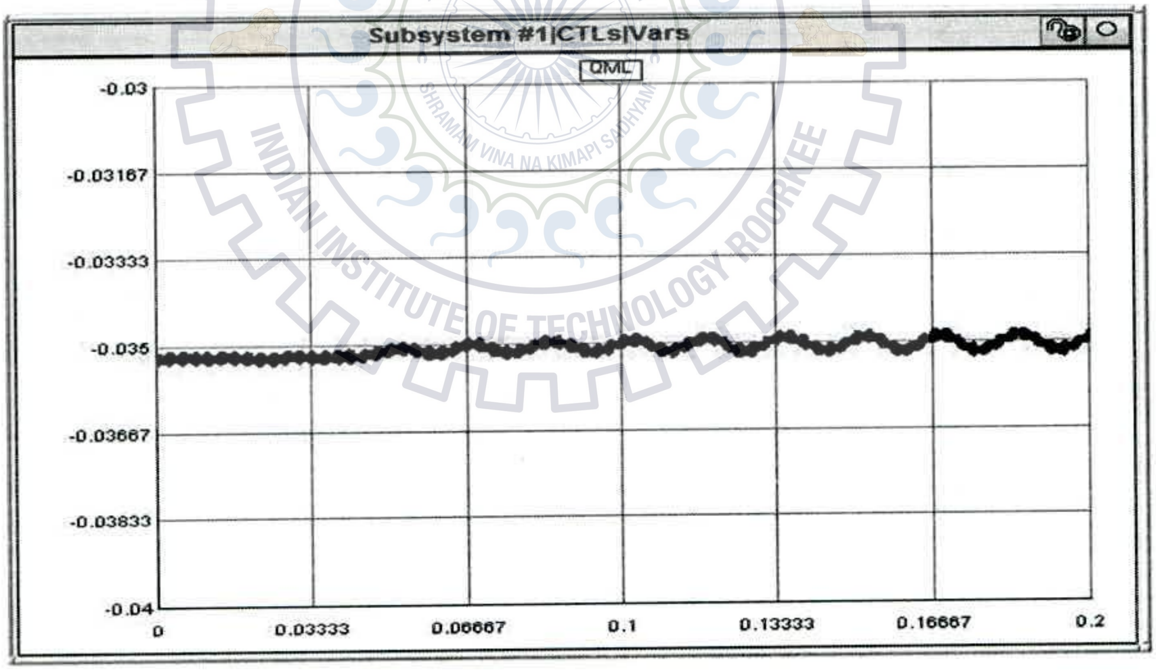

Fig 6.8 change of reactive power of PV with decrease in load

6.4.2 EFEECT OF THREE PHASE FAULT

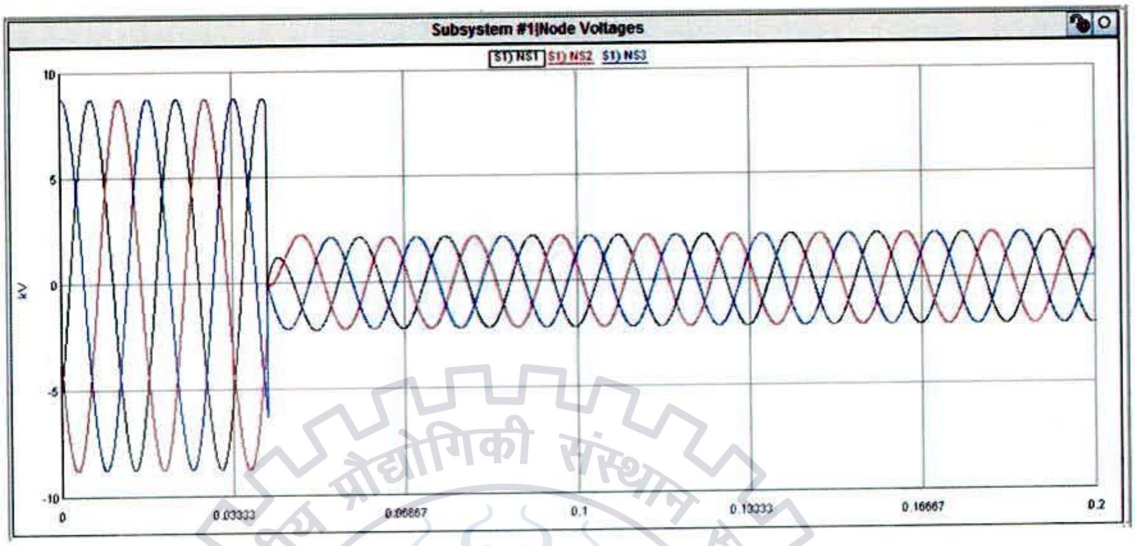

Fig 6.9 bus voltage waveform during three phase fault

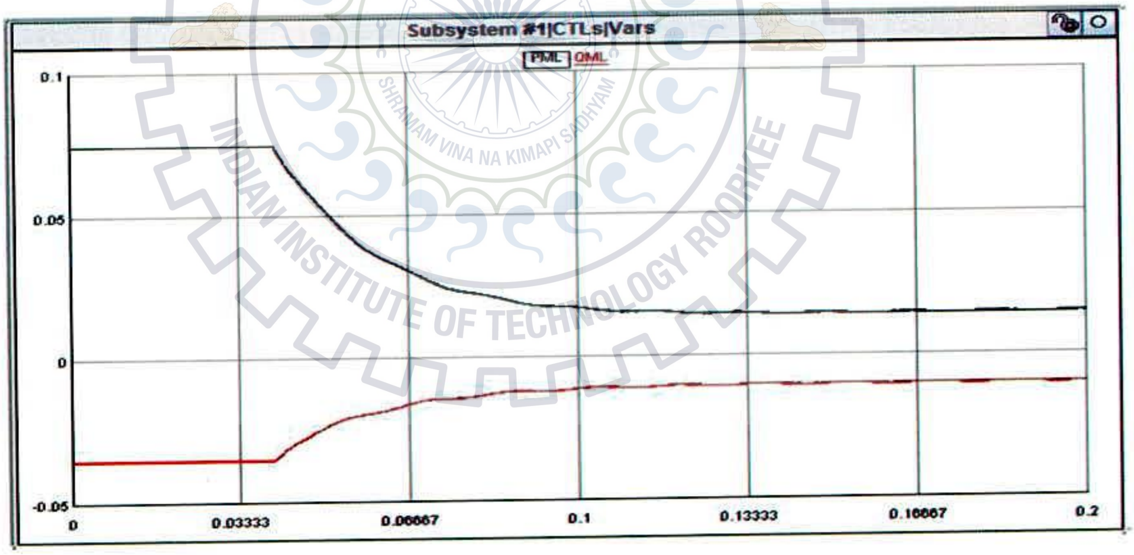

Fig 6.10 active and reactive power output during three phase fault

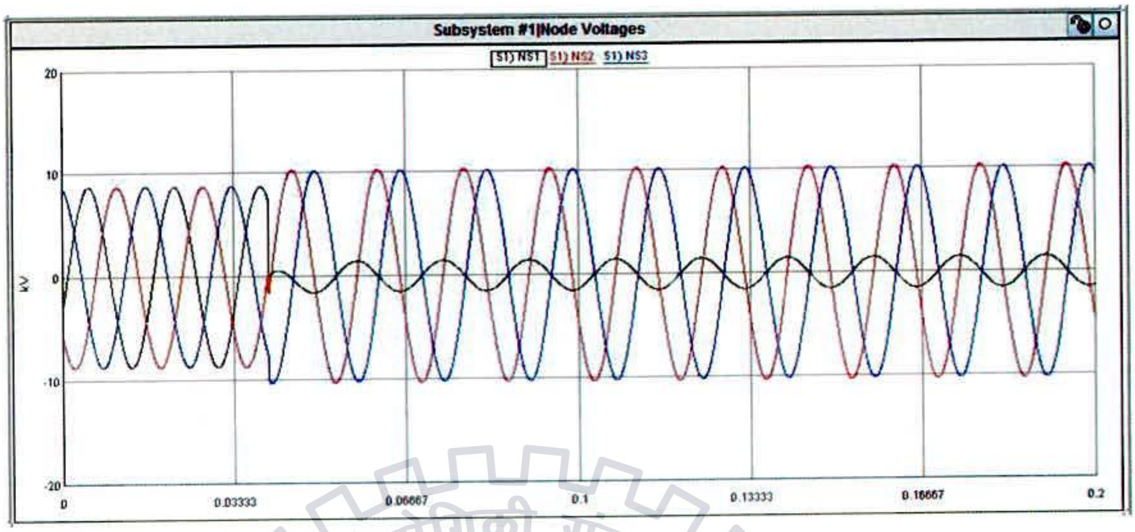

Fig 6.11 bus voltage variation during LG fault

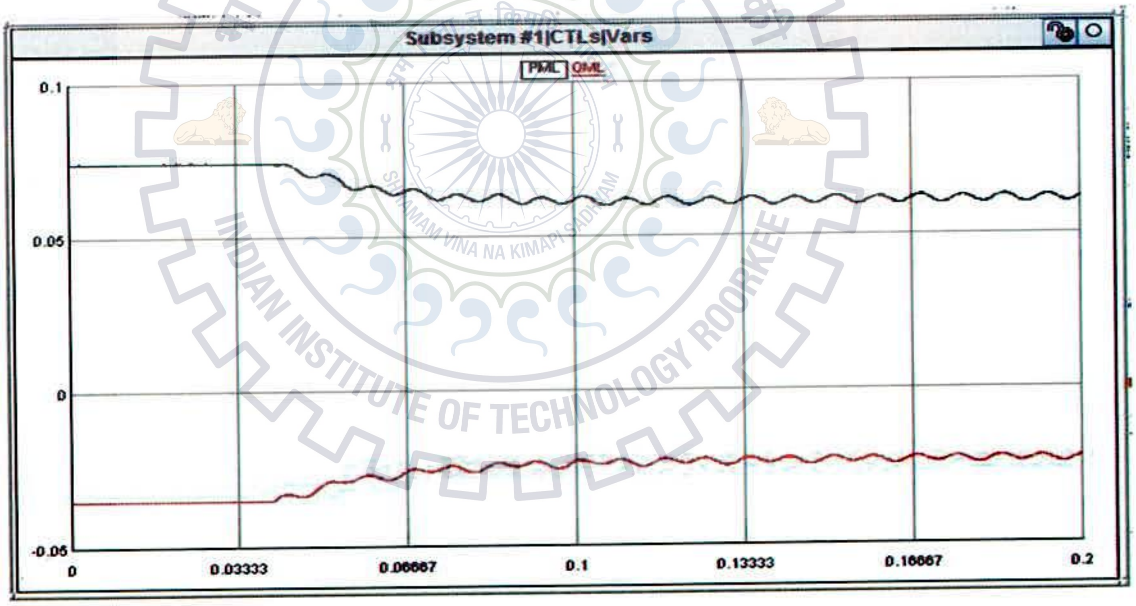

Fig 6.12 active and reactive power output during LG fault

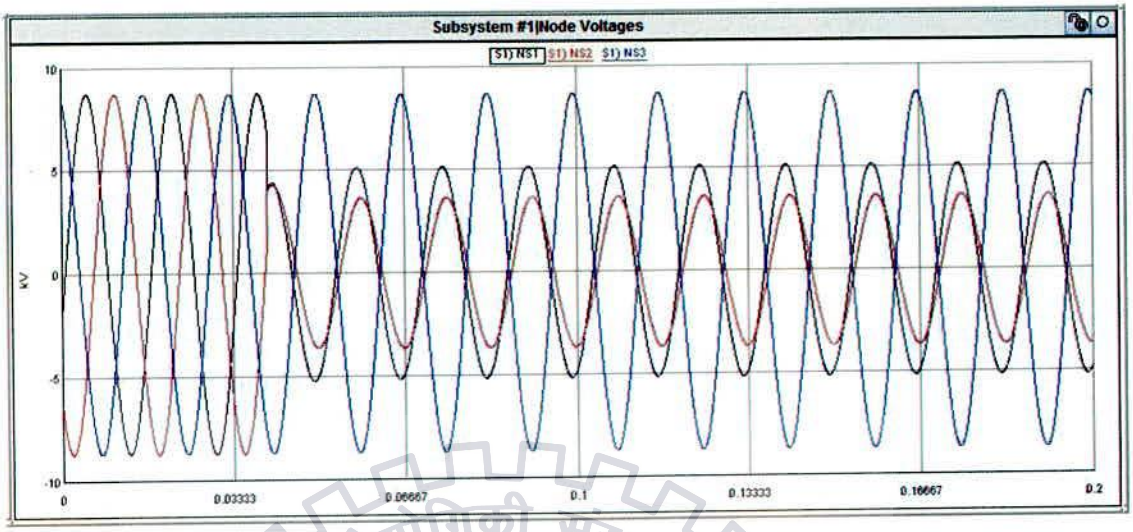

Fig 6.13 bus voltage during LLG fault

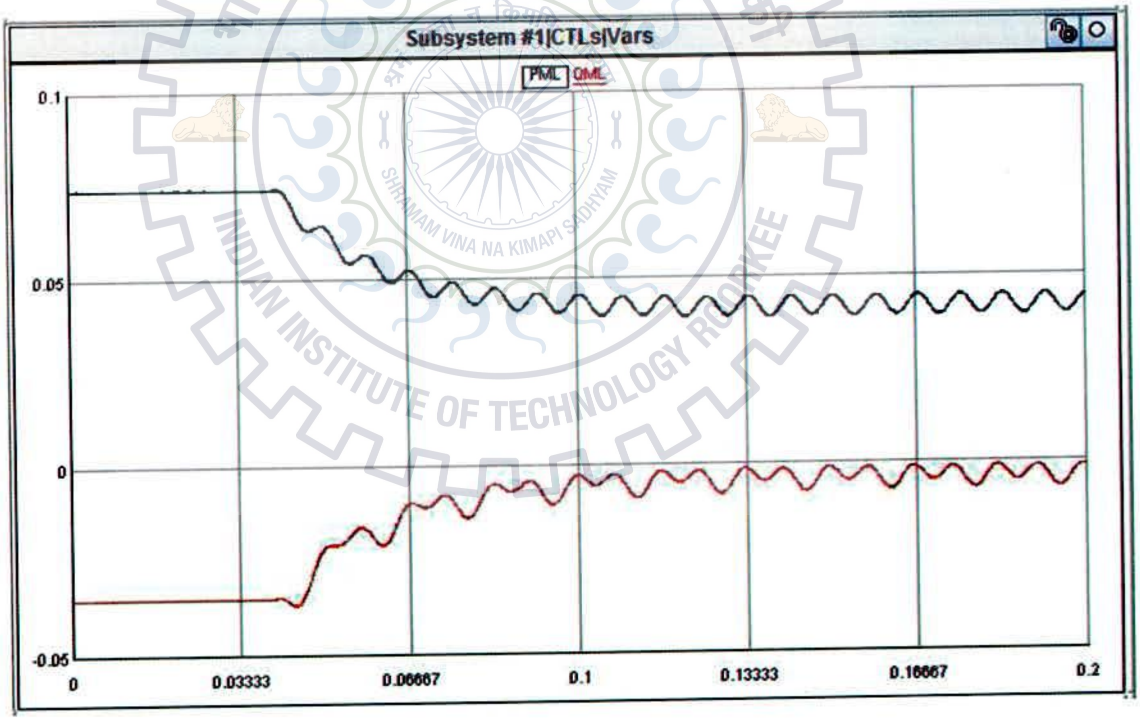

Fig 6.14 active and reactive power output during LLG fault

Chapter-7

CONCLUSION AND FUTURE SCOPE OF WORK

7.1 CONCLUSION

Simulation of a real hardware PV panel is done with the digital simulated 13 bus distribution using RTDS. A hypothetical simulation model of distribution system and PV converters are created on RSCAD by arranging the electrical circuits from modified model libraries. Analog interface port is also modelled for connecting external PV cell. The whole model is compiled through RTDS based on PHIL test.

Real time-PHIL testing is a hybrid form of the external device and virtual simulation methods. It has benefits of accuracy, costs and safety. This helps to rectify the future smart grid issues. Pretesting can be done of any complex devices, distributed generation systems by real time PHIL simulation. Analysis of various utility grid conditions are done by creating virtually faults. The PHIL result is very helpful for solar power generation system. Through this PHIL simulation result it can be concluded that uncertainty of utility grid system affects the PV power generation system.

7.2 FUTURE SCOPE OF WORK

The PHIL methodology used can be extended for development of in-house testing, emerging of distribution testing, simulation, virtual testing and gaming.

It can be analysed to a PV power generation system for better efficiency and better operation during several condition of grid.

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APPENDIX-A:

IEEE 13BUS DISTRIBUTION TEST FEEDER DATA

TABLE 1: LINE DATA

from	to	R	X
1	2	0.176	0.138
2	3	0.176	0.138
3	4	0.045	0.035
4	5	0.089	0.069
5	6	0.045	0.035
5	7	0.116	0.091
7	8	0.073	0.073
8	9	0.074	0.058
8	10	0.093	0.093
7	11	0.063	0.05
11	12	0.068	0.053
7	13	0.062	0.053

TABLE 2: BUS DATA

BUS	P(KW)	Q(KVAR)
1	0	0
2	890	468
3	628	470
4	1112	764
5	636	378
6	474	344
7	1342	1078
8	920	292
9	766	498
10	662	480
11	690	186
12	1292	554