Power-Quality Improvement of Renewable Energy Sources at the Distribution Level in exchange with Grid

(Sustainable Power for Empowering Future)

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***Abstract*— Renewable energy resources (RES) are being increasingly connected in distribution systems utilizing power electronic converters. This paper presents a novel control strategy for achieving maximum benefits from these grid-interfacing inverters when installed in 3-phase 4-wire distribution systems. The inverter is controlled to perform as a multi-function device by incorporating active power filter functionality. The inverter can thus be utilized as: 1) power converter to inject power generated from RES to the grid, and 2) 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. With such a control, the combination of grid-interfacing inverter and the 3-phase 4-wire linear/non-linear unbalanced load at point of common coupling appears as balanced linear load to the grid. This new control concept is demonstrated with extensive MATLAB/Simulink simulation studies and validated through digital signal processor-based laboratory experimental results.**

***Index Terms*—Active power filter (APF), distributed generation (DG), distribution system.**

I. INTRODUCTION

Today photovoltaic (PV) power systems are becoming more and more popular, with the increase of energy demand and the concern of environmental pollution around the world. Four different system configurations are widely developed in grid-connected PV power applications: the centralized inverter system, the string inverter system, the multi string inverter system and the module-integrated inverter system. Generally three types of inverter systems except the centralized inverter system can be employed as small-scale distributed generation (DG) systems, such as residential power applications. The most important design constraint of the PV DG system is to obtain a high voltage gain. For a typical PV module, the open-circuit voltage is about 21 V and the maximum power point (MPP) voltage is about 16 V. And the utility grid is 220 or 110 Vac. Therefore, the high voltage amplification is obligatory to realize the grid-connected function and achieve the low total harmonic distortion (THD). The conventional system requires large numbers of PV modules in series, and the normal PV array voltage is between 150 and 450 V, and the system power is more than 500 W. This system is not applicable to the module-integrated inverters, because the typical power rating of the module-integrated inverter system is below 500 W, and the modules with power ratings between 100 and 200 W are also quite common. The other method is to use a line frequency step-up transformer, and the normal PV array voltage is between 30 and 150 V. But the line frequency transformer has the disadvantages of larger size and weight. In the grid-connected PV system, power electronic inverters are needed to realize the power conversion, grid interconnection, and control optimization.

Generally, gird-connected pulse width modulation (PWM) voltage source inverters (VSIs) are widely applied in PV systems, which have two functions at least because of the unique features of PV modules. First, the dc-bus voltage of the inverter should be stabilized to a specific value because the output voltage of the PV modules varies with temperature, irradiance, and the effect of maximum power-point tracking (MPPT). Second, the energy should be fed from the PV modules into the utility grid by inverting the dc current into a sinusoidal waveform synchronized with utility grid. Therefore, it is clear that for the inverter-based PV system, the conversion power quality including the low THD, high power factor, and fast dynamic response, largely depends on the control strategy adopted by the grid-connected inverters. In this paper, a grid-connected PV power system with high voltage gain is proposed. The steady-state model analysis and the control strategy of the system are presented. The grid connected PV system includes two power-processing stages:

A high step-up ZVT-interleaved boost converter for boosting a low voltage of PV array up to the high dc-bus voltage, which is not less than grid voltage level; and a full-bridge inverter for inverting the dc current into a sinusoidal waveform synchronized with the utility grid. Furthermore, the dc–dc converter is responsible for the MPPT and the dc–ac inverter has the capability of stabilizing the dc-bus voltage to a specific value. The grid-connected PV power system can offer a high voltage gain and guarantee the used PV array voltage is less than 50 V, while the power system interfaces the utility grid. On the one hand, the required quantity of PV modules in series is greatly reduced. And the system power can be controlled in a wide range from several hundred to thousand watts only by changing the quantity of PV module branches in parallel. Therefore, the proposed system can not only be applied to the string or multi string inverter system, but also to the module-integrated inverter system in low power applications. On PV systems employing neutral-point-clamped (NPC) topology, highly efficient reliable inverter concept (HERIC) topology, H5 topology, etc., have been widely used especially in Europe. Although the transformer less system having a floating and non-earth-connected PV dc bus requires more protection, it has several advantages such as high efficiency, lightweight, etc. Therefore, the non-isolation scheme in this paper is quite applicable by employing the high step-up ZVT-interleaved boost converter, because high voltage gain of the converter ensures that the PV array voltage is below50Vand benefits the personal safety even if in high-power application. Fig. 1 shows the proposed grid-connected PV power system. . Seventy five percent of total global energy demand is supplied by the burning of fossil fuels. But increasing air pollution, global warming concerns, diminishing fossil fuels and their increasing cost have made it necessary to look towards renewable sources as a future energy solution. Since the past decade, there has been an enormous interest in many countries on renewable energy for power generation. The market liberalization and government's incentives have further accelerated the renewable energy sector growth. Renewable energy source (RES) integrated at distribution level is termed as distributed generation (DG). The utility is concerned due to the high penetration level of intermittent RES in distribution systems as it may pose a threat to network in terms of stability, voltage regulation and power-quality (PQ) issues. Therefore, the DG systems are required to comply with strict technical and regulatory frameworks to ensure safe, reliable and efficient operation of overall network. With the advancement in power electronics and digital control technology, the DG systems can now be actively controlled to enhance the system operation with improved PQ at PCC. However, the extensive use of power electronics based equipment and non-linear loads at PCC generate harmonic currents, which may deteriorate the quality of power. Generally, current controlled voltage source inverters are used to interface the intermittent RES in distributed system. Recently, a few control strategies for grid connected inverters incorporating PQ solution have been proposed. In an inverter operates as active inductor at a certain frequency to absorb the harmonic current. But the exact calculation of network inductance in real-time is difficult and may deteriorate the control performance.

II. SYSTEM CLASSIFICATION:

2.1 PV SYSTEM

A photovoltaic system (or PV system) is a system which uses one or more solar panels to convert sunlight into electricity. It consists of multiple components, including the photovoltaic modules, mechanical and electrical connections and mountings and means of regulating and/or modifying the electrical output.

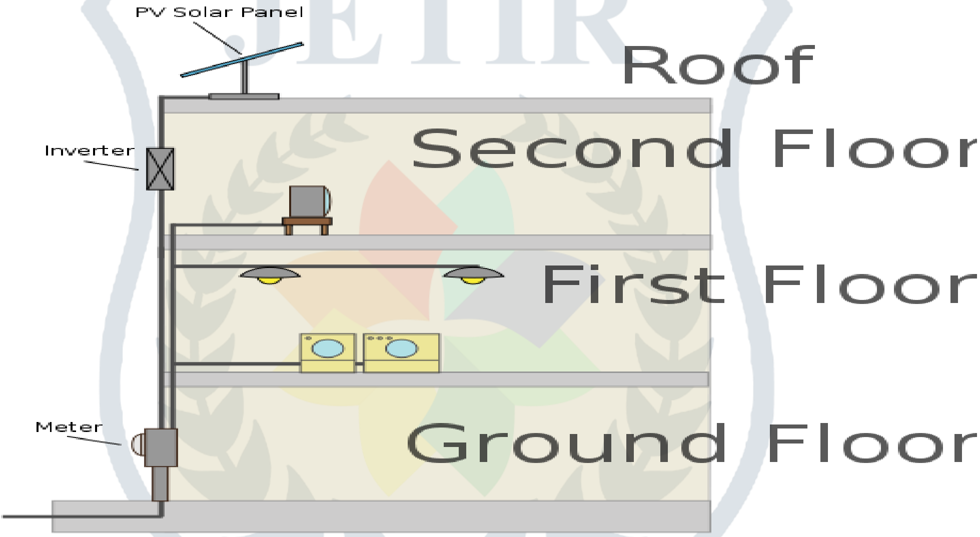


Fig 1.1 PV system

2.1.1 Photovoltaic modules

Due to the low voltage of an individual solar cell (typically ca. 0.5V), several cells are wired in series in the manufacture of a "laminate". The laminate is assembled into a protective weatherproof enclosure, thus making a photovoltaic module or solar panel. Modules may then be strung together into a photovoltaic array. The electricity generated can be either stored, used directly (island/standalone plant)or fed into a large electricity grid powered by central generation plants (grid-connected/grid-tied plant) or combined with one or many domestic electricity generators to feed into a small grid (hybrid plant). Depending on the type of application, the rest of the system ("balance of system" or "BOS") consists of different components. The BOS depends on the load profile and the system type. Systems are generally designed in order to ensure the highest energy yield for a given investment.

2.1.2 Photovoltaic arrays

The power that one module can produce is seldom enough to meet requirements of a home or a business, so the modules are linked together to form an array. Most PV arrays use an inverter to convert the DC power produced by the modules into alternating current that can power lights, motors, and other loads. The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current. Solar arrays are typically measured under STC (Standard Test Conditions) or PTC (PVUSA Test Conditions), in watts, kilowatts, or even megawatts. Costs of production have been reduced in recent years for more widespread use through production and technological advances. One source claims the cost in February 2006 ranged $3–10/watt while a similar size is said to have cost $8–10/watt in February 1996, depending on type. For example, crystal silicon solar cells have largely been replaced by less expensive multi crystalline silicon solar cells, and thin film silicon solar cells have also been developed recently at lower costs of production. Although they are reduced in energy conversion efficiency from single crystalline "si-wafers", they are also much easier to produce at comparably lower costs.

2.2 APPLICATIONS

2.2.1. Standalone systems

Fig 1.2 Solar powered parking meter.

A standalone system does not have a connection to the electricity "mains" (aka "grid"). Standalone systems vary widely in size and application from wristwatches or calculators to remote buildings or spacecraft. If the load is to be supplied independently of solar insolation , the generated power is stored and buffered with a battery. In non-portable applications where weight is not an issue, such as in buildings, lead acid batteries are most commonly used for their low cost. A charge controller may be incorporated in the system to: a) avoid battery damage by excessive charging or discharging and, b) optimizing the production of the cells or modules by maximum power point tracking (MPPT). However, in simple PV systems where the PV module voltage is matched to the battery voltage, the use of MPPT electronics is generally considered unnecessary, since the battery voltage is stable enough to provide near-maximum power collection from the PV module. In small devices (e.g. calculators, parking meters) only direct current (DC) is consumed. In larger systems (e.g. buildings, remote water pumps) AC is usually required. To convert the DC from the modules or batteries into AC, an inverter is used.

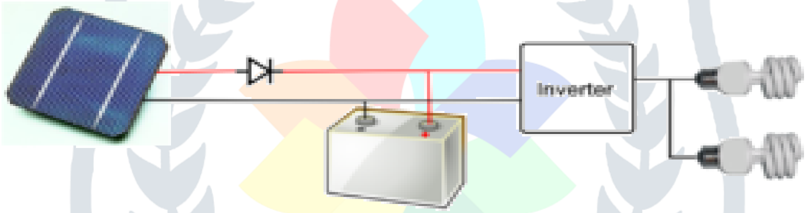


Fig 1.3 PV system with Battery charger

A schematic of a bare-bones off-grid system, consisting (from left to right) of photovoltaic module, a blocking-diode to prevent battery drain during low insolation, a battery, an inverter, and an AC load such as a fluorescent lamp

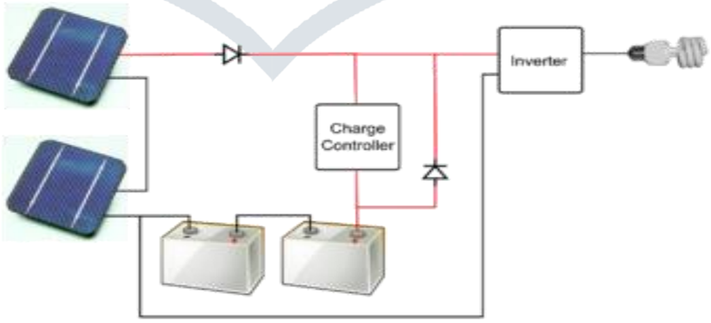


Fig 1.4 Off-grid PV system with battery charger

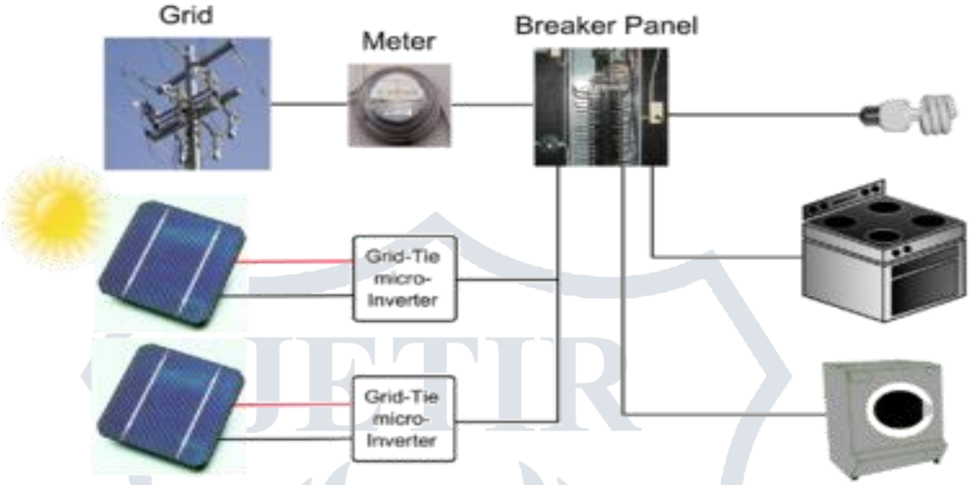
2.2.2. Solar vehicles

Main article: Solar vehicles

Ground, water, air or space vehicles may obtain some or all of the energy required for their operation from the sun. Surface vehicles generally require higher power levels than can be sustained by a practically-sized solar array, so a battery is used to meet peak power demand, and the solar array recharges it. Space vehicles have successfully used solar photovoltaic systems for years of operation, eliminating the weight of fuel or primary batteries.

2.2.3. Small scale DIY solar systems

With a growing DIY-community and an increasing interest in environmentally friendly "green energy", some hobbyists have endeavoured to build their own PV solar systems from kits or partly DIY. Usually, the DIY-community uses inexpensive and/or high efficiency systems (such as those with solar tracking) to generate their own power. As a result, the DIY-systems often end up cheaper than their commercial counterparts. Often, the system is also hooked up unto the regular power grid to repay part of the investment via net metering. These systems usually generate power amount of ~2 kW or less. Through the internet, the community is now able to obtain plans to construct the system (at least partly DIY) and there is a growing trend toward building them for domestic requirements. The DIY-PV solar systems are now also being used both in developed countries and in developing countries, to power residences and small businesses.



2.2.4. Grid-connected system

Fig 1.5. Diagram of a residential grid-connected PV system

A grid connected system is connected to a large independent grid (typically the public electricity grid) and feeds power into the grid. Grid connected systems vary in size from residential (2-10kWp) to solar power stations (up to 10s of GWp). This is a form of decentralized electricity generation. In the case of residential or building mounted grid connected PV systems, the electricity demand of the building is met by the PV system. Only the excess is fed into the grid when there is an excess. The feeding of electricity into the grid requires the transformation of DC into AC by a special, grid-controlled inverter.

In kW sized installations the DC side system voltage is as high as permitted (typically 1000V except US residential 600V) to limit ohmic losses. Most modules (72 crystalline silicon cells) generate about 160W at 36 volts. It is sometimes necessary or desirable to connect the modules partially in parallel rather than all in series. One set of modules connected in series is known as a 'string'.

2.2.5. Building systems

In urban and suburban areas, photovoltaic arrays are commonly used on rooftops to supplement power use; often the building will have a connection to the power grid, in which case the energy produced by the PV array can be sold back to the utility in some sort of net metering agreement. Solar trees are arrays that, as the name implies, mimic the look of trees, provide shade, and at night can function as street lights. In agricultural settings, the array may be used to directly power DC pumps, without the need for an inverter. In remote settings such as mountainous areas, islands, or other places where a power grid is unavailable, solar arrays can be used as the sole source of electricity, usually by charging a storage battery. There is financial support available for people wishing to install PV arrays. In the UK, households are paid a 'Feedback Fee' to buy excess electricity at a flat rate per kWh. This is up to 44.3p/kWh which can allow a home to earn double their usual annual domestic electricity bill. The current UK feed-in tariff system is due for review on 31 March 2012, after which the current scheme may no longer be available.

2.3 POWER PLANTS

Fig 1.6 Waldpolenz Solar Park, Germany

A photovoltaic power station is a power station using photovoltaic modules and inverters for utility scale electricity generation, connected to an electricity transmission grid. Some large photovoltaic power stations like Waldpolenz Solar Park cover a significant area and have a maximum power output of 40-60 MW.

2.3.1. System performance

Insolation and energy

At high noon on a cloudless day at the equator, the power of the sun is about 1 kW/m² on the Earth's surface, to a plane that is perpendicular to the sun's rays. As such, PV arrays can track the sun through each day to greatly enhance energy collection. However, tracking devices add cost, and require maintenance, so it is more common for PV arrays to have fixed mounts that tilt the array and face due South in the Northern Hemisphere (in the Southern Hemisphere, they should point due North). The tilt angle, from horizontal, can be varied for season, but if fixed, should be set to give optimal array output during the peak electrical demand portion of a typical year. For the weather and latitudes of the United States and Europe, typical insolation ranges from 4 kWh/m²/day in northern climes to 6.5 kWh/m²/day in the sunniest regions. Typical solar panels have an average efficiency of 12%, with the best commercially available panels at 20%. Thus, a photovoltaic installation in the southern latitudes of Europe or the United States may expect to produce 1 kWh/m²/day. A typical "150 watt" solar panel is about a square meter in size. Such a panel may be expected to produce 1 kWh every day, on average, after taking into account the weather and the latitude. In the Sahara desert, with less cloud cover and a better solar angle, one could ideally obtain closer to 8.3 kWh/m²/day provided the nearly ever present wind would not blow sand on the units. The unpopulated area of the Sahara desert is over 9 million km², which if covered with solar panels would provide 630 terawatts total power. The Earth's current energy consumption rate is around 13.5 TW at any given moment (including oil, gas, coal, nuclear, and hydroelectric).

2.3.2. Tracking the sun

Trackers and sensors to optimize the performance are often seen as optional, but tracking systems can increase viable output by up to 100%. PV arrays that approach or exceed one megawatt often use solar trackers. Accounting for clouds, and the fact that most of the world is not on the equator, and that the sun sets in the evening, the correct measure of solar power is insolation the average number of kilowatt-hours per square meter per day. For the weather and latitudes of the United States and Europe, typical insolation ranges from 4kWh/m²/day in northern climes to 6.5 kWh/m²/day in the sunniest regions. For large systems, the energy gained by using tracking systems outweighs the added complexity (trackers can increase efficiency by 30% or more).

2.3.3. Shading and dirt

Photovoltaic cell electrical output is extremely sensitive to shading. When even a small portion of a cell, module, or array is shaded, while the remainder is in sunlight, the output falls dramatically due to internal 'short-circuiting' (the electrons reversing course through the shaded portion of the p-n junction). If the current drawn from the series string of cells is no greater than the current that can be produced by the shaded cell, the current (and so power) developed by the string is limited. If enough voltage is available from the rest of the cells in a string, current will be forced through the cell by breaking down the junction in the shaded portion. This breakdown voltage in common cells is between 10 and 30 volts. Instead of adding to the power produced by the panel, the shaded cell absorbs power, turning it into heat. Since the reverse voltage of a shaded cell is much greater than the forward voltage of an illuminated cell, one shaded cell can absorb the power of many other cells in the string, disproportionately affecting panel output. For example, a shaded cell may drop 8 volts, instead of adding 0.5 volts, at a particular current level, thereby absorbing the power produced by 16 other cells. Therefore it is extremely important that a PV installation is not shaded at all by trees, architectural features, flag poles, or other obstructions. Most modules have bypass diodes between each cell or string of cells that minimize the effects of shading and only lose the power of the shaded portion of the array (The main job of the bypass diode is to eliminate hot spots that form on cells that can cause further damage to the array, and cause fires.). Sunlight can be absorbed by dust, snow, or other impurities at the surface of the module. This can cut down the amount of light that actually strikes the cells by as much as half. Maintaining a clean module surface will increase output performance over the life of the module.

2.3.4. Temperature

Module output and life are also degraded by increased temperature. Allowing ambient air to flow over, and if possible behind, PV modules reduces this problem.

2.3.5. Module efficiency

In 2010, solar panels available for consumers can have a yield of up to 19%, while commercially available panels can go as far as 27%.Thus, a photovoltaic installation in the southern latitudes of Europe or the United States may expect to produce 1 kWh/m^2/day· A typical "150 watt" solar panel is about a square meter in size. Such a panel may be expected to produce 1 kWh every day, on average, after taking into account the weather and the latitude Effective module lives are typically 25 years or more.

2.3.6. Components

- **Trackers**

A solar tracker tilts a solar panel throughout the day. Depending on the type of tracking system, the panel is either aimed directly at the sun or the brightest area of a partly clouded sky. Trackers greatly enhance early morning and late afternoon performance, substantially increasing the total amount of power produced by a system. Trackers are effective in regions that receive a large portion of sunlight directly. In diffuse light (i.e. under cloud or fog), tracking has little or no value. Because most concentrated photovoltaic systems are very sensitive to the sunlight's angle, tracking systems allow them to produce useful power for more than a brief period each day. Tracking systems improve performance for two main reasons. First, when a solar panel is perpendicular to the sunlight, the light it receives is more intense than it would be if angled. Second, direct light is used more efficiently than angled light. Special Anti-reflective coatings can improve solar panel efficiency for direct and angled light, somewhat reducing the benefit of tracking.

- **Inverters**

On the AC side, these inverters must supply electricity in sinusoidal form, synchronized to the grid frequency, limit feed in voltage to no higher than the grid voltage including disconnecting from the grid if the grid voltage is turned off.

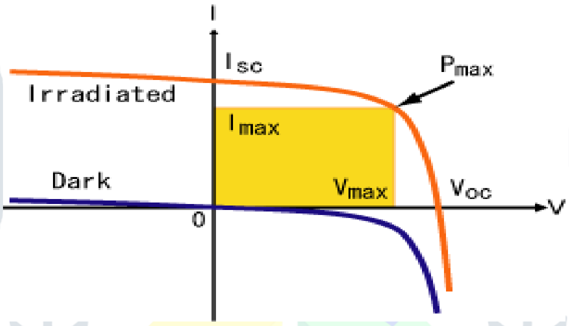


Fig 1.8. Isc verses V

On the DC side, the power output of a module varies as a function of the voltage in a way that power generation can be optimized by varying the system voltage to find the 'maximum power point'. Most inverters therefore incorporate 'maximum power point tracking'. A solar inverter may connect to a string of solar panels. In small installations a solar micro-inverter is connected at each solar panel. For safety reasons a circuit breaker is provided both on the AC and DC side to enable maintenance. AC output may be connected through an electricity meter into the public grid. The meter must be able to run in both directions. In some countries, for installations over 30kWp a frequency and a voltage monitor with disconnection of all phases is required.

2.4 HYBRID SYSTEMS

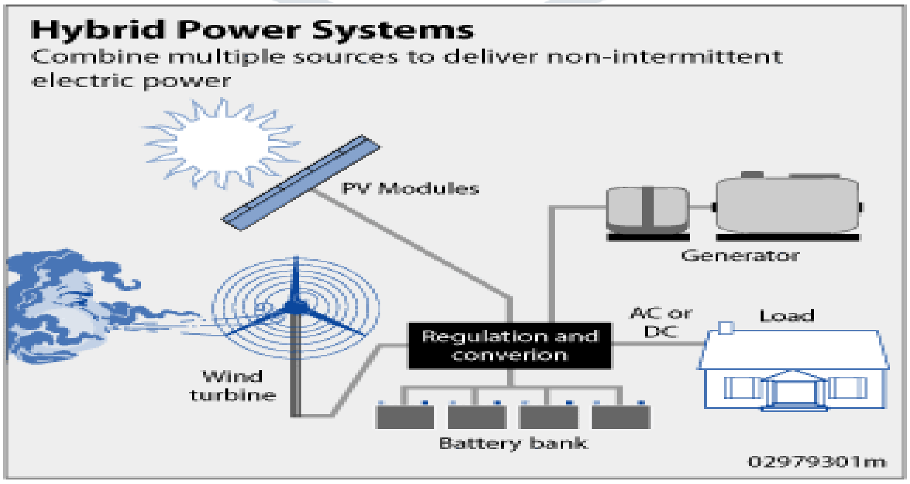


Fig 1.10 Hybrid power system

A hybrid system combines PV with other forms of generation, usually a diesel generator. Biogas is also used. The other form of generation may be a type able to modulate power output as a function of demand. However more than one renewable form of energy may be used e.g. wind. The photovoltaic power generation serves to reduce the consumption of non-renewable fuel. Hybrid systems are most often found on islands. Pell worm Island in Germany and Kythnos Island in Greece are notable examples (both are combined with wind). The Kythnos plant has diocane diesel consumption by 11.2%. There has also been recent work showing that the PV penetration limit can be increased by deploying a distributed network of PV+CHP hybrid systems in the U.S. The temporal distribution of solar flux, electrical and heating requirements for representative U.S. single family residences were analysed and the results clearly show that hybridizing CHP with PV can enable additional PV deployment above what is possible with a conventional centralized electric generation system. This theory was reconfirmed with numerical simulations using per second solar flux data to determine that the necessary battery backup to provide for such a hybrid system is possible with relatively small and inexpensive battery systems. In addition, large PV+CHP systems are possible for institutional buildings, which again provide back up for intermittent PV and reduce CHP runtime.

2.5 POWER QUALITY

The power quality of power supply of an ideal power system means to supply electric energy with perfect sinusoidal waveform at a constant frequency of a specified voltage with least amount of disturbances. Power quality is an issue that is becoming increasingly important to electricity consumers at all levels of usage. Sensitive equipment and non-linear loads are now more commonplace in both the industrial commercial sectors and the domestic environment. Because of this a heightened awareness of power quality is developing amongst electricity users. Occurrences affecting the electricity supply that were once considered acceptable by electricity companies and users are now often considered a problem to the users of everyday equipment. However the harmonic is one of the major factor due to which none of condition is fulfilled in practice. The presence of harmonics, disturbs the waveform shape of voltage and current, and increases the current level and changes the power factor of supply and which in turn creates so many problems.

In this part we introduces the commonly accepted definitions used in the field of power quality and discusses some of the most pertinent issues affecting end-users, equipment manufacturers and electricity suppliers relating to the field. This Special Feature contains a range of articles balanced to give the reader an overview of the current situation with representation from the electricity industry, monitoring equipment manufacturers, solution equipment manufacturers, specialist consultants and government research establishments. The term ‘power quality’ has come into the vocabulary of many industrial and commercial electricity end-users in recent years. Previously equipment was generally simpler and therefore more robust and insensitive to minor variations in supply voltage. Voltage fluctuations coming from the public supply network were therefore not even noticed. Now equipment is used which depends on a higher level of power quality and consumers expect disruption-free operation. Wide diversity of solutions to power quality problems is available to both the distribution network operator and the end-user. More sophisticated monitoring equipment is readily affordable to end-users, who empower themselves with information related to the level of power quality they receive. the following paragraphs introduce the definitions of power quality measurable quantities or occurrences. A voltage dip is a reduction in the RMS voltage in the range of 0.1 to 0.9 p.u. (retained) for duration greater than half a mains cycle and less than 1 minute. Often referred to as a ‘sag’. Caused by faults, increased load demand and transitional events such as large motor starting . A voltage swell is an increase in the RMS voltage in the range of 1.1 to 1.8 p.u. for a duration greater than half a mains cycle and less than 1 minute. Caused by system faults, load switching and capacitor switching. A transient is an undesirable momentary deviation of the supply voltage or load current. Transients are generally classified into two categories: impulsive and oscillatory.

2.5.1 Harmonics

Harmonics are periodic sinusoidal distortions of the supply voltage or load current caused by non-linear loads. Harmonics are measured in integer multiples of the fundamental supply frequency. Using Fourier series analysis the individual frequency components of the distorted waveform can be described in terms of the harmonic order, magnitude and phase of each component. The electricity is produced and distributed in its fundamental form as 50 Hz in India.

A harmonics is defined as the content of signal who’s frequency is integer multiple of the have stand and it became non-sinusoidal or complex waveform. The complex waveform consists of a fundamental wave of 50 Hz and a number of other sinusoidal waves whose frequencies are integral multiple of fundamental wave like 2f(100hz), 3f (150 Hz), 4f (200 Hz) etc. Wave having frequency of 2f, 4f, 6f etc. are called the even harmonics and those having frequency of 3f, 5f, 7f etc., are called as odd harmonics. When fundamental frequency is super imposed with high-level harmonics, it results into complex wave and which is non sinusoidal. When non-linear load draws current that current passes through all of the impedance that is between the load and the system source (See Figure 4). As a result of the current flow, harmonic voltages are produced by impedance in the system for each harmonic. These voltages sum and when added to the nominal voltage produce voltage distortion. The magnitude of the voltage distortion depends on the source impedance and the harmonic voltages produced. If the source impedance is low then the voltage distortion will be low. If a significant portion of the load becomes non-linear (harmonic currents increase) and/or when a resonant condition prevails (system impedance increases), the voltage can increase dramatically.

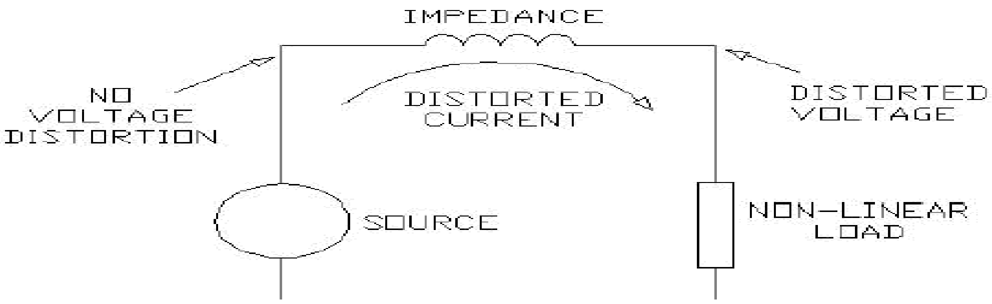


Fig 1.11 Distorted-current induced voltage distortion

2.5.2 Total harmonic Distortion (Distortion factor)

The THD is defined as the ratio of the rms value of the harmonic components to the rms value of the fundamental component and usually expressed in percent. This index is used to measure the deviation of a periodic wave form containing harmonics from a perfect sine wave. For a perfect sine wave at fundamental frequency, the THD is zero.

2.5.3 Active power filter

Active power filters are powerful tools for compensating for not only the current harmonics produced by non-linear loads, but also the reactive power and unbalance of non-linear and fluctuating loads. The shunt active power filter operates as a controlled current source connected in parallel to the non-linear loads for injecting current harmonics into the ac source. The injected current harmonics are equal in magnitude but opposite to the load current harmonics.

2.5.4 Shunt active power filter

Along with increasing demand on improving power quality, the most popular technique that has been used is Active Power Filter (APF); this is because APF can easily eliminate unwanted harmonics, improve power factor and overcome voltage sags.

Harmonic is defined as “a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency”. Harmonic is turnout of several of frequency current or voltage multiply by the fundamental voltage or current in the system. Previous technique used to compensate load current harmonics is L-C passive filter; as a result the filter cannot adapt for various range of load current and sometimes produce undesired resonance. In electrical power supply there are many nonlinear power loads drawing non-sinusoidal current. Non sinusoidal current will pass through the different kind of impendence in the power system and produce voltage harmonics. This will affect to the power system components especially sensitive equipment.

“The increasing use of power electronics-based loads (adjustable speed drives, switch mode power supplies, etc.) to improve system efficiency and controllability is increasing the concern for harmonic distortion levels in end user facilities and on the overall power system”.

III. PROPOSED CONCEPT

It is shown in this paper that the grid-interfacing inverter can effectively be utilized to perform following important functions: 1) transfer of active power harvested from the renewable resources (wind, solar, etc.); 2) load reactive power demand support; 3) current harmonics compensation at PCC; and 4) current unbalance and neutral current compensation in case of 3-phase 4-wire system.

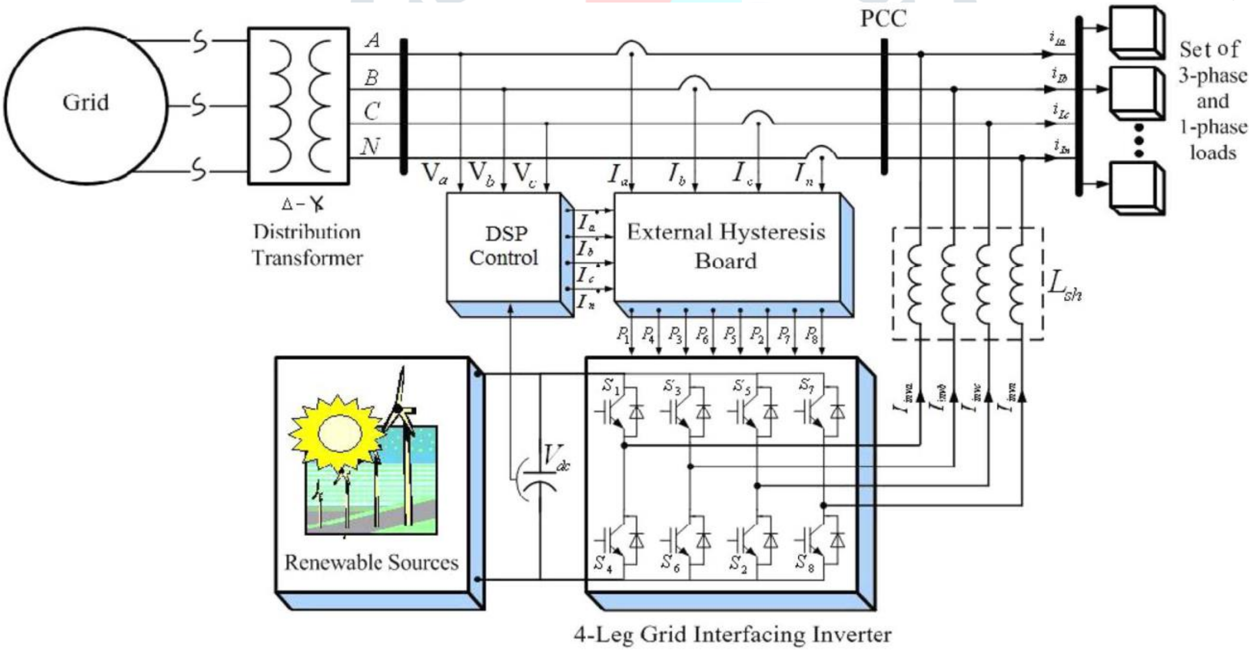


Fig.3.1 Schematic of proposed renewable based distributed generation system.

Moreover, with adequate control of grid-interfacing inverter, all the four objectives can be accomplished either individually or simultaneously. The PQ constraints at the PCC can therefore be strictly maintained within the utility standards without additional hardware cost.The proposed system consists of RES connected to the dc-link of a grid-interfacing inverter as shown in Fig. 1. The voltage source inverter is a key element of a DG system as it interfaces the renewable energy source to the grid and delivers the generated power. The RES may be a DC source or an AC source with rectifier coupled to dc-link. Usually, the fuel cell and photovoltaic energy sources generate power at variable low dc voltage, while the variable speed wind turbines generate power at variable ac voltage. Thus, the power generated from these renewable sources needs power conditioning (i.e., dc/dc or ac/dc) before connecting on dc-link. The dc-capacitor decouples the RES from grid and also allows independent control of converters on either side of dc-link. A. DC-Link Voltage and Power Control Operation. Due to the intermittent nature of RES, the generated power is of variable nature. The dc-link plays an important role in transferring this variable power from renewable energy source to the grid. RES are represented as current sources connected to the dc-link of a grid-interfacing inverter. Fig. 2 shows the systematic representation of power transfer from the renewable energy resources to the grid via the dc-link. The current injected by renewable into dc-link at voltage level V_{dc} can be given as

$$I_{\mathrm{dc1}} = \frac{P_{\mathrm{RES}}}{V_{\mathrm{dc}}}$$

Where P_{RES} is the power generated from RES.

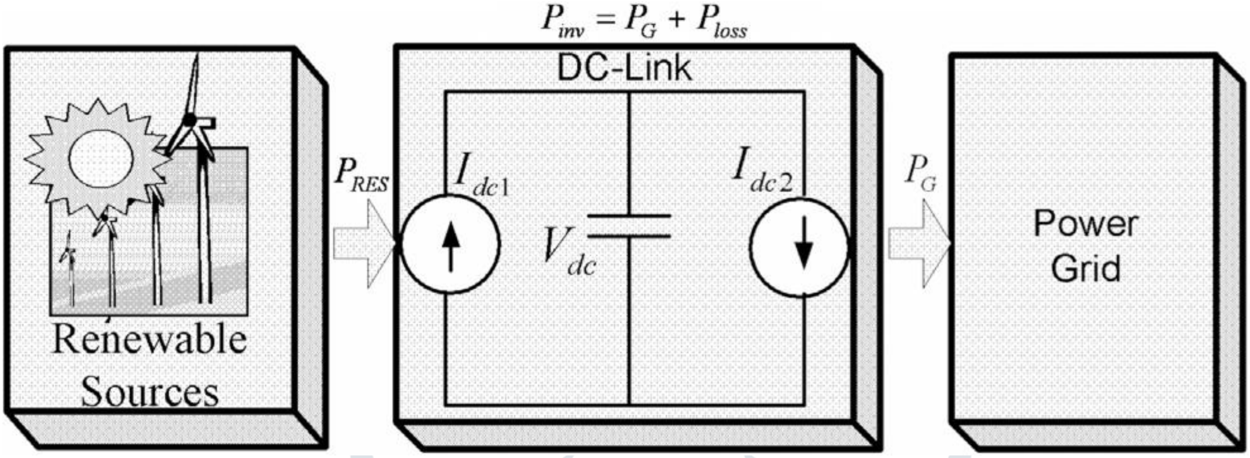


Fig 3.2. DC-Link equivalent diagram.

The current flow on the other side of dc-link can be represented as

$$I_{\mathrm{dc2}} = \frac{P_{\mathrm{inv}}}{V_{\mathrm{dc}}} = \frac{P_G + P_{\mathrm{Loss}}}{V_{\mathrm{dc}}}$$

Where P_{inv}, P_G, and P_{loss} are total power available at grid-interfacing inverter side, active power supplied to the grid and inverter losses, respectively. If inverter losses are negligible then $P_{RES} = P_G$

B. Control of Grid Interfacing Inverter

The control diagram of grid- interfacing inverter for a 3-phase4-wire system is shown in Fig. 3. The fourth leg of inverter is used to compensate the neutral current of load. The main aim of proposed approach is to regulate the power at PCC during: 1) $P_{RES} = 0$; 2) $P_{RES} <$ total load power (P_L); and 3) $P_{RES} > P_L$

While performing the power management operation, the inverter is actively controlled in such a way that it always draws/ supplies fundamental active power from/ to the grid. If the load connected to the PCC is non-linear or unbalanced or the combination of both, the given control approach also compensates the harmonics, unbalance, and neutral current. The duty ratio of inverter switches are varied in a power cycle such that the combination of load and inverter

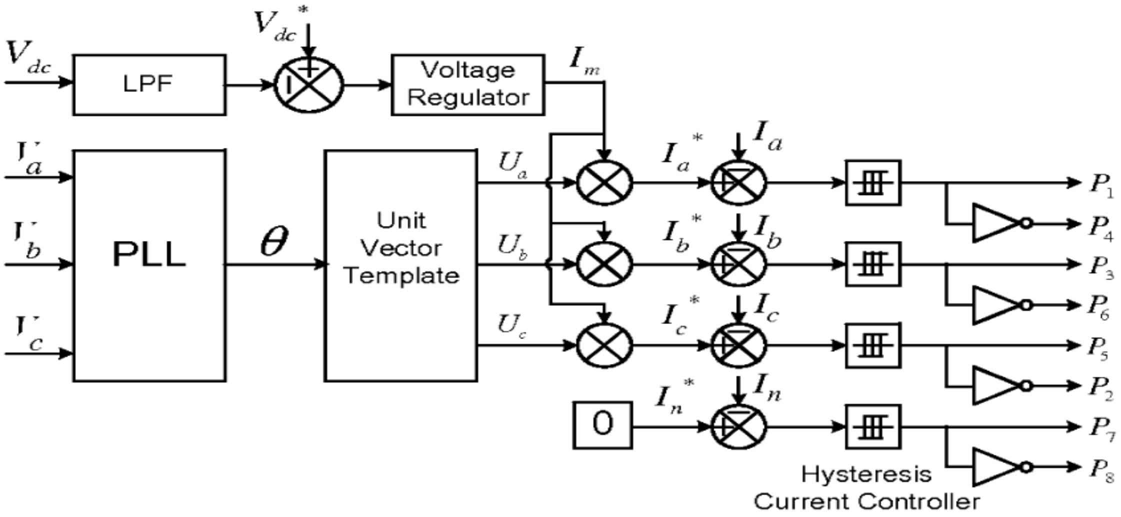


Fig 3.3 Block diagram representation of grid-interfacing inverter control.

Appears as balanced resistive load to the grid. The regulation of dc-link voltage carries the information regarding the exchange of active power in between renewable source and grid. Thus the output of dc-link voltage regulator results in an active current- I_m. The multiplication of active current component I_m with unity grid voltage vector templates (U_a, U_b and $U_{c)}$ generates the reference grid currents (I_a^*, I_b^* and I_c^*). The reference grid neutral current (I_n^*) set to zero, being the instantaneous sum of balanced grid currents. The grid synchronizing angle obtained from phase locked loop (PLL) is used to generate unity vector template as

$$U_a = \mathrm{Sin}(\theta)$$
$$U_b = \mathrm{Sin}(\theta - \frac{2\pi}{3})$$
$$U_c = \mathrm{Sin}(\theta + \frac{2\pi}{3}).$$

The actual dc-link voltage is sensed and passed through a first-order low pass filter (LPF) to eliminate the presence of switching ripples on the dc-link voltage and in the generated reference current signals. The difference of this filtered dc-link voltage and reference dc-link voltage is given to a discrete- PI regulator to maintain a constant dc-link voltage under varying generation and load conditions. The dc-link voltage error at nth sampling instant is given as:

$$V_{\mathrm{dcerr}(n)} = V^*_{\mathrm{dc}(n)} - V_{\mathrm{dc}(n)}.$$

The output of discrete-PI regulator at the sampling instant is expressed as

$$I_{m(n)} = I_{m(n-1)} + K_{PV_{\mathrm{dc}}}(V_{\mathrm{dcerr}(n)} - V_{\mathrm{dcerr}(n-1)}) + K_{IV_{\mathrm{dc}}} V_{\mathrm{dcerr}(n)}$$

Where $K_{PVdc}=10$ and $K_{IVdc} = 0.05$ are proportional and integral gains of dc-voltage regulator. The instantaneous values of reference three phase grid currents are computed a

$$I_a^* = I_m \cdot U_a$$
$$I_b^* = I_m \cdot U_b$$
$$I_c^* = I_m \cdot U_c.$$

The neutral current, present if any, due to the loads connected to the neutral conductor should be compensated by forth leg of grid-interfacing inverter and thus should not be drawn from the grid. In other words, the reference current for the grid neutral current is considered as zero and can be expressed as

$$I_n^* = 0.$$

The reference grid currents (I_a^*, I_b^* , I_c^* and I_n^*) with actual grid currents (I_a, I_b, I_c and I_n) to compute the current errors as

$$I_{\mathrm{aerr}} = I_a^* - I_a$$
$$I_{\mathrm{berr}} = I_b^* - I_b$$
$$I_{\mathrm{cerr}} = I_c^* - I_c$$
$$I_{\mathrm{nerr}} = I_n^* - I_n.$$

These current errors are given to hysteresis current controller. The hysteresis controller then generates the switching pulses ($P_1 - P_8$) for the gate drives of grid-interfacing inverter.

The average model of 4-leg inverter can be obtained by the following state space equations

$$\frac{dI_{\text{Inva}}}{dt} = \frac{(V_{\text{Inva}} - V_a)}{L_{\text{sh}}}$$
$$\frac{dI_{\text{Invb}}}{dt} = \frac{(V_{\text{Invb}} - V_b)}{L_{\text{sh}}}$$
$$\frac{dI_{\text{Invc}}}{dt} = \frac{(V_{\text{Invc}} - V_c)}{L_{\text{sh}}}$$
$$\frac{dI_{\text{Invn}}}{dt} = \frac{(V_{\text{Invn}} - V_n)}{L_{\text{sh}}}$$
$$\frac{dV_{\text{dc}}}{dt} = \frac{(I_{\text{Invad}} + I_{\text{Invbd}} + I_{\text{Invcd}} + I_{\text{Invnd}})}{C_{\text{dc}}}$$

WhereV_{Inva}, V_{Invb}, V_{Invc} and V_{Invn} are the three-phase ac switching voltages generated on the output terminal of inverter. These inverter output voltages can be modeled in terms of instantaneous dc bus voltage and switching pulses of the inverter as

Similarly the charging currentsI_{Invad}, I_{Invbd}, I_{Invcd} and I_{Invnd} on dc bus due to the each leg of inverter can be expressed as

$$V_{\text{Inva}} = \frac{(P_1 - P_4)}{2} V_{\text{dc}} \qquad I_{\text{Invad}} = I_{\text{Inva}}(P_1 - P_4)$$
$$V_{\text{Inva}} = \frac{(P_3 - P_6)}{2} V_{\text{dc}} \qquad I_{\text{Invbd}} = I_{\text{Invb}}(P_3 - P_6)$$
$$V_{\text{Inva}} = \frac{(P_5 - P_2)}{2} V_{\text{dc}} \qquad I_{\text{Invcd}} = I_{\text{Invc}}(P_5 - P_2)$$
$$V_{\text{Inva}} = \frac{(P_7 - P_8)}{2} V_{\text{dc}}. \qquad I_{\text{Invad}} = I_{\text{Inva}}(P_7 - P_8).$$

The switching pattern of each IGBT inside inverter can be formulated on the basis of error between actual and reference current of inverter, which can be explained as:

If $I_{\text{Invad}} < (I^{*}_{\text{Inva}} - h_b)$, then upper switch S_1 will be OFF (P_1=0) and lower switch S_4 will be ON (P_4=1) in the phase "a" leg of inverter.

If $I_{\text{Invad}} > (I^{*}_{\text{Inva}} - h_b)$, then upper switch S_1 will be ON (P_1=1) and lower switch S_4 will be OFF (P_4=0) in the phase "a" leg of inverter.

Where h_b is the width of hysteresis band, on the same principle, the switching pulses for the other remaining three legs can be derived.

IV. FEATURING IN SIMULATION:

In our simulation we had integrated the PQ Converter along with Hybrid Renewable Energy Source to get quantified and Improved Output

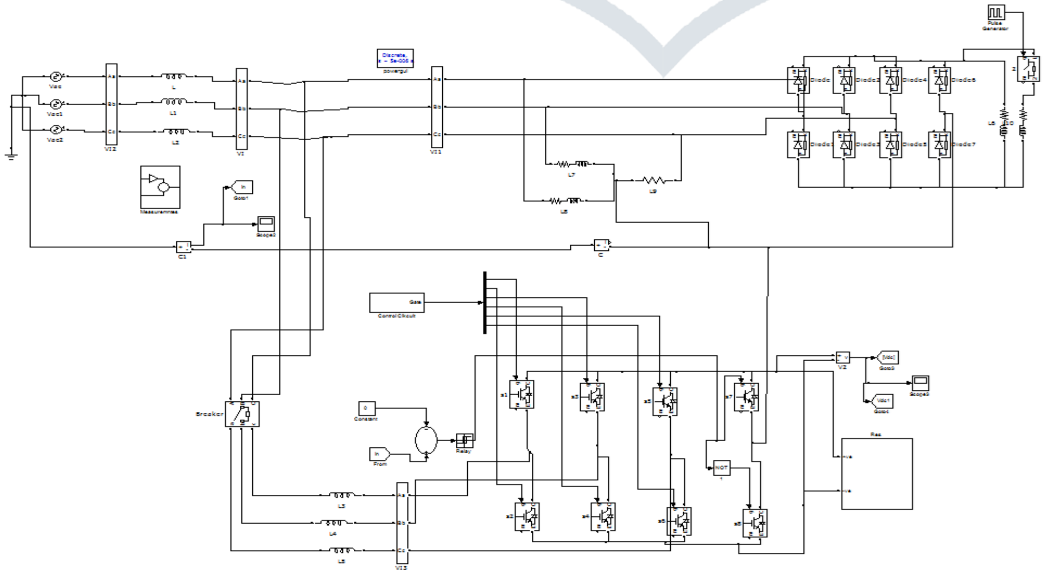


Fig 4.1 Simulink of grid inter connection

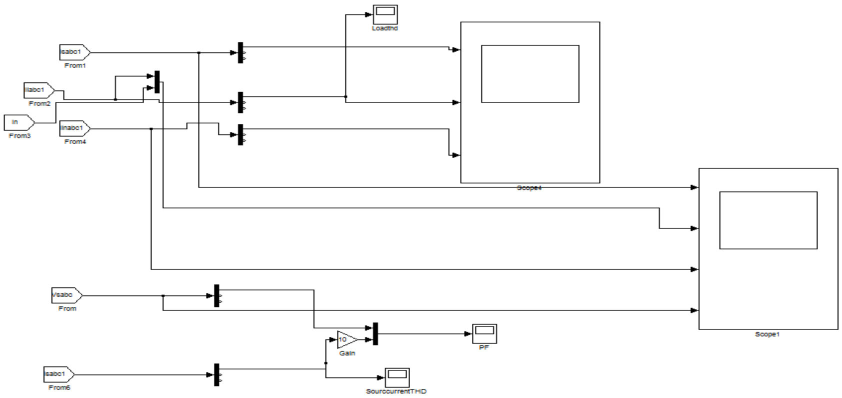


Fig 4.4 Simulink of output

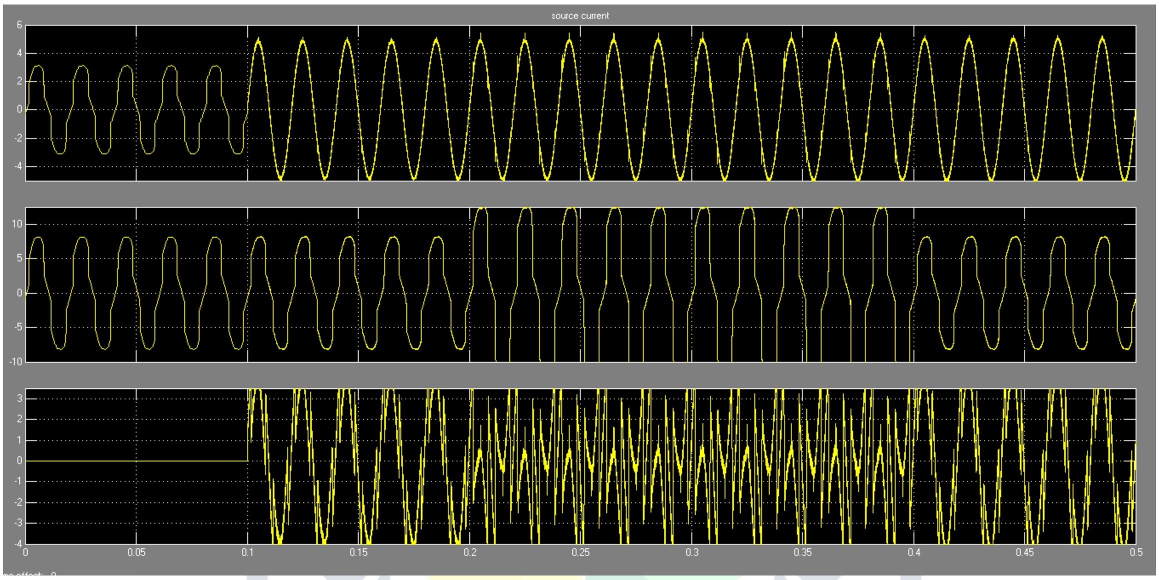


Fig 4.5 single phase output current waveform

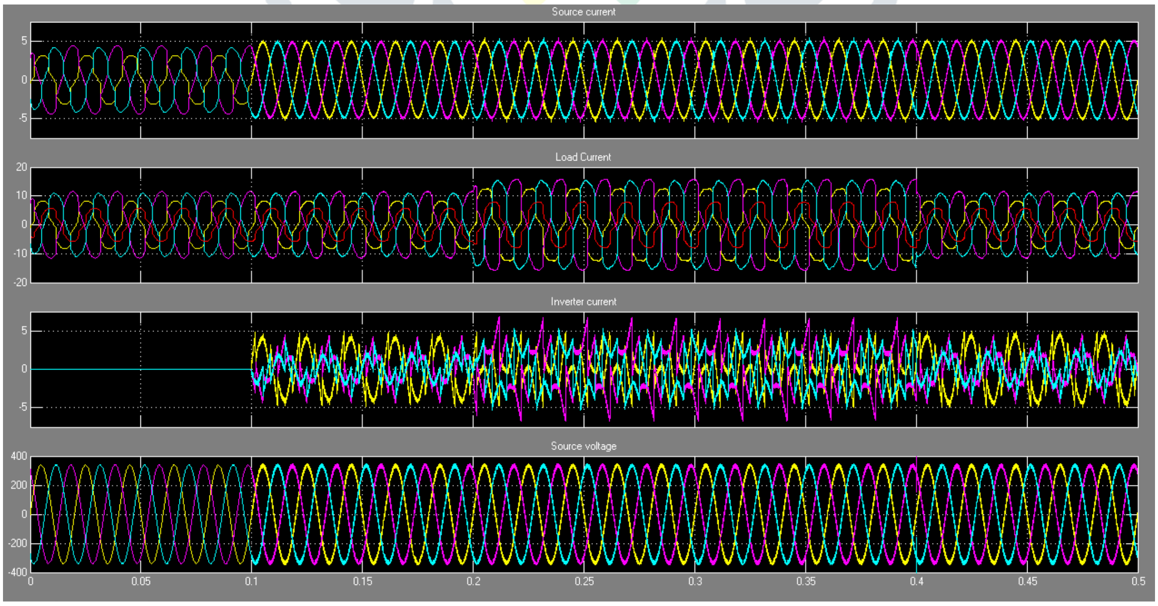


Fig 4.6 Three phase output current waveform

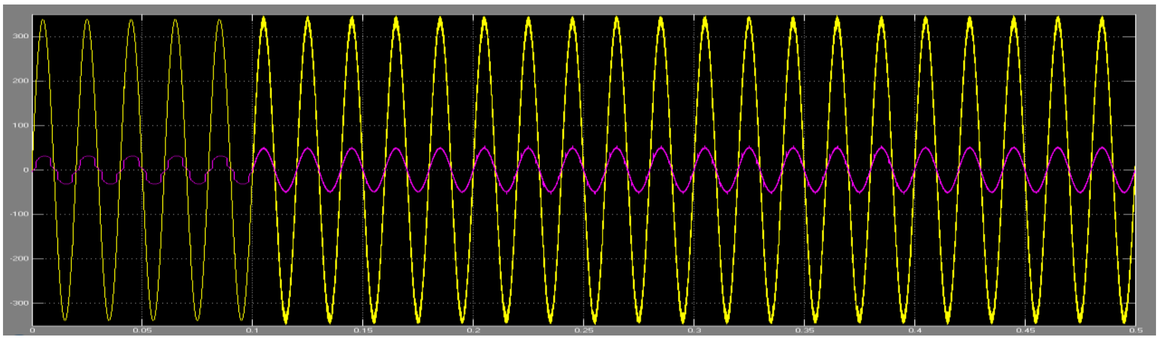
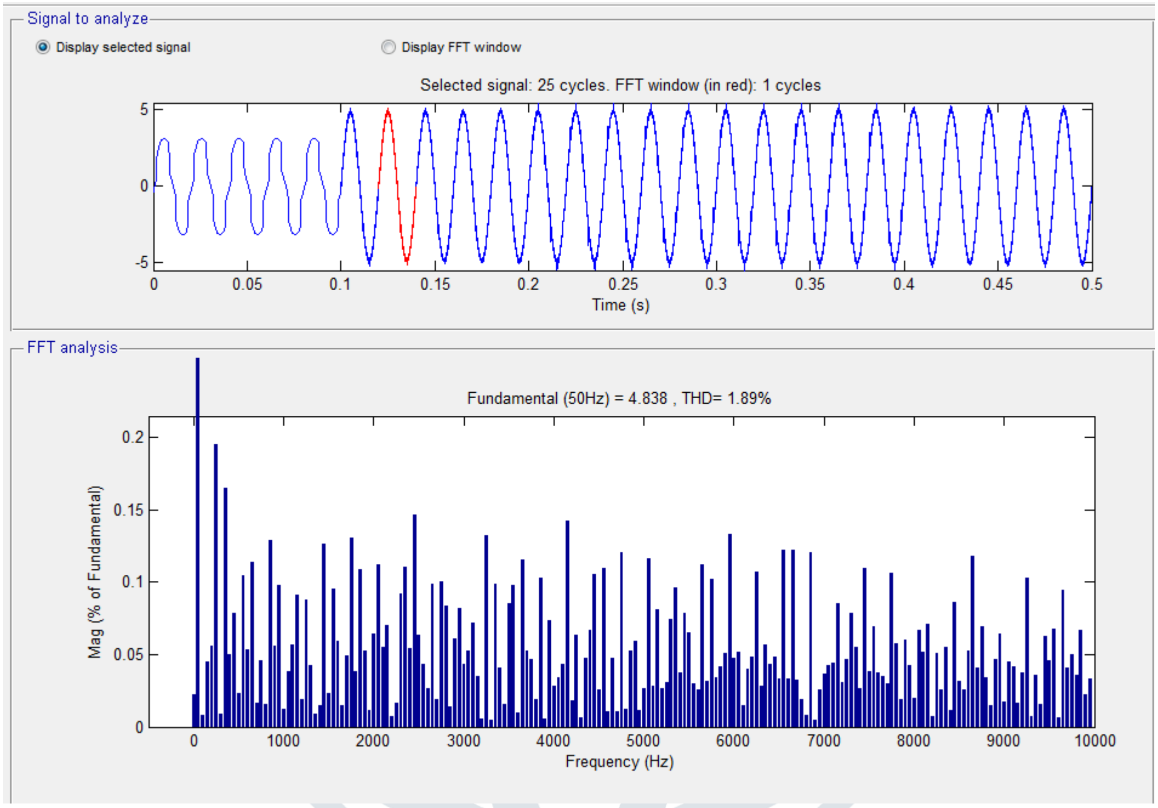


Fig 4.7 output waveform showing unity power factor



Selected signal: 25 cycles. FFT window (in red): 1 cycles

Fundamental (50Hz) = 4.838 , THD= 1.89%

Fig 4.8 Total harmonic distortion

V. CONCLUSION:

This paper has presented a novel control of an existing grid interfacing inverter to improve the quality of power at Point of Common Coupling (PCC) for a 3-phase 4-wireDGsystem. It has been shown that the grid-interfacing inverter can be effectively utilized for power conditioning without affecting its normal operation of real power transfer. The grid-interfacing inverter with the proposed approach can be utilized to:

i) Inject real power generated from RES to the grid, and/or,

ii) Operate as a shunt Active Power Filter (APF).

This approach thus eliminates the need for additional power conditioning equipment to improve the quality of power at PCC. Extensive MATLAB/Simulink simulation as well as the DSP based experimental results have validated the proposed approach and have shown that the grid-interfacing inverter can be utilized as a multi-function device.

The current unbalance, current harmonics and load reactive power, due to unbalanced and non-linear load connected to the PCC, are compensated effectively such that the grid side currents are always maintained as balanced and sinusoidal at unity power factor. Moreover, the load neutral current is prevented from flowing into the grid side by compensating it locally from the fourth leg of inverter. When the power generated from RES is more than the total load power demand, the grid-interfacing inverter with the proposed control approach not only fulfils the total load active and reactive power demand (with harmonic compensation) but also delivers the excess generated sinusoidal active power to the grid at unity power factor.

Finally we can say that the power generation in future is made qualified and sustainable with our proposed system design and its modelling using simulation.

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