IMPROVING THE EFFICIENCY OF SOLAR PHOTOVOLTAIC IN GENERATION

Puspendra Rawal[1], Shailesh Kumar Singh[2]

[1]*M.Sc. Student, Monad University, Ghaziabad, India*
[2]*Professor ,Monad University, Ghaziabad, India*

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Abstract- As the native and national clamor for foreign energy freelance us continues to grow unabated; renewable energy has been receiving enhanced focus and it's wide believed that it's not solely the solution to ever increasing demand for energy during this country, however additionally the environmentally friendly means that of meeting such demand. throughout the spring of 2010, i used to be attached a 5KW alternative energy system style project; the project concerned coming up with and building star panels and associated accessories just like the electrical device mounts and star electrical converter system. one in all the key problems we tend to saw throughout the initial stage of the project was the way to choose economical star cells for panel building at an inexpensive value. whereas we tend to were able to purchase sensible star cells at intervals our allotted budget, the difficulty of style for potency wasn't totally understood , not simply within the contest of star cells performance , however additionally within the overall system potency of the complete alternative energy system, therefore the door was opened for this thesis. My thesis explored and swollen on the far side the scope of the said project to analysis completely different avenues for up the potency of star electrical phenomenon power grid from the photovoltaic cell level to the electrical device mounting, array following and DC-AC inversion system techniques.

1. Introduction

Solar energy is clean and is profusely accessible. star technologies use the sun to produce heat, light electricity, etc for domestic and industrial applications. With the fearful rate of depletion of the main typical energy resources resembling Coal, fossil oil and fossil fuel, including the environmental degradation caused by the method of harnessing these energy sources, it's become associate pressing necessity to take a position in renewable energy resources that will power the longer term sufficiently while not degrading the surroundings through inexperienced house gas emission. The energy potential of the sun is Brobdingnagian, however despite this unlimited solar power resource, harvest home it's a challenge in the main thanks to the restricted potency of the array cells. the simplest conversion potency of most commercially accessible star cells is within the vary 10-20s% [1], [8]. though recent breakthrough within the technology of cells shows vital improvement however the very fact that the utmost star cell potency still falls within the not up to 20s% vary shows there square measure monumental space for improvement. The goal of this thesis is to spot these rooms and ways that to up them. one in all such space is array mounting and following mechanism that moves or positions electrical device to engrossing extended star irradiance for optimum power output. Another such space is researching differing kinds of star cells from past to gift and therefore the future trend and identifies the sources of losses and the way to mitigate them. Lastly, some vital elements that square measure necessary for economical operation of alternative energy electrical converter system square measure investigated.

2. Improving the efficiency of solar photovoltaic power system

Solar Cell Conversion Efficiency η:

The conversion efficiency of a typical solar cell is the ratio of the maximum output generated power to the input or incident power. Certain output parameters greatly influences how efficient a solar cell is and are defined as follows.

Short circuit current I_{SC}: This is the current that flows through the external circuit when the electrodes of a solar cell are short circuited. The short-circuit current is dependent on the incident photon flux density and the spectrum of the incident light. The spectrum is standardized to the AM1.5 (see Figure 1.9 and 1.10 below) for standard solar cell parameter measurements. For Ideal solar cell, $I_{sc} = I_{photon.}$ And this is the maximum current delivery capacity of the solar cell at any given illumination level. From Figure 1.10, the maximum I_{SC} is found by the integration of the spectrum distributions from low wavelengths up to the maximum wavelength at which electron-hole pairs can be generated for a given semiconductor. The common relationship between the wavelength and the photon energy is $E_{(eV)}=1.24/\lambda$. Silicon has a band gap of 1.1eV and the λ corresponding to this is about 1.13um. Crystalline silicon solar cell can deliver a maximum of 46mA/cm² under an AM1.5 spectrum [1].

Open Circuit Voltage (V_{oc}):

The open-circuit voltage is the voltage at which no current flows through the external circuit; i.e. when the solar cell terminals are opened or not connected to a load. It is the maximum voltage that a solar cell can deliver under any given illumination. An ideal PN-Junction cell Voc is given as follows in equation:

Voc = ^{KBT} ln (^{Iphoton} ? 1)

From this equation, The V_{oc} depends on the photo-generated current density I_{photon} and the saturation current Io. Also since the saturation current depends largely on the recombination in the solar cell, the open circuit voltage is a measure of the recombination in the device. For silicon solar cell, the maximum open circuit voltage is about 700mV.

Maximum Power (P_{MP}):

The Maximum current and voltage of a typical solar cell are represented at the 4th quadrant of the IV characteristic curve of Figure 1.6, the maximum power is the area of the product of the maximum current I_{mp} and Voltage V_{mp} as shown in the equation:

PM VMP IMP

Fill Factor FF:

The fill factor FF is the ratio of the maximum power (PMP) generated by the solar cell to the product of the voltage open circuit Voc and the short circuit current Isc

FF= *PMP* *VMP?MP*

From the above set of equations we define the solar cell conversion efficiency η as the ratio of the maximum generated power (PMP=VMP.IMP) to the input or incident power Pin as given by equation below:

VMP ? IMP VOC ? ISC ? FF

Pin is the total power of sunlight illumination on the cell. Energy-conversion efficiency of commercially available solar cells typically lies between 10 and 25 % [8]. These three important parameters (Voc, Isc and FF) as described above are the most important factors that determine how efficient a solar cell is and are optimized for efficient solar cell design.

Light Energy (Photons) Absorption:

Sunlight is a portion of the electromagnetic radiation (Infrared, Visible and Ultraviolet lights) that is emitted by the Sun. Solar irradiance is greatest at wavelengths of between 300-800 nm. Figure 1.8 below shows the solar spectrums. The spectrum of the Sun's solar radiation closely matches that of a black body with a temperature of 5,800 deg K. [3]

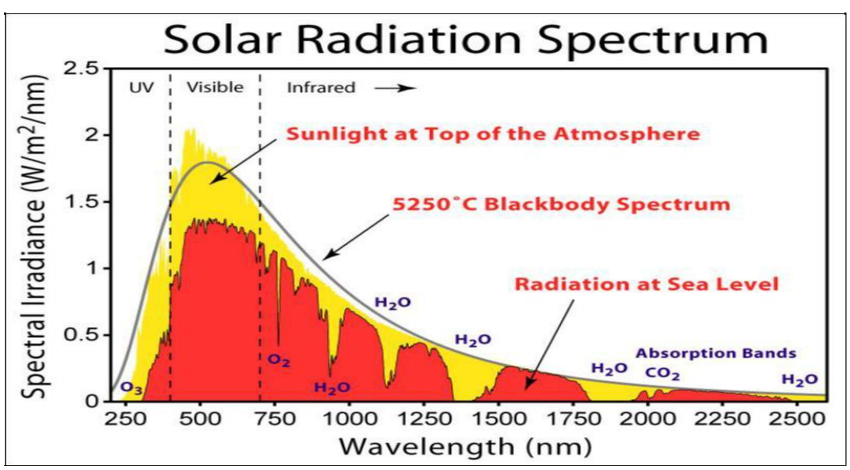

Figure 1.1 Solar Radiation Spectrums [2], [17]

The path length of the solar radiation through the Earth's atmosphere in units of Air Mass (AM) increases with the angle from the zenith. For a path length L through the atmosphere and solar radiation incident at angle θ relative to the normal to the Earth's surface, the air mass coefficient (AM) is:

$AM = L/L_o \approx 1/\text{Cos}$

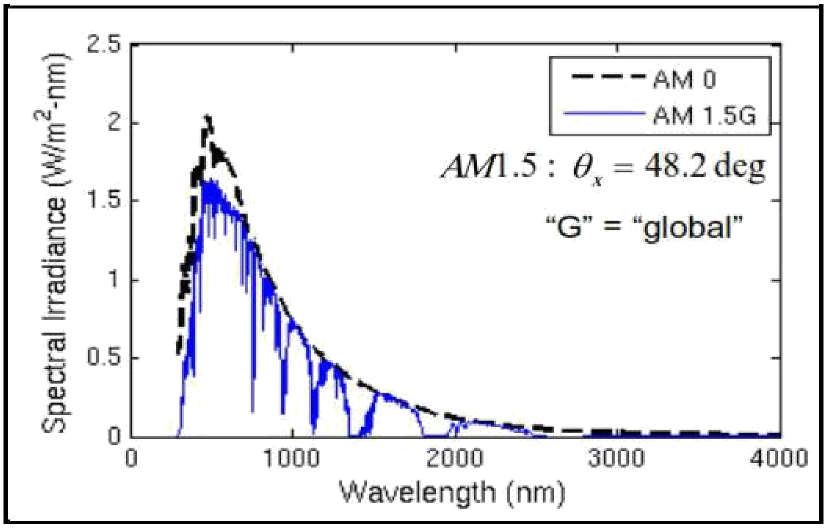

Figure 1.2 Solar Radiation Air Mass standards and corresponding Latitude [22]

The AM 1.5 spectrum which correspond to Latitude 48.2˚ is the preferred standard spectrum for solar cell efficiency measurements. Where Lo (the zenith path length) is perpendicular to the Earth's surface at sea level and θ is the zenith angle in degrees. The air mass number is dependent on the Sun's elevation path through the sky and therefore varies with time of day and with the passing seasons of the year, and also with the latitude of the observer. At the outer space i.e. beyond our terrestrial environment, the solar spectrum has an Air Mass coefficient of zero (AM0) as seen in Fig. 1.2 and 1.3.

Figure 1.3 Solar Spectrums Terrestrial [2], [17]

The integrated power of the sun at AM0 spectrum is 136.6mW/cm^2 [4]. Since the sun's radiation travels through the atmosphere and would encounter various atmospheric diffusion and attenuation, the solar spectrum Air mass coefficient from the surface of the earth atmosphere at typical latitude 48.2˚ is AM1.5G, the integrated power is reduced approximately to 100mW/cm^2 [4]. This is the standard power that most solar cells conversion efficiency is measured against. This means for example, if a solar array produces a power output of 15mW/cm^2, then the conversion efficiency would be 15%. The question then is how many photons can be absorbed per unit area of solar array? Let us consider silicon cell as example to answer this question; if we have a Silicon solar cell with energy band gap of E= 1.1eV. Only photons with energy greater than 1.1eV and wavelength $\lambda < \lambda_{bandgap}$, about 1.13um would be absorbed and the rest will be lost as heat [28]. Also, even when the incident light with the adequate energy level and wavelength strikes the surface of the cell material, some photons are reflected from the surface of the solar cells; All these leads to reduced efficiency. One way to ensure maximum absorption is through the use of cell material with very low reflective coefficient or placing a thin film anti-reflective coating over cell surface. Another method that can be employed in reducing reflection is using textured surface, in which the direction of reflected light on the textured surface is downward so that reflected photons can be reabsorbed again by the cell, thereby improving the conversion efficiency [28].

Losses Due to parasitic resistance:

Another source of loss is through parasitic resistance. The equivalent circuit of practical solar cell is shown in the Figure 1.11 below and the ideal diode equation 3 as modified below. This is different from the ideal solar cells because of the introduction of series resistance (R_s) which arises from the cell material surface to the contacts. Series resistance is worse at high photo-current. And the Shunt resistance (R_{sh}) arises from the leakage of current around the edges of the device and between contacts of different polarity. It is particularly profound with the cell material of poor rectifying characteristic. The effect of parasitic resistances is that it reduces the area of the maximum power rectangle ($V_{OC}.I_{SC}$) of the IV characteristic curves and hence the efficiency suffers. However, latest cells manufacturing improvement and control of material chemistry has shown significant improvement in achieving optimum cell resistivity and thus improved efficiency. [18], [19]

$I= I_L - I_o \left(e^{q(V+IRS)/KBT-1}\right)$ - *V ▯ IRS*

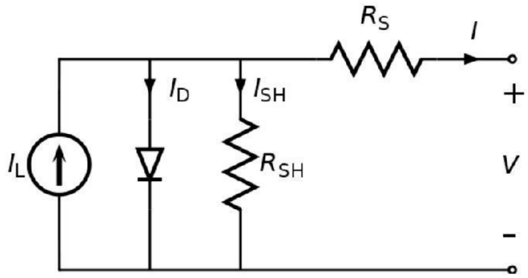

Figure 1.4 Practical Solar Cell Equivalent circuits. [17]

Table 1.1. Performance of some types of PV cell [Green *et al.*, 2001].

Cell Type	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	Efficiency (%)
crystalline Si	4.0	0.706	42.2	82.8	24.7
crystalline GaAs	3.9	1.022	28.2	87.1	25.1
poly-Si	1.1	0.654	38.1	79.5	19.8
a-Si	1.0	0.887	19.4	74.1	12.7
$CuInGaSe_2$	1.0	0.669	35.7	77.0	18.4
CdTe	1.1	0.848	25.9	74.5	16.4

Table 1.1 Different Solar Cells performance table -2001 [6]

2. Grid-Integrated Photovoltaic Inverter System:

The process of converting the dc power from the solar array to ac power which can then be used to power industrial or household ac loads or interfaced into the grid is known as inversion. Other than dc-ac inversion, the other major functions or features that are common to most grid-tied solar inverter systems are;

- Maximum power point Tracking,
- Grid integration and disconnection.
- Remote Monitoring

Within the inverter system, dc power from the PV array is inverted or converted to ac power via a set of solid state switches, typically MOSFETs and or IGBTs which essentially switches the dc power back and forth, creating ac (alternating current) power. The arrangement of these semiconductor switches comes in different format known as topology. Figure 1.5 below shows a 2-level 3-phase inverter topology. The inverter electronics power stage consist of 6-IGBT power switches arranged in a 3-phase bridge. By alternately closing the top left and bottom right switches and vise versa of each phase the dc voltage is inverted from positive to negative triangular ac waveforms. These 3-phase waveforms are pulse width modulated to create modified sine waves which are then fed into the line filter inductor and capacitors to smooth out the high frequency components of the modified ac waveforms. Approximated ac voltage is typically about 208Vac 60HZ line to line which is then fed into the transformer. The transformer serves two major purposes in this configuration; to convert the ac voltage to the correct grid ac voltage both in magnitude and phase angle. The transformer also serves to provide isolation between the grid and the PV. The DC input voltage is typically about 300 -600Vdc in the US and can go up to about 1KV in Europe.

SWITCH	V OUT=V+	V OUT=V0	VOUT=V-
Q1	1	0	0
Q2	1	1	0
Q3	0	1	1
Q4	0	0	1

Table 1.2: Truth table for output voltage and switching states

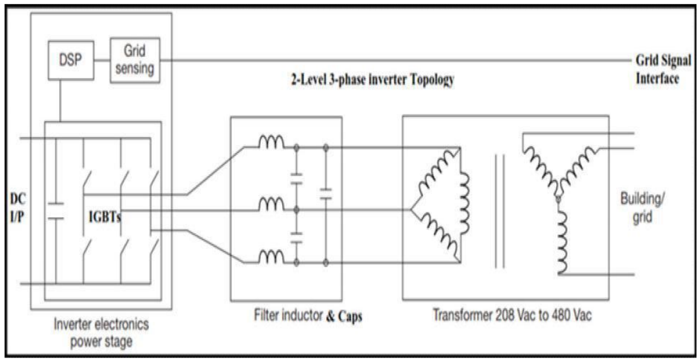

Figure 1.5 2-level 3-phase Inverter Topology [18]

Multi-level Inverter Topology:

Another type of inverter topology is the multi-level inverter. Figure 1.6 below shows a 3-level topology. Each phase has four IGBTs connected in series. The applied voltage on the IGBT is half of a typical conventional two level inverter because of the connection of the series bus capacitors; therefore the topology has the capability of handling higher bus voltage. Voltage steps and lower output current ripple for the same switching frequency as that used in a two level inverter. Because of the staircase waveform characteristics of multilevel inverters, they tend to have reduced electromagnetic compatibity (EMC) issues and lower dv/dt spikes.

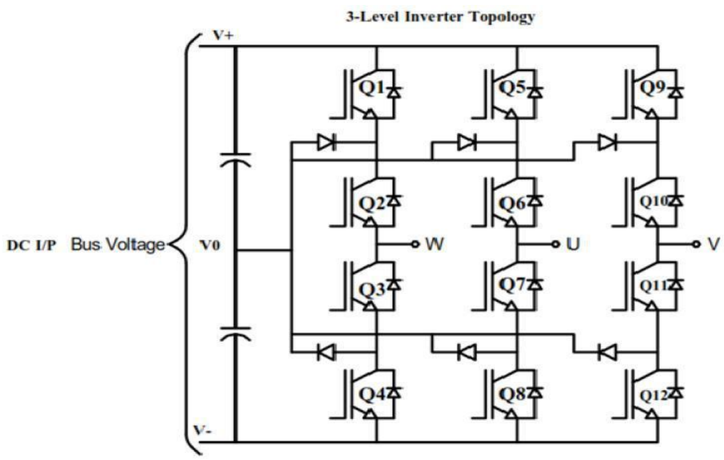

Figure 1.6 3-level 3-phases Inverter Topology [31]

Output Voltage and Switching States: The 3- level inverter topology produces three different output voltage levels namely; the DC bus voltage V+, zero voltage and DC bus negative voltage whereas a two level inverter can only connect the output to either the plus bus or the negative bus. From the Figure 1.28 above and considering the single phase 'W' operation; when switch Q1 and Q2 are turned on, the output is connected to V+; when Q2 and Q3 are on, the output is connected to V0; and when Q3 and Q4 are on, the output is connected to V-. From table 1.6, it is shown that Q2 and Q3 would have about 50% duty cycle much longer than Q1 and Q4 which operates at 25% duty cycle. Clamp diodes D1 and D2 provide the connection to the neutral point. Therefore, Q2 and Q3 would have greater conduction loss than Q1 and Q4 but far less switching loss. This topology also has another key advantage, higher efficiency due to decreased switching losses and also reduced output filter component size and cost as compared to a two level inverter.

The Maximum power point tracking (MPPT): The feature that allows an inverter to remain on the ever-moving maximum power point (MPP) of a PV array is called maximum power point tracking (MPPT). As discussed in the section of the solar cell device physics, the IV characteristic curve of PV modules includes the short-circuit current value (Isc) at 0 Vdc, the open-circuit voltage (Voc) value at 0 A and a "knee", the point where maximum power point (MPP) is found on the curve, this is the location on the IV curve where the voltage multiplied by the current yields the highest value of power. Figure 1.29 shows the MPP for a module at full sun at various temperature conditions. As cell temperature increases, voltage decreases and module conversion efficiency suffers. Other than temperature, module performance is also affected by sun irradiance. When sun is full i.e. at irradiance of 1000W/m^2, module current is highest and when there is less sunlight, module current decreases and so is conversion efficiency. Since sunlight intensity and module or cell temperature vary substantially throughout the day and the year, array MPP (current and voltage) also varies accordingly. The ability of an inverter to accommodate these environmental variations and optimize its performance to meet grid criteria and other regulatory standards (NEC, IEEE and UL etc) at all the time of operation is achieved largely due to effective maximum power point tracking feature.

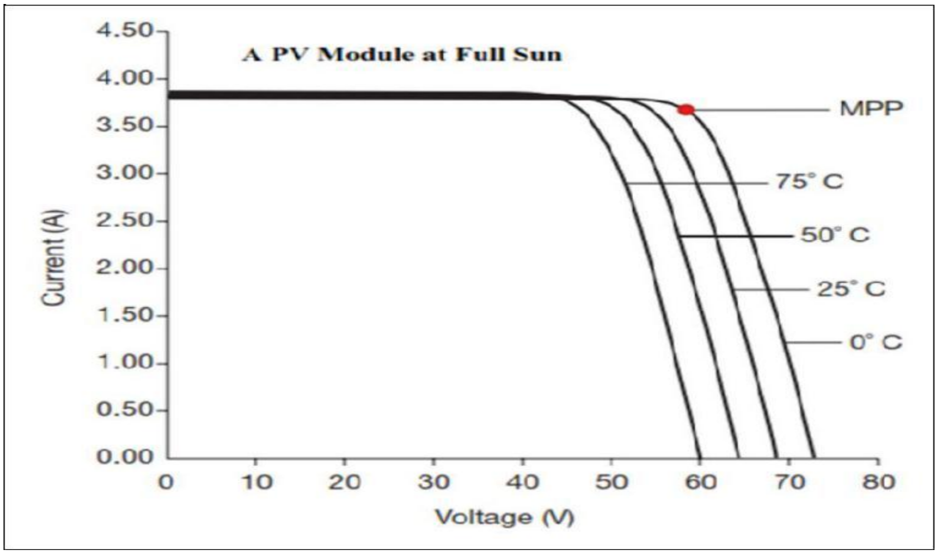

Figure 1.7 MPP on IV-Curve of a PV Module. [18]

Grid integration and disconnection:

All grid-tied solar inverter systems are bound by certain regulatory standards. Typically in the US, these standards are defined by bodies like the IEEE, UL (Under-writer Laboratory) and NEC (National Electrical Codes) NEC. The standards that govern grid-tied photovoltaic inverter systems are UL 1741 and IEEE 1547. One of the critical requirements of these standards is that all grid-tied inverters must disconnect from the grid if the ac line voltage or frequency goes above or below limits prescribed in the standard. Also if the grid is not present due to a fault or for some other reasons, the inverter must shut down to avoid the solar power system of being an island. In any of these cases, the solar inverter system must not interconnect or feed power into the grid until the inverter is sure that proper utility voltage and frequency is recorded at the grid for a period of 5 minutes. This is to protect against the inverter feeding power into the grid during a fault or during a utility scheduled maintenance exercise.

Inverter type, size and voltage	Voltage range [V]	Clearing time(s) (seconds)	Frequency range [Hz]	Clearing time(s) (seconds)
Residential 240 Vac	V < 211.2	2.00	f > 60.5	0.16
	211.2 < V < 264	operational	f < 59.3	0.16
	264 < V	1.00	59.3 < f < 60.5	operational
Commercial, 3-phase 208 Vac, <30 kW inverter	V < 104	0.16	f > 60.5	0.16
	104 < V < 183	2.00	f < 59.3	0.16
	183 < V < 228.8	operational	59.3 < f < 60.5	operational
	228.8 < V < 249.6	1.00	—	—
	249.6 < V	0.16	—	—
Commercial, 3-phase 480 Vac, >30 kW inverter	V < 240	0.16 [1]	f > 60.5	0.16
	240 < V < 422.4	2.00 [1]	57.0< f < 59.8	0.16 [1]
	422.4 < V < 528	operational	f < 57.0	0.16
	528 < V < 576	1.00 [1]	59.8 < f < 60.5	operational
	576 < V	0.16 [1]		

Table 1.3: Utility grid voltage and frequency limits for grid-tied PV: [18]

Monitoring and Communications:

The interactions of the various components that make up the solar power systems namely; The Grid, Inverter, and the solar array and all the various components and interconnect are achieved by effective software and monitoring communication gadgets. For example looking at Figure 1.26 above, to reliably control the inverter, the software designed to run on the inverter's digital signal processor which controls the PWM waveforms and other feedback signals to and from the grid must function to meeting all the appropriate UL 1741 and IEEE 1547 safety requirements. Another important function of the software and monitoring portion of the system is the controls of the MPPT features that vary the dc voltage and current level as appropriate to accurately and quickly follow the moving MPP of the PV array. Software is also used to drive the contactor that connects the inverter to the grid in the morning and remove it from the grid at night when the sun goes out.

The Key Components of a Grid-Tied Photovoltaic inverter system:

Looking at Figure 1.26 above, some of the critical components of an inverter systems are: solid state switches i.e. IGBTs and or MOSFETs which are used to invert the DC voltage into ac voltage. Other key components in the main power inversion circuit are line inductors, capacitors and power transformer. The design selection of these critical components is very important for the efficient operation of the solar power system.

IGBT Module:

The IGBT, Insulated Gate Bipolar Transistor, is a solid state switching transistor that combines the collector-emitter voltage characteristics of a bipolar transistor and the drive characteristic of a MOSFET. It is controlled by voltage applied to the gate terminal. The IGBT, MOSFET and BJT are all solid state devices that can be used in switching applications. A brief comparison between the structures of these solid state Switching devices is that; The NPN BJT is a three junction device that requires a continuous current flowing into the base region to operate the junctions to conduct current. Whereas MOSFET and the IGBT are voltage controlled devices, they only require voltage on the gate to maintain conduction through the device. The IGBT has one junction more than the MOSFET, and this junction allows higher blocking voltage and conductivity modulation for reduced on-state conduction losses. The additional junction in the IGBT does however limit switching frequency during conduction. MOSFET does not have this switching speed limitation. Inverters IGBT modules must be designed to be rugged, low loss and low on-state saturation voltages and must also be able to maintain a relatively high switching speed, up to 20KHZ with less loss.

Power Magnetics:

Another very critical portion of the Grid-tied solar inverter system is the power magnetic components, Line inductor and transformer.

Inductor: The function of the inductor is to smoothen out the raw and noisy triangular waveform of the pulse width modulated power switches. The IEEE 1547 requires that the current harmonics of grid-tied photovoltaic inverters be less than 5% THD and voltage harmonics less than 2%THD. The main component that helps the inverter achieve these requirements is the inductor. A snap picture of the harmonics measurements on a Yokogawa power analyzer and data of power quality characteristic of a grid-tied inverter system that I worked on during the course of this thesis is as shown in Figure 1.32 below. As seen from the Figure, the current THD is about 2.1% and the Voltage THD about o.4% well below the requirement. A high level of harmonics could be a sign that the inductor is not efficient since harmonics are losses. Some other key specification of power line inductor is low winding temperature rise and low dc resistance. Insulation class should be N or R (200 to 220˚C). Another key feature of a good inductor is low acoustic noise typically below 50dB at full load. Inductor construction is also very important, there must be proper insulation between the laminations and the core brackets and other supporting structures to avoid close eddy current loop.

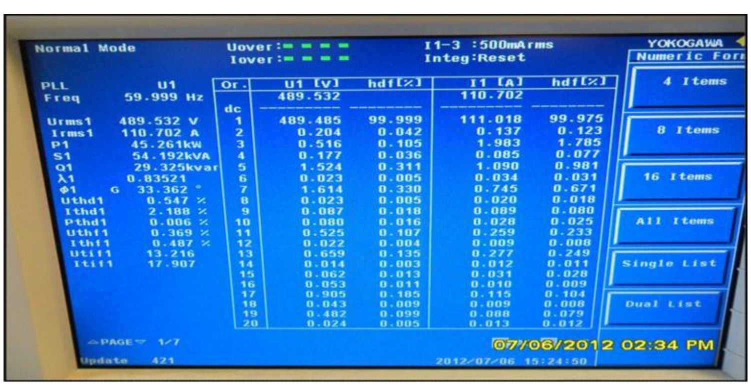

Figure 1.8 Harmonics of a 3-phase Grid-tied Inverter system.

Transformer:

The main function of the transformer in a grid-tied solar power system is to convert the ac input voltage from the inverter core to the correct grid ac voltage both in magnitude and phase angle typically 208Vac RMS or 480V RMS Delta-Wye depending on configuration. The transformer also serves to provide isolation between the grid and the PV. The efficiency of the power magnetic (transformer and Inductor) is key to the efficiency of the solar power system. Some of the key specifications that define an efficient transformer are; very low No-load and Load losses, low winding temperature rise, good dielectric voltage withstand, good load regulation less than 1.5%, ability to withstand transient overvoltage situation up to 120% of rated voltage without saturation and no excessive audible noise (IEEE-1547). The efficiency of grid-tied inverter system is typically measured using the CEC (California Energy Commission) efficiency model. The CEC models basically assign weighted values based on load levels and then the cumulative of all the load levels would be the overall efficiency. One of such transformer that I tested was a 100KVA 208/480V delta-wye transformer with a CEC efficiency spec on the name plate of 99.30% at 40 degree C ambient temperature.

Figure 1.9: Snap picture of a 3-Phase100KVA Transformer under test.

4.Conclusion

This analysis has modified the attitude regarding renewable energy generally and has given an amazing sensible intuition regarding solar energy system specifically. star cells development has come back an extended approach and nevertheless, it seems the technology is way from perfection decision making from the very fact that the simplest electric cell conversion potency for commercially accessible star cells continues to be within the two hundredth vary. whereas electric cell technology has evolved over the years, one factor I recognized is that tremendous analysis and breakthrough area unit still occurring year when year to excellent the breakthrough of the past and lay the inspiration for consequent generation star cells. i used to be additionally ready to leverage the chance that I even have as AN engineer operating in one among the foremost dynamic trade (Renewable Energy) of now. I had the chance to go to star farms and knowledge firsthand however solar energy system works and the way they're integrated into the grid system. i used to be additionally ready to expertise the detail that goes into the planning and therefore the producing processes that area unit peculiar to star electrical converter system and therefore the varied regulative (national and International) standards that a selected solar energy system should meet. Having been assigned to 1 of the key side of the business, part engineering, the analysis ready ME to dig deep into the varied parts just like the Dry-type Power Transformers, transmission line Reactors or Inductors, Power Film capacitors, IGBTs, Power MOSFET, and Power provides among others that goes into the star electrical converter system and the way their performance specifications affects the potency of the solar energy system. This thesis has additionally shown with empirical information the energy and value edges of fine array mounting and additionally the benefits of half-track array vs. mounted arrays. Finally, extra studies area unit required to completely perceive the scope of smart grid as it relates to solar photovoltaic power system.

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