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Analysis of Impact of Large Scale Photovoltaic Solar Systems on the Power Quality in Distribution Networks

A thesis submitted in partial fulfillment of the requirements for the degree of Master science of engineering

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Dedication

It's a wonderful feelings when I'm surrounded by my parents love, brothers riots, teachers memories and all my family, who granted me the best encouragement to survive, and success.

To my parents
To my family
To my friends

Mathhar A. Bdour

Acknowledgment

It has been mine good fortune to have the advice and guidance of mine talented instructor Dr.Mohammad Al-Zoubi whose knowledge and skills have enhanced this thesis in many ways.

I also would like to thank all doctors and engineers who helped me to reach this thesis.

Mathhar A. Bdour

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Abstract

Renewable energy resources became one of the important energy sources in the recent years because of many constraints associated with fossil fuel. Solar energy industry is now one of the leading industries in the world.

In this work solar photovoltaic systems are employed to produce large scale power by connecting it to the Medium Voltage distribution network. As an impact of this connection, the harmonic spectrum was studied. The harmonic voltage and harmonic currents were studied in two cases, before and after connecting the large scale PV. The presence of PV has significantly increased the level of harmonics. The obtained values were compared with the standard ones and the deviation was calculated. The impact of solar radiation and temperature variation on the obtained harmonic level was also assessed. In addition to the standard harmonic measurement, the present worked has evaluated the level of interharmonics in all studied cases. The main source of harmonic in the PV system was the inverter and other nonlinear electronic equipment. The presence

of odd harmonics such as the 5^{th}, 7^{th}, 11^{th} and 13^{th} are related to the presence of six-pulse and twelve -pulse rectifiers. The analysis was done by using MATLAB/Simulink to build the model of PV-grid connection. The LabVIEW software was used to analyze the voltage and current waveforms. The capacity of the used PV system was 150kW connected to a distribution feeder with a total load of approximately 750 kW.

Keywords: Photovoltaic solar system (PV), Pulse Width Modulation Inverter (PWM), Harmonic compensation, Total Harmonic Distortion (THD), Interharmonics, Voltage Source Converter control (VSC).

CHAPTER I

Introduction

1.1 Theoretical back ground.

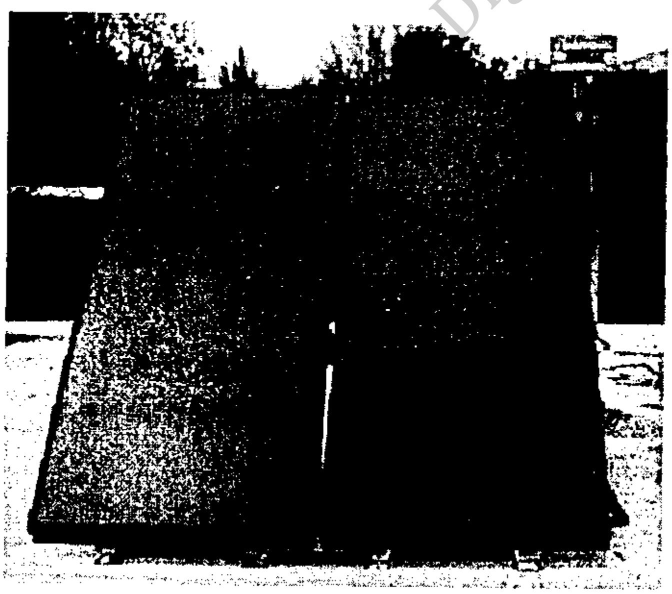
In general, energy exists in several forms including mechanical, electrical, potential, kinetic, thermal, magnetic, nuclear, radiation and others. Despite this variety of energy forms, fossil fuels were always the main sources of the world energy. However, with increasing energy demand and depending basically on fuel to provide customers with electricity, fuel cost was always exposed to uncontrolled increase. Simultaneously, there was a growing concern about environmental issues such as pollution and global warming associated with burning such fuels. Even if these hurdles were being overcome, the world's reserves of coal, as an example, which is the most abundant fossil fuel sources is approximately 150 years [2].

Although the nuclear energy was initially introduced as a promising alternative to the conventional sources, it is now unaccepted for most of the countries for safety reasons. Therefore, the energy sector in national and international scales was in a real challenge for tens of years. The question which needed a clear answer is how to secure a source of energy to be efficient safe, clean and cheap.

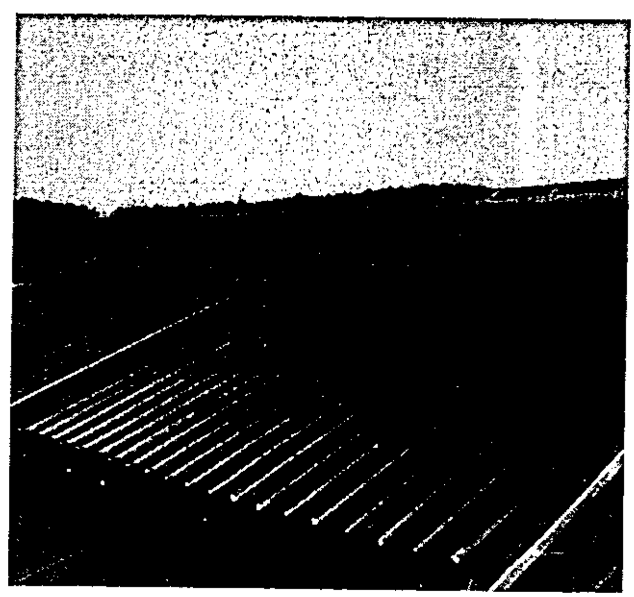
On the light of the above information, the only solution to energy dilemma was found in renewable energy sources which satisfy the majority of the above requirements. Renewable energy resources are environmentally friendly, safe and inexhaustible with time. Although, most of renewable resources have the above features, solar energy has found a wider acceptance in many countries [1, 3].

The exploitation of solar energy was going in two tracks, direct and indirect. To generate energy by direct method there is a group of techniques like solar thermal power plants, solar collectors for water heating and photovoltaic solar cells for direct electricity generation. In solar thermal power plants, the electricity is generated in a similar way to that used for steam power plants by producing a high temperature steam [3]. However, solar thermal heating process can be utilized by converting radiation into heat using absorbers (solar collectors). This process depends on converting short wave solar radiations into heat and, therefore, it is sometimes called photo-thermal process [4].

The first solar water heater was patented by William J. Bailey in California in 1909 [5].This industry was developed with the boom of oil prices in 1970. The production of solar collectors was augmented sharply with different forms like unglazed panels, flat plate collectors, flat plate air collectors, evacuated tube collectors; line focus collectors and point focus collectors as shown in Figure 1.1 [5].



a-Flat plate collectors



b- Evacuated tubes collectors

Figure 1.1 Two types of solar heating collectors

In addition to the absorbers, solar thermal system consists of several important components such as liquid or gaseous medium for heat transfer, pipes, heat exchangers, sensors, pumps and controlling system [4].

1.2 Photovoltaic solar cells.

The term photovoltaic consists of two parts, photos and volts. These two terms are necessary to express the electromotive force that causes the motion of electrons, and generates electricity from sun light [5].

The main goal of photovoltaic is to achieve electrical energy from sun light. This idea is firstly launched by Becquerel who discovered the photo effect in 1839. However, the real exploitation of this idea started 100 years later by the beginning of semiconductor age. The first PV cell was produced in 1954 by Bell laboratories after Shockley had developed a model for the p–n junction. The efficiency of the first cells did not exceed 5 % [3].

The development of these cells did not stop until reaching higher efficiencies. Meanwhile, the silicon still the main material in producing these cells although other materials were introduced to achieve higher efficiencies or lower costs [3]. Figure 1.2 shows one of the modern solar cells constructions [6].

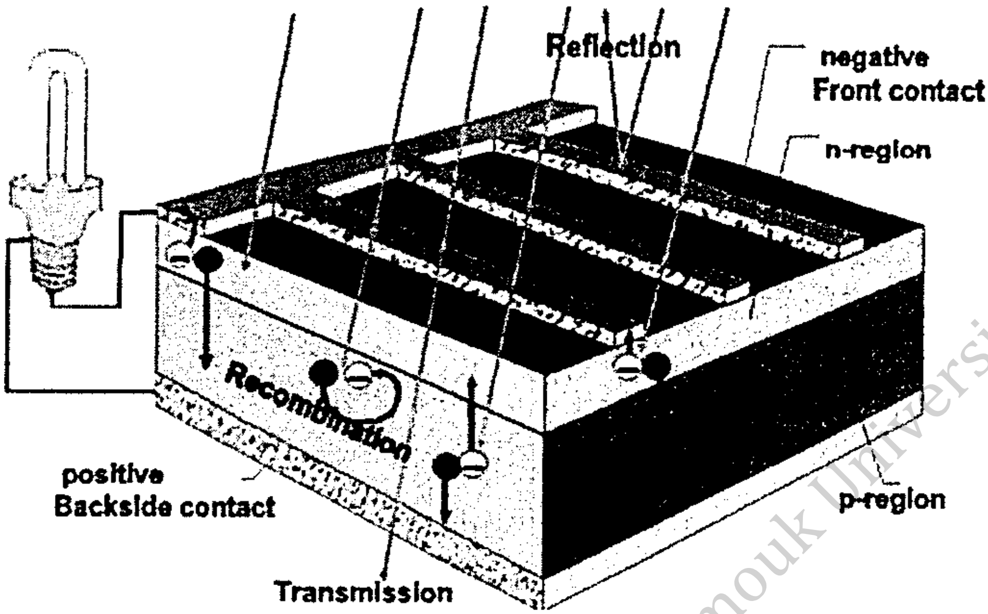


Figure 1.2 solar cell construction.

In order to understand the principle of operation of semiconductor and then the energy band model for solids, it is better to start with Bohr's atomic model which gives the electron mass m_e as [3]:

$$m_e = 9.1 * 10^{-31}\,Kg$$

Electrons rotate around the atomic nucleus at orbit with a radius of r_n and angular frequency ω_n showing a centrifugal force F_z as illustrated in equation 1.1 [3]:

$$F_z = m_e * r_n * \omega_n^2 \qquad (1.1)$$

Where:

r_n : *Orbit n radius.*

ω_n: *Angular frequency.*

The attractive force, F_c, which holds the electron around the nucleus, is [3]:

$$F_c = \frac{1}{4\pi\varepsilon_0} * \frac{Z * e^2}{r_n^2} \quad (1.2)$$

Where:

$e = 1.6 * 10^{-19}\, As$ *elementary charge of an electron*

$\varepsilon_0 = 8.85 * 10^{-12} \frac{A\, s}{V\, m}$ *permitivity or dielectric constant*

Where Z is the number of positively charged protons.

The balance between Coulomb and centrifugal force keeps the electron in its orbit. Referring to Planck's theorem, electrons remains in its orbits if the orbital angular momentum is an integer of [3].

$$H = \frac{h}{2\pi} \quad (1.3)$$

Where:

$h = 6.626 * 10^{-34}\, Js$ *Planck's Constant*

Now due to the quantization of the orbital angular momentum we get [3]:

$$n * H = m_e * \omega_n * r_n^2 \quad (1.4)$$

Using the previous expression and solving for $F_Z = F_C$(in case of balanced forces), the orbital radius is [3]:

$$r_n = \frac{n^2 * H^2 * 4\pi\varepsilon_0}{Z * e^2 * m_e} \quad (1.5)$$

Where Z is the number of positively charged protons.

Now the energy for electron at orbit n can be given by:

$$E_n = \frac{1}{2} * m_e * v_e^2 = \frac{1}{2} * m_e * r_n^2 * \omega_n^2 = \frac{1}{n^2} * \frac{Z^2 * e^4 * m_e}{32 * \pi^2 * \varepsilon_0^2 * H^2} \quad (1.6)$$

The photo effect

This means that in order to move an electron from an orbit to next higher orbit it requires an amount of energy equals the difference of energy between two orbits ($\Delta E = E_n - E_{n+1}$) and this energy is achieved by an outer source like light. The energy in light expressed in photons energy is given by [3]:

$$E = \frac{h * c}{\lambda} \quad (1.7)$$

Where:

λ : Wave length.

C: the speed of light ($3*10^8$ m/s)

This energy has the ability to separate electron from the nucleus which is called ionization energy. The total separated group of electrons causes the external photoelectric effect [3].

1.3 Principle of operation of solar cell

The material that can be exploited in photovoltaic systems is usually semiconductor one. The materials, which have four electrons in their outer shell called valence electrons are mainly silicon (Si), germanium (Ge), tin (Sn) or a combination between two elements [3].

The most used material is silicon which is widely available in nature but not as pure form. It has four valance electrons in its outer orbit and in order to be in balance configuration it shares other atoms by electron pair binding. In this case, the valance band becomes fully occupied and no conduction band exists. By receiving enough energy from incident light or heat, an electron is elevated from the valance band and freely moved in the crystal lattice leaving a hole in the valance band which is responsible for the so-called intrinsic conduction process of semiconductor. As much electrons arise as much holes appear. Figure 1.3 shows a simplified representation of this process [3].

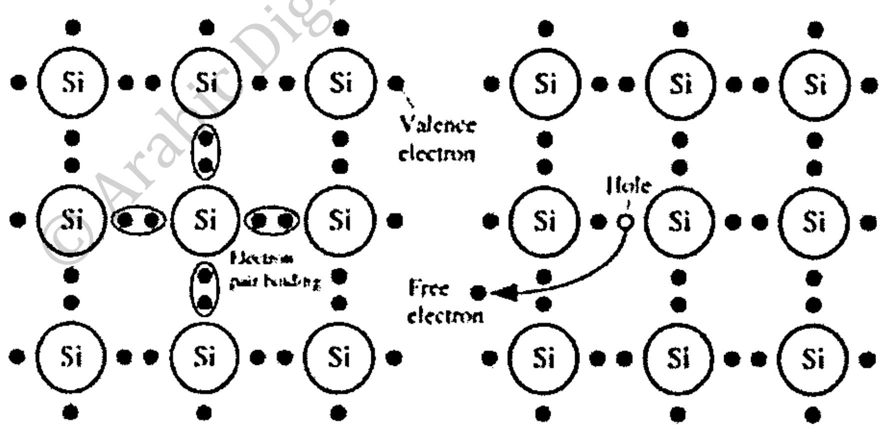


Figure 1.3 crystal structure of silicon intrinsic conduction due to defect electron in the crystal lattice

The intrinsic carrier density given by [3]:

$$n.p = n_i^2 = n_{i0}^2 * T^2 * \exp\left(-\frac{E_g}{K * T}\right) \tag{1.8}$$

Where:

n : electron density.

P: hole density.

T : temperature.

E_g: band gap.

K : Boltzmann constant ($1.38 * 10^{-23} J/K$)

$n_{i0} = 4.62 * 10^{15} cm^{-3} K^{-3/2}$

It is worth noting that at absolute temperature zero (T= 0K = -273.15°C) there are no free electrons and so do holes. When applying external voltage to the silicon crystal, electrons moves to the anode if the applied voltage is negatively charged. Electrons will move as a current to holes and the holes move in the opposite direction. This mobility is expressed as follows [3]:

$$\mu_n = \mu_{0n} * \left(\frac{T}{T_0}\right)^{-\frac{3}{2}} \tag{1.9}$$

$$\mu_p = \mu_{0p} * \left(\frac{T}{T_0}\right)^{-\frac{3}{2}} \tag{1.10}$$

Where:

μ_n and μ_p are electrons and holes mobility respectively

$$\mu_{0n} = 1350\ cm^2/V\ s$$

$$\mu_{0p} = 480\ cm^2/V\ s$$

$$T_0 = 300\ K$$

The electrical conductivity of the semiconductor is the sum of electron and hole currents:

$$k = \frac{1}{\rho} = e * (n * \mu_n + p * \mu_p) = e * n_i * (\mu_n + \mu_p) \quad (1.11)$$

For electricity generation, it is worth considering the extrinsic or defect conduction. In this case the embedding atoms from group V in the periodic table (like phosphorus (p)) which has five valance electrons with silicon having four valance electrons will result in a free electron. This electron will not participate in electron pair binding and it is easy to be separated using small amount of energy. This process is called n-doping. Embedding atoms from group III (like boron (B) and aluminum (Al)) have three valance electrons with silicon creating one missing electron in the valance orbit which is called p-doping process. This process is shown in Figure 1.4 [3].

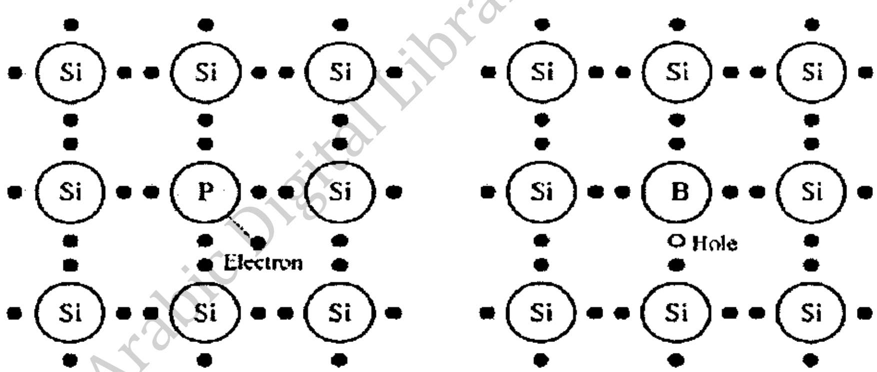


Figure 1.4 Defect conduction for n- type and p- type doped silicon.

Placing p-type in contact with n-type produces a p-n junction, in which electrons will diffuse from n- region into p- region and holes in vice versa process. This leads to an electric field between two regions operating against charge carriers and stopping the diffusion continuity till infinity. This causes a diffusion voltage between two regions [3].

Because, solar cell depends on converting part of photon energy into electrical current, when photon energy is less than band gap energy, electrons will not move from valance band to conduction band. However, this doesn't mean that all photons near to band gap energy are converted to electricity. Some photons are reflected from the surface of the cell and the rest go back to the holes before arriving conducting band as shown in figure 1.5. In general, solar cell uses energies equal to band gap from high energy photons with low wavelengths.

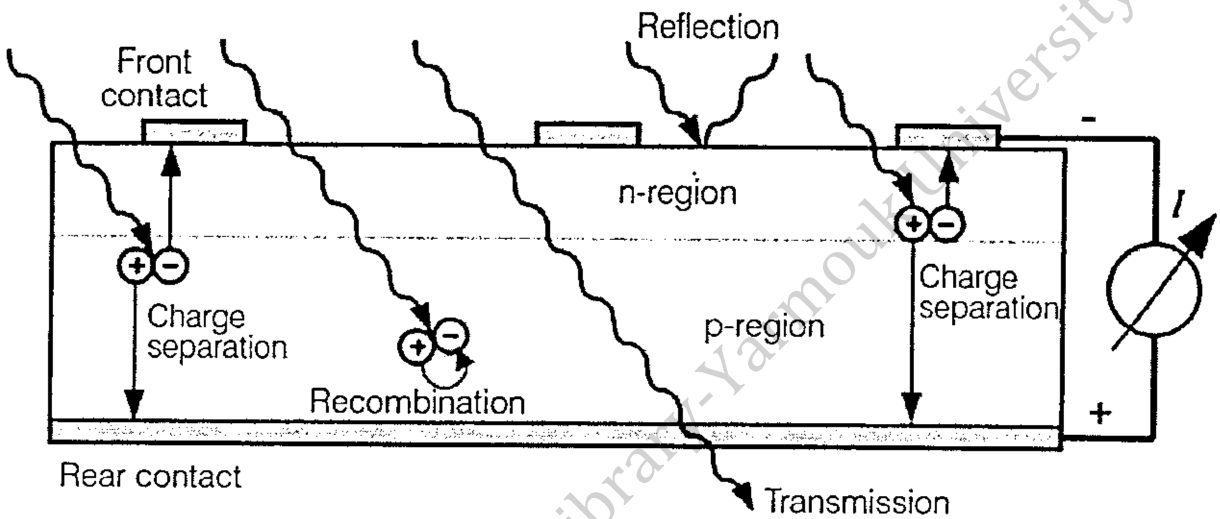


Figure 1.5 Processes in an Irradiated Solar Cell.

Electrically, short circuiting solar cell leads to the presence of photocurrent (I_{ph}), which can be calculated as follows [3]:

$$I_{ph} = \int S(\lambda) * E(\lambda) * A * d\lambda \quad (1.12)$$

Where:

$S(\lambda)$: Spectral response as a function of wave length.

$E(\lambda)$: Irradiance absorbed by the semiconductor.

A : Solar cell area.

Modeling of solar cell

Solar cell simply operates as a large area diode and the equivalent circuit of that cell can be described as shown in Figure 1.6 [3].

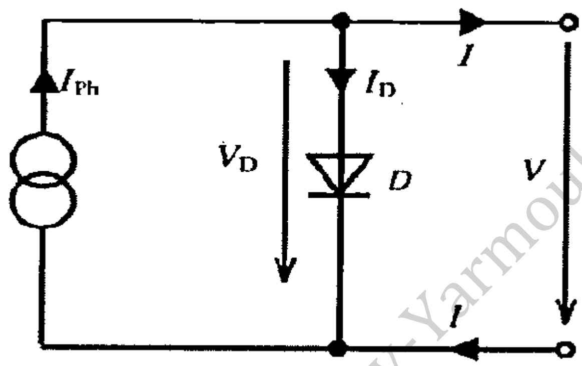


Figure 1.6 Simplified-equivalent circuit of ideal solar cell.

The cell current in case of non-irradiation (i.e. $I_{ph} = 0$) is given by the following equation [3]:

$$I = -I_D = -I_s * \left(\exp\left(\frac{V_D}{m * V_T}\right) - 1\right) \quad (1.13)$$

Where:

V_T: is the thermal voltage at temperature of 25°which is 25.7 mV

I_s: is the saturation current in order of 10^{-10} to 10^{-5} A.

m: diode factor (for an ideal diode it is 1)

V_D: Diode voltage.

This means that the photocurrent, generated by current source which is connected in parallel with the diode depends on irradiance in general ($I_{ph} = c_o E$). Figure 1.7 shows an extended equivalent circuit of a solar cell. Applying Kirchhoff's first law will result in a current–voltage (I-V) characteristic of the simple solar cell at different irradiances [3]:

$$I = I_{ph} - I_D = I_{ph} - I_s * \left(\exp\left(\frac{V_D}{m * V_T}\right) - 1\right) - \frac{V + IR_s}{R_p} \quad (1.14)$$

Where: R_s and R_p are series and parallel resistances which perform the practical model.

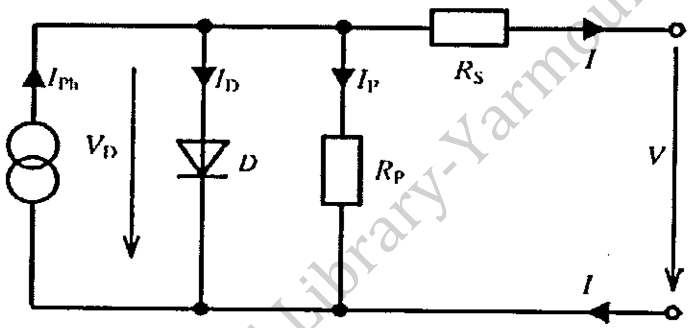


Figure 1.7 Extended Equivalent Circuit of a Solar Cell.

The solar cell characteristics are obtained by drawing the relationship between current and voltage at different solar radiation and temperature values. Figure 1.8 shows the I-V characteristics of a PV cell for several cases due to changing of temperature and irradiation. At zero voltage the short circuit current Is.c is obtained, whereas at zero current we get Vo.c (Open circuit voltage). Starting from Is.c, the curve is slightly decreased until reaching the knee point and then it is reduced to Vo.c very fast [4].

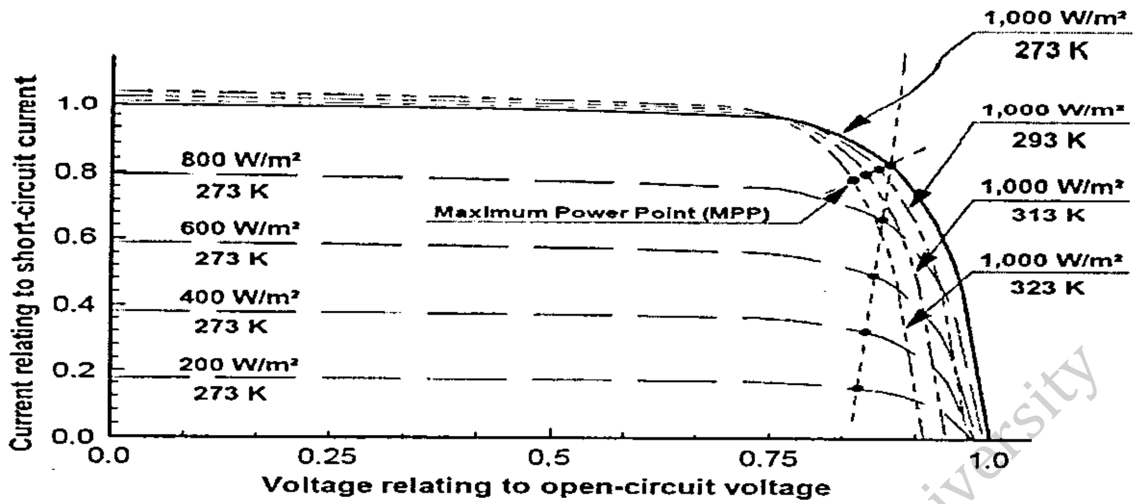


Figure 1.8 I-V characteristics of a PV cell for different temperatures and irradiation

Figure 1.8 shows the solar system components starting from the solar cell until the arrays [8].

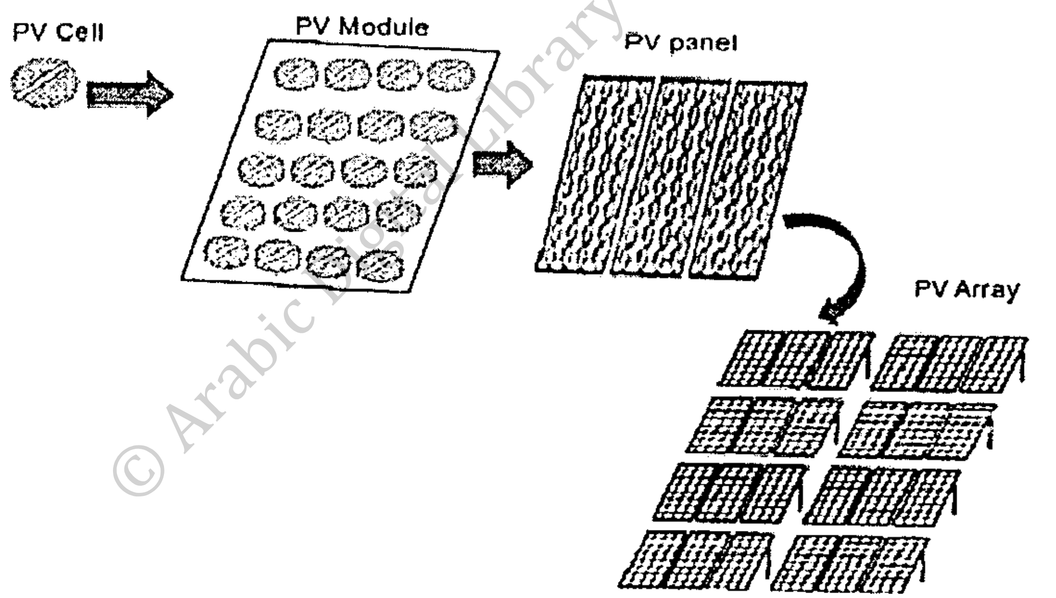


Figure 1.8 Solar cells family.

1.4 Photovoltaic generation system

Building PV system depends on group of cells connected in series or parallel to achieve a desired value of power. The basic unit of PV generation system is the module, which consists of several cells electrically interconnected in a frame including connection box, wires and other accessories. Sometimes frameless modules are applied [4].The nominal Vo.c of a model is obtained by connecting series of cells, whereas Is.c is reached by linking parallel cells. Finally, the rated power of module depends on the number of cells and, the typical PV modules are approximately between 50-75 w for 36 serial connected cells in 100m^2 areas [4]. Group of cells are connected in modules, and these modules are connected in arrays to obtain a specific generation capacity as shown in Figure 1.9.

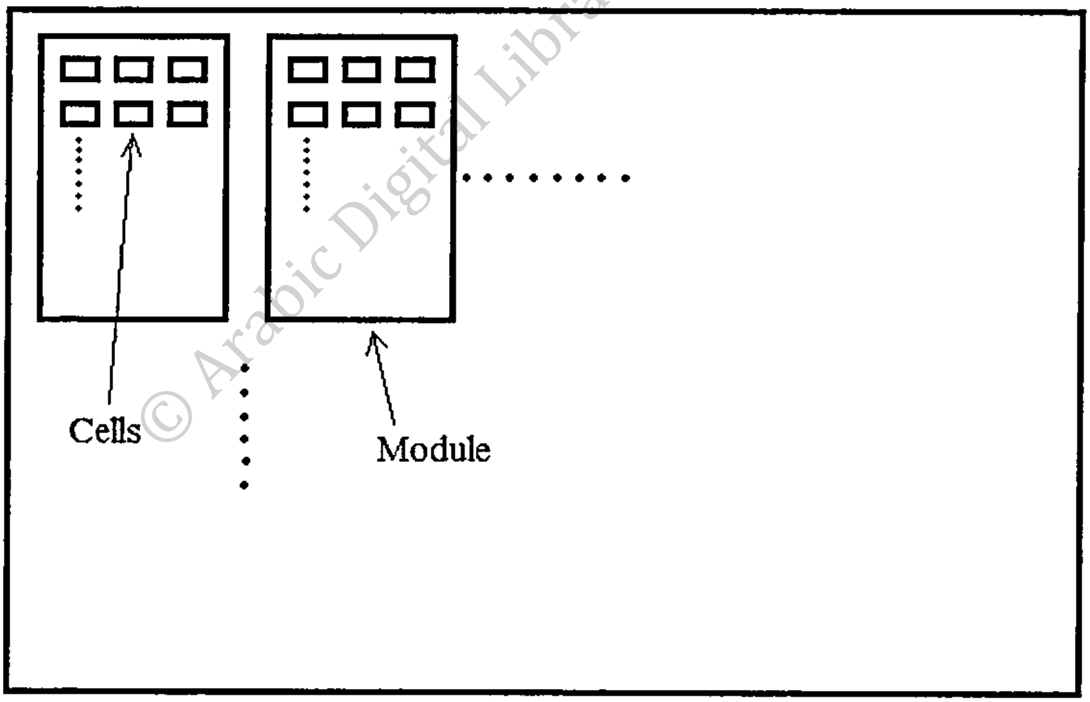


Figure 1.9 Connection of solar cells inside solar modules.

The connection of PV arrays to the system needs to be with a special substation designed to join the leads, controlling and monitoring, this substation facilities the solar energy transformation to the medium voltage network, it is designed to be enclosed with a suitable enclosure. Figure 1.10 shows an image of photovoltaic substation [8].

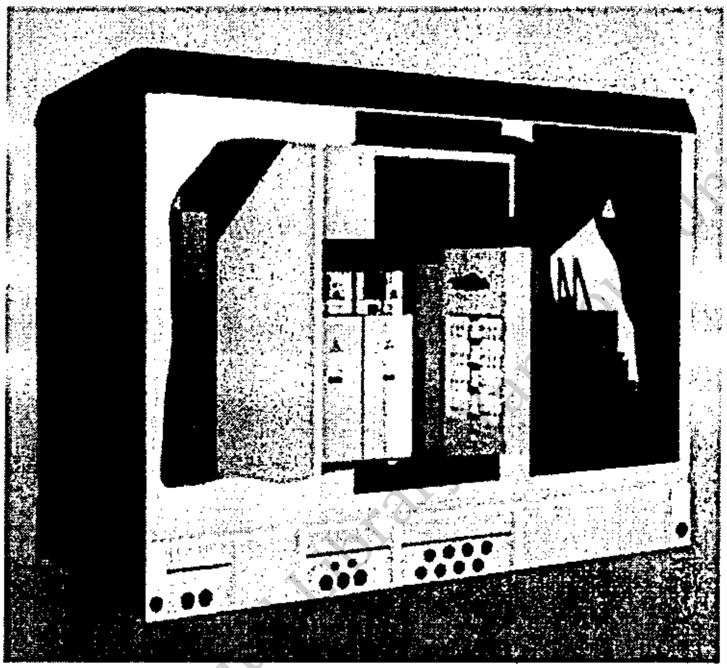


Figure 1.10 Photovoltaic substation

1.5 Grid connected PV generation system

In order to provide grid with solar power, an inverter is necessary to convert DC (direct current) generated power from PV into AC (alternating current). Unlike the stand-alone system inverters, grid connected inverters are directly connected to PV system without any storage units. Figure 1.11 shows a schematic diagram of a grid-connected PV-system [8].

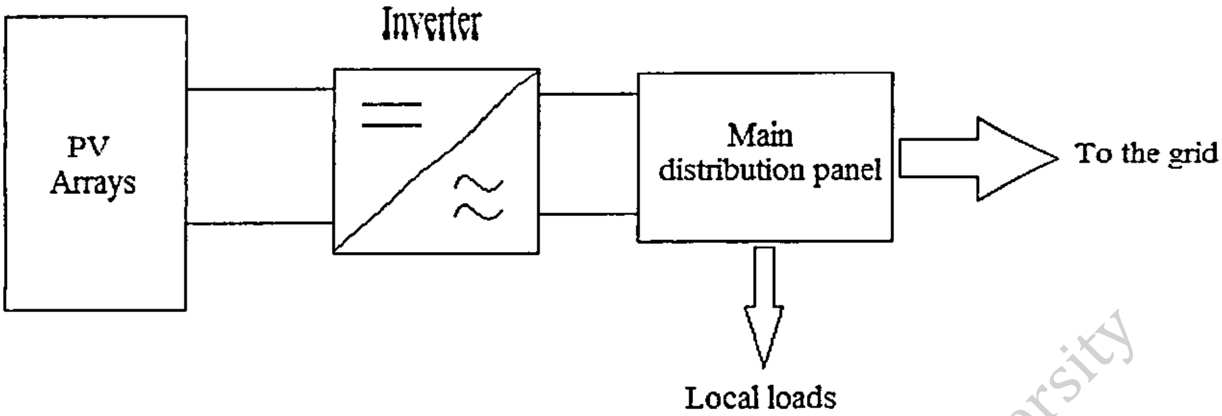


Figure 1.11 Grid connected PV-system without storage units

These inverters are generally designed with high efficient at rated power in a range of 10 kW up to several 100 kW. For large scale generation (MWs) group of inverters are used. These inverters should meet several requirements in order to gain reliable grid connection [4]:

1. The output voltage should be synchronized with grid.
2. The output voltage waveform should be sinusoidal as possible and distortion must not exceed a certain level.
3. The output current shouldn't include DC bias in order to prevent transformer pre-magnetizing and weakening in the function of earth leakage protection switches.
4. The supplied current and grid voltage should be in-phase to prevent additional losses from the oscillating of reactive power between grid and inverter.
5. Inverter should be able to disconnect on abnormal conditions like excessive main voltage, large deviation from operating frequency, short circuits and insulation errors.
6. Inverters may be provided with insulation and earth leakage protections for both sides.
7. Ripple controlling signals integrated in the grid which is provided by generation companies shouldn't be affected by inverter operation.

8. The entry side of the inverter should be compatible with generation units by using maximum power point tracking point.
9. Voltage ripple shouldn't exceed 3% for single phase inverters.

Photovoltaic arrays are installed to be either fixed or movable. Currently, tracking systems are used to harvest the highest energy by concentrating the arrays to follow the changes in sun's position during the day. The installation system should be exactly adapted to meet the site conditions. The stationary system is usually oriented to the south and the optimal inclination is commonly determined by the latitude of the desired position [4].

Figure 1.12 shows a simplified diagram for the photovoltaic switch-gear system with the required connections including the inverter, medium voltage coupling point, circuit breakers and transformer [8].

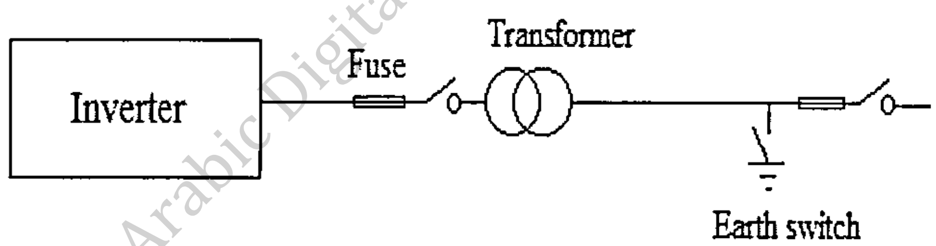


Figure 1.12 Simplified diagram of PV switch-gear system

1.6 Power Quality definition

Power quality can be defined as "Any power problem manifested in voltage, current, or frequency deviations that result in failure or miss operation of customer equipment" [7].

Power quality becomes one of the important topics in power industry since 1980. It includes a group of disturbances in power system and the engineers focus on this topic as a system approach, not as individual problems. The current concern in power quality problems is increasing for the following reasons. Firstly, the requirements for sensitivity of microprocessor-based controllers and power electronic devices in generation and load equipment are increased. Secondly, the concern in power system efficiency, which leads to the use of equipment such as high efficient adjustable speed motors and power factor correction capacitor banks, is also increased. Thirdly, the awareness in power quality problems among utilities customers becomes a noticeable phenomenon these days. Finally, the interconnected networks lead to integrated processes, which mean that any failure in equipment may produce severe consequences [7]. Despite the rich knowledge gained about power quality, it is something difficult to quantify it but in general the real measurement of power quality can be determined by the performance of the end user equipment [7].

1.7 Power quality classification

For categorizing power quality phenomenon, measurements should be classified to describe such problems. Table 1.1 provides information for typical spectral contents, duration and magnitude [7].

Table 1.1 Categories and Characteristics of Power System Electromagnetic Phenomena

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5-ns rise	<50 ns	
1.1.2 Microsecond	1-μs rise	50 ns–1 ms	
1.1.3 Millisecond	0.1-ms rise	>1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	<5 kHz	0.3–50 ms	0–4 pu
1.2.2 Medium frequency	5–500 kHz	20 μs	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 μs	0–4 pu
2.0 Short-duration variations			
2.1 Instantaneous			
2.1.1 Interruption		0.5–30 cycles	<0.1 pu
2.1.2 Sag (dip)		0.5–30 cycles	0.1–0.9 pu
2.1.3 Swell		0.5–30 cycles	1.1–1.8 pu
2.2 Momentary			
2.2.1 Interruption		30 cycles–3 s	<0.1 pu
2.2.2 Sag (dip)		30 cycles–3 s	0.1–0.9 pu
2.2.3 Swell		30 cycles–3 s	1.1–1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s–1 min	<0.1 pu
2.3.2 Sag (dip)		3 s–1 min	0.1–0.9 pu
2.3.3 Swell		3 s–1 min	1.1–1.2 pu

3.0 Long-duration variations 3.1 Interruption, sustained 3.2 Undervoltages 3.3 Overvoltages		 >1 min >1 min >1 min	 0.0 pu 0.8–0.9 pu 1.1–1.2 pu
4.0 Voltage unbalance		Steady state	0.5–2%
5.0 Waveform distortion 5.1 DC offset 5.2 Harmonics 5.3 Interharmonics 5.4 Notching 5.5 Noise	 0–100th harmonic 0–6 kHz Broadband	 Steady state Steady state Steady state Steady state Steady state	 0–0.1% 0–20% 0–2% 0–1%
6.0 Voltage fluctuations	<25 Hz	Intermittent	0.1–7% / 0.2–2 Pst
7.0 Power frequency variations		 <10 s	

1.7.1 Transients

Transients are included in the AC waveform as a sharp discontinues period which last for less than one cycle. It happens individually at each AC cycle, i.e. there is no relation between transients in different cycles. There are different names for the transients such as spikes, bumps, power pulses impulses and surges [9].

In general, transients can be classified into two main categories [7]:

a) Impulsive transients

Impulsive transient can be defined as a sudden non power frequency change in voltage or current or both. In case of steady state conditions, which is unidirectional (could be positive or negative); it is described by rise and decay times. For example, 1.2*50 μs/2000 means that this transient needs 1.2μs to reach the maximum value (2000) from zero, and 50 μs for decaying from peak to half peak value. Figure 1.13 shows an example of such phenomenon [7].

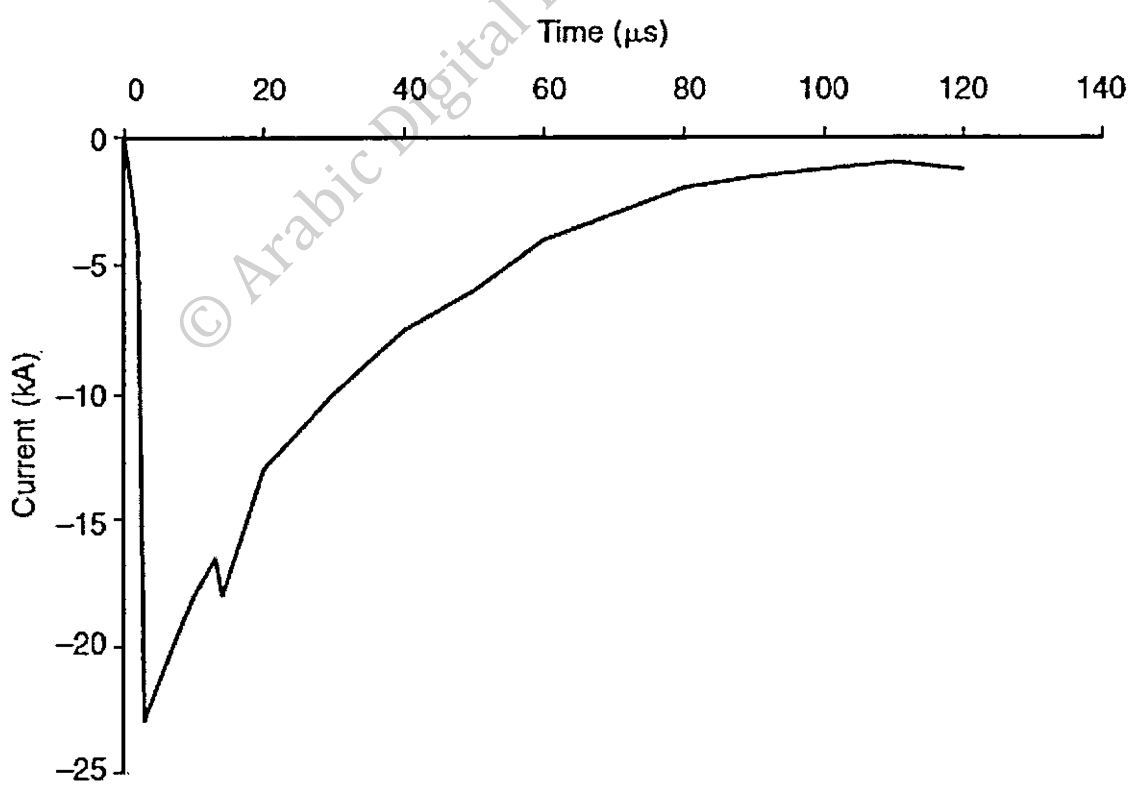


Figure 1.13 Lightning stroke current impulsive transient.

b) Oscillatory transient

Oscillatory transient can be defined as a sudden non power frequency change in voltage or current or both, and in case of steady state conditions, it includes both positive and negative polarities. The changing in polarity of the voltage or current happens so fast. This oscillation is usually resulted from the system response to the impulsive transient. When the primary frequency is more than 500 kHz it is assumed as a high frequency transient, and when it is between 5-500 kHz it is assumed as a medium frequency transient [7]. Oscillatory transients can be produced from energizing back to back capacitors, cable switching. Figure 1.14 shows a shape of oscillatory transients [7].

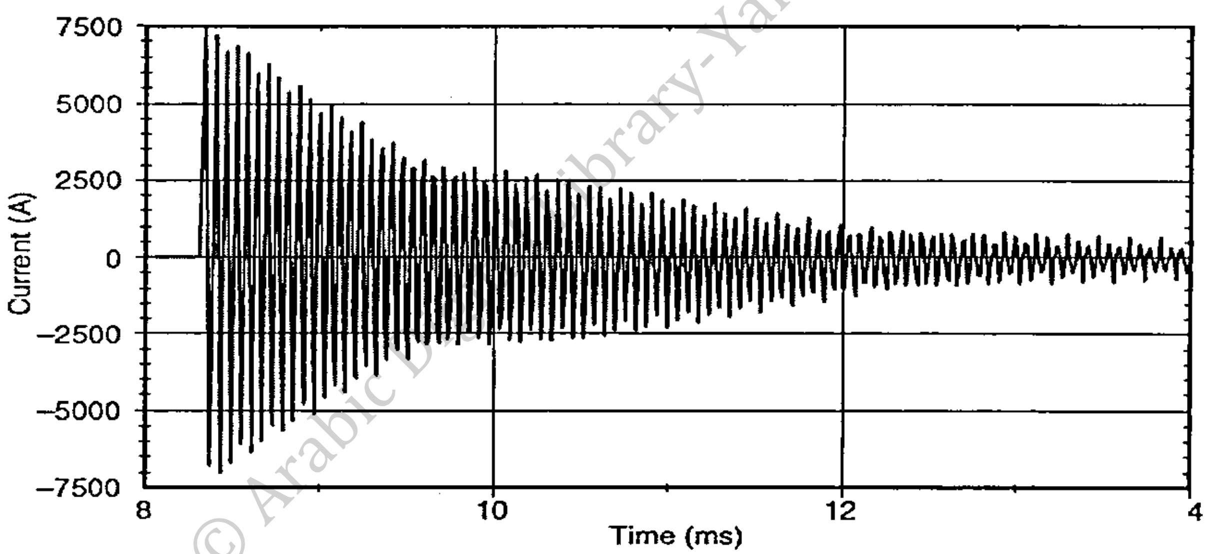


Figure 1.14 Oscillatory transient current caused by back-to-back capacitor switching.

1.7.2 Long-Duration Voltage Variations

It is the variation of root mean square value at power frequency for longer than 1 min. It can appear as the following [7]:

a) Over voltage

Over voltage is an increase in the rms value for more than 110% and for duration longer than 1 min. It can be caused by wrong tap settings in transformers or because the system is too weak for the desired voltage regulations.

b) Under Voltage

Under voltage can be defined as a decrease in rms voltage for less than 90% and for a period of time more than 1 minute. It can be as a result of overloaded systems or switching operation of large loads.

c) Sustained interruptions

Sustained interruption is losing supply voltage for a period of time more than 1 minute. This kind of interruption is usually permanent and needs human intervention for repairing system.

1.7.3 Short-Duration Voltage Variations

When a very fast conditions happens on the system like faults, energization of large loads, or losing connection intermediately due to poor wiring, voltage will vary for a small period of time until protection equipment operate. This change appears as the following events [7].

a) ***Interruption:*** Interruption can be defined as a decreasing in the supply voltage less than 0.1 p.u for a period of time not exceeding 1 minute. In fault cases, the protection devices operation time determines the interruption period.

b) ***Sags (dips):*** Voltage sag generally can be defined as a voltage collapsing to a value between 0.1 and 0.9 p.u and for duration of time from 0.5 cycles to 1 minute [7]. Voltage sag is a result of starting large loads such as electrical motors and arc furnaces. As an example, induction motors starts with a current value varies between 600 and 800% of their rated current, which causes voltage dips [9].

c) ***Swells:*** Voltage swell can be defined as an increasing in rms voltage or current for a period of time between 0.5 cycle and 1 minute, with a magnitude varies from 1.1 to 1.8 p.u in the rms value. One of swells reasons is single line to ground fault which causes healthy phases voltage to raise temporary. Also, switching of large loads can cause swells.

1.7.4 Voltage Imbalance

Voltage imbalance happens when there is a difference between three phase voltages or currents. It can be defined as the ratio of the maximum deviation from the average of three phase voltages or currents over the average three phase voltage or current. It can be caused by single phase loads on three phase system and blown fuses at one phase.

1.7.5 Waveform Distortion

Waveform distortion appears on the sinusoidal signal as a non-ideal shape of this signals at power frequency. It is characterized by the spectral contents of the deviation, and there are mainly five types of wave form distortion which are DC offset, harmonics, inter harmonics, notching and noise.

1.7.6 Harmonics

Harmonics can be defined as a sinusoidal voltage or currents with a frequencies defers from the fundamental voltage frequency. The values of these frequencies are multiples of the fundamental one.

The voltage and current waveforms are sinusoidal in shape, and they have the following expressions [9]:

$$v(t) = V\sin(\omega t) \quad (1.8)$$

$$i(t) = I\sin(\omega t \pm \emptyset) \quad (1.9)$$

Where

ω: is the angular frequency.

$\emptyset$: the phase angle.

The periodic non-pure sinusoidal signal can be expressed in the Fourier expression as the following [9]:

$$v(t) = V_0 + V_1\sin(\omega t) + V_2\sin(2\omega t) + V_3\sin(3\omega t) + \cdots + V_n\sin(n\omega t) + \cdots + V_{n+1}\sin((n+1)\omega t) \quad (1.15)$$

V_0 indicates the DC component of the waveform and V_1, V_2, V_3,..., V_n are the peak values of the other terms in the expression in which the fundamental and other frequencies appear. The first harmonic order (or the fundamental frequency) and other frequencies appear with frequencies as shown in the Table 1.2 [9]:

Table 1.2 Harmonics frequencies

Harmonic order	Frequency
1 (Fundamental)	f
2	$2 * f$
3	$3 * f$
n	$n * f$

Figure 1.15 shows a distorted signal due to the influence of the third harmonic.

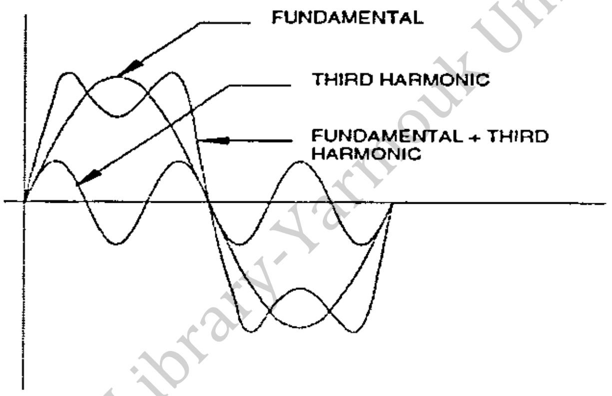


Figure 1.15 Non-linear wave form resulted from the addition of the third harmonic.

The pure sinusoidal signal is not practically found in the power system, because the generated signal itself has a small distortion level due to the excitation magnetic field and the distribution of the stator coils in the slots are not exactly uniform. Moreover, the generated voltage is delivered to the end user after passing more than voltage level through transformers and transmission lines. The user equipment include a non-linear loads that cause a distortion in the current signal, which in turn leads to a distorted voltage waveform on the terminals of the load. It is worth noting that the largest source for the harmonics is the adjustable speed drives. Also, the operation of Uninterrupted Power Sources (UPS) can cause a distortion in the voltage signal due to the inverter operation which converts the signal from DC to AC.

Harmonic contents can be expressed by Individual Harmonic Distortion (IHD) and Total Harmonic Distortion (THD). The IHD can be defined as the ratio between the root mean square (RMS) values of any harmonic order to the fundamental one. The THD is used to express the deviation of the non-linear waveform from the pure sinusoidal waveform. The THD voltage is expressed as follows [9]:

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1} * 100\% \qquad (1.16)$$

The application of power electronic devices spreads widely. More than 70% of used equipment are power electronics, which urges the manufactures to design them to produce less distorted current. The improvements appear on several devices like fluorescent lamp ballast, adjustable speed drives, battery chargers, uninterruptable power supplies and others. However, convertors generate significant values of harmonics according to the following equation [9]:

$$n = kq \pm 1 \qquad (1.17)$$

Where:

n : The harmonic order.

k : Positive integer.

q : Pulse number of the power conversion equipment.

As an example, the harmonics associated with six-pulse power convertor are the 5^{th}, 7^{th}, 11^{th}, 13^{th} and so on.

CHAPTER 2

Literature Survey

2.1 Introduction

The first paper that discussed the photo effect was by the French physicist Edmond Becquerel in 1839, in which he found that when silver plates are exposed to the sun light the voltage will increase on the terminals of the 'wet cell' that he made his experiments on [5].

In 1877, two Cambridge-scientists (W.G. Adams and R.E. Day) discussed and studied the electrical properties of selenium when exposing it to the light. After six years, a selenium solar cell was constructed by Charles Edgar Fritts. It was approximately similar to current silicon solar cells. The basic construction of the selenium cell was from a thin wafer of selenium covered by a grid of gold wires and protective sheet of glass. The percentage of converted solar energy into electrical was less than 1% for these cells [5].

High efficient solar cells were appeared in 1950 at Bell Telephone Laboratories in New Jersey by a group of scientists, who conducted a research about the effect of light on semiconductors like germanium and silicon. Three years later, doped silicon slices were invented by Chapin Fuller Pearson to become more efficient than previous ones, then they published a paper on their research and their success in achieving 6% efficient solar cells. In that period, the solar cells were used in small applications like powering rural telephone amplifiers and small radio transmitter [5].

Then the researches were continued to develop and improve such cells passing through several stages. The focus was about cells efficiency, used materials and concentrating light technologies. The industry of photovoltaic systems started to be employed in the last 10 years with a rate of growing more than 40 percent. In 2007, the generated power from photovoltaic systems was more than 3.5 GW [10].

In 2001, Archer, Mary D. Hill Robert have provided "Clean Electricity from PV ". The first in a series of four in multi authorial works on the photovoltaic conversion of solar energy. The discussion was about the construction, design and materials of solar cells. Then they discussed the storage system [11].

Roger A.Messenger and Jerry Ventre discussed the stand alone PV systems and utility interactive PV Systems, the advantages of using such source on customers and utilities from economical and technical point of views. The standards about Voltage disturbances, harmonic distortion, frequency disturbances, injection of DC into AC systems and power factor are also mentioned [12].

In 2006, Florentin Batrinu, Gianfranco Chicco, Jurgen Schlabbach and Filippo Spertino discussed in their paper "Impacts of grid-connected photovoltaic plant operation on the harmonic distortion". Some aspects are related to harmonic distortion found in PV plants which have been increased recently due to several improvements in these plants. The power quality term when talking about this generation type performance depends on several factors like inverter structure, external conditions such as solar irradiance and temperature, type and amount of load and characteristics of the supply system. The analysis in this paper concentrates on the performance of PV generation at a specific connection and the evaluation of time variation of individual harmonics [13].

In 2007 PrajnaParamita Dash and Amirnaser Yazdani have built a mathematical model and performance evaluation for a single stage grid connected photovoltaic system in order to improve the grid connecting operation by controlling strategies like inner current controlled loop and an outer DC-link voltage control loop. The idea of Voltage Source Converter (VSC) control is applied in the model built here [14].

The idea of using suitable simulator to study photovoltaic generation systems and connecting them with the grid was employed by I. H. Altas1 and A.M. Sharaf [15]. In their paper "A Photovoltaic Array Simulation Model for Matlab-Simulink GUI Environment", they used the equations of solar cell which are included in their mathematical model and in building other components from inverter to load. Then, this model was implemented in the studied interconnected system [15].

In the research entitled "Characterization and Assessment of the Harmonic Emission of Grid-Connected Photovoltaic Systems, 2007", which was published by Gianfranco Chicco, Jürgen Schlabbach and Filippo Spertino, several results were presented related to measurements on LV PV generation stations. From these results, it was found that the total harmonic distortion increases with low levels of generation in response for different irradiations intensities. They also discussed the description of the converters connecting the PV systems to the grid [16].

The predicted performance of grid connected PV systems and the actual behavior was discussed by Jayanta Deb Mondola, Yigzaw G. Yohanis and Brian Norton in their paper "Comparison of measured and predicted long term performance of grid a connected photovoltaic system, 2007". They calculate the beam and diffuse components of global and horizontal insolation using a developed model provided with beam and diffuse corrections. The obtained results were compared with the practical data and they were so close. They also used the simulation tool for performing detailed analysis of systems with real operating conditions, discussing the variation of different loads and their impact, sizing and cost issues [17].

For modeling the detailed components of PV system,N. Hamrouni and A. Chérif presented a paper entitled "Modeling and control of a grid connected photovoltaic system" in 2007. In this paper, they represented the main components of PV system, boost converter and the grid side inverter. They also discussed the possibility of a better controlling in order to achieve the maximum amount of generation. In this work, they use Matlab/Simulink in order to build such model. The power quality control was also presented in this paper [18].

PV generation system is affected by its inclination and installing angles. This topic was discussed by Jayanta Deb et al, who showed the impact of surface orientation on the performance of grid connected PV generation systems in maritime climates. They also presented the impact on insolation, PV output, system and inverter efficiencies and performance ratio at different angles of inclination. They found the maximum and minimum output of PV generation [19].

The generalized model for PV module was simulated in order to achieve its characteristics for voltage, current and power due to the variation of temperature and insolation. This subject was published by Huan-Liang Tsai, Ci-Siang Tu, and Yi-Jie Su, in 2008 [20]. The influence of the power contribution of a grid-connected photovoltaic system and its operational particularities were also discussed. The relationship between a grid connected PV system and the normal operation of the distribution grid were highlighted. This paper has focused on the influence of power quality parameters (total harmonic distortion and power factor) and the RMS voltage. The analysis, depending on the experimental results, was used in distributed generators in the domestic area [21].

As a distributed generation source, PV has its own characteristics which differ from other sources as power electronics devices are used to connect these systems to the grid. PV system includes step up the output DC voltage level by boost converters and then uses inverters. In addition, other power electronic devices are used to improve the power quality of the transmitted power like Active Power Filter. G. M. S. Azevedo et al. discussed a new topology for PV generation systems integrating current harmonic compensation by using two inverters. The first one were with a feedback loop to compensate the low order harmonics, and the second one with a feed forward loop for compensating high order harmonics [22].

For reliable and safe grid connection process, inverters technology is the most important point in order to provide high quality power to AC utility system with suitable cost. The current technologies were able to develop high switching inverters to provide high power factor and low harmonic distortion by working on semiconductor devices used in PWM inverters. Inverters do not degrade the quality of the supply, but the poor quality of the supply will be added to the system through the inverter. This topic was thoroughly discussed in "Renewable and Sustainable Energy Reviews" [23].

In 2007, the total power supplied by PV modules reached 3.4 GW around the world which makes it significant to study such industrial issues. Therefore, the research works in the last 30 years were about improving PV efficiencies.

CHAPTER 3

System Model and Data Preparation

3.1 Introduction

This chapter introduces a part of distribution feeder in Jordanian network which consists of Thevenin equivalent generation at the beginning of the feeder, transformers, transmission lines; several load types and other components. This section is modeled by using MATLAB/Simulink software which is also used to connect a Photovoltaic generation unit with boost and inverting devices. All needed components were built in order to analyze simulation results, additional software is used to study precisely harmonic contents in voltage and current wave forms. This software is called LabVIEW package, developed by National Instruments Company [25].

3.2 Problem Overview

This study concentrates on investigating harmonic distortion, which is caused by connecting large scale PV generation system with the medium voltage network. Then, the effect of temperature and irradiation variation on total harmonic distortion in current and voltage wave forms will be studied.

Jordan, as one of non-oil producing countries, suffers from increasing energy demands and high fuel costs. However, the deficiency in energy can be compensated by promoting reliable solutions such as PV systems, which can be efficiently exploited in Jordan [31]. However, introducing such solution will be accompanied by some problems related to power quality. Jordan receives more than 5.2 kWh/m^2/day, which makes the solar energy a reliable source and worth investigating one. Table 3.1 shows the average monthly solar radiation and temperature in Jordan – Amman [26].

Table 3.1 Average monthly global radiation ant temperature in Jordan - Amman

Month	Radiation (KWh/m^2/day)	Temperature (C^o)
January	2.856	7.9
February	3.72	9
March	4.512	11.8
April	5.616	15.9
May	6.648	20.5
June	7.368	23.5
July	7.296	25
August	6.816	25.5
September	5.808	23.5
October	4.656	20.5
November	3.432	15
December	2.688	9.9

3.3 Methodology

This work was started with building a large scale PV generation model on Simulink to provide a power up to 150 kVA at maximum power point. The next step was to build radial power system chosen from a real distribution network from Irbid District Electrical Company- Jordan (IDECO). After that, the jointing process has been made using PWM inverter. In this system, the

PV model operates as a distributed generation feeding the network with electrical supply. The main components that included in this model are:

1- Current network configuration without connecting the PV system and its normal harmonic distortion.
2- The existing loads taking into consideration nonlinear ones.
3- Transmission lines and transformers impedances in addition to generation part which is modeled by 132kV generator with step down transformer.
4- Boost chopper followed by controlled inverter.
5- Photovoltaic generation unit with a suitable interface to enter temperature value, insolation and PV module parameters.
6- Measuring and monitoring system for voltage and power values.

The first step in this process is to know the harmonic contents in current by monitoring the THD on the current system at the supply point. Then, it was necessary to connect PV system through an inverter and determine the influence of such system on the current THD. The aim is not restricting the analysis on one harmonic value, but to study the effect of radiation and temperature variations on different THD values. This approach provides a better predicting for THD value during daily and seasonally variations..

3.4 MATLAB/SIMULINK software

MATLAB is one of the high-level technical computing languages that have an interactive environment for algorithm development, data visualization, analysis, and numeric computation. MATLAB can be used in several applications like signal and image processing, communications, control design, test and measurement, financial modeling and analysis, and computational biology [24]. In addition, it has the ability for documenting and sharing, in addition to integrate codes with other languages and applications. The main features it has are [25]:

- High-level language for technical computing
- Development environment for managing code, files, and data
- Interactive tools for iterative exploration, design, and problem solving
- Mathematical functions for linear algebra, statistics, Fourier analysis, filtering, optimization, and numerical integration
- 2-D and 3-D graphics functions for visualizing data
- Tools for building custom graphical user interfaces
- Functions for integrating MATLAB based algorithms with external applications and languages, such as C, C++, FORTRAN, Java, COM, and Microsoft Excel.

Concentrating on Simulink part, this software has the ability to model, simulate, and analyze dynamic systems by posing questions about a system and then modeling it. With Simulink, it is possible to build models from scratch, or modify existing models to meet several needs. In addition, Simulink supports linear and nonlinear systems, modeled in continuous time, sampled time, or both.

3.5 LabVIEW

LabVIEW programming uses the concepts from other programming languages such as C++ and Java, including class structure, encapsulation, and inheritance. These concepts can be used to create a code that is easier to maintain and modify without affecting other sections of code within the application. Also, it is easy to create user defined data types [25]. Most LabVIEW applications run on a general-purpose operating system (OS) like Windows. Some applications require real-time performance that general-purpose operating systems cannot guarantee [25].

By using LabVIEW, Harmonic analysis interface is built to give brief results about voltage and current harmonic contents, total harmonic distortion and inter harmonics depending on wave forms taken from Simulink results. The user interface is shown in Figure 3.1 [25].

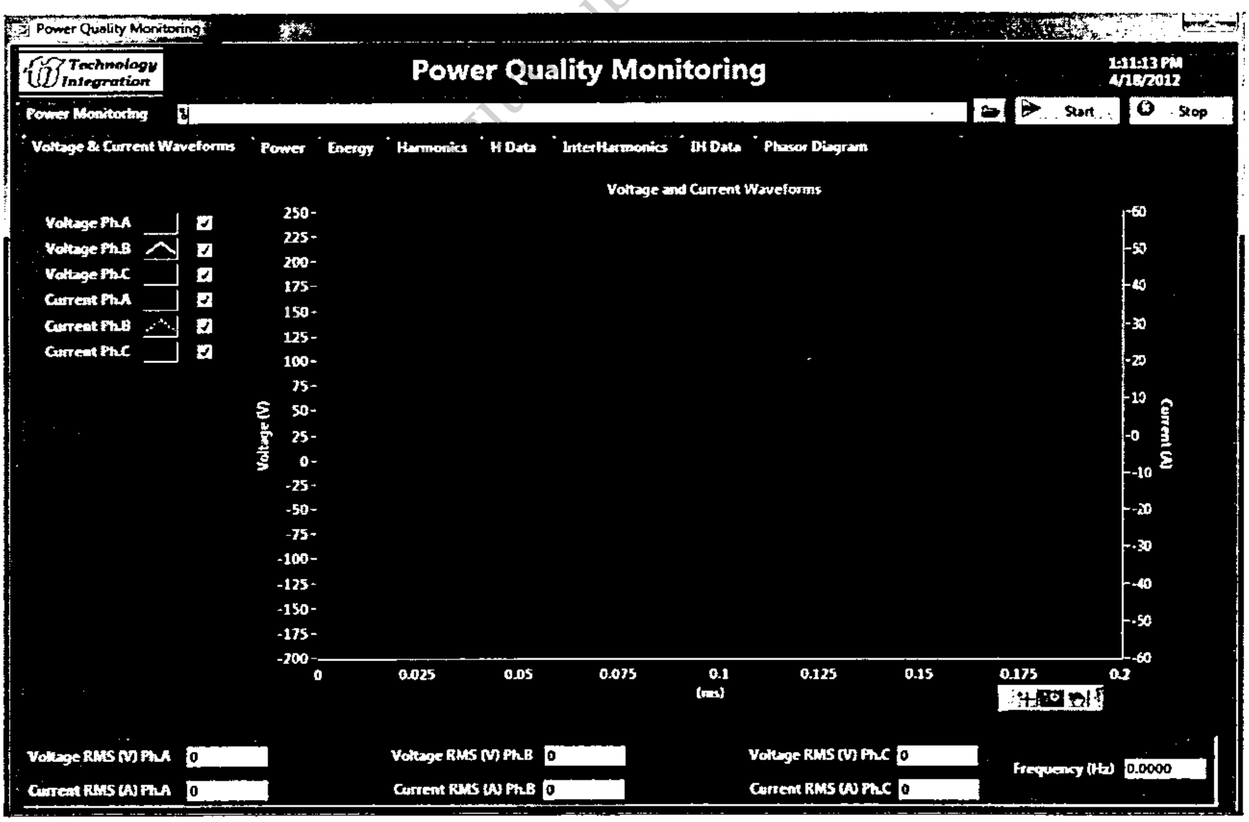


Figure 3.1Lab View interface

3.6 The data used in building model

The data used in modeling the radial power system were obtained from (IDECO) [27].The main components to operate such system were transformers, medium voltage transmission lines and loads. In addition to that, harmonic load sources were presented by nonlinear loads with rectifying devices. The system is modeled as shown in Figure 3.2 [27].

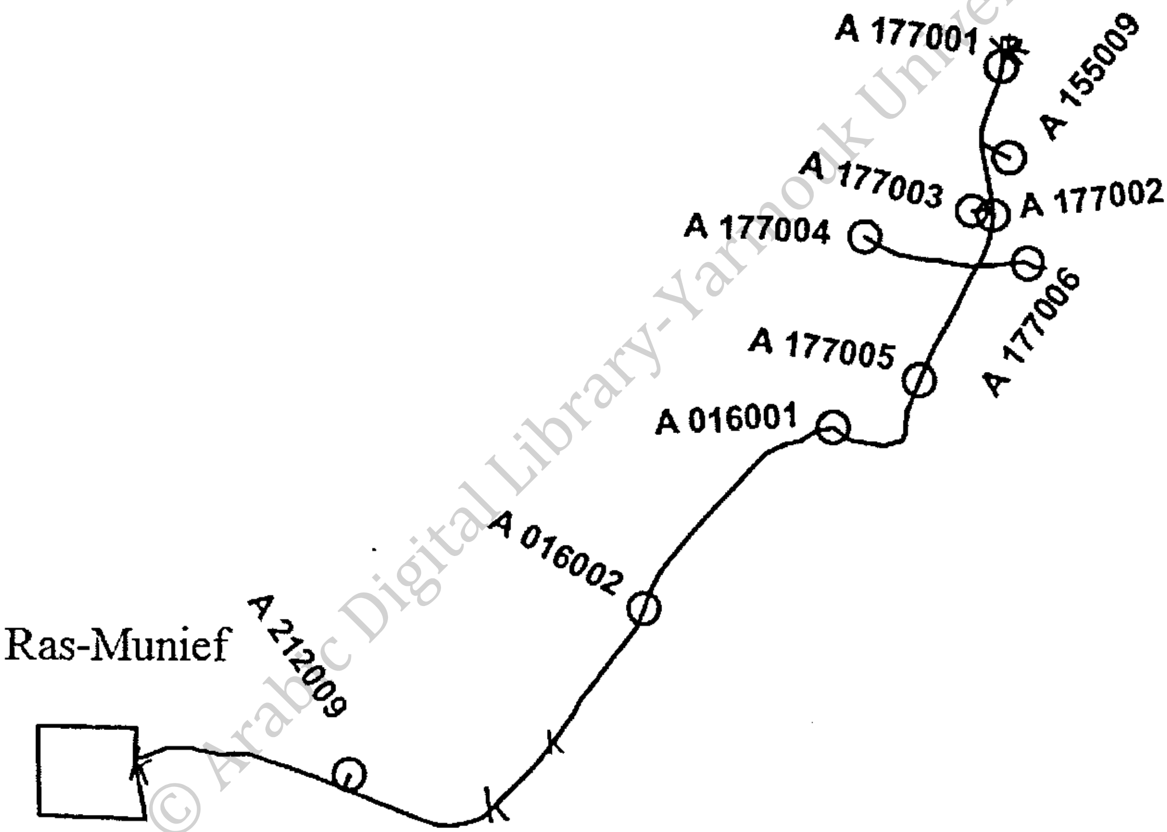


Figure 3.2 the single line diagram of the distribution section

3.6.1 Transmission lines data

The data for medium voltage lines parameters and nominal voltages are shown in Table 3.2 and the section names are illustrated in Figure 3.3 [27].

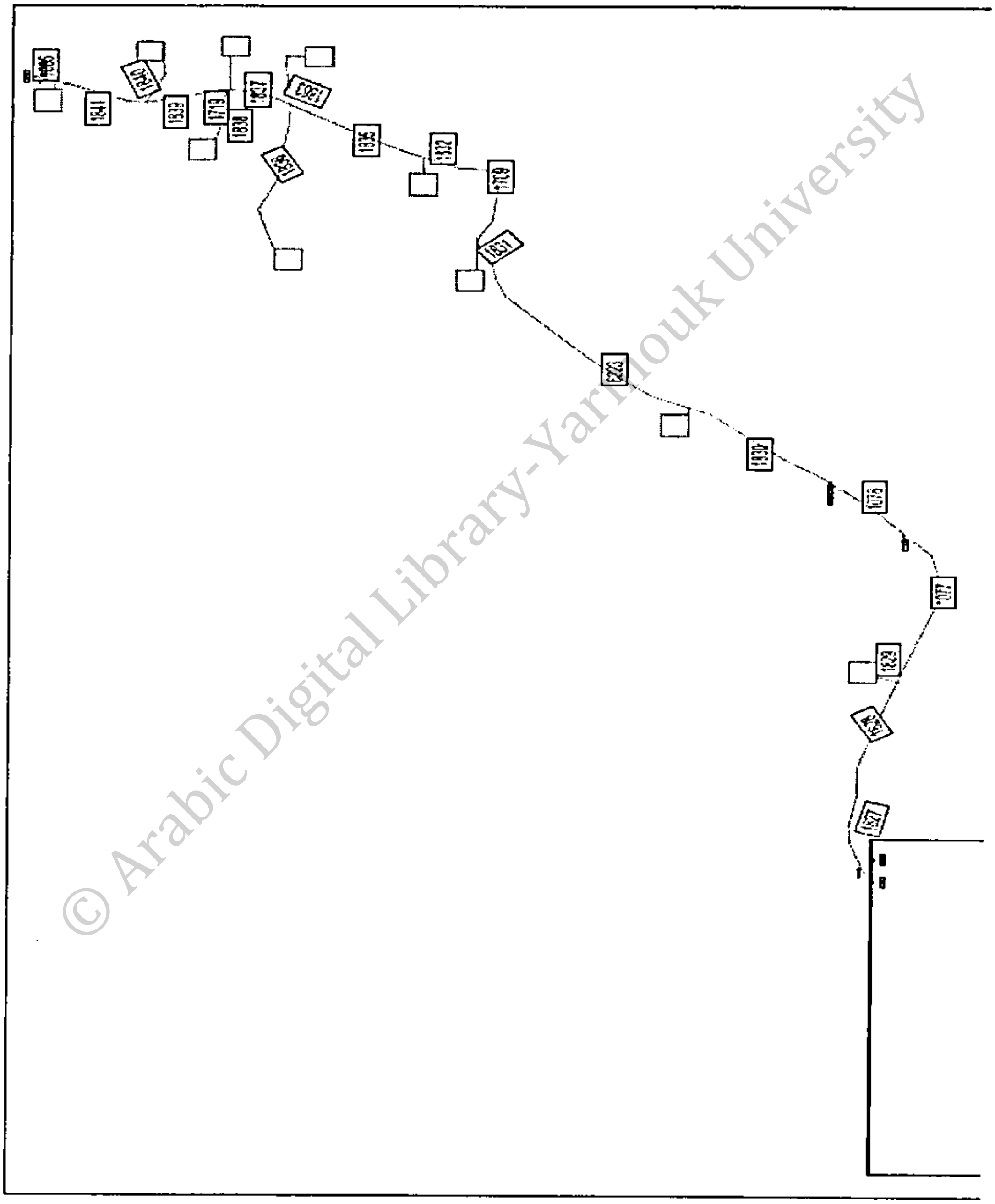


Figure 3.3 Line sections names

Table 3.2 line sections parameters [27].

Line Name	*Nominal Voltage (kV)*	*Length L(m)*	*Resistance R (Ohm)*	*Reactance X_L (Ohm)*
1827	33	324	0.074	0.118
1828	33	600.4	0.136	0.22
1829	33	59.9	0.014	0.022
1077+1078+1830	33	1687.3	0383	0.616
6223	33	969.3	0.22	0.354
1831	33	144.9	0.048	0.055
1709	33	427.6	0.142	0.163
1832	33	129	0.029	0.047
1835	33	524.8	0.119	0.192
1836	33	485.7	0.161	0.186
1863	33	208.5	0.047	0.076
1837	33	218.6	0.05	0.08
1838	33	58.3	0.019	0.022
1839	33	301.2	0.068	0.11
1840	33	130.7	0.03	0.048
1841	33	327.8	0.074	0.12

3.6.2 Transformers Data

The data for Transformers parameters and nominal voltages are shown in Table 3.3 [27]:

Table 3.3 Transformers parameters

Transformer Name	*Rated KVA*	*Rated voltage (kV)*	*Z_1 (%)*	*X1 R1 Ratio*
A_016002_T	250	33/0.4	6	4.39
A_177004_T	400	33/0.4	6	4.22
A_177003_T	1000	33/0.4	6	7.94
A_155009_T	400	33/0.4	6	4.22
A_177001_T	100	33/0.4	4.5	3.31
A_177002_T	250	33/0.4	6	4.39
A_177006_T	250	33/0.4	6	4.39
A_177005_T	250	33/0.4	6	4.39
A_016001_T	50	33/0.4	6	3.31
A_212009_T	250	33/0.4	6	4.39

3.6.3 Load Data

The data for load values in kVA, also their power factor are shown in table 3.4 [27]:

Table 3.4 Load data

Load Name	*Aver. PF*	*Total KVAR*	*Total kW*	*Total kVA*
A_016002_T	83	55	83	99
A_177004_T	82	96	137	167
A_177003_T	88	41	77	87
A_155009_T	58	179	128	220
A_177001_T	73	39	41	57
A_177002_T	79	63	81	103
A_177006_T	100	0	9	9
A_177005_T	74	50	55	74
A_016001_T	62	115	91	147
A_212009_T	95	15	45	47

3.6.4 Solar Photovoltaic Module parameters

Solar module parameters are selected from Centro Solara Company and they are shown in table 3.5 in which the S520P36 Ultra module is used [29]:

Table 3.5 solar module parameters (S520p36 Ultra)

Module parameter	*Value*
Peak power Pmax	130 Wp
Daily output in summer (Germany)	520 Wh/d
System voltage	12
Voltage at peak power	17.8 V
Open circuit Voltage	21.7 V
Current at peak power	7.3 A
Short circuit current	8.18 A
Temperature coefficient (power) (ΔPmmp)	-0.45 %/k
Temperature coefficient (voltage) (ΔVoc)	-0.36 %/k
Temperature coefficient (current) (ΔPsc)	0.025 %/k
Number of cells	36
Cell dimension	156*156 mm
Dimension in mm	1500*680*40
Height including juncyion box	40 mm

The solar module characteristics that used in building the arrays are shown in Figure 3.4. The power supplied by the module depends on the value of the radiation. As the solar radiation decreases the generated power also decreases. This is because the current provided depends on the solar radiation as shown in chapter 1. The following Figure illustrates this situation.

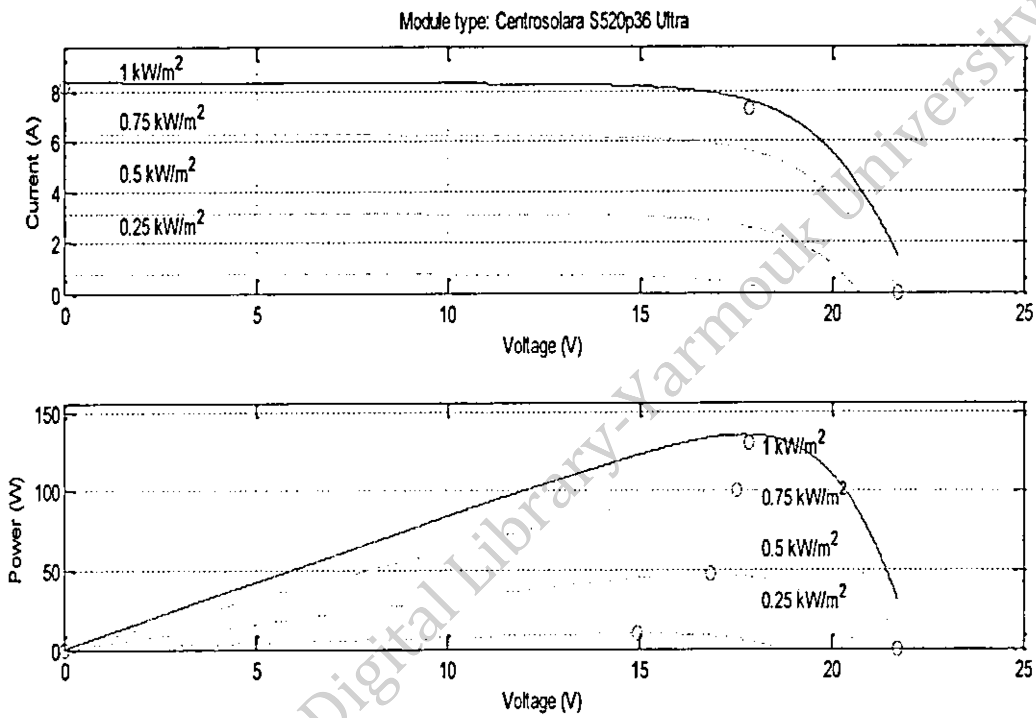


Figure 3.4 Solar module characteristics

CHAPTER 4

System Simulation and Results

4.1 Introduction

This chapter introduces a real model containing nonlinear loads that cause harmonic distortion. Initially, the results of this model will not include PV system and based on data collected. The results will then consider various cases of solar radiation and temperature. Finally, they will be compared with those obtained before connecting PV system to the grid.

MATLAB/Simulink program contains all components required for conducting such study including the PV generation system, boost and six-pulse inverter blocks [28], transformers, lines and loads [27,28].

The influence of harmonic distortion on current and voltage waveforms will be studied at several values of solar radiations and temperatures. The influence of such systems on distribution grid from power quality point view will also be discussed. This requires that power flow from PV arrays to the network will be shown as a part of the discussion about this generation systems.

The present thesis will focus on the solar PV system as a source of harmonics rather than considering harmonic effect caused by loads. It is expected that PV systems will add a new power quality effect on the distribution systems. If such influence is not clear now because of low penetration level of solar energy, it will be a significant factor in future when large scale PV systems are adopted. All sensitive devices in the distribution systems at points of common coupling with PV systems will suffer from this phenomenon. It is expected that the main source of harmonics during the operation of PV system will be the inverter. The harmonic composition in this case will be a function of its capability to convert the DC output of the solar panels into pure AC sine wave. Figure 4.1 shows the MATLAB/Simulink interface for solar module parameters.

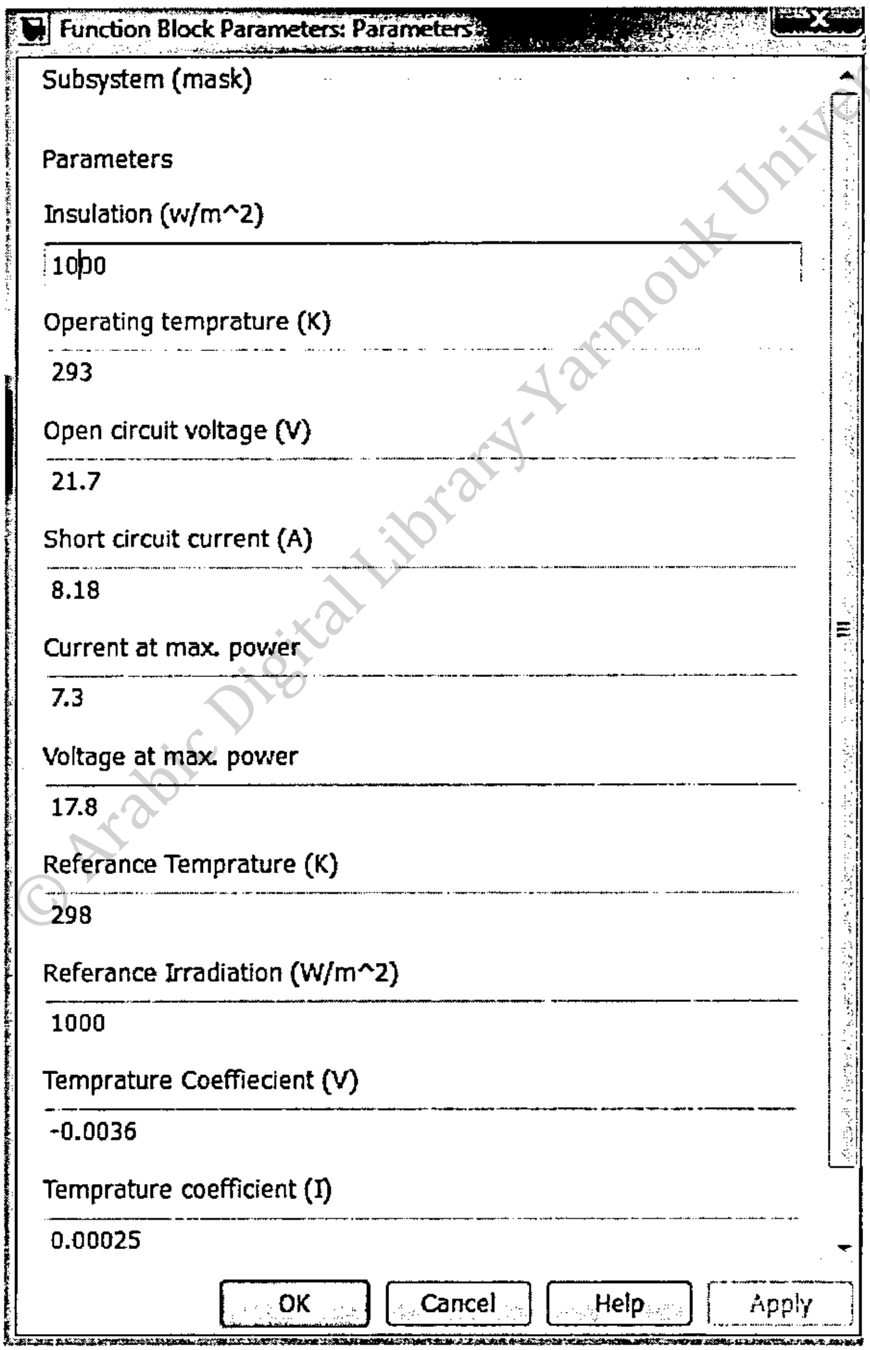
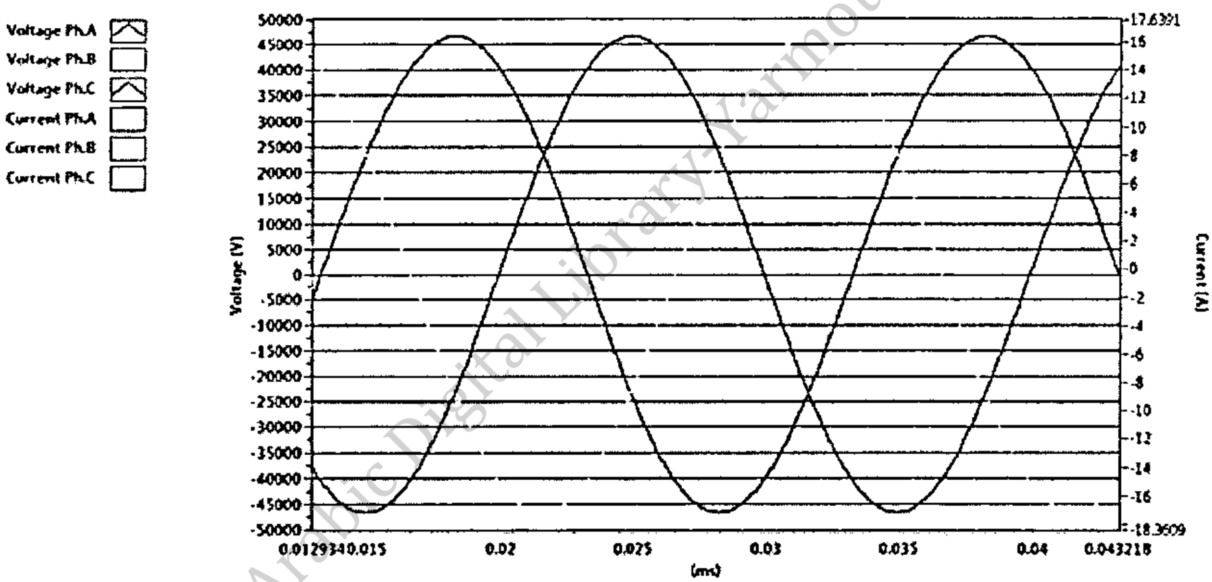


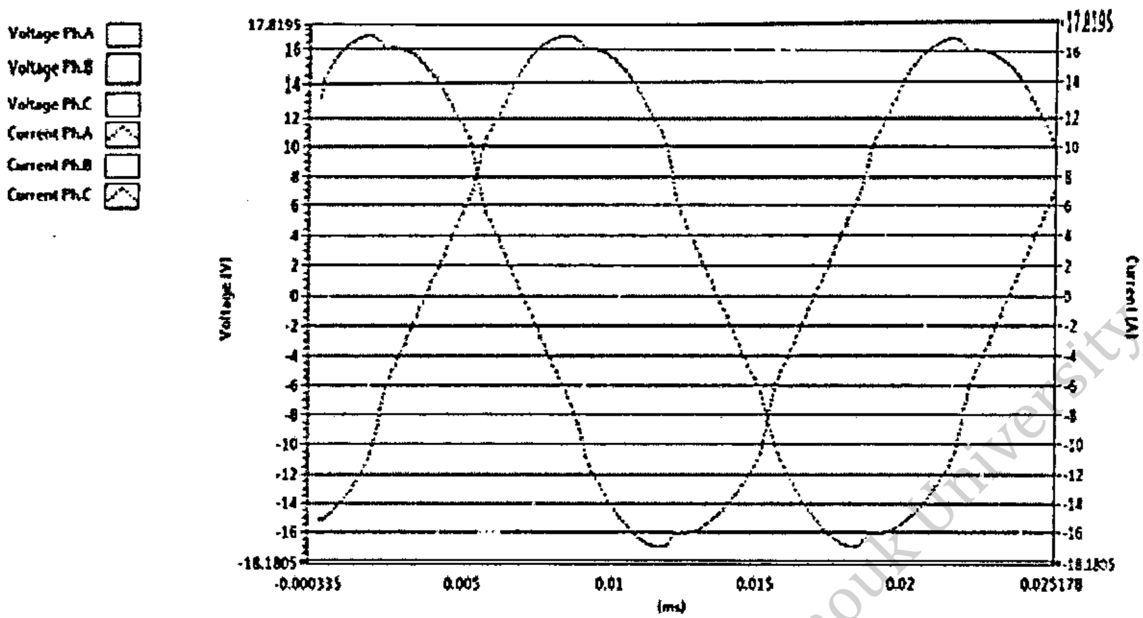
Figure 4.1 photovoltaic solar module parameters interface

4.2 The harmonic contents before connecting PV arrays

In order to get an idea about the harmonic spectrum before installing PV generators, the studied distribution system was simulated with its actual load under normal conditions as shown in Tables specified in Chapter 3. The measuring point was selected to be at the beginning of the line, directly after the power source. The simulation results have shown the waveforms of the three phase voltages and currents in addition to the harmonic contents. Figure 4.2 illustrates these results.



a. Voltage



b. Current

Figure 4.2 Currents and voltages waveforms for normal operation of the system at the source point.

It is clear from the graph that the current has a non-pure sinusoidal waveform which indicates to the existence of nonlinear loads. Figure 4.3 shows the phasor diagram of three phase voltages and currents.

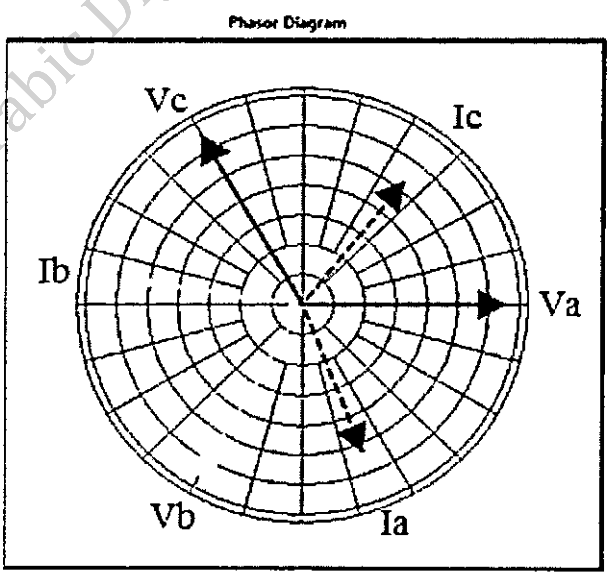


Figure 4.3 Phasor diagram for 3-phase voltage and current.

The harmonic contents up to the 50^{th} order were analyzed for each voltage and current and they are shown in Figure 4.4. (The analysis of harmonics will be on phase A only and other phases will have the same effect).

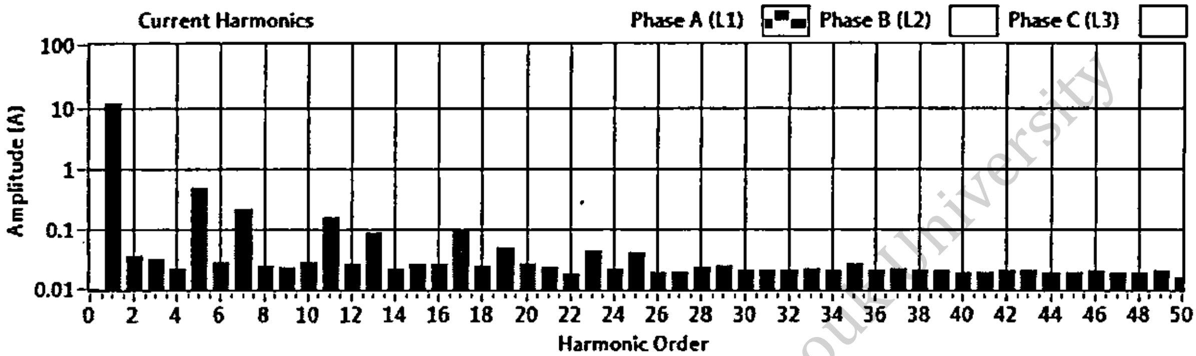


Figure 4.4 Currents harmonics

The total harmonic distortion was evaluated by LabVIEW software and found to be 4.7%. From figure 4.4, the significant harmonic values are the 5^{th}, 7^{th}, 11^{th}, and 13^{th} which are resulted from the operation of six-pulse load rectifiers. The small value of current denoted by harmonic I_0, represents the DC component in the current waveform. This is normal for such system compared with standard values [30].

The voltage waveform is distorted due to the flow of the distorted current to the load and the presence of inverter. However, the effect is less than that of the current. The results are shown in Figure 4.5.

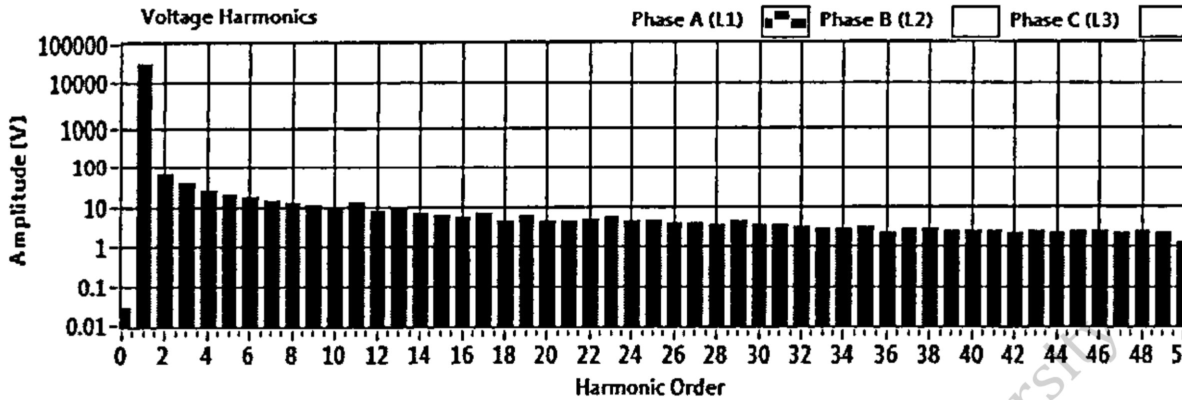


Figure 4.5 Voltage harmonics

The total harmonic distortion in each phase is approximately 0.58%, which explains the difficulty in recognizing such values in Figure 4.2. Therefore, the voltage waveform has appeared as if it is pure sinusoidal compared to that of the current waveform.

To get more precise analysis about harmonics, interharmonic are also taken in consideration while analyzing this system. Interharmonics, are non-integer multipliers of the fundamental wave as discussed in Chapter 1. The histogram of current interharmonics is shown in Figure 4.6 below.

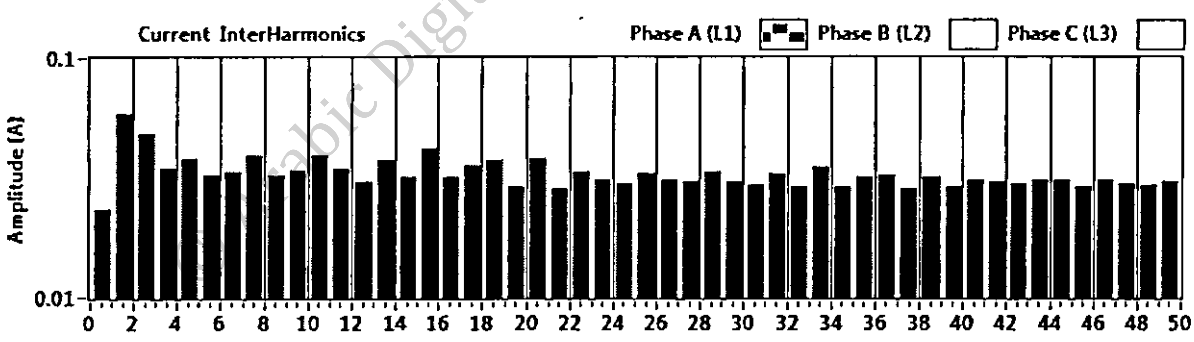


Figure 4.6 Currents interharmonics

It is worth noting that interharmonics have magnitudes less than 0.1A for such system. This low values have an orders 0.5, 1.5, 2.5, 3.5… as analyzed by LabVIEW. Figure 4.7 shows voltage interharmonics.

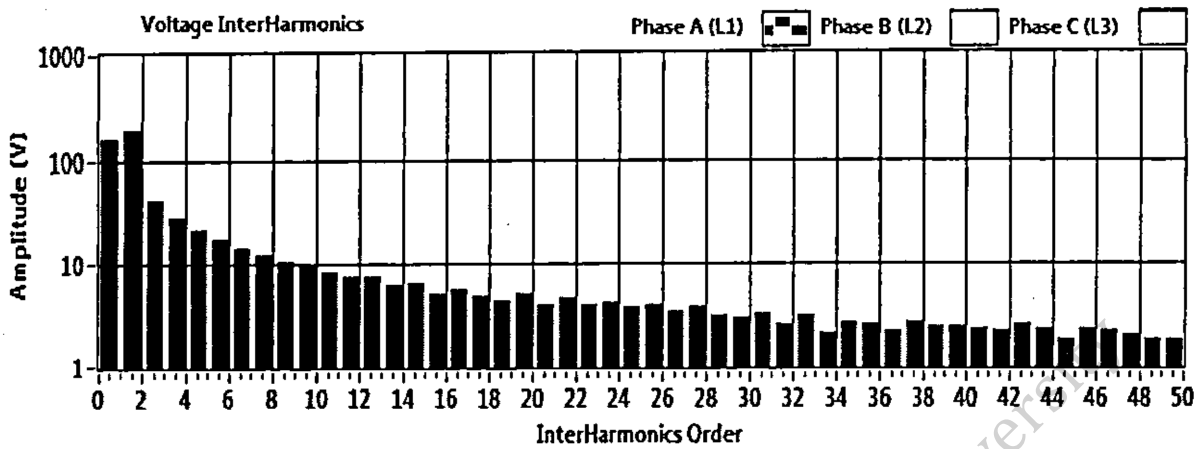


Figure 4.7 Voltage interharmonics.

It's appears from figure 4.7 that the 0.5 and 1.5 inter harmonic orders have the highest values and other decreases continually.

4.3 Harmonic contents after connecting the PV generation

After introducing the harmonic distortion at normal operation of the system, it is worth discussing the presence of harmonics in the studied system due to the integration of solar PV to the examined grid. Such connection will be via the inverter, the operation of which will be the dominant effect on the production of harmonics. This response is not difficult to predict if it is remembered that semiconductor devices are the main components of this inverter. Therefore, it is worth giving this PV system element more concentration and discussing it as a source of harmonic regardless of specific details and several types of it. The one employed in this thesis is a pulse width modulation (PWM) inverter with operating switching frequency of 5 kHz [28]. Step up chopper is also used before the inverter to provide rms voltage at the second side of the inverter. The voltage is then stepped up to 33kV using a step up transformer to match the distribution voltage connection point. Additionally, a Voltage Source Converter control (VSC) is used to achieve constant AC output value from the inverter with the variation of generation values and this improves the operation of such generation system by keeping the voltage level constant [28]. DC-DC boost converter, inverter and VSC control are assumed to operate as constant parameters in the simulation since this study will concentrate on the effect of the variation of irradiation and temperature on the power quality in general and harmonics in particular. Figure 4.8 shows the whole system.

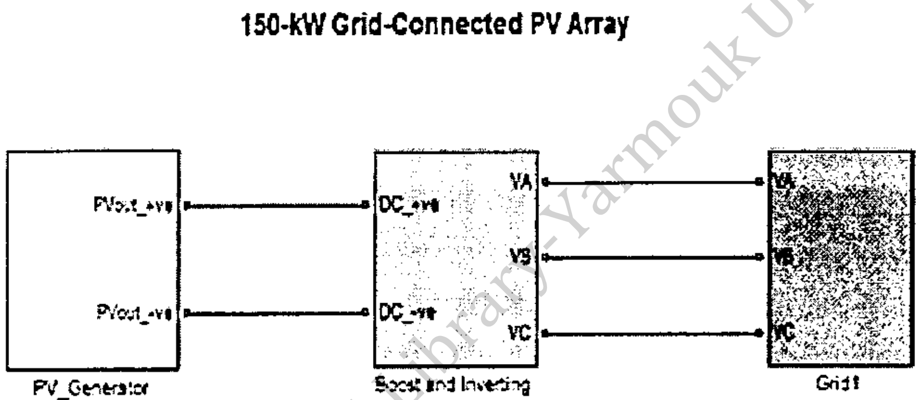


Figure 4.8 150-kW grid connected PV array

4.3.1 The effect of changing of solar radiation on the harmonics.

After connecting photovoltaic generation system to the grid, it will share with the existing distribution system a certain amount of power through the inverter. However, the operation of switching devices in inverting process from DC to AC system will cause a non-pure sinusoidal output signal delivered to the grid while providing power. The analysis process will start at a high value of insolation and then it will be decreased to a specific value in order to have a general view about the behavior of harmonic contents. Figure 4.9 shows voltage waveforms at the source of the power system which is the same point that used to analyze the harmonics before connecting PV system. In this figure the values of harmonics are produced at a solar radiation values of 1000 W/m^2, and temperature 25° C.

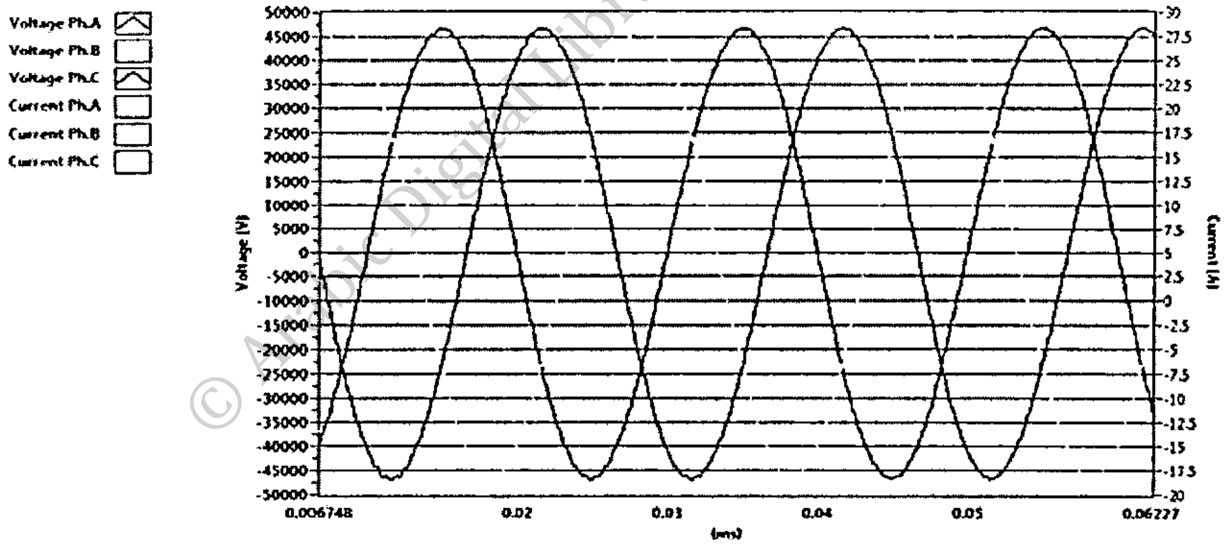


Figure 4.9 Voltage wave forms

Currents waveforms appear with high distortion in it and the three phase currents are shown in Figure 4.10.

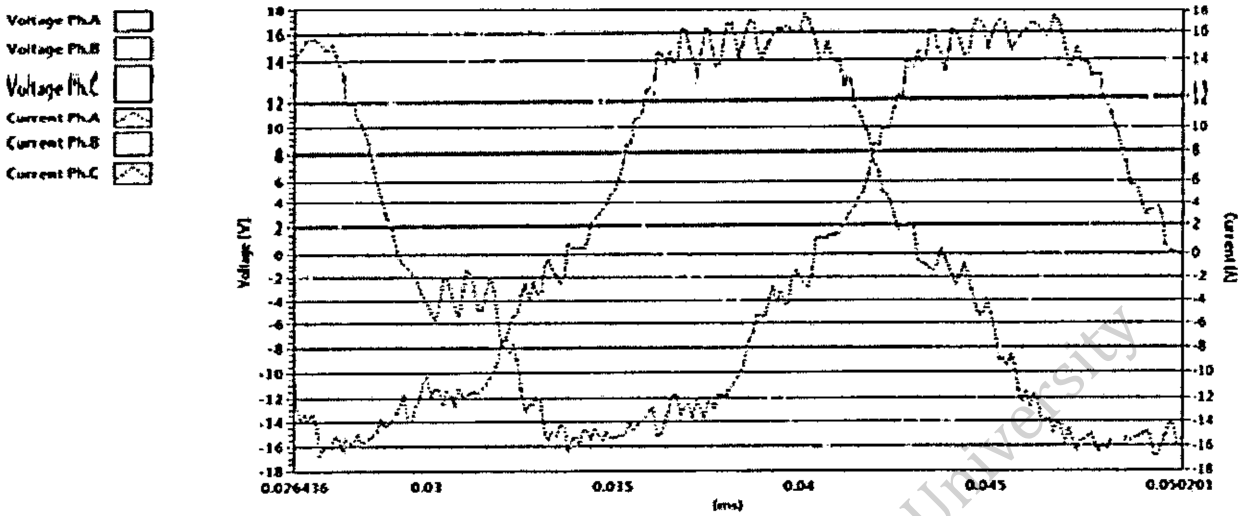


Figure 4.10 Current wave forms

Figure 4.10 illustrates that the distortion in current was increased after adding PV system. The histogram shown in Figure 4.11 clearly determines the harmonic values and orders.

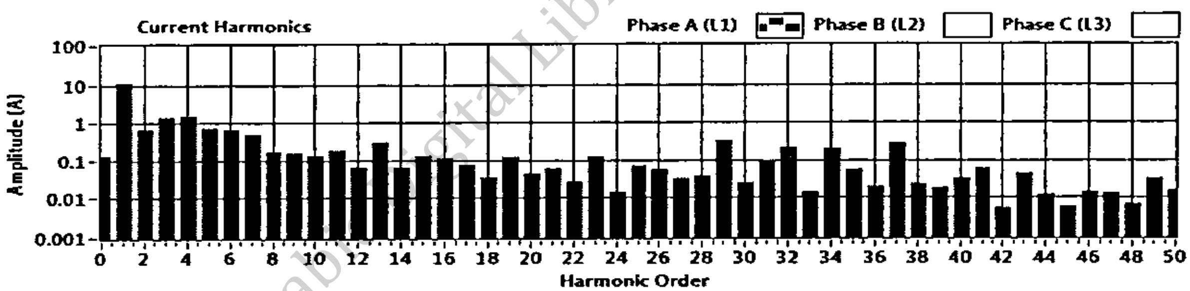


Figure 4.11 Current harmonic values in phase A.

The values of voltage harmonics are shown in figure 4.12

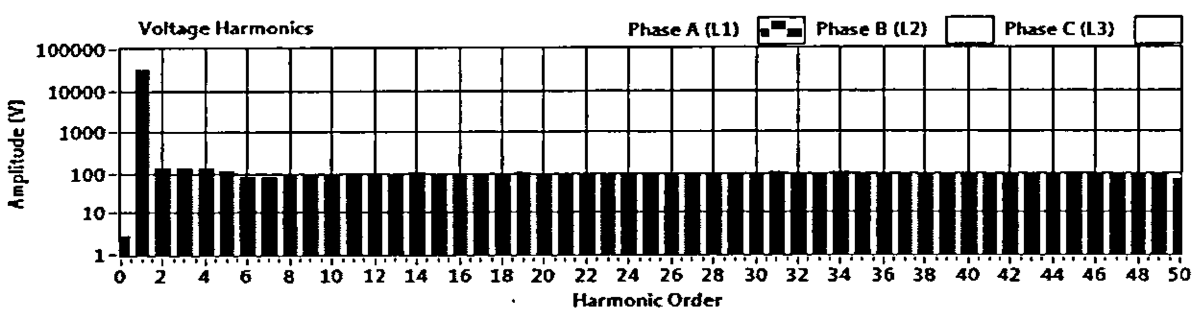


Figure 4.12 Voltage harmonic values in phase A.

The interharmonic current values are shown in Figure 4.13

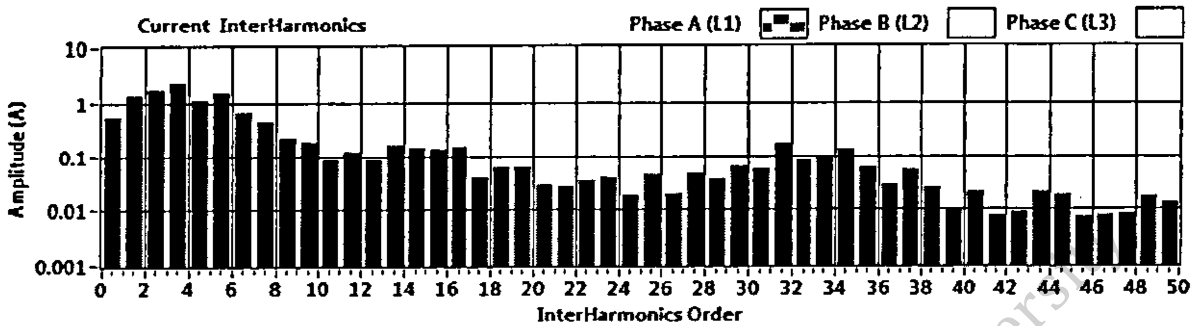


Figure 4.13 Current inter harmonic for phase A

The values of voltage interharmonics are shown in Figure 4.14

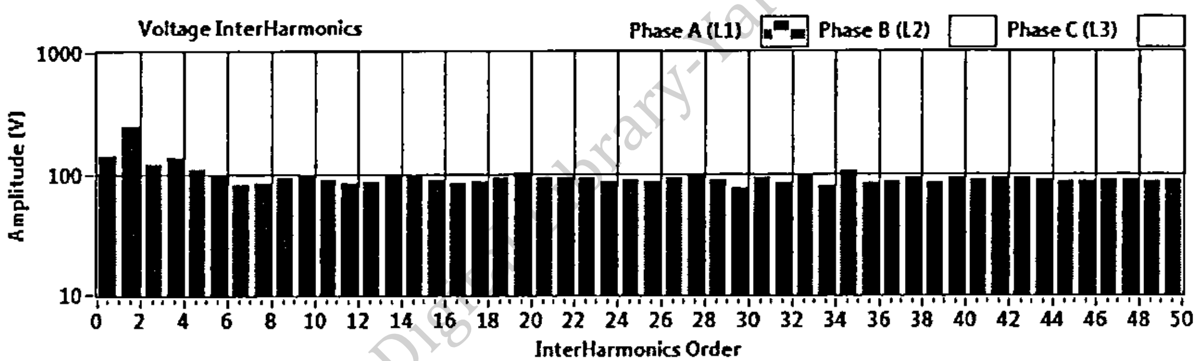
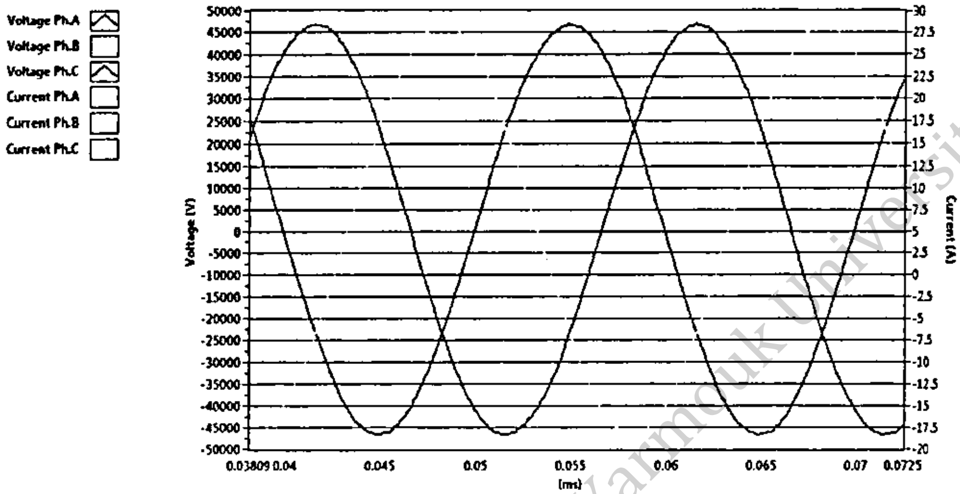


Figure 4.14 Voltage interharmonics

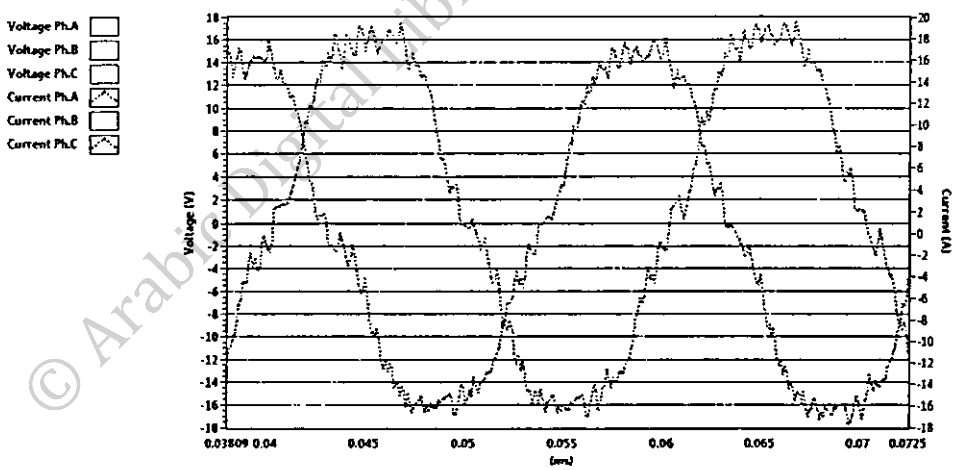
The resulted THD in current waveforms is 13.3% which exceeds the standard limits by approximately 150%. This value is much higher than that of the studied system before connecting PV to it.

From figures above it clearly seen that the existence of the solar system under normal conditions will raise the THD to a very high value, 3rd and 4th harmonic orders appear significantly in voltage and current waveforms.

For solar radiation 850 W/m^2 and 25°C temperature, the voltage and current waveforms appear in figure 4.15.



a. Voltage



b. Current

Figure 4.15 Voltage and current waveforms

Current harmonic values are shown in Figure 4.16, whereas voltage harmonic histogram is shown in figure 4.17.

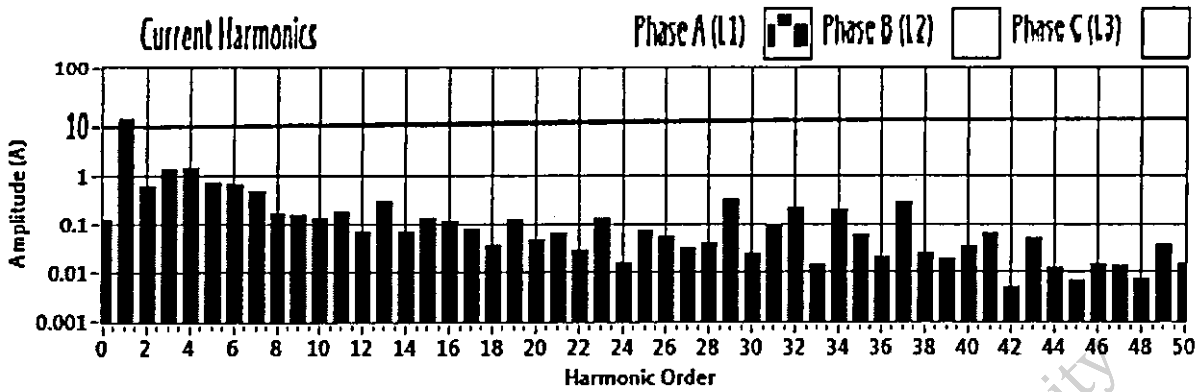


Figure 4.16 Current harmonics in phase A.

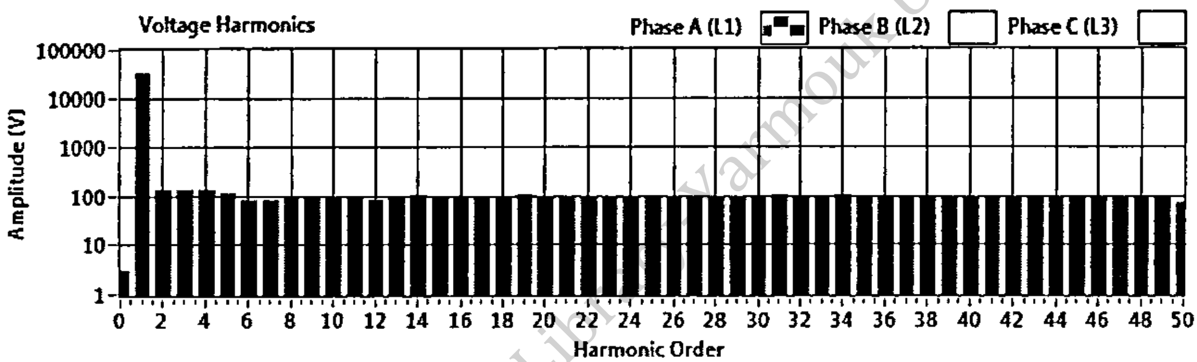


Figure 4.17 Voltage harmonics in phase A

Interharmonic values for current signal are shown in Figure 4.18, whereas voltage interharmonics are shown in Figure 4.19.

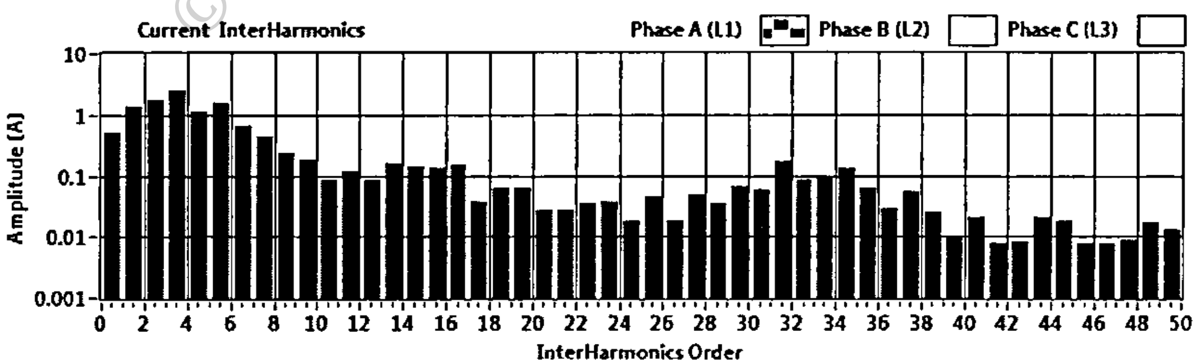


Figure 4.18 Current interharmonics.

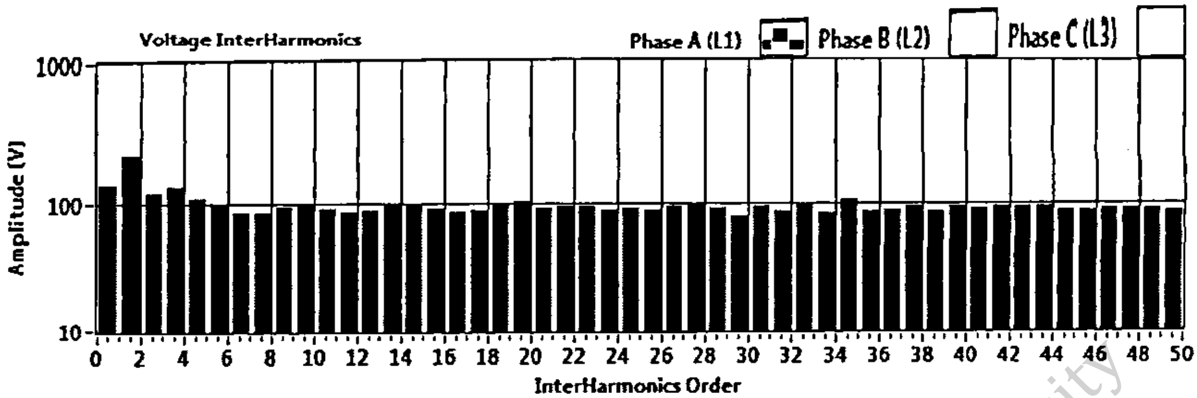


Figure 4.19 Voltage interharmonics.

The value of THD in current is 13.17 % in phase A.

The system is also simulated at 700 W/m^2 and 25°C which is less than standard value of solar radiation. In order to investigate the effect of decreasing the solar radiation on harmonics, the same parameters were assessed. Figure 4.20 shows the voltage waveform provided that the temperature is kept constant and the insolation is variable.

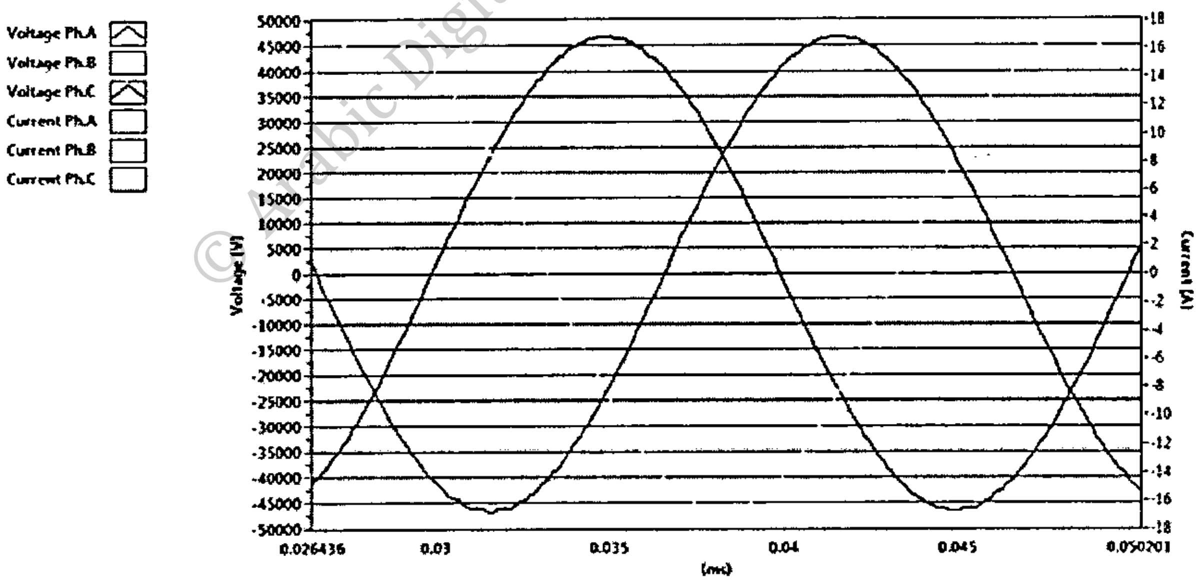


Figure 4.20 Voltage Waveforms

The current signal shown in Figure 4.21 contains a high degree of distortion generated from the connection of PV solar panels into distribution system.

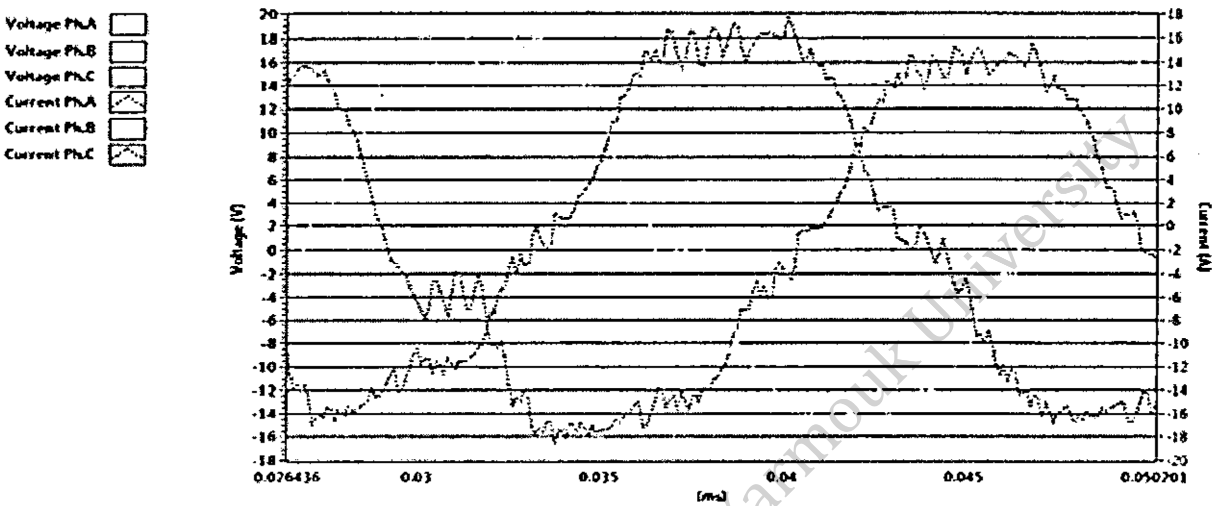


Figure 4.21 Three phase current waveforms

Current harmonic values are shown in Figure 4.22, whereas voltage harmonic histogram is shown in Figure 4.23.

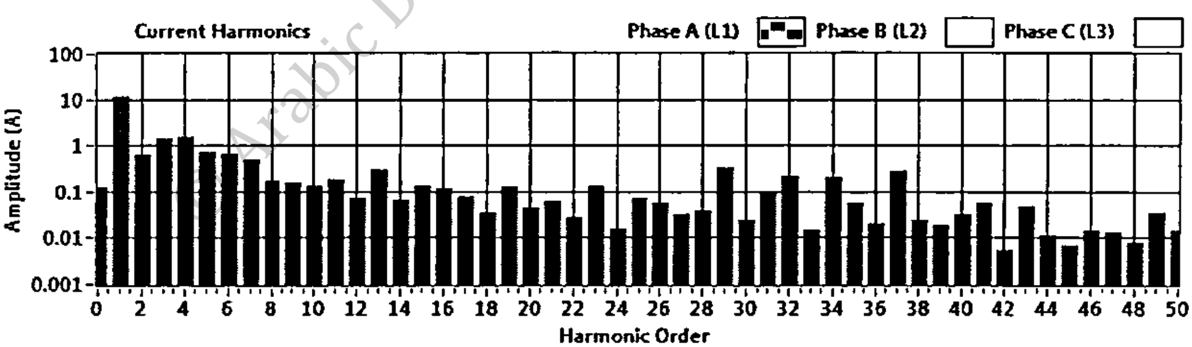


Figure 4.17 Current harmonics in phase A

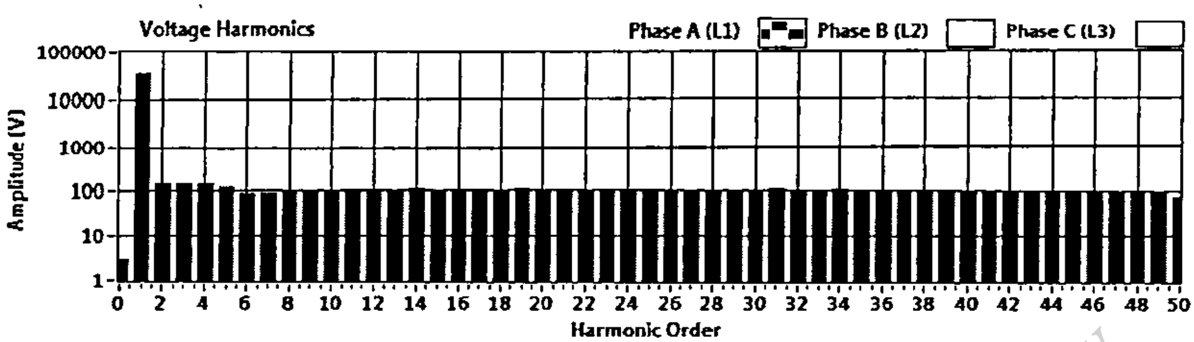


Figure 4.23 Voltage harmonics in phase A

Interharmonic values for current signal are shown in Figure 4.24, whereas voltage interharmonics are shown in Figure 4.25.

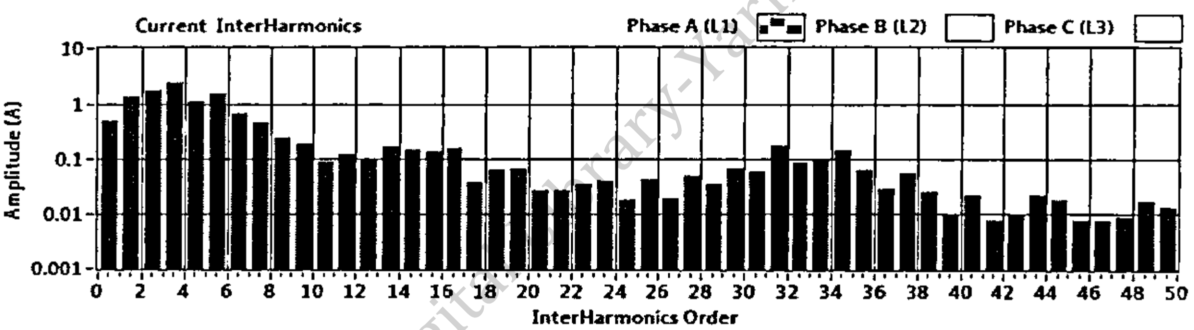


Figure 4.24 Current interharmonics in phase A

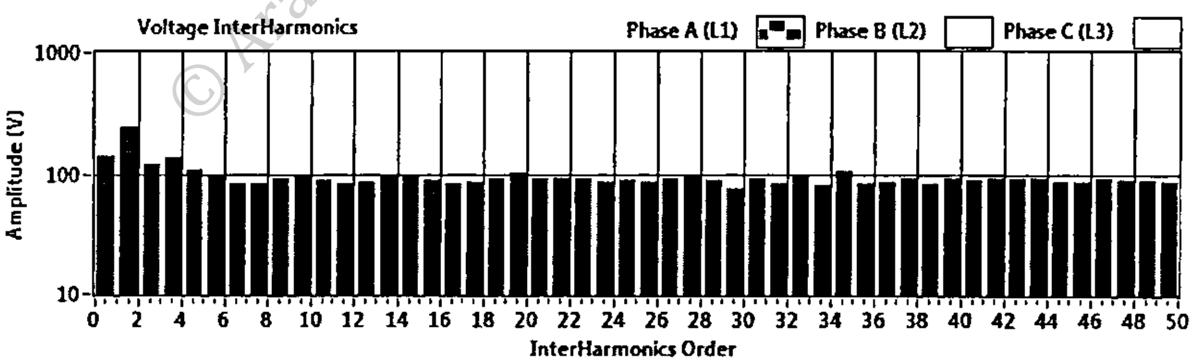
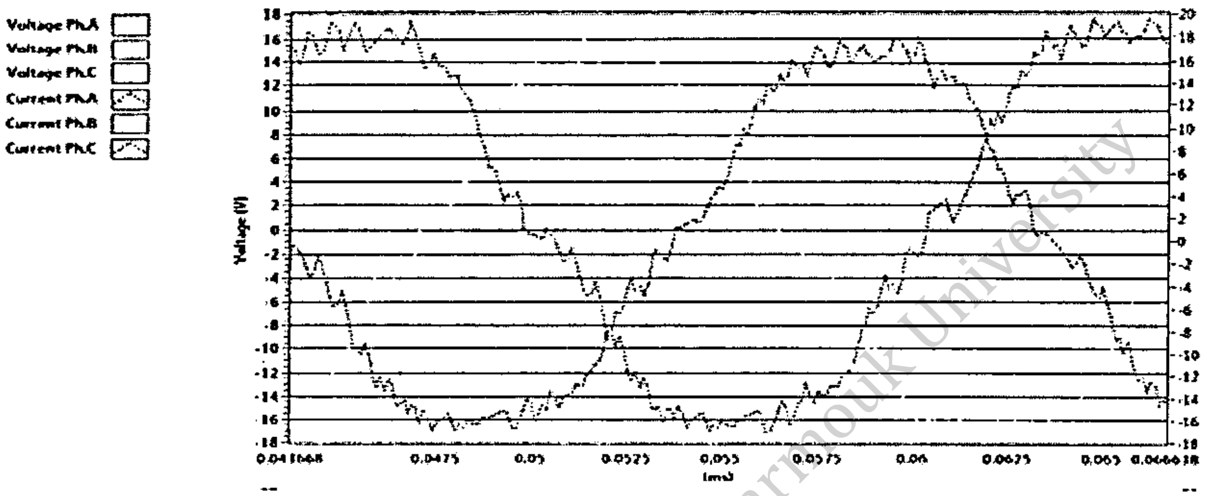


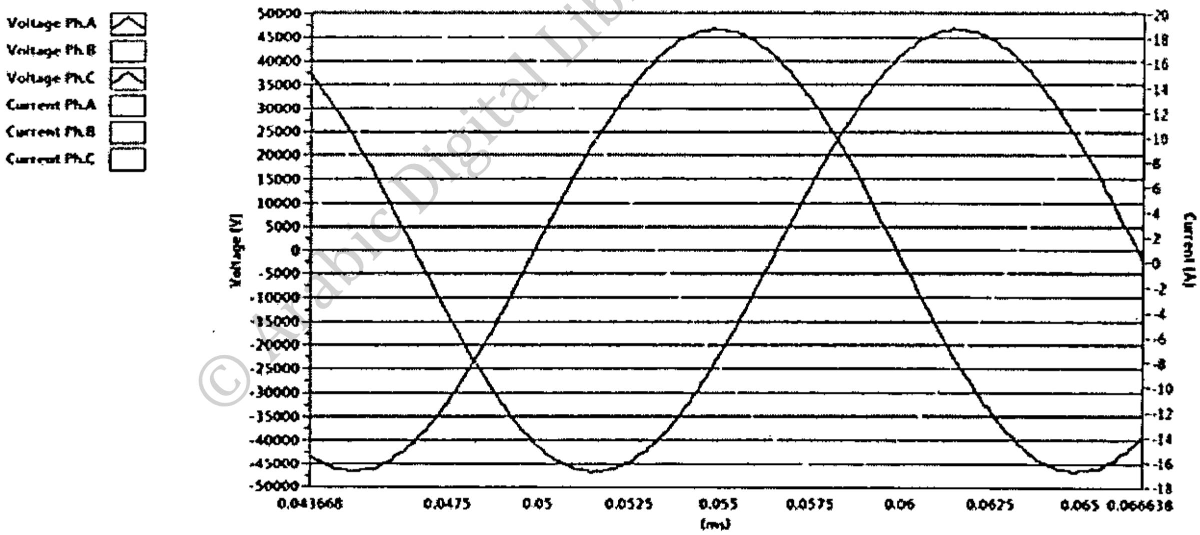
Figure 4.25 Voltage Interharmonics in phase A.

The THD is 13.09% at 700W/m^2 solar radiation value.

For 500 W/m^2 insolation, the same process was repeated. Figure 4.26 shows current and voltage wave forms, whereas Figure 4.27 shows current and voltage harmonic values.

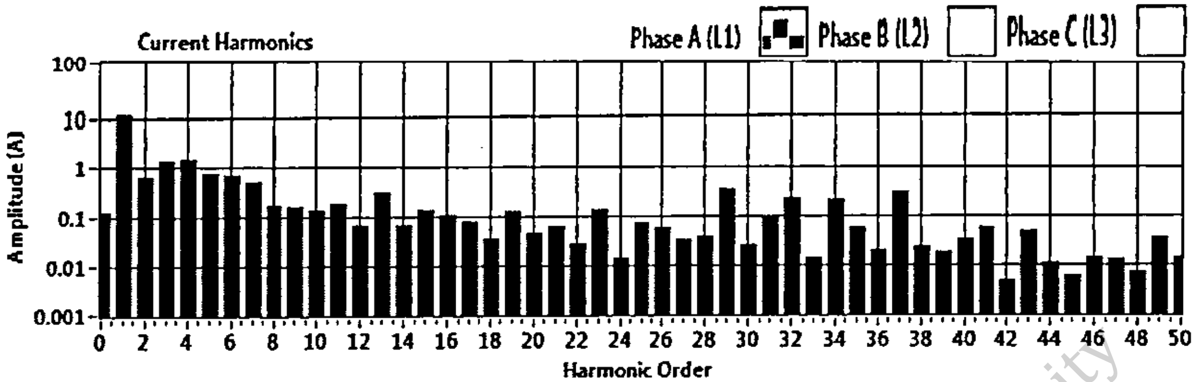


a. Current waveforms.

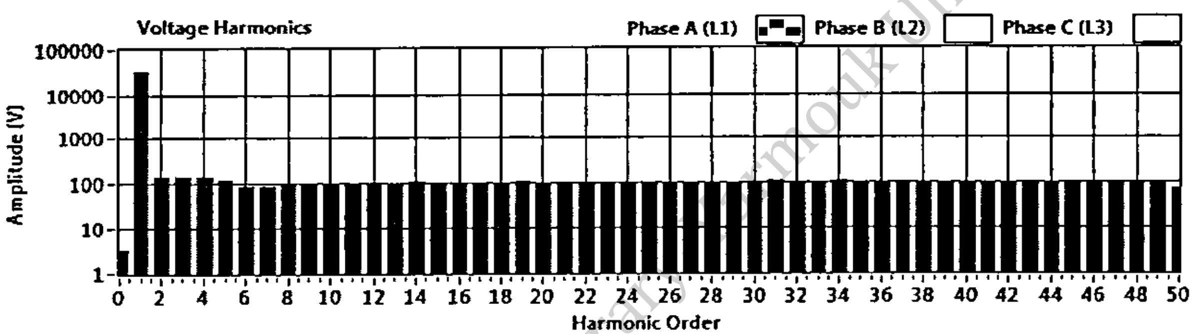


b. Voltage waveforms.

Figure 4.26 Current and voltage waveforms.



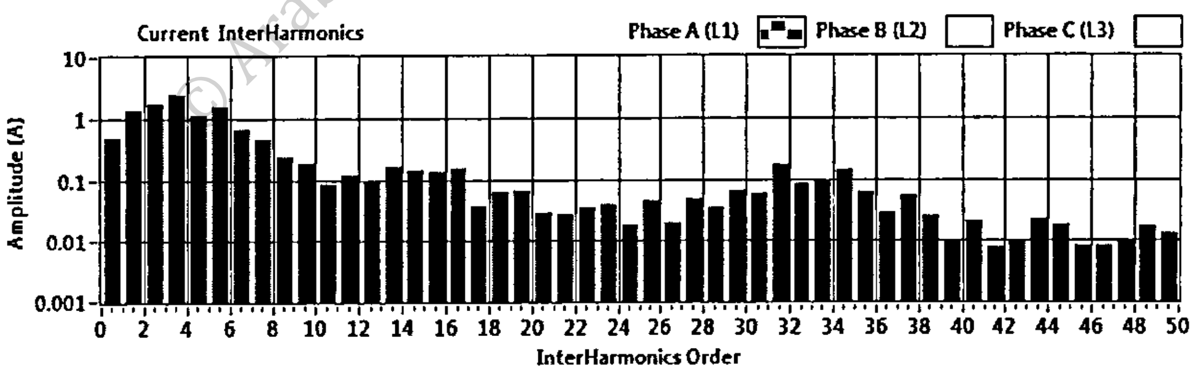
a. Current harmonic contents in phase A.



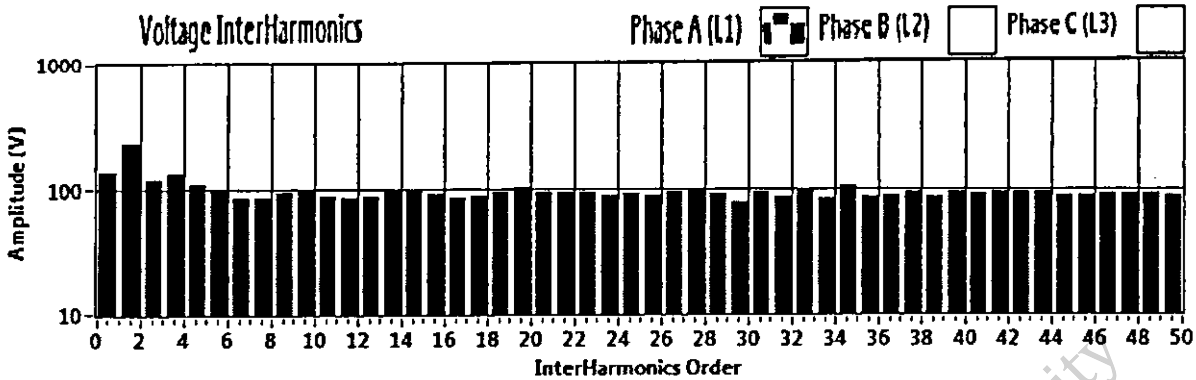
b. Voltage harmonic contents in phase A.

Figure 4.27 Current and voltage harmonic contents.

Both interharmonic values for current and voltage at 500 W/m^2 are shown in figure 4.28.



a. Current interharmonics in phase A.

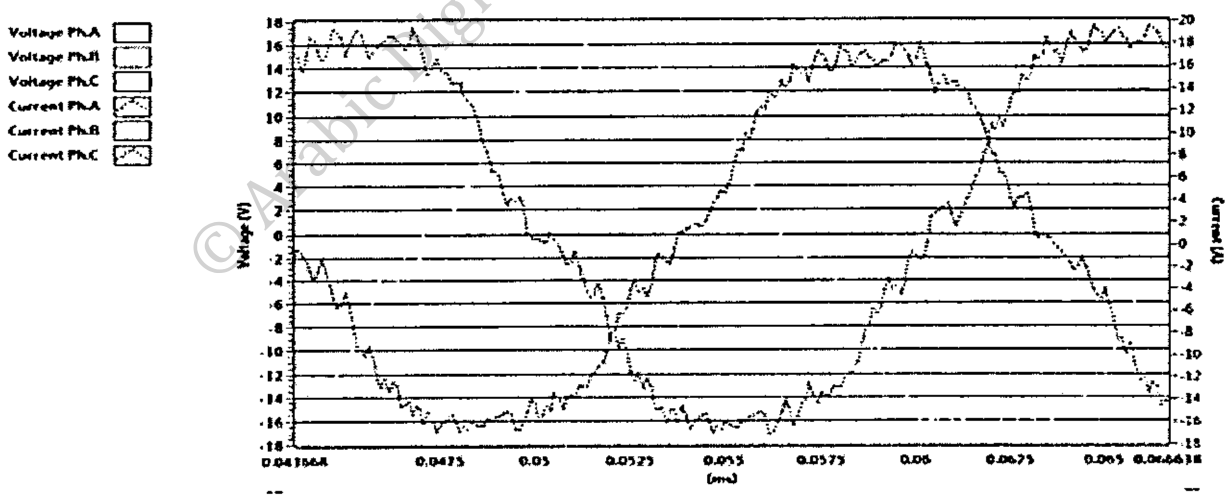


b. Voltage interharmonics in phase A.

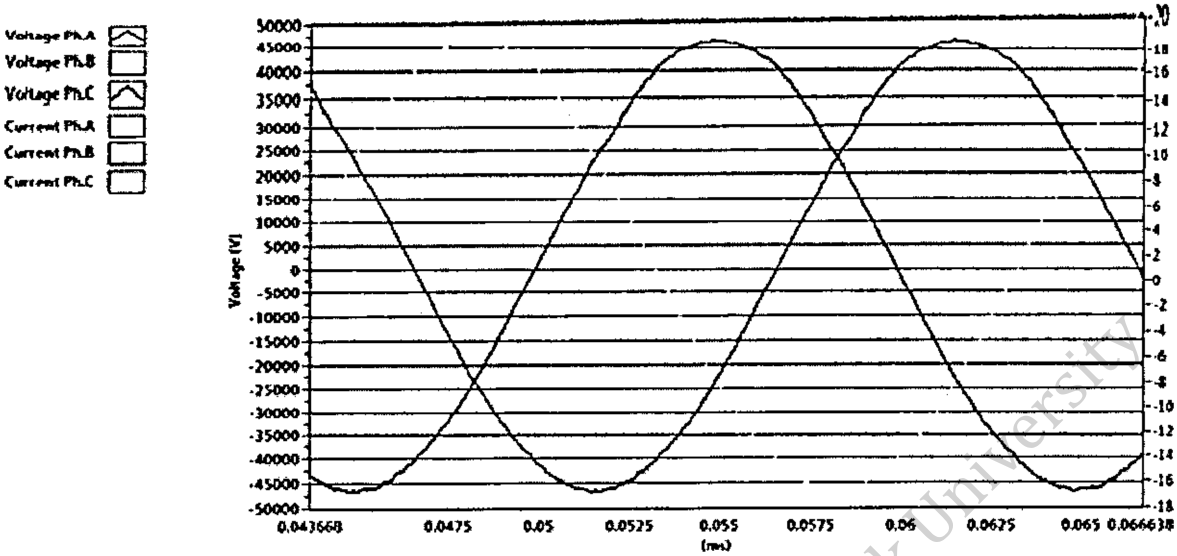
Figure 4.28 Voltage and current interharmonics.

The THD is 13.07% at 500W/m^2 solar radiation value.

For 200 W/m^2 insolation, the same process was repeated. Figure 4.29 shows current and voltage wave forms, whereas Figure 4.30 shows current and voltage harmonic values.

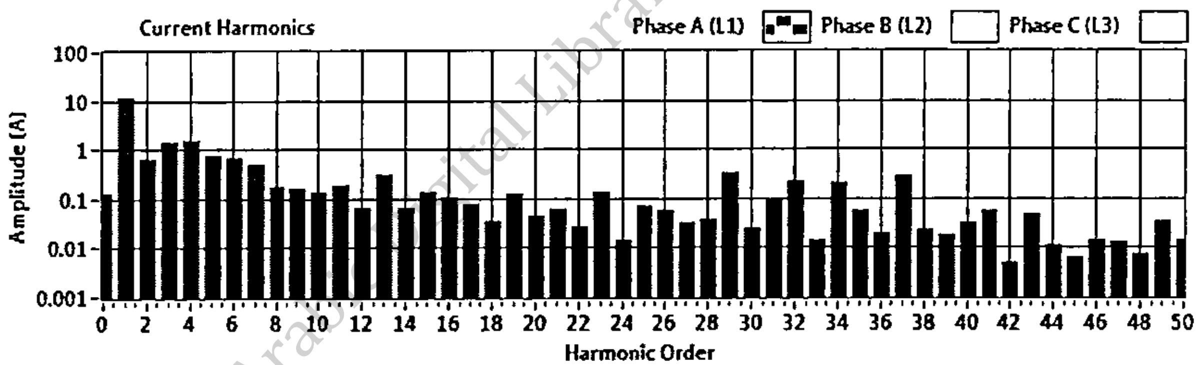


a. Current waveforms.

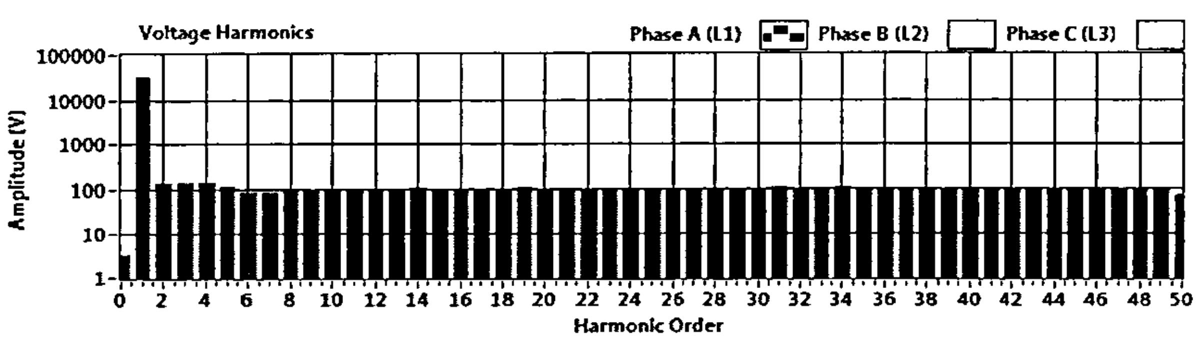


b. Voltage waveforms

Figure 4.29 Current and Voltage waveforms



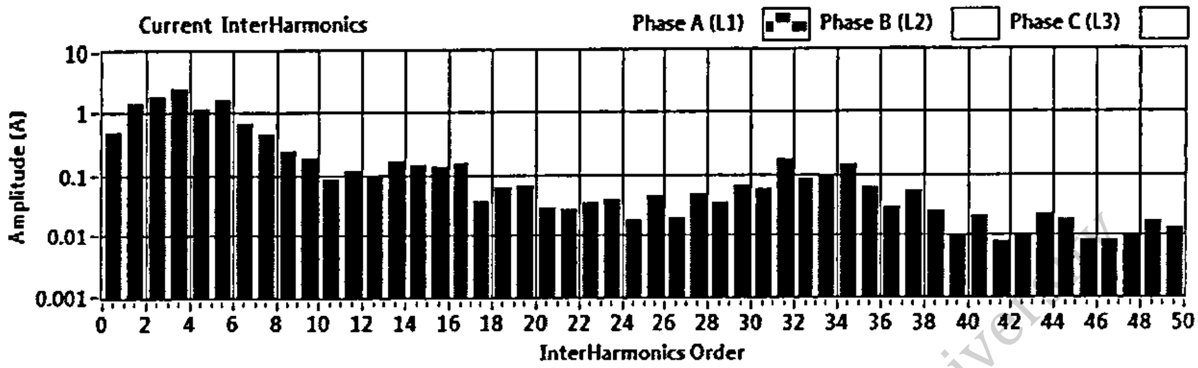
a. Current harmonic contents in phase A



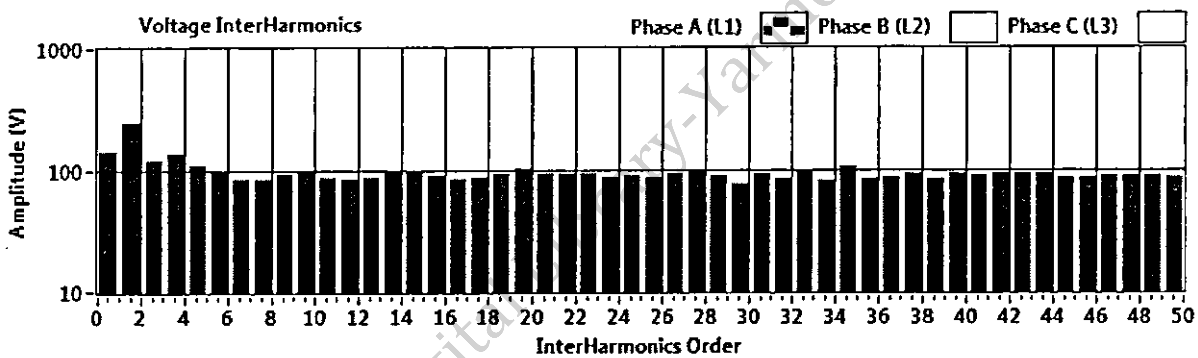
b. Voltage harmonic contents in phase A

Figure 4.30 Current and voltage harmonic contents.

Both interharmonic values for current and voltage at 200 W/m^2 are shown in figure 4.31



c. Current interharmonics in phase A



d. Voltage interharmonics in phase B

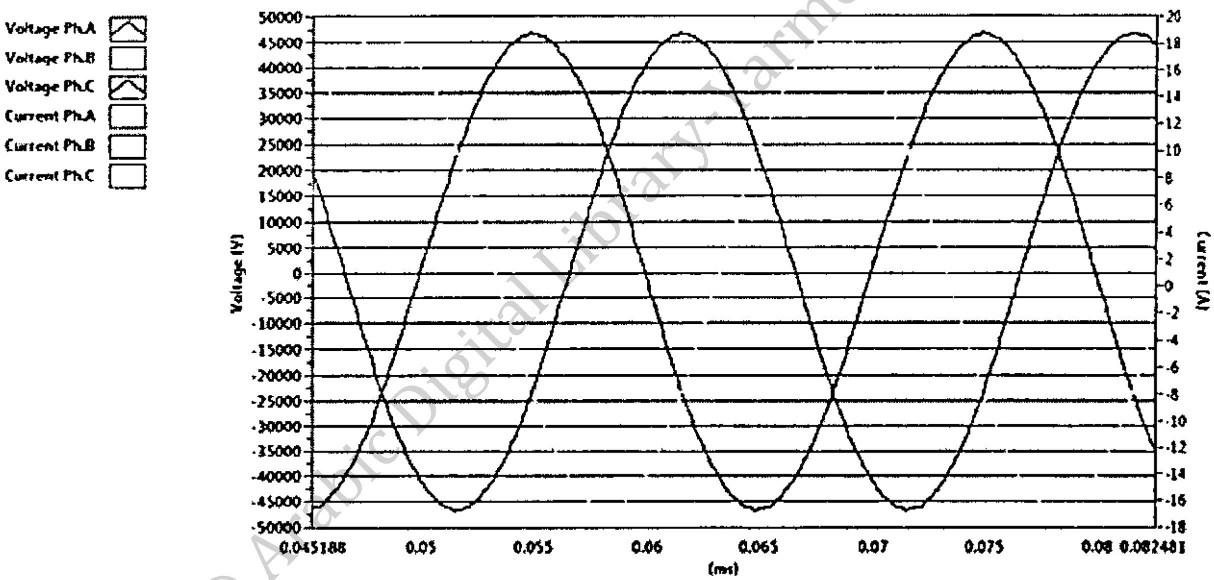
Figure 4.31 Voltage and Current interharmonics

The THD is 13.06% at 200 W/m^2 solar radiation value.

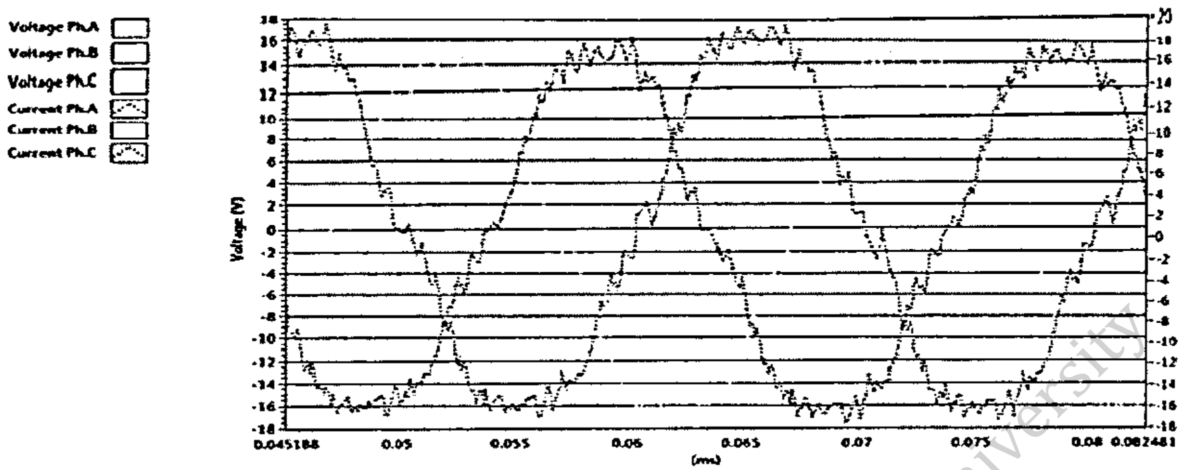
4.3.2 The effect of changing of temperature on the harmonics.

In the previous section the value of solar radiation was the variable one, and the temperature was considered a constant parameter during all simulation steps. In this part of the work the solar radiation will be considered as a constant and the temperature will be the variable factor. The results will be taken at different values of temperatures namely, 30°C, 25°C, 20°C, 15°C and 10°C. In all cases the solar radiation was assumed to be 1000 W/m^2.

The voltage and currents wave forms at 30°C are shown in Figure 4.32



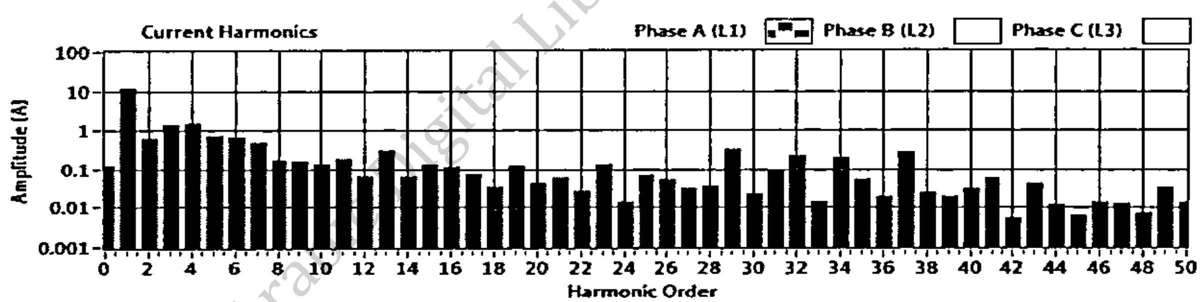
a. Voltage waveforms



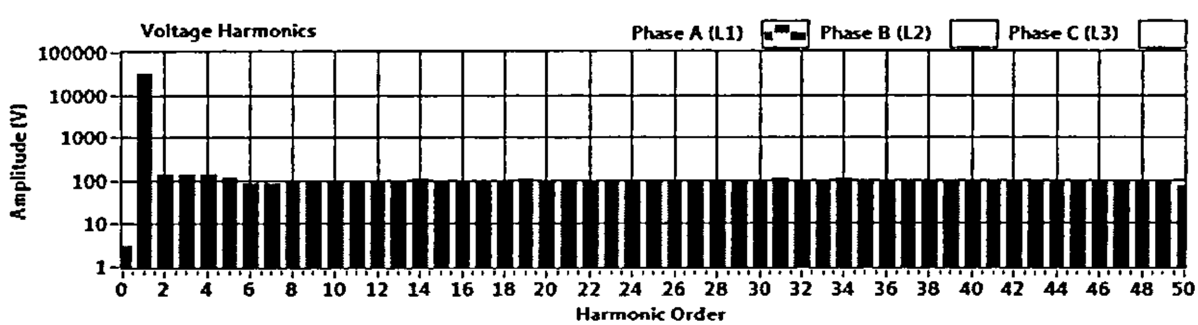
b. Current waveforms.

Figure 4.32 Voltage and current waveforms.

The values of harmonics are shown in Figure 4.33 for both voltages and currents, whereas, the interharmonics are analyzed and shown in Figure 4.34.

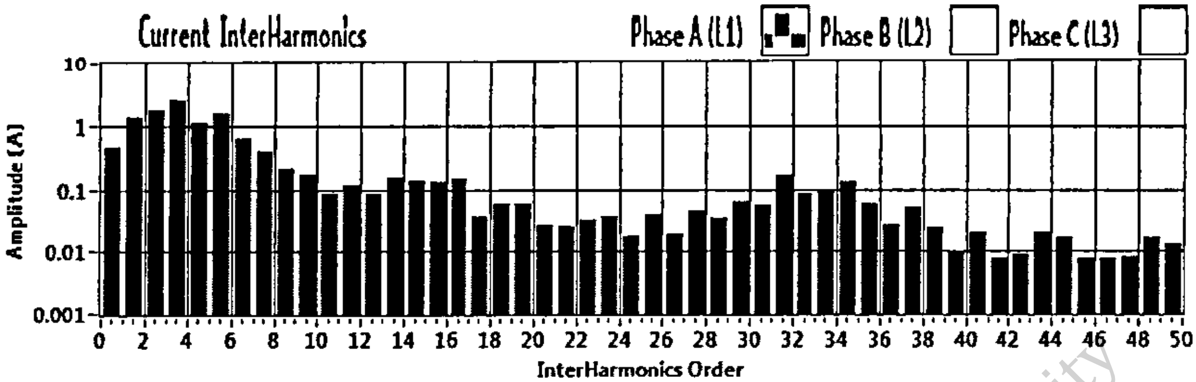


a. Current harmonics in phase A

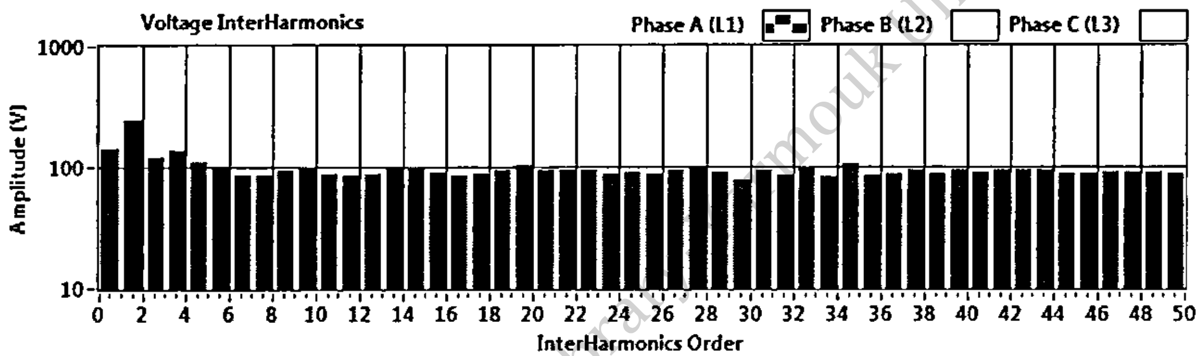


b. Voltage Harmonics in phase A

Figure 4.33 Current and Voltage harmonics



a. Current interharmonics in phase A

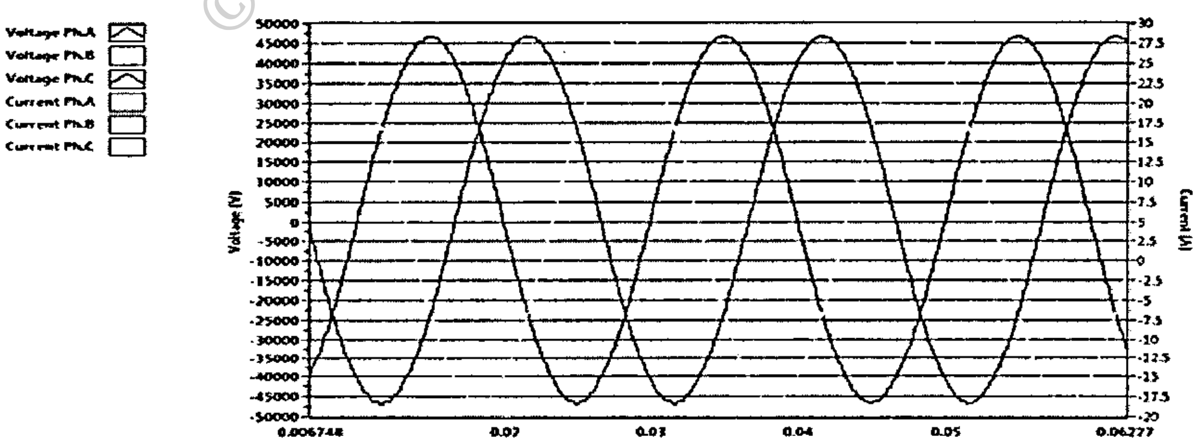


b. Voltage inter harmonics in phase A

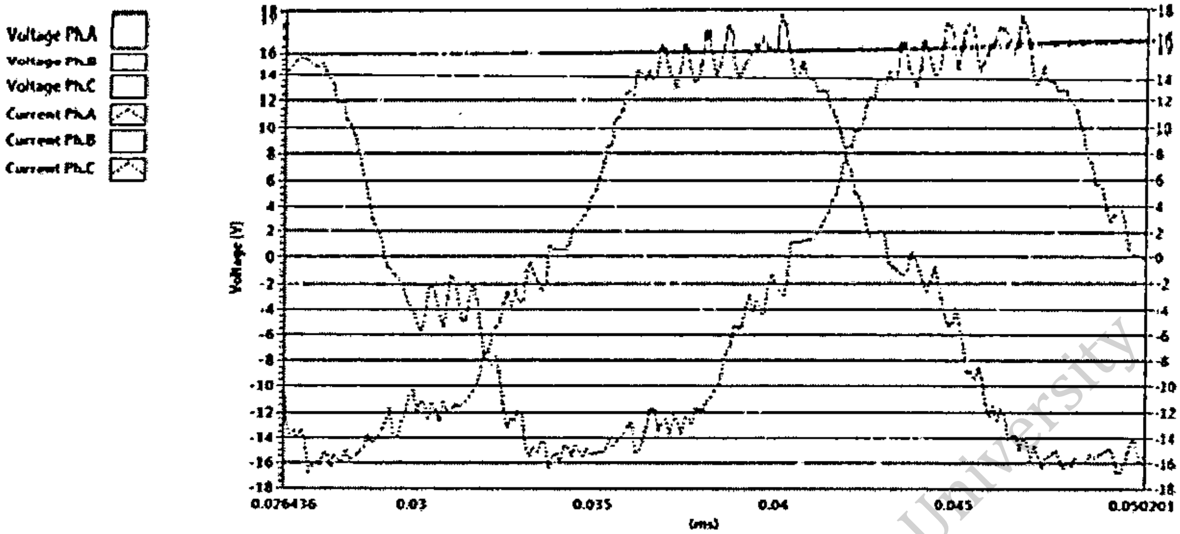
Figure 4.34 Voltage and current interharmonics

The THD is 13.22% at phase A.

For 25°C, the results are shown in Figure 4.35 for both voltage and currents.



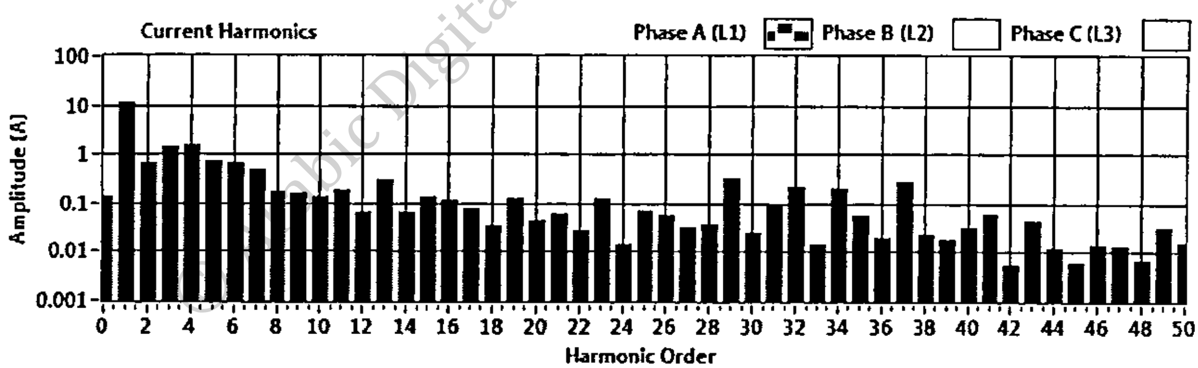
a. Voltage waveforms



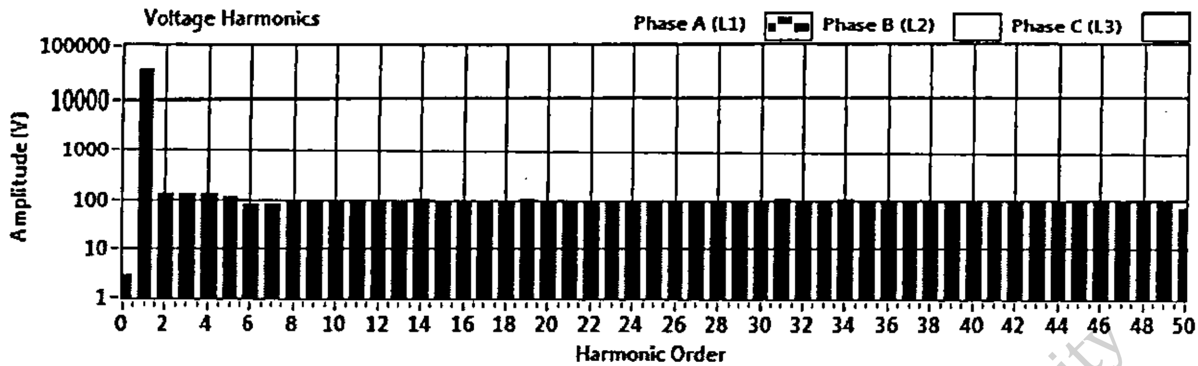
b. Current waveforms

Figure 4.35 Voltage and current waveform.

The harmonic histogram in both voltage and current is illustrated in Figure 4.36, whereas the interharmonics are shown in Figure 4.37.

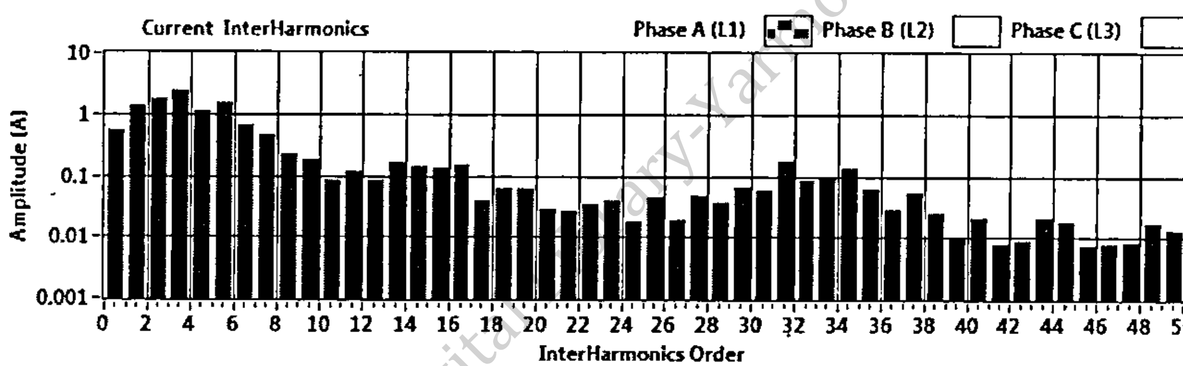


a. Current harmonic values in phase A

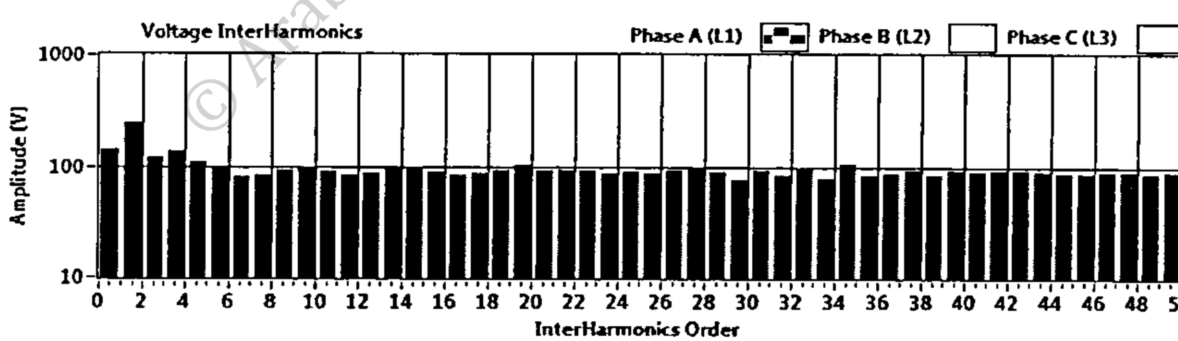


b. Voltage harmonic values in phase A

Figure 4.36 Current and voltage harmonic levels



a. Current inter harmonics for phase A

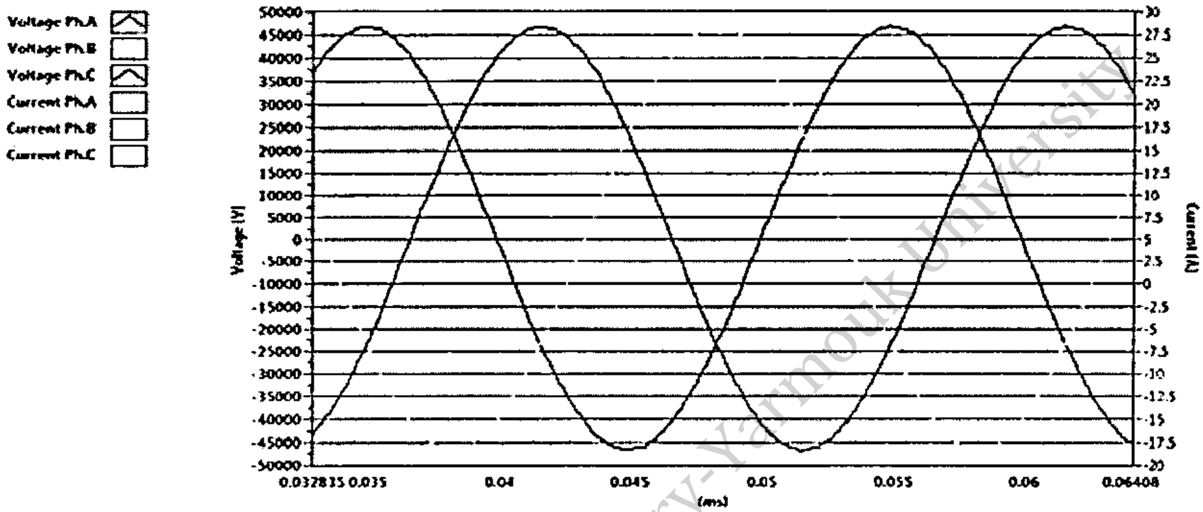


b. Voltage interharmonics in phase A

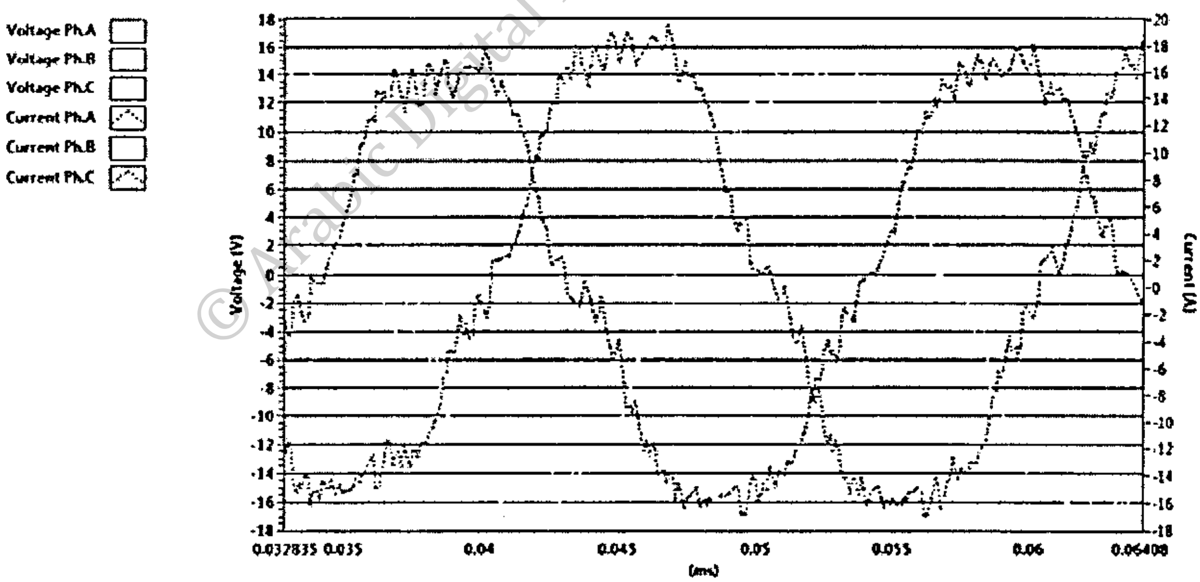
Figure 4.37 Current and voltage interharmonics

The THD in current wave forms is 13.3%,.

The same simulation is repeated when the temperature is adjusted to 20°C. Figure 4.38 shows the current and voltage waveforms at this temperature, whereas the harmonic histograms are illustrated in Figure 4.39 for both voltages and currents.

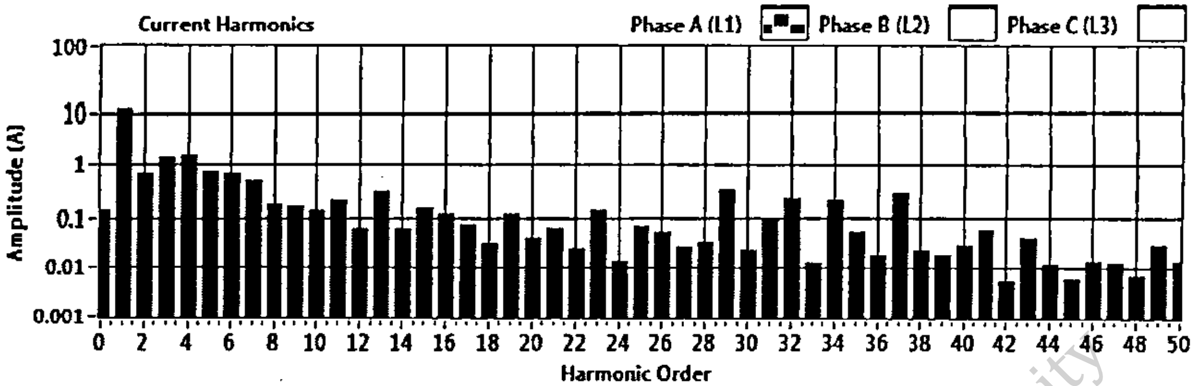


a. Voltage waveforms.

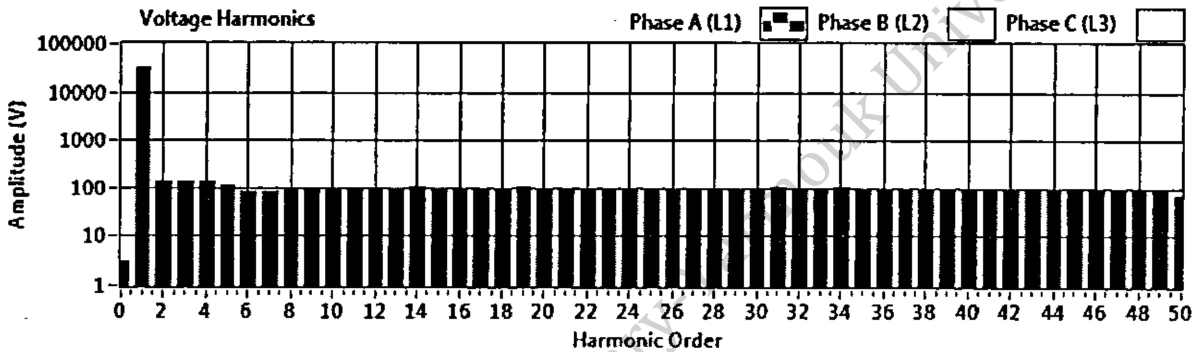


b. Current waveforms

Figure 4.38 Voltage and current wave forms at 20°C



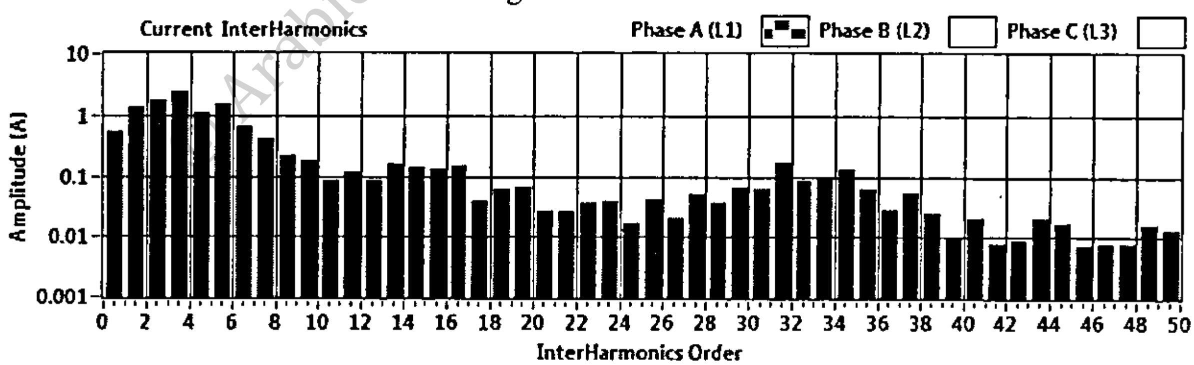
a. Current harmonics in phase A



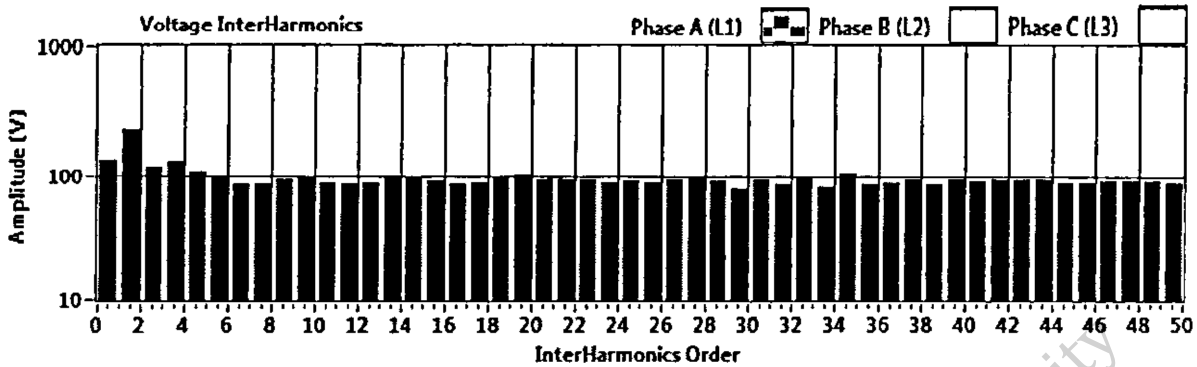
b. Voltage harmonics in phase A

Figure 4.39 Current and voltage harmonics at 20°C

The interharmonic values are shown in Figure 4.40.



a. Current interharmonic in phase A

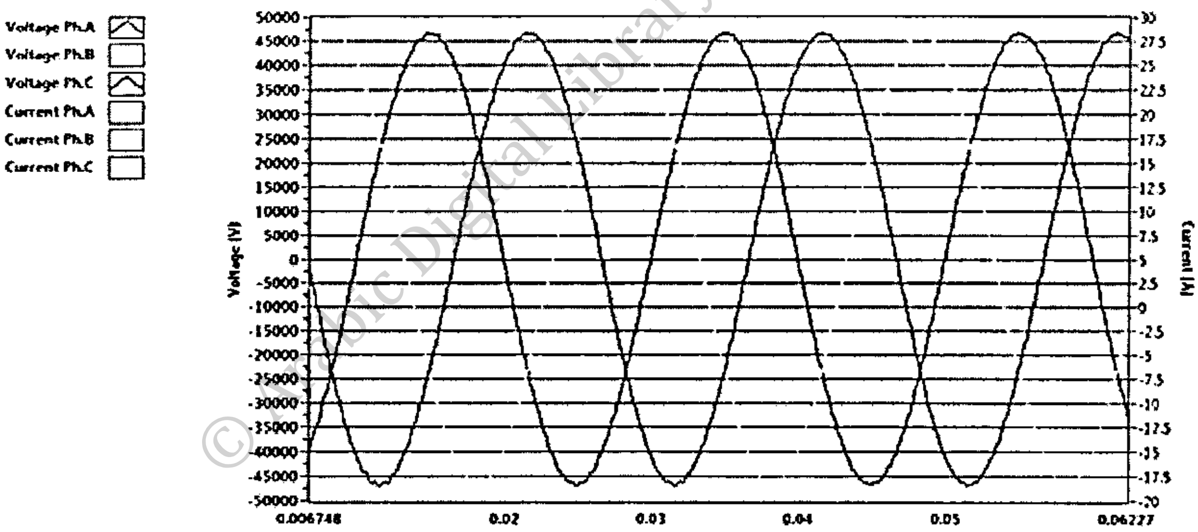


b. Voltage interharmonic in phase A

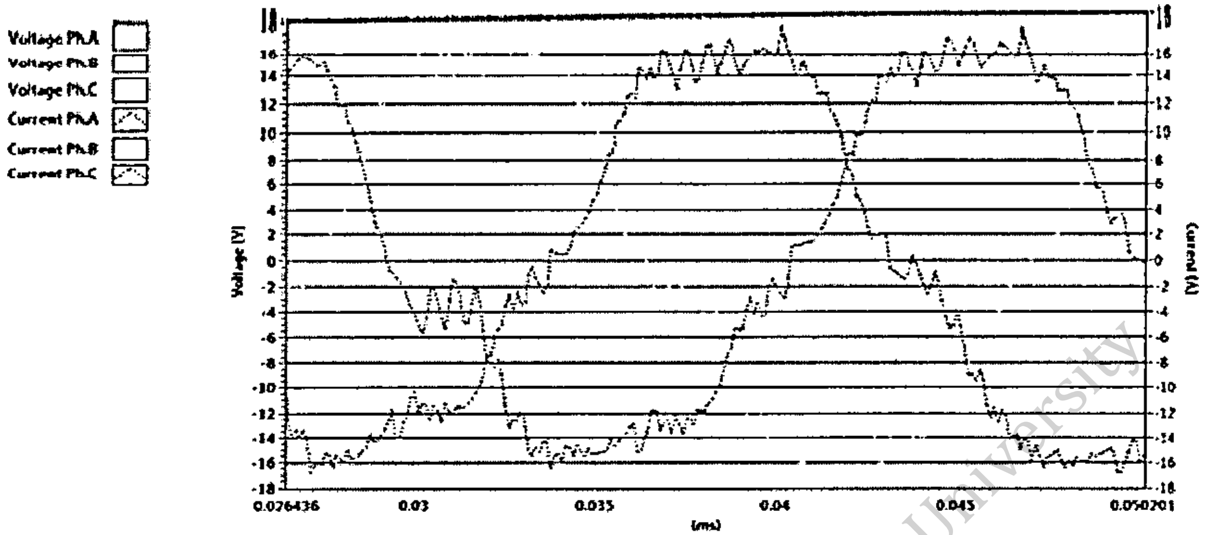
Figure 4.40 Voltage and current interharmonics at 1000 W/m^2, 20°C

The THD is 13.4% in current signal.

For 15°C, the results are shown in Figure 4.41 for both voltage and currents.



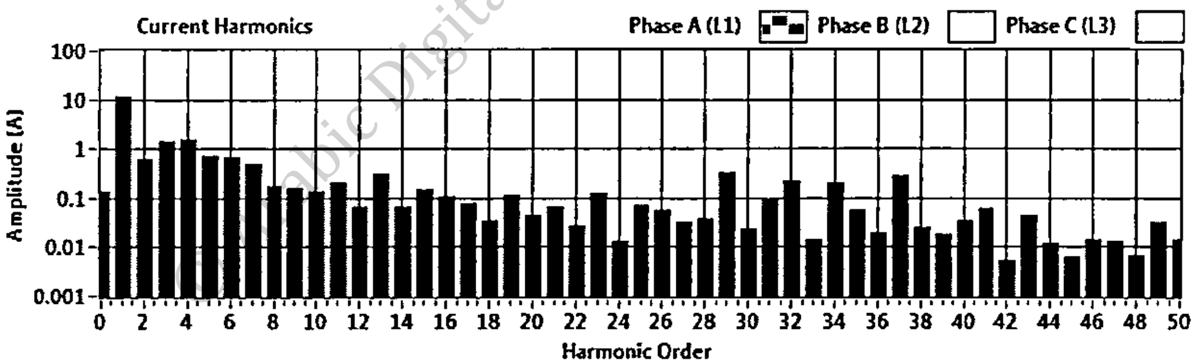
c. Voltage waveforms



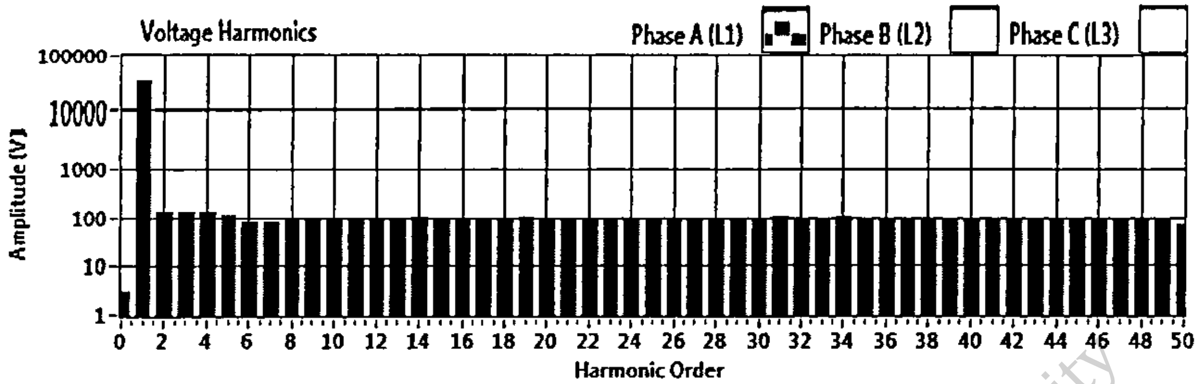
d. Current waveforms

Figure 4.41 Voltage and current waveform.

The harmonic histogram in both voltage and current is illustrated in Figure 4.42, whereas the interharmonics are shown in Figure 4.43.

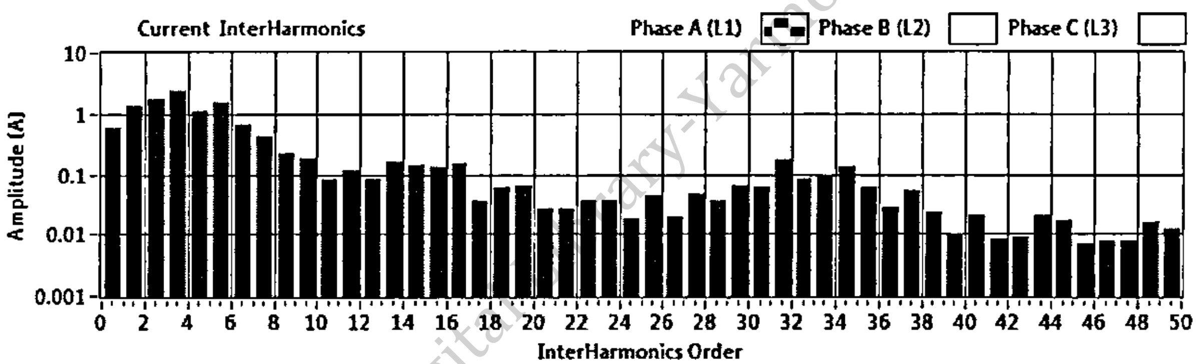


c. Current harmonic values in phase A

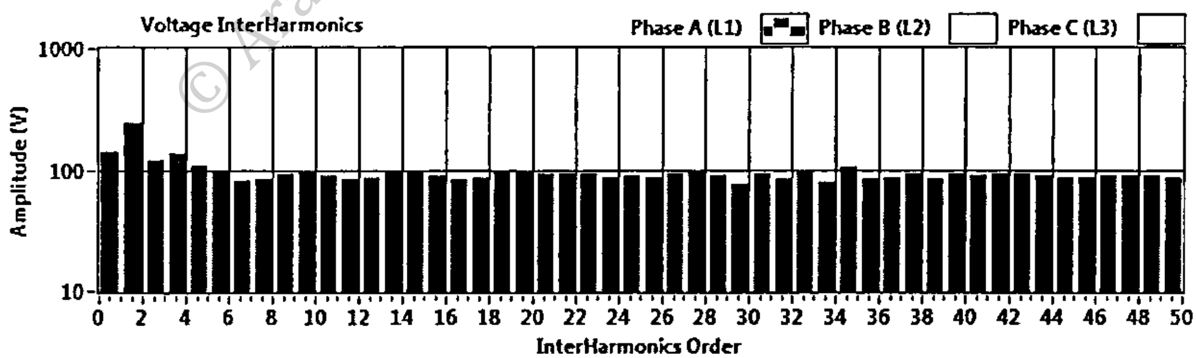


d. Voltage harmonic values in phase A

Figure 4.42 Current and voltage harmonic levels



c. Current inter harmonics for phase A

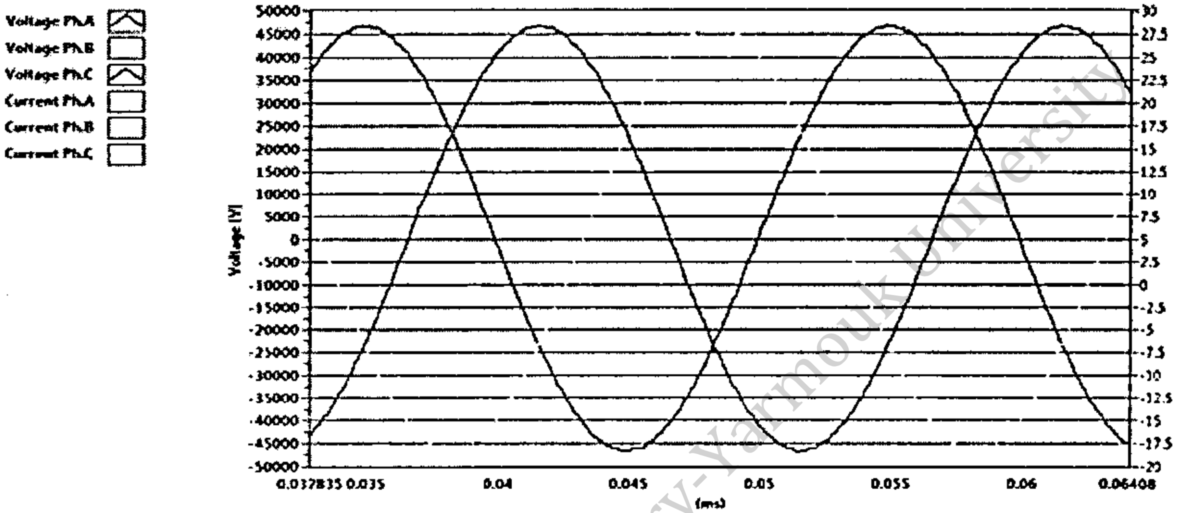


d. Voltage interharmonics in phase A

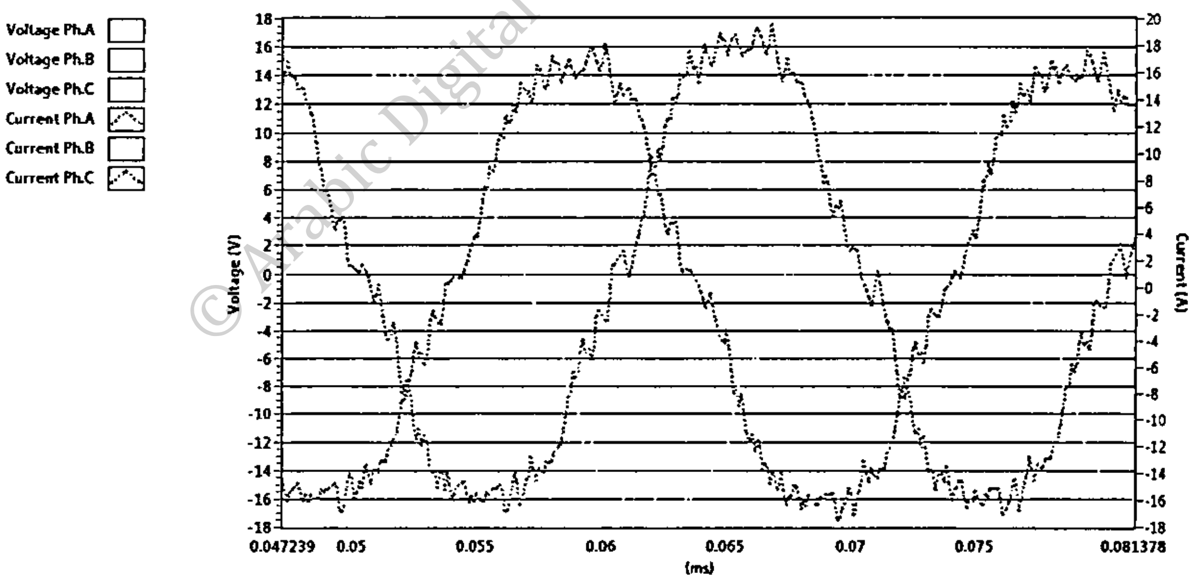
Figure 4.43 Current and voltage interharmonics

The THD in current wave forms is 13.44%.

Finally, the same simulation is repeated when the temperature is adjusted to 10°C. Figure 4.44 shows the current and voltage waveforms at this temperature, whereas the harmonic histograms are illustrated in Figure 4.45 for both voltages and currents.

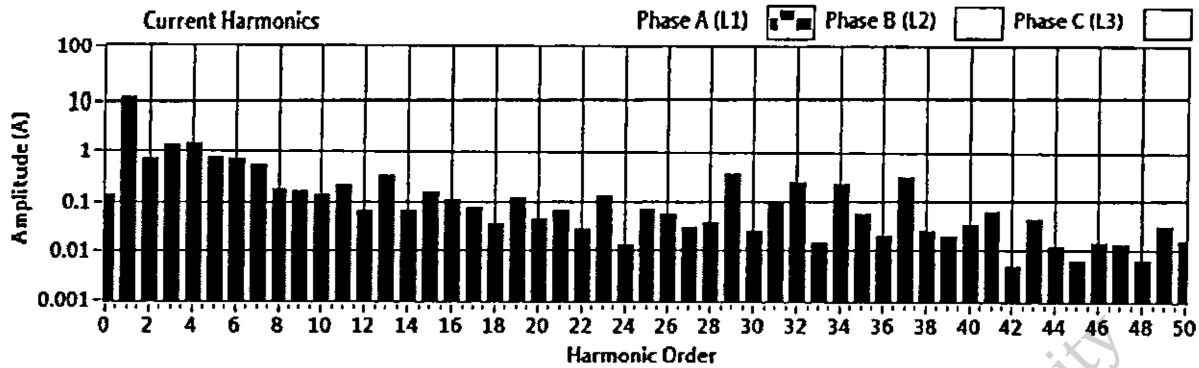


c. Voltage waveforms.

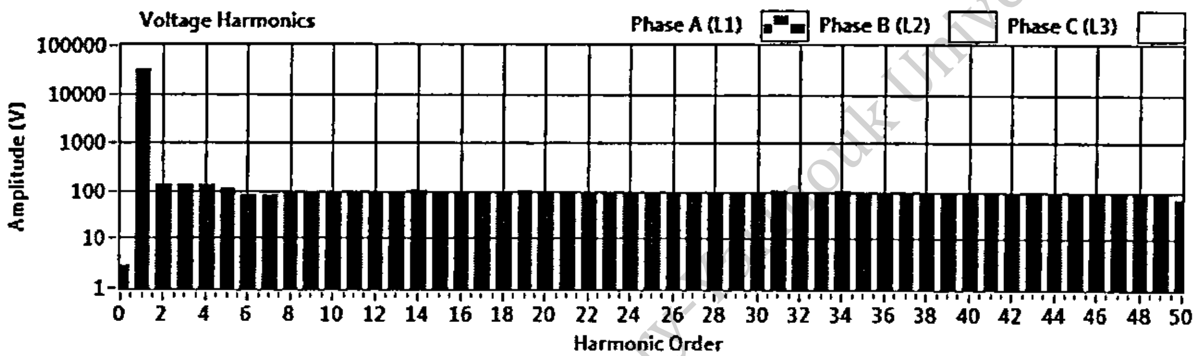


d. Current waveforms

Figure 4.44 Voltage and current wave forms at 10°C



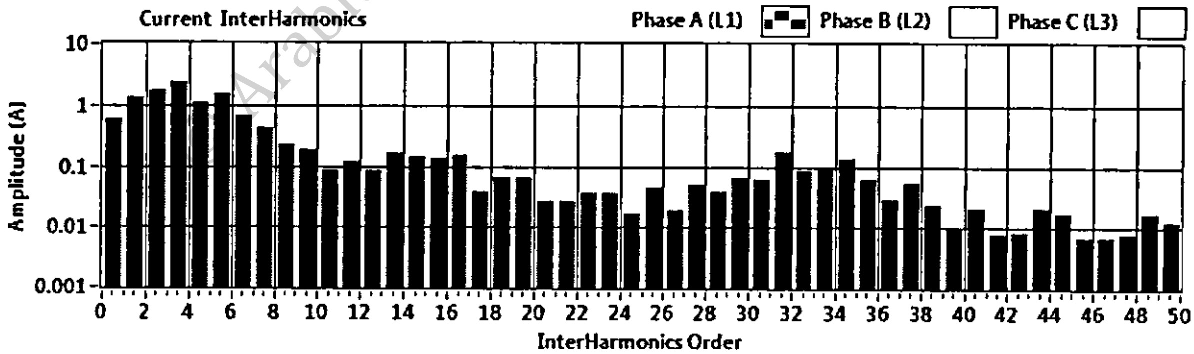
c. Current harmonics in phase A



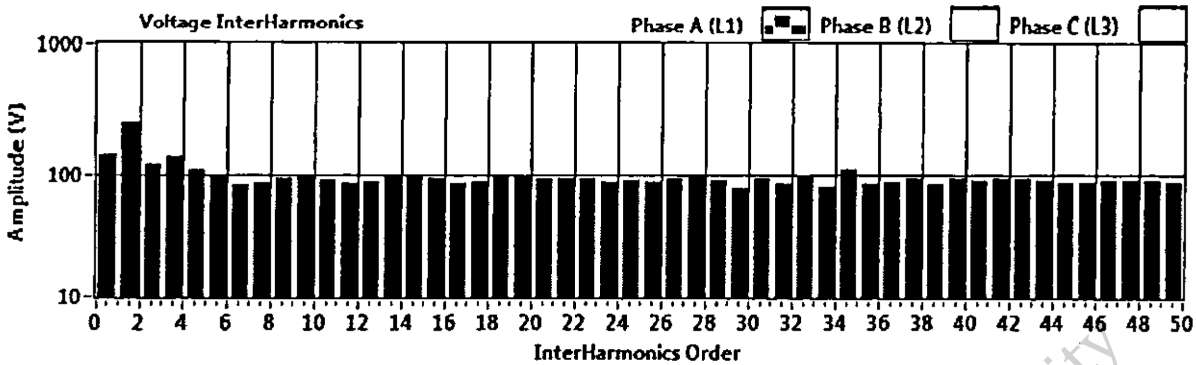
d. Voltage harmonics in phase A

Figure 4.45 Current and voltage harmonics at 10°C

The interharmonic values are shown in Figure 4.46.



c. Current interharmonic in phase A



d. Voltage interharmonic in phase A

Figure 4.46 Voltage and current interharmonics at 10°C

The THD is 13.55% in current signal.

It is clearly shown that the PV generation system is associated with non-pure sinusoidal signal exported to the grid with a high value of THD once it is connected and started to feed the distribution grid with energy.

CHAPTER 5

5.1 Introduction

The aim of this chapter is to discuss the obtained results and to explain the relationships highlighting the influence of photovoltaic generation systems on the waveform distortion and, more precisely, on harmonics and interharmonics. This kind of analysis needs a deep knowledge in PV generation characteristics that vary with solar radiation and temperature. It also needs to employ the knowledge about converting devices and other nonlinear equipment to obtain a correct interpretation of the resulted harmonic waveforms and histograms. The employment of high performance simulator, which is based on MATLAB/Simulink program, provides a model that can be easily adopted for various temperature and radiation values to set a precise solar generator models. One of the strong points in this work is the possibility of taking the waveforms of current and voltages obtained from Simulink and analyze the min another tool, LabVIEW program. The latter is well-known as a strong tool in harmonic analysis. This approach provides an accurate and effective way in analyzing the variation of parameters governing the harmonic behavior. It simulates a real power system and then adds one of renewable resources to it.

It is one of difficult missions to analyze the effect of large scale PV generation system on a real part of the power system and to build a model for both systems. This also includes the way of connecting both systems, the conventional and the solar one. Despite these difficulties, the examined model was able to provide valuable findings and being a successful approach.

Moreover, the current work has facilitated the future tasks to illustrate harmonic phenomena and expect its levels regardless of the size of the examined system under different temperatures and sun radiations.

5.2 The effect of influence of PV generation plants in general

Before connecting the PV system to the distribution network, the THD was found to be 4.6%. Although this factor is a good indication of harmonic level, it is usually advisable to inspect the individual harmonics. In comparison of harmonic voltage and harmonic current values, the latter was more noticeable.

Usually, the main source of harmonics is the nonlinear loads in the system. However, after connecting PV arrays to the grid, the harmonic level has shown a significant increase. By installing large amounts of PV arrays (in this case 150 kW), the THD level becomes remarkably high (13.2 %).This value reflects the seriousness of the problem and the high percentage of electronic devices involved. The continuous operation of power electronic devices in the inverter and the currents that are injected to the grid are indicators about the degree of distortion that can be sensed during measurements. Any adjacent load will draw a distorted current and by passing through impedances more distortion can be recorded. With time the system becomes completely "polluted" and the THD gets higher and higher. This high value of THD may affect sensitive controlling systems and loads.

The DC component in the system increased to a remarkable value and it affects the transformers operation by saturating them at normal operating conditions. This usually causes an overheating and transformers de-rating.

However, the influence of PV system supplying the grid with 150kW (at maximum operating condition) leads to a decrease in the source current from 12A to 10A approximately (on 33KV level). This decreases the losses in the transmission lines.

The individual harmonics that appear significantly before adding the PV system were the 5^{th},7^{th} , 11^{th} ,13^{th} and so on as in the equation 1.17 and that is due to the six pulse power rectifiers in the loads. After connecting the PV system, the harmonics were increased because the influence of the inverter in the solar generation system.

Even harmonics also appear due to the operation of the transformer between PV system and the grid but with small values. The THD increased remarkably after adding the PV system from 4.7% up to 13.2% which is higher than standard limits.

5.3 The effect of variation of solar radiation

Solar radiation is one of the main parameters that affect the generation levels of PV arrays. Its role is clear from the equations of the PV module, on which the simulation depends on [2]. It appears from the characteristics that the value of output power from PV arrays will increase as the radiation increases. The variation of solar radiation occurs in a random manner during cloudy days and varies from day to day, which makes the predicting of the exact value of generation a difficult task. However, the model used can provide the flexibility to change the insolation level to any value, which facilitates prediction the generated power and its influence on the harmonics.

As seen from the simulation results, the THD was decreasing with a decreasing the insolation level. It was found to be 13.3% at 1000 $W/m^2$where the generated power was approximately 150 kW under the standard conditions. When the simulation was conducted at 850 W/m^2, the THD was 13.17%. Then, at 700 W/m^2 the THD was 13.09% and at 500 W/m^2 the THD was 13.07%.

Finally, when the insulation level was 200 W/m^2 the THD was 13.06%. It is clear that the THD levels decreases slightly with decreasing the radiation. This could be related to the decrease in the value of generated power, and consequently, a less distorted current will be delivered to the grid. The voltage waveform will behave to change as the current changes since current distortion is the cause of voltage wave distortion.

5.4 The effect of variation of temperature

One of the most important factors that affect the operation of all electrical devices is the temperature. The excessive increase in temperature causes less efficient operation of devices in general. Here in PV arrays, the temperature is one of the main dominant factors that affect the generated power by variation the efficiency of PV cells.

When running the simulation at a temperature of 30°C, the THD was found to be 13.22% and then, at 25°C it is found to be 13.3% after that, at 20°C the THD was 13.4% and at 15°C the THD was 13.44% finally, the THD was 13.55% at 10°C. Therefore, it is not difficult to conclude that the temperature decreasing causes an increase in the THD in the system. This is related to the characteristics of PV modules. When the temperature increases, the generated power will decrease, so less current delivered to the grid and then less distorted signal presented in the system.

CHAPTER 6

Conclusions and Recommendations

6.1 Conclusions

The power quality, in general, and harmonics in particular have become a sensitive measure of the system reliability. The economic losses associated with harmonic problems are in continuous increase. Therefore, the international trend in developing solar energy and spending huge investments in such field should be protected from the harmonic problems associated with PV systems.

The present work was a real assessment of the above problem and the analysis of the obtained results constitutes a good step in the right direction. By completing the present work, several conclusions have to be introduced.

Firstly, there is no alternative to the renewable energy solution for the energy problem in Jordan, at least for the near future. All studied options were not feasible for one reason or another. Among all renewable energy sources, the solar PV is the best candidate for the future energy industry in Jordan since the cost of 1kWh produced by photovoltaic systems is 0.12 JD which is relatively cheaper than fuel cost [32].

Secondly, the distribution systems, which will be as incubators for PV generators, have already some harmonic problems. Although these problems are still not dangerous, but they are in continuous increase and they might cause serious problems in future.

Thirdly, the present work has clearly illustrated that the connection of large scale PV to the distribution grid will significantly increase the THD level and will augment the problem of distribution system performance. The obtained level of THD exceeds the permissible limit for normal operating systems. Some individual odd harmonics were also high.

Fourthly, the impact of solar radiation and temperature on the harmonic spectrum and THD level was clear. The increase in radiation and the decrease in temperature lead to an increase in the output of the PV, which means an increase in the distorted current and an increase in the harmonic level. However, the change in THD was small in some cases due to the selected range of variation.

The interharmonics level was not so high and because no agreed international standards for such interharmonics, it is difficult to judge about its severity. The other noticeable effect of harmonics is the presence of DC components, which in some case was a reasonably high value. This reflects the distortion in the system which was significantly increased with the application of PV generation.

6.2 Recommendations

Upon studying the impact of PV connection to the distribution grid and the picture of obtained harmonics, several recommendations can be introduced to effectively and reliably utilize such type of renewable source.

Firstly, the harmonic spectrum should be studied thoroughly in terms of individual and total harmonic distortion patterns to design the suitable filter and eliminate unacceptable harmonics. Secondly, different PV capacities should be tested to measure the threshold value of THD and individual harmonic In this case, it is also useful to examine the different arrangement schemes of PV distribution on the various parts of distribution grid rather than connecting all PV capacity on one point. With increasing the level of PV penetration it is recommended to make a regular measure for the harmonics and non-linear load intensity in the system.

It is also recommended to conduct more assessments and measures with a wide band of temperature and solar radiation values to make the picture of harmonic impact more clear in the future.

Finally, the above topic should be given more interest and focus by all distribution utilities and to take the power quality issue in all evaluation procedures during the adaptation and installation of new PV systems.

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الملخص

بدور، مظهر عبد المهدي، "تحليل تاثير انظمة الخلايا الشمسية واسعة النطاق في نوعية الطاقة في شبكات التوزيع الكهربائية" 2012 (المشرف د.محمد حسن الزعبي).

تتناول هذه الاطروحه موضوع توليد الطاقة الكهربائية باستخدام الطاقة الشمسية والتي اصبحت احدى المصادر الرائدة في مجال التزويد بالطاقة الكهربائية بعد ظهور عدد من المشاكل المرافقة لاستخدام للوقود الاحفوري كمصدر للطاقة. وتم التركيز على استخدام الخلايا الكهروضونية لتوليد الطاقة الكهربائية وبعد ذلك تم ربطها مع شبكة الضغط المتوسط في جزء من شبكة التوزيع الكهربائية، وكنتيجة لهذا الربط الكهربائي تم تحليل ودراسة نوعية الطاقة الكهربائية المزودة من الخلايا الكهروضونية الى الشبكة الكهربائية.

تم دراسة وجود التوافقيات قبل ربط الخلايا الكهروضونية مع الشبكة ومن ثم مقارنتها بما اصبحت عليه بعد عملية الربط، حيث تم ملاحظة ارتفاع تشوة الموجة الكهربائية بشكل كبير مقارنة مع القيم المعيارية وتم دراسة مدى ارتفاعها عن المستوى المسموح به بسبب وجود الخلايا الكهروضوئية.

ان استخدام الطاقة الشمسية كمصدر مجاني لتوليد الكهرباء لا يخلو من وجود بعض المشاكل المرافقة خصوصا عند استخدامها بشكل واسع النطاق، مثل هذا النوع من المشاكل يظهر اثره في باقي اجزاء النظام الكهربائي بحيث تكون نوعية موجة الفولتية والتيار سيئة تؤثر في الاحمال الحساسة لردائة الكهرباء المقدمة لها ، وعليه، فإن هذه الاطروحة تتوقع بشكل دقيق هذه المشاكل بحيث يتم تفاديها في اي مشروع مستقبلي.

تمت دراسة نوعية الطاقة الكهربائية المزودة من قبل الخلايا الكهروضونية باستخدام برنامج متخصص في هذا المجال والمقارنة بين وجود وغياب الخلايا الكهروضوئية حيث لوحظ ان هناك ارتفاع كبير في تشوة الموجة الكهربائية بعد اضافة الخلايا اللكهروضوئية تؤدي الى تلوث كامل في اجزاء النظام الكهربائي.

لم يتم الاكتفاء بذلك بل تم استخدام النموذج المبني لدراسة تاثير الاشعاع الشمسي ودرجة الحرارة على نوعية الطاقة الكهربائية مما يعزز النتائج التي تم التوصل اليها ويدعم ما تقدمت به هذة الاطروحة.

تعتبر نوعية الطاقة الكهربائية من اهم الظواهر التي يتم دراستها في الانظمة الكهربائية خصوصا بعد زيادة الاحمال التي تستخدم دارات تحكم حديثة، وايضا استخدام اجهزة حساسة للتشوهات في الموجة الكهربائية تعمل الخلايا الكهروضونية كمصدر يزودنا بالتيار الثابت، هذا التيار يحتاج الى التحويل الى تيار متردد باستخدام العاكس الكهربائي الذي بدوره يكون اساس الربط بين الشبكة الكهربائية والخلايا الكهروضوئية، هذا العاكس الكهربائي هو السبب الرئيسي في التشوهات الكهربائية، ولكن تم التعامل معه في هذه الاطروحة على انه معامل ثابت اخذين بعين الاعتبار متغيرات اخرى.

ان البحث في هذا المجال كبير وحيثيات هذه الدراسة اكبر ولذلك فان ما توصلنا اليه في هذه الاطروحة هو خطوه في علم نوعية الطاقة الكهربائية.

الكلمات المفتاحية : الخلايا الشمسية، العاكس الكهربائي، نوعية الطاقة الكهربائية ، التوافقيات في الموجة الكهربائية ، التحكم بفولتية الطاقة المولده من الخلايا الشمسية.