THE REPUBLIC OF TURKEY
BAHCESEHIR UNIVERSITY

# VOLTAGE CONTROL OF A STAND-ALONE PHOTOVOLTAIC SYSTEM

**Master's Thesis**

**REZVANEH REZAEI**

**ISTANBUL, 2016**

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**Supervisor: Asst. Prof. Dr. Gürkan SOYKAN**

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I certify that this thesis meets all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Sadettin ÖZYAZICI
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This is to certify that we have read this thesis and we find it fully adequate in scope, quality and content, as a thesis for degree of Master of Science.

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# ABSTRACT

VOLTAGE CONTROL OF A STAND-ALONE PHOTOVOLTAIC SYSTEM

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Recently solar energy as a very important source is more noticed all over the world to generate electrical energy. All the time, researchers try to find cheap and useful method to utilize solar energy. Several systems can be used to convert this alternative energy to electrical energy. The conversion can be done either directly or indirectly. Photovoltaic (PV) panels are designed to take the solar radiation from the sun and generate electrical energy. Any PV system consists of this type of panel.

There are two types connection for the system; grid connected PV system and the stand-alone PV system. In this thesis, the voltage control on the stand-alone PV system was studied. The main components that build the basic structure of the system are PV panel, an inverter and a controller.

The proposed model for the voltage control was designed by using Matlab-Simulink environment. It is used to show the voltage control performance of the stand-alone photovoltaic system. The simulation results show how the voltage on the load terminals can be controlled in the stand-alone PV system.



**Keywords:** Solar System, PV System, PV Panel and Voltage Control.

## ÖZET


ŞEBEKEDEN BAĞIMSIZ ÇALIŞAN BİR FOTOVOLTAİK SİSTEMİN GERİLİM KONTROLU

Rezvaneh Rezaei

Elektrik Elektronik Mühendisliği

Danışman: Yrd.Doç.Dr. Gurkan Soykan

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Son zamanlar da elektrik enerjisi üretmek için güneş enerjisi çok önemli bir kaynak olarak tüm tünyada daha fazla göze çarpmaktadır. Araştırmacılar sürekli güneş enerjisini faydalı hale getirmek için ucuz ve kullanışlı bir yöntem bulmak için uğraşıyorlar.. Bu alternatif enerjiyi elektrik enerjisine çevirmek için birçok sistem kullanılabilir. Dönüşüm doğrudan yada dolaylı olarak yapılabilir. Güneş ışınımını güneşden alarak elektrik enerjisine çeviren fotovoltaik paneller tasarlanmaktadır. Herhangi bir PV system bu panellerden oluşmaktadır.

PV system iki çeşit bağlantı tipi vardır. Bunlar şebekeye bağlı PV sistem ve şebekeden bağımsız çalışan PV sistem şeklindedir. Bu tez çalışmasında, şebekeden bağımsız çalışan bir PV sistemin gerilim kontrolu konusunda çalışılmıştır. Sistemin ana bileşenleri PV panel, çevirici ve kontrollör dür.

Gerilim kontrolü için önerilen model Matlab-Simulink ortamı kullanılarak tasarlanmıştır. Şebekeden bağımsız olarak çalışan PV sistemin gerilim kontrol performansı Matlab ortamı kullanılarak gösterilir. Simulasyon sonuçları yük uçlarında gerilimin nasıl kontrol edilebildiğini gösterir.



**Anahtar Kelimeler:** Güneş Sistemi, PV Sistem, PV Panel ve Gerilim Kontrol.

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## FIGURES

# ABBREVIATION

| | | |
|---|---|---|
| AC | : | Alternating Curren |
| CSI | : | Current Sources Inverter |
| DC | : | Direct Current |
| GDP | : | Gross Domestic Product |
| GHG | : | Greenhouse Gases |
| GTO | : | Gate Turn-off Transistor |
| IEC | : | International Electro technical Commission |
| IEEE | : | The Institute of Electrical and Electronics Engineers |
| IG | : | Induction Generator |
| MOSFET | : | Metal Oxide Semiconductor Field Effect |
| MPPT | | Maximum Power Point Tracking |
| N | : | N Type Semiconductor |
| NOX | : | Nitrogen Oxide |
| P | : | P Type Semiconductor |
| PI | : | Proportional Integral Controller |
| PLC | : | Programmable Logic Controller |
| PM | : | Permanent Magnet |
| PV | : | Photovoltaic |
| PWM | : | Pulse Width Modulation |
| THD | : | Total Harmonic Distortion |
| SG | : | Synchronous Generator |
| SMPS | : | Switched Mode Power Supply |

# SYMBOLS

| | | |
|---|---|---|
| Angular Velocity | : | ω |
| Flux Linkage | : | λ |
| Inductance | : | L |
| Park Transformation Matrix | : | [ ] |
| Power | : | P |
| Resistance | : | Ω |
| Voltage | : | V |

# 1. INTRODUCTION

## 1.1. BACKGROUND

Providing new energy sources becomes very important issue for the developing countries. New researches show how energy consumption can affect on the level of development in the countries. Conventional energy sources are unreliable for the world demands. Environmental and air pollution, costly energy transformation are some other problems which can be solved by using renewable energy sources.

Renewable energy such as sunlight or solar, geothermal, wind, tides, water, biomass, hydrogen comes from natural sources without any limitation.

Solar energy is the most important energy source in the world. The light energy from the radiation of sun, in one hour supplies the earth’s consumption more than one year. One of the common methods of converting solar energy into electrical energy is using photovoltaic panels.

Nearly last two decades, the photovoltaic system has entered into the public life. Energy policy tries to find more economical way to get use of solar energy for the electricity production while it uses for heating, producing hot water, cooking, drying in the building without environmental pollution.

## 1.2. MOTIVATION

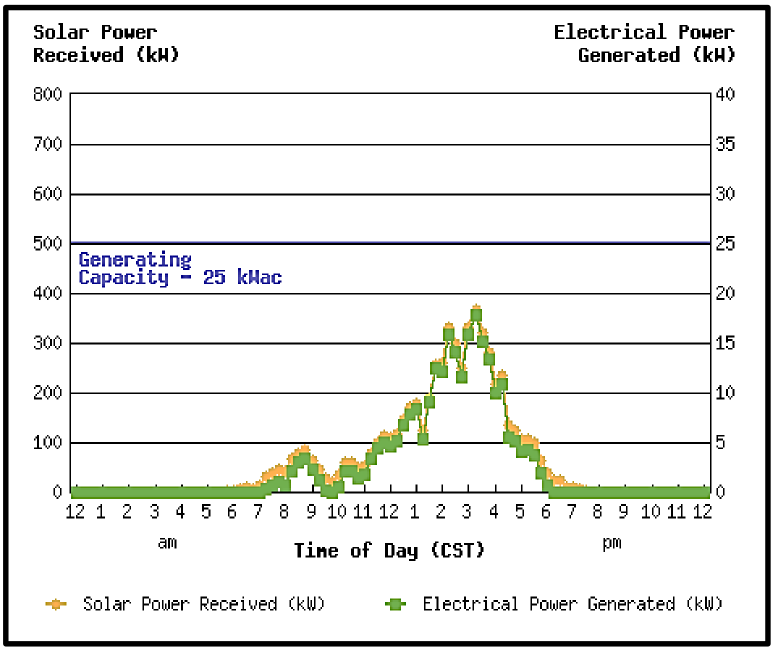
Solar energy has a widespread usage as an alternative energy source for providing feature demands. The PV systems are installed in all of over the world in order to produce electrical energy. Therefore, the optimization of the PV systems is important issue nowadays.

As an example, the department of Water and Power in LA considered a plan to install solar power systems on the roofs of buildings. Under the plan, 100,000 photovoltaic systems were installed on the roofs of buildings, both residential and commercial buildings in LA. These systems work in conjunction with the network and every building provides some part of its electricity consumption from this system. If the generated power is less than demands, the lack of electricity will be compensated from the utility power grid even at night, and if the buildings consumption is less than their producing, the excess energy will flow to utility power grid. The department imposed the following conditions to install solar systems on roofs of buildings:

a. Building should have one floor and the roof must be shingle.
b. Life cycle of building should be less than 10 years.
c. Free space on the roof should be at least 300 square meters and the slope of that between 10 to 25 degrees.
d. The roof slope should be in south or southwest, and between the hours of 11 am to 4 pm receive direct sun continuously.

Tennessee Valley Authority (VA) in Tennessee of America has done research on green energy. The range of energy production on the Cumberland Science Museum in a Day is 5/7 kWh. The amount of energy produced at this site is 146 kWh per day and its production capacity is 25 kW per day. The daily electrical production at this site is given in Figure (1.1).

**Figure 1.1: The curve of power generation in Cumberland Museum in US**




*Source*: Tennessee, World mark, Encyclopedia of the States, 2007

The usage of PV system depends on PV module' price and efficiency. For instance, the price per watt of crystalline silicon PV modules was 76.67 USD in 1977 compared to 3.00 USD in 2005. More recently, due to the mass production, a further decline has been observed in the price of PV module. In 2013 the price in per watt of similar PV modules was 0.74 USD.

The efficiency of solar cell (by using the ratio of electrical output power to the total light energy covers a cell) varies from 6% to around 40%. Using high efficiency cells is not always economically justifiable because of the production cost. Energy conversion efficiencies for commercial purpose available solar cells are around 14 to 19% 0. The designer of stand-alone system aims to convince customer satisfaction by finding a good designed durable system with more than twenty years' life expectancy. Depending on the usage of stand-alone PV system, the voltage contest gradually increases. The voltage control of a stand-alone photovoltaic system is handled in this study.

## 1.3. SCOPE OF THESIS

The target of this thesis is present to the voltage control method for three-phase stand-alone PV system with both theoretical analysis and simulation results. The ordered controller is applied in a three-phase stand-alone photovoltaic system and its performance is compared with a traditional PI proportional integer controller to regulate and control the output voltage.

Voltage control is done by designing the controller with dq0 method and sends the signal to PWM power inverter. In this design, harmonics that is resulted during the power conversion process should be prevented because of their negative effects on the loads in terms of power quality.

## 1.4. THESIS ORGANIZATION

The thesis includes seven chapters. In this chapter the objective and scope of this thesis are presented. In the second chapter the literature review is given. Third chapter topic followed by reviewing different type of PV system and the definition of stand-alone PV system, which is used in this thesis scheme. The chapter three is mainly about the components of photovoltaic system and the importance of voltage control in stand-alone PV system. To get the point of this thesis all of the important methods or function, which is applied in this scheme, are explained by meaning and applications. In the forth chapter the voltage control method in the stand-alone PV system is proposed by giving the explanation of connection between the functions. In the fifth chapter the simulation result in MATLAB program is presented by classified in a table. Chapter six explained summary of thesis content in the conclusion. Chapter seven shows the references include books and articles, which help this thesis to achieve the proposed scheme.

# 2. LITERATURE REVIEW

The research (A. Boue, R. Valverede, F. RuzaVila, and J. Ponce. 2012) focused on the three-phase single-stage in a grid-connected Photovoltaic system. In this study, a DC-AC inverter has been applied between the Photovoltaic modules and utility-grid. The inverter operates in the current controlled mode to verify a high-power factor. The output inductor filter is used to decrease the current ripples according to the switching in the operation.

In the study (M. Kazmierkowaski and L. Malesani, M. Kazemierkowski. Blaabjerg, 1998, 2002) several control methods have been proposed on grid-connected PV systems. Although these control method can reach the same goals, their performances are quite different. Three main controllers were investigated during the last few decades: linear PI regulators hysteresis, regulators and predictive dead-beat regulators.

This research (S. Buso and P. Mattavelli, 2006) shows that a PI controller will guarantee the tracking (zero tracking) error on constant signals, by applying the PI controller in the dq0 reference frame, with no additional provisions, has an ability to track the DC reference and the tracking error will be zero.

In several research studies, like, (M. Liserre, F. Blaabjergb, and A. DellAquilaa, 2004, S. Golestan, M. Monfared, J. Guerrero, and M. Joorabian, 2011, S. R. Nanndurkar and M. Rajeev, 2012, J. Selvaraj and N. Rahim, 2009, M. Ciobotaru, R. Teodorescu, and F. Blaabjerg, 2005, E. Villanueva, P. Correa, J. Rodriguez, and M. Paccas, 2009,) proportional-integral (PI) controllers are implemented in a PV system to control the AC part of currents.

In this study (H. Komurcuagil and O. Kukerer, 1999) a control loop controls the DC-link voltage, and a PI controller implemented on the DC voltage error to produce references for the AC current in the (abc or dq0) stationary or synchronous (dq0) frames. PI current regulators ensure the AC current by feeding in a grid.

In this research (X. Ye, X. Xia, J. Zhang, and Y. Chen, 2012) since PI controller has been largely used in the grid-connected PV systems, this controller will be benchmarked for this research to compare with the fractional order controllers. Fractional order controllers, which use fractional order operators in their structures, provides more robustness and more degree of freedom compared to the integer order controllers. Since solar radiation and ambient temperature variations have a fractional order dynamic.

This paper (Miyamoto Y, Hayashi, 2011, Alatrash H, Amarin RA 2012, Carvalho PMS, Correia, 2008, Liu X, Aichhorn A, Liu L 2012) demonstrates the voltage control capability of the PV. PV system can utilize both active and reactive power injection in controller. Based on this capability, many PV control strategies are presented.

In this thesis (Bae, Y, K., Kim, 2013) defined the control method in the grid-connected PV system. This control strategy is trying to find both the active and reactive power control, by neglecting the DC-link over-voltage.

These papers (Bouzelata Y, Kurt E, Chenni R, Altın N. 2015) Studies about an electric utility network in the three-phase grid-connected PV system. This method by using three-level control system in a separately active and reactive power exchange, Otherwise and by getting use of an newest model of control scheme which is based on PI regulators.

The study (Schonardie Mateus, 2012) has presented the modeling and control method by using of dq0 transformation in a connection with a three-phase PWM power inverter in a PV system, to find a dual function system to generate reactive power by connection with the loads in a system. Also the system filters the harmonics by applying the LC filter. A different input voltage technique is used to control the power thorough the grid connected and PV system to find and get the maximum power point operation.

In the study (Orawan Phochai, Weerakorn Ongsakul,2010) the reactive power has an effect in PV system to increase the voltage more than maximum range by using four different voltage strategies to limit the voltage. These strategies by using PI inverter try to find a best control way for the active and reactive power. The voltage limitation automatically by utilizing a combined structure of dynamic power method is suitable to control the voltage.

The study (.Layate T,Bahi, I. Abadlia, H. Bouzeria, S. Lekhchine, 2015) to control and find the effective value of power in PV system some techniques are used in a power system which are based on the d-q components control by utilizing the PI controller.

In this study (Xiao Liu, Aaron M. Cramer, Yuan Liao, 2015) inverters are used to substitute the reactive output power by controlling the fluctuations in the solar power. This method is designed the controllers with using the 123-bus IEEE feeder distribution system, to mitigate voltage magnitude fluctuations. The output reactive power is a linear function in the solar energy and scope to describe the control parameters. This method only needs local information to find a high quantification and compare the performance of the system. These controllers feed the distribution system by using three different methods, including different degrees and distributions of PV penetration. It is proved the reactive power control strategies decrease voltage magnitude frequency, voltage magnitude variation and severity.

This paper (Refdinal Nazira, Kiki Kanadaa, Andalas, 2015) uses the simple method to control power reactive and voltage in grid connected PV systems. Two variables; one of them output voltage of the inverter and other one the angle of power, are defined as the roots with two simultaneous. Newton Raphson method is used in this study to gain the maximum and minimum reactive power. In this model, PV modules type of ND T060 with a fixed capacity is used.

This method (Umer Asif, Badar Bashir, Bilal Masood, 2013) designed, and modeled to evaluate its performance and (PI) controller to control the output voltage. Stand-alone systems are used in a design of renewable energy system for areas without connection to the electric grid. The target of this study is to find a reliable autonomous system with the optimization of the components. The working and performance of standalone photovoltaic system is discussed in this study.

In this article (Liu Jie, Liu Sanjun, 2010) a stand-alone PV System is proposed to push-pull the output of system. This system is included of PV panel, charger, battery and inverter. Closed-loop control strategy is simple and has an impressive effect to improve efficiency of system. This paper shows a new kind of push-pull output independent PV power circuit, which uses PWM modulation and closed loop (CL) control methods.

In this paper (Ali Najah Al-Shamani1, Mohd Yusof Hj Othman, 20121, S. Mat, M. Ruslan, Azher M. Abed,K, 2011) by selecting the equipment's in a stand-alone photovoltaic system based on the Watt-Hour demand. Every piece of equipment that used in the system has also been presented to explain the controller method.

This thesis (Chandrashekhar N. Bhende, 2012) studied on PV system based on pumping system without battery for more economical purpose. In this study an integrated controller is proposed in a stand-alone PV system with two controllers (power and voltage based). The inverter, controls the voltage, also acts as maximum power point tracker and doesn't need DC converter to extract maximum power because inverter itself acts as MPPT circuit. The integrated controller requires only measurements of dc-link voltage.

(S.S. Kumar, G. Dharmireddy, P.Raja S.Moorthi, 2013) The output of the PV panel is unregulated by the DC supply according to the changes in weather condition. The maximum power track is found by using DC-DC converter in a diffrent temperature and irradiance levels. The observation algorithm is implemented to find a maximum power point tracking purpose. This algorithm is found due to its ability to withstand adverse any parameter variation by a high affection. The output of DC-DC converter is utilized to convert the AC voltage in inverter. The AC output voltage and frequency are regulated and controlled in the closed loop controller by controlling the inverter and applying unipolar sine wave pulse width modulation

This research (Afshin Samadia, Mehrdad Ghandharia, Lennart Söder, 2012) is used the comprehensive model by plan a PV model controllers including parameters tuning. Two different model of reactive power is developed in PSCAD and integrated by two PV systems in a distribution system. This method is showing three different reactive power regulations and the dynamic effect of them on the system. It is also proved the lack of coordination between PV systems at the set point in AC bus voltage regulator, which causes the interaction when PV system is installed negatively.

# 3. PHOTOVOLTAIC SYSTEMS

In 1839, Becquerel has found that the light of sun could be converted directly to the electricity by observing the photo galvanic effect. Then, in 1876, Adams and Day found that selenium has photovoltaic properties. Chapin, Fuller and Pearson developed the first solar cell was in 1954. After four years, the first solar cell was implemented on the Vanguards I orbiting satellite 0.

## 3.1. SYSTEMS OF CONVERTING SOLAR ENERGY TO ELECTRICAL ENERGY

The energy from sunlight can be converted into electrical energy by using special technologies. These technologies are divided into two main categories:

a. Photovoltaic (PV) systems

PV system is the most popular system that converts the suns energy into electricity. General facilities of this system are solid and immobile (except in the case of sun-tracking system). This is a safe, reliable and low-maintenance source of electricity without any pollution or hazardous waste. Photovoltaic system made up photovoltaic array and an inverter. Photovoltaic panel is composed of solar cells (photovoltaic cells) that generate the electricity.

b. Solar thermal systems

Solar thermal system is used to generate electricity. In this type of systems, energy is concentrated light of the sun directly to generate heat. Solar thermal panel (collector) is the main component of the system. Solar thermal panel traps the heat from the sun then heats water or heat-transferring fluid like molten salt to generate steam in the glass panel and spin the turbine and generate electricity. To absorb the maximum energy from the sun, the glass panel is painted black. Structure and position of this panel help to absorb the maximum sunlight during the daytime.

## 3.2. TYPES OF PV SYSTEMS

PV systems are categorized due to their operational, requirements and their connection to other power sources and electrical loads. The types of PV systems are grid-connected systems or (utility-interactive system), stand-alone systems and hybrid systems.

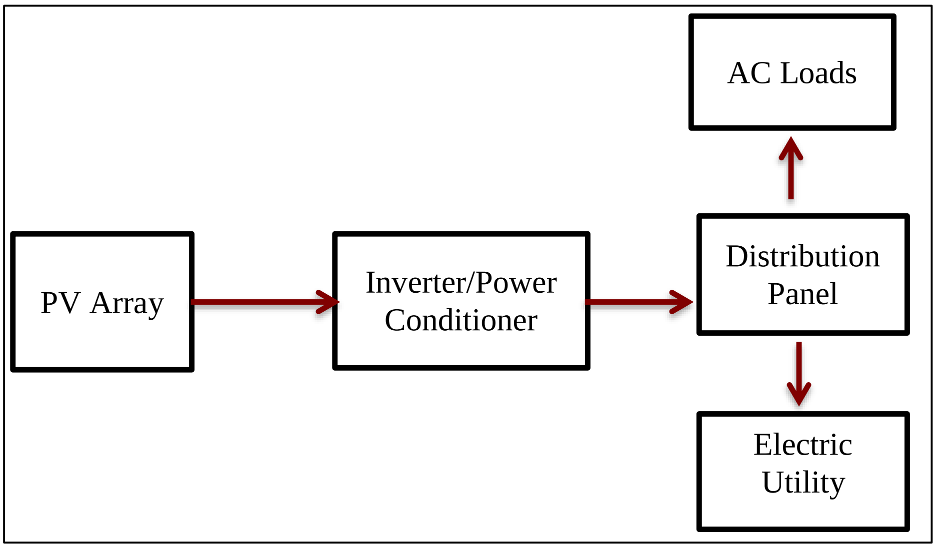
### 3.2.1. Grid-Connected System

Grid connected or utility-intertie PV system is generally designed to work in parallel with and interconnected with electric utility grid to provide specific DC and/or AC electrical loads. The PV systems also are connected to the other energy sources and storage system. The simplest type of this one is a direct-coupled system, which is connected to the DC load directly at the output DC port of PV array. The simple grid- connected system includes inverter to convert the DC power to AC power consistent with the voltage and power quality in the utility grid connection. The inverter doesn’t supply power when the utility grid is not energized. At nighttime while electrical demand is more than the PV system output, electric utility in grid-connected keep the balance of power grid. Moreover, Photovoltaic systems cannot operate and feed back in the utility grid when the grid is in a down situation.

However, these larger 'grid-connect' models will often need an expensive 'MPPT' charge controller to convert the high PV voltages to charge an off-grid battery bank. If a standard PWM controller is used, much of the power can be wasted.

Other than the size and electrical specifications, there is little or no difference between most on-grid and other types of PV systems. When PV panel gets really hot, voltage drop occurs in the output voltage. In fact, PV panel is used more efficiently in a cool climate.

**Figure 3.1: The diagram of three-phase grid-connected in PV system**

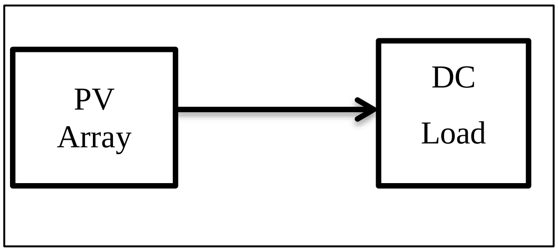



*Source:* Book, Dennis J hall, Nina M Giglio /2010

### 3.3. Stand-Alone Systems

A stand-alone system is designed to work without connection to the electric utility grid this system supplies the energy to DC and AC electrical loads. The primary model of this system is direct-coupled one where the output of PV panel is connected directly to DC load. Many photovoltaic systems operate in stand-alone mode. It's more simple and affordable to design the system without battery backup. This system is easily used in remote locations for daily and seasonal DC loads.

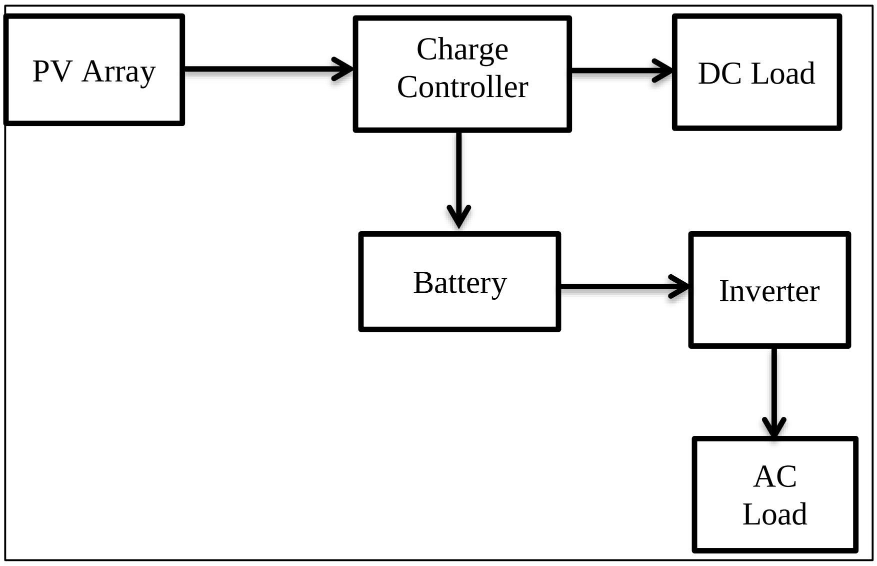
**Figure 3.2: The diagram of the directed coupled system**




*Source:* Book, Dennis J hall, Nina M Giglio, 2010

The stand-alone system includes the energy storage consists of PV panel, controller, battery charge, inverter and load. Affordability, reliability and flexibility are the benefits of the stand-alone system. System with battery backup provides power to the loads as long as the battery charge is above a minimum charge level. This system is more complex to design because of the daily and seasonal variation of irradiation and the energy consumption profile 0. Some stand-alone systems without battery provide power to the load only during sunlight hours, water pumps, and small circulation electrical pumps in solar thermal water for heating system. The electrical load has direct connection to the maximum output power of the PV panel as a critical section of designing. The figure (3.3) indicates the diagram of stand-alone system by using energy storage device.

**Figure 3.3: The diagram of Stand-Alone three-phase system by using the storage device**

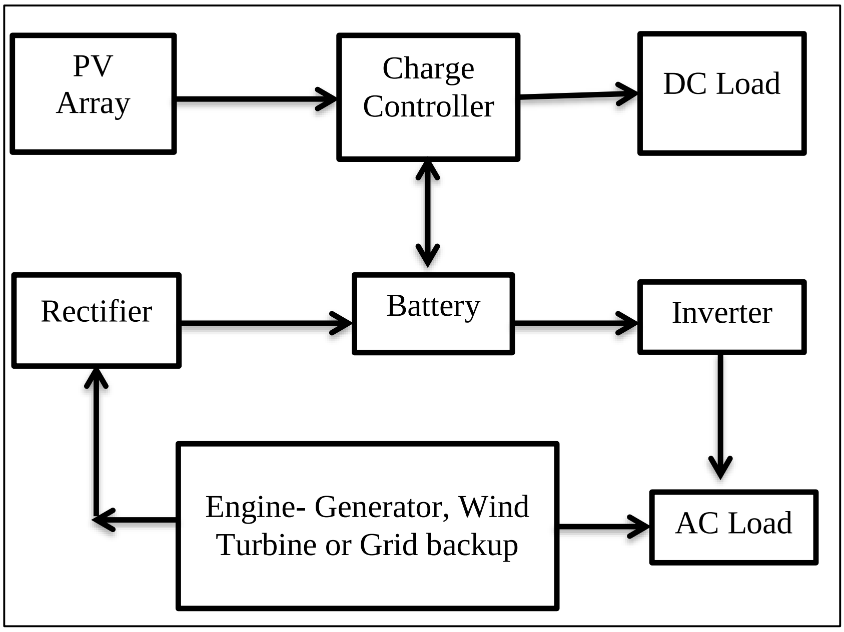



*Source:*Book, Dennis J hall, Nina M Giglio, 2010

### 3.3.1 Hybrid system

The PV system that incorporates hydro wind turbines or diesel generators is called as a hybrid system. Hybrid system is one type of supplying electrical power in remote areas without any connection to power grid. This system integrates two or more power generation sources. This type of system eliminates problems associated with both PV and diesel stand-alone systems. (Hybrid systems use more than one method to provide electricity).

**Figure 3.4: The diagram of hybrid system**




*Source:* Book, Dennis J hall, Nina M Giglio , 2010

## 3.4. COMPONENTS OF PV SYSTEM

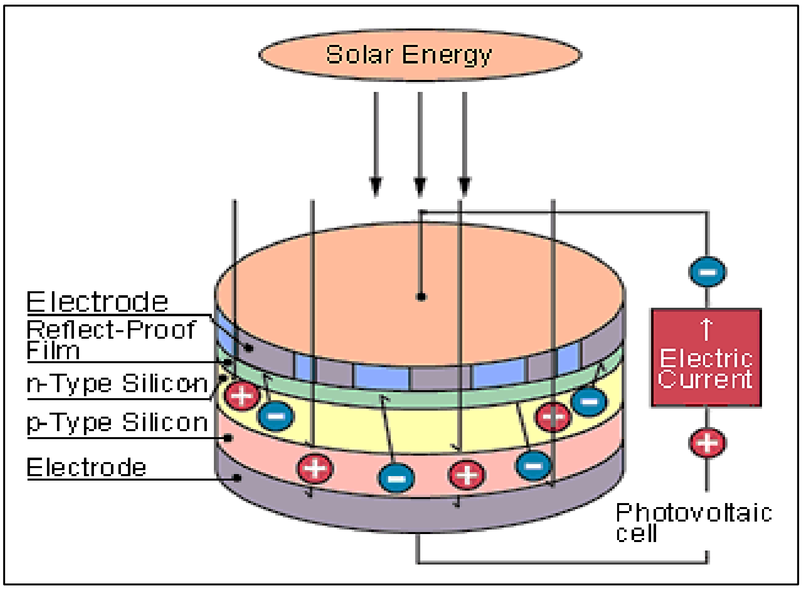
Each types of the PV system have several components that can be use by consideration the individual needs, climate effect, site location and expectations. This chapter reviews the components structure and some necessary definitions. Every PV system should have a PV array and load, so the stand-alone one is also includes PV array, load, inverter, filters, and controller.

### 3.4.1 Photovoltaic Panel

Photovoltaic panel is a main part of any photovoltaic system. It converts the sunlight into DC current and voltage. Photovoltaic panels, which are exposed to the sun, are composed of photovoltaic cells. The cells are made of semiconductor material silicon. When sunlight hits a photovoltaic cell, electrons will make more energy, with solar radiation, electrons polarize in the semiconductor; negative electrons arise in N-type silicon and positive ions arise in P-type silicon. The current flows between the two electrodes because of the potential difference. Figure (3.5) shows the process of electricity generation in a photovoltaic cell.

Solar panels are made against the entire hardships situation like severe cold polar, desert heat, tropical humidity and high-speed wind. However, these devices are made of glass and may break due to heavy blows.

**Figure 3.5: The process of electricity generation in a PV cell**




*Source*: Book, Dennis J hall, Nina M Giglio , 2010

### 3.4.2 Inverter

Most solar panels provide 12 V DC power and household devices use 120 V AC power this is a purpose of using inverter in PV panel. An inverter in the photovoltaic system is an electrical circuit capable of converting DC power to AC power with either single-phase or three-phase out put voltage while regulate the voltage, current, and frequency of the signal at the same time. The input DC power is fed by solar cell. The output voltage AC can be variable or fixed by applying electronic devices in the structure of inverters. This conversion will be done by controlled turn on and turn off devices like (IGBT, FET, MOSFET, BJT, e.g.). In an ideal inverter the output voltage waveform should be sinusoidal but in a practical one voltage waveforms however non-sinusoidal and contain harmonics. Switching technique of semiconductor device can minimize these harmonics. The resulted rate of semiconductor device, which can be switched on and off by implementing the inverter control circuitry determine the inverter's output frequency.

Changing the amplitude and frequency of the output voltage with low distortion is the main feature of the inverter. Inverters have various structures, shapes and sizes for different purposes with an output from 50-5000 W. Figures (3.6), (3.7) and (3.8) indicate the simple structure of a single-phase and a three-phase inverter.

**Figure 3.6: Simplified circuit schematic for an inverter**

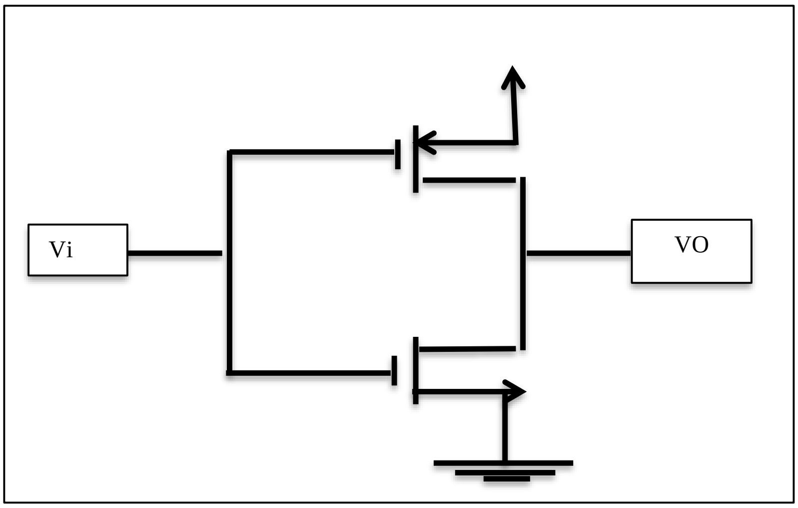
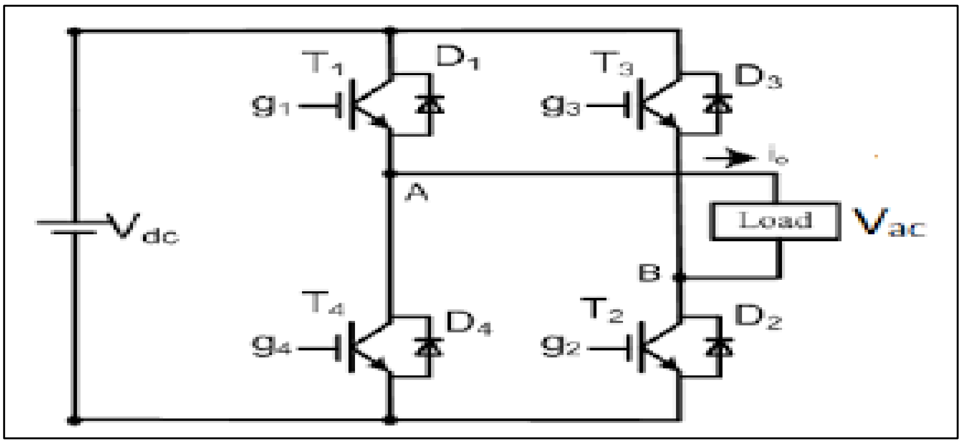
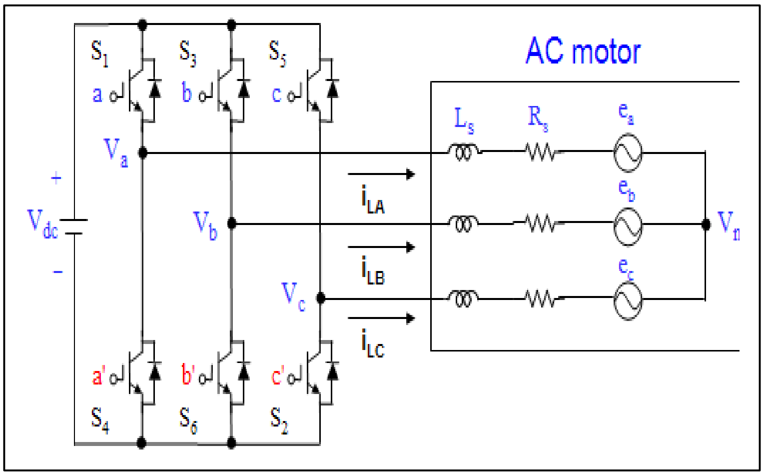



**Figure 3.7: The structure of an IGBT based single-phase inverter**




*Source*: Design and implementation in a specific grid-tie inverter Paper, H.Abdar· May 2012

**Figure 3.8: The structure of an IGBT based three-phase inverter**




*Source*: Phase Voltage Source Inverter book, ali keyhani

## 3.5. PWM INVERTERS

Pulse Width Modulation is used in an electrical system as a way to control voltage digitally. This type of inverter pulses voltage rapidly by reducing the voltage to catch the desired and suitable voltage for the system. The output voltages can be adjusted by changing in amplitude, frequency and voltage phase.

The input voltage of PWM is a DC voltage and the output voltage of PWM is AC voltage. PWM is fed by constant DC voltage to produce pulse. Therefore, the feeder source uses the DC voltage. It can be connected to the inverter directly. In the case of applying AC voltage sources in the system, the diode bridge inverter should be connected in the way between PWM and AC source.

The important parts of a PWM signal are period and its duty cycle. The duty cycle determines its voltage. The period length determines the device plan by finding the higher frequency. PWM pulse width modulation describes a digital signal, which is used in applications with a sophisticated control circuitry.

There is a defined mathematical relationship to measure and find the specific amount for breaker pressure in a duty cycle. The important duty of this controller is how to find the best control way in the digital system during an analog signal with different amplitude, changing DC to AC voltage and reducing harmonic and distortion.

There are several methods to generate pulse width modulation in PWM inverters such as PWM sinusoidal method, PWM uniform sampling method and optimal PWM method. Sinusoidal PWM techniques and uniformity is implemented in an analog circuit and the optimal PWM method needs to be controlled by microprocessor. This inverter controls the voltage by the output-based microcontroller. Microcontroller bases are defined as zero and one in order to create a voltage difference.

### 3.6. SINUSOIDAL PULSE WIDTH MODULATION

In this modulation, the width of all pulses is same. Pulse width is changed at the middle of the sine wave pulse due to the amplitude of the evaluated sine wave.

In the voltage source inverter, by turning on and off the switches, the required pulse can be gained. The simplest waveform is the square one, which is resulted by turning on the top switches in a cycle. To find the desired modulating signal with high frequency, the resulted signal should compare with a triangular carrier wave. DC voltage will apply at the output depending on the comparing result between carrier waveform and signal voltage waveform. Over the period of one triangle wave, the average of applied voltage is the proportional to the amplitude of the signal.

Three voltage references $V_a$, $V_b$, $V_c$) with a variable domination (A), in triangular carrier wave ($V_t$), with domination ($A_m$) are compared by three comparators. It is shown in Figure (3.10) and (3.11). The output results of three comparators are control signals that are connected to the three legs. Each leg includes one pair of switches such as; the switches ($S_5$, $S_2$) is formed in the third leg, switches ($S_3$, $S_6$) is formed in the second leg and switches ($S_7$, $S_4$) is formed in the first leg.

The switches ($S_7$, $S_4$) control the voltage of phase A in a system while it is connecting to the inverter. Phase A is defined depending on the middle point of DC source which is called O. Figure (3.11) shows the reference wave ($V_a$) with the career voltage ($V_t$) are compared in the first comparator.

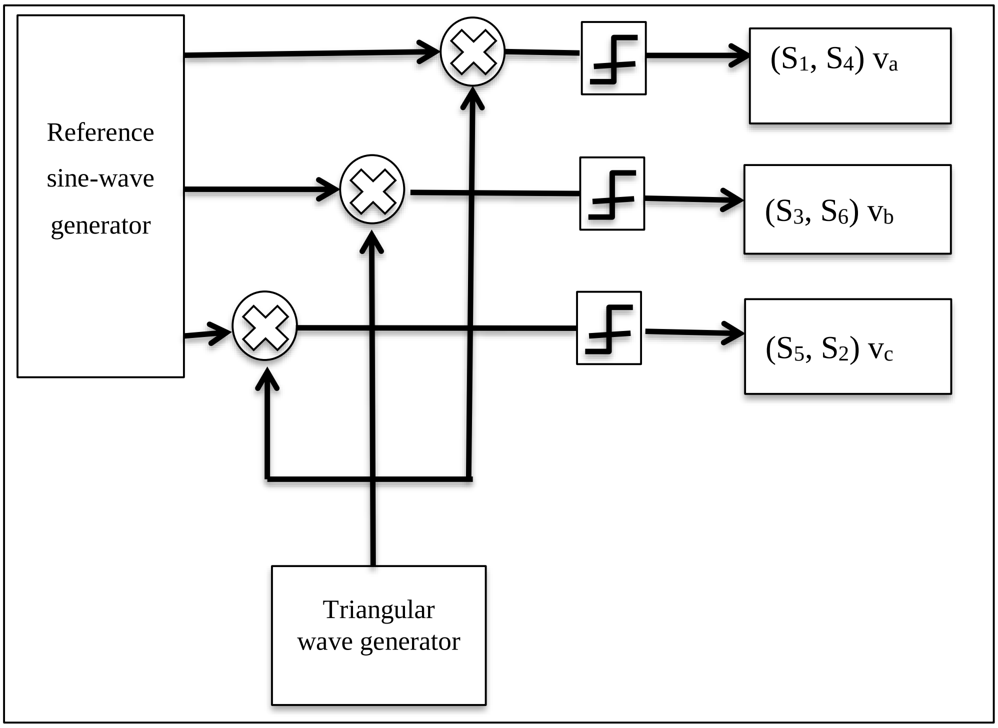
When ($V_a$) is greater than ($V_t$), the command signal will send to the switch ($S_1$) and when ($V_a$) is smaller than ($V_t$), the command signal will send to the switch ($S_4$). The resulted waveform ($V_{ao}$) is equal to the half period of the signal.

Figure (3.11) shows the waveforms when the reference wave cycle is symmetrically equal to twelve cycles of triangular wave. In the same way, ($V_{bo}$) and ($V_{co}$) by considering the situation of the switches ($S_3$, $S_6$) and ($S_5$, $S_2$) are obtained.

The above scheme is called sinusoidal PWM because the pulse modulation is a sinusoidal function of the pulse angle in a period. This modulation is called triangular modulation or PWM modulation.

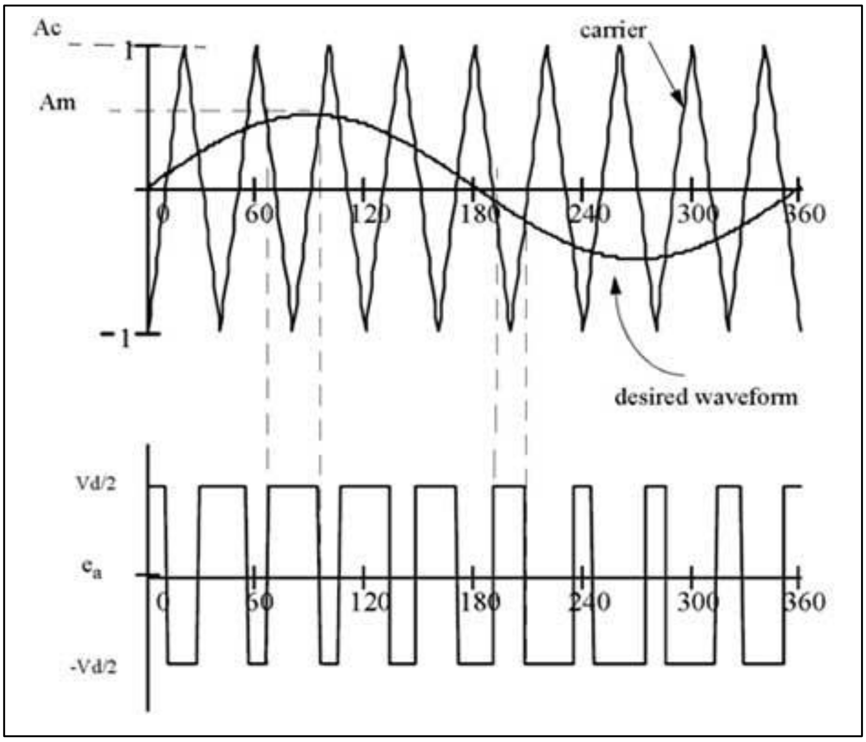
Voltage ($V_{ab}$) is obtained by subtracting ($V_{b0}$) from ($V_{ao}$). In the same way voltage ($V_{bc}$) and ($V_{ca}$) can be obtained. Figure (3.12) shows the waveforms when each cycle of reference wave includes six triangle cycles.

**Figure 3.9: Sinusoidal Pulse Width Modulation**




*Source*: The Journal of Scientific & Engineering Research, 2012

**Figure 3.10: Sinusoidal Pulse Signal**

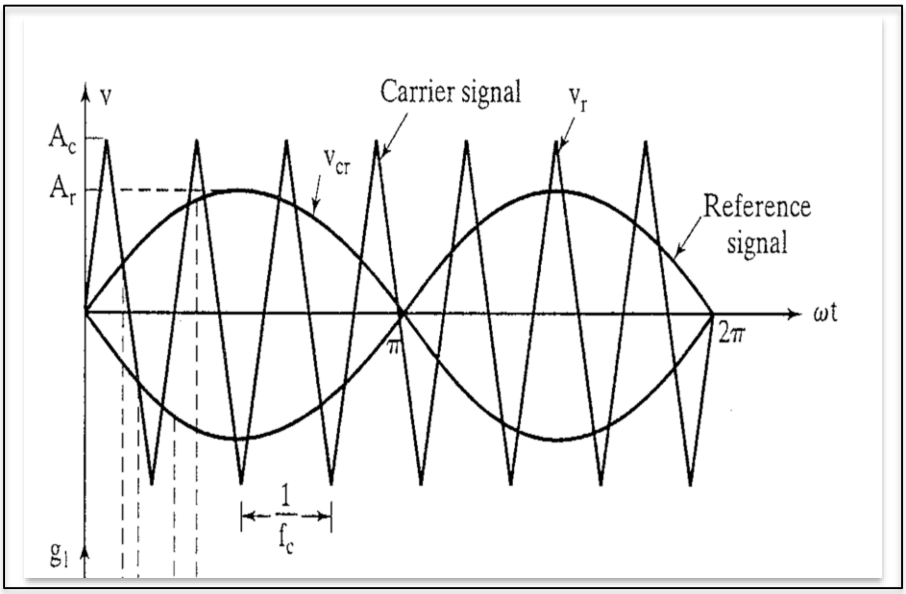



*Source*: The Journal of Scientific & Engineering Research, 2012

Modulation index (m) is defined as the ratio of $A_m$ to the amplitude of the triangular carrier $A_c$. Equation (3.1) shows it.

$$m = \frac{A_m}{A_c} \quad \textbf{(3.1)}$$

**Figure 3.11: Principal of career wave in Pulse Width Modulation**




*Source*: The Journal of Scientific & Engineering Research, 2012

Generally, in three-phase power systems, the ranges of switching frequencies are designed between 2 to 15 kHz.

$$\frac{f_c}{f_m} = 3k, k \in N \quad \textbf{(3.2)}$$

The effective value in a waveform ($V_{ao}$) is calculated as bellow equation.

$$V_1 = \frac{mV_d}{2\sqrt{2}} \quad \textbf{(3.3)}$$

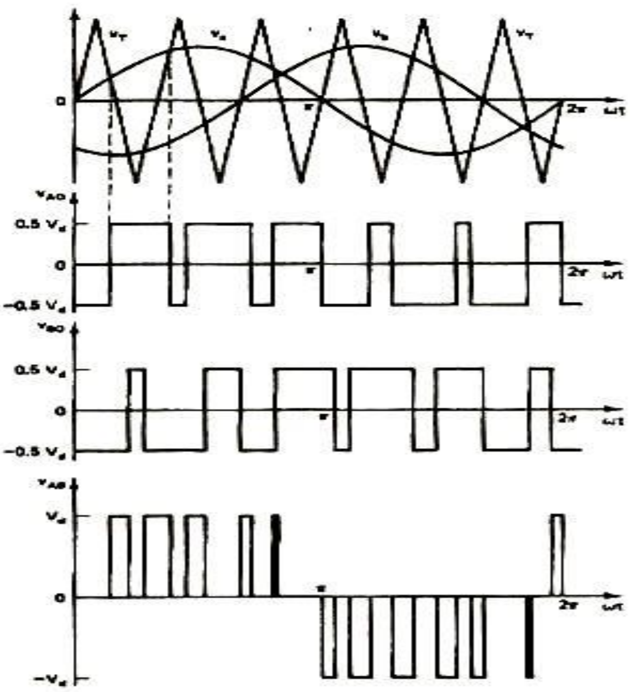
The main component of (rms) value linearly increases by changing m. At the point of modulation index equal to two (m=2) the domination of the reference voltage will be equal to the carrier voltage. If modulation index larger than one (m> 1) the number of (Vao) pulses will decrease and modulation is not be as a sinusoidal PWM form any more.

The waveform of (Vao) has the odd-integer harmonic frequencies in the ($f_c$) waveform equation (3.2). The even-integer harmonics of ($f_c$) are equal to zero. Their waveform frequency is calculated by using equation (3.4).

$$f_h = kf_c \pm kf \tag{3.4}$$

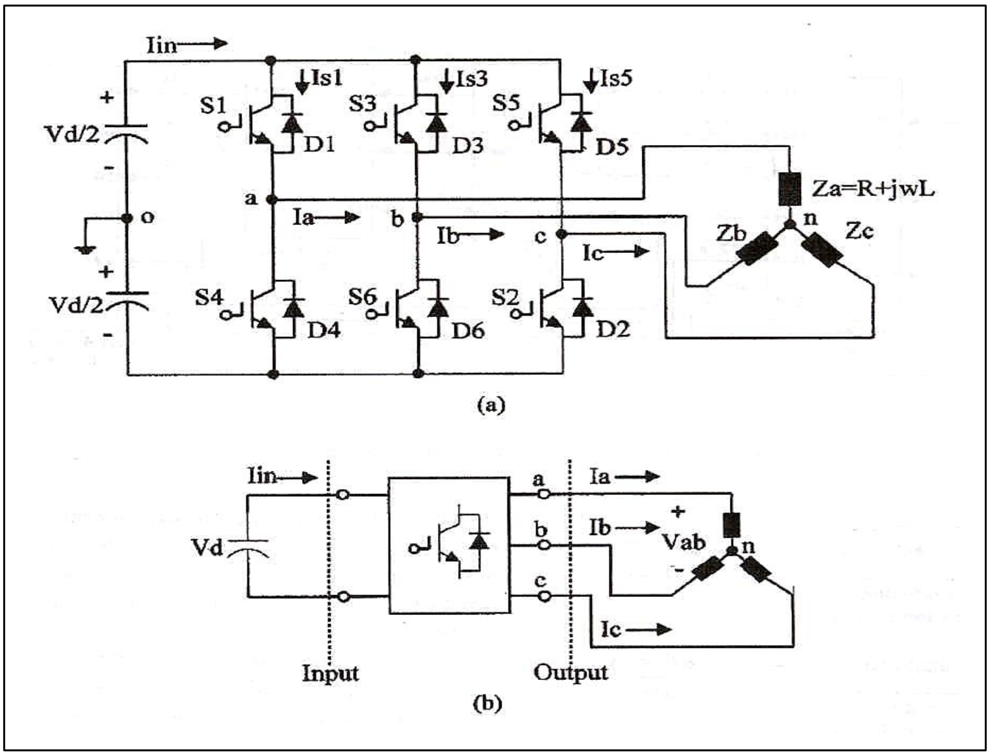
In the equation (3.4), the fundamental harmonic is called ($f_h$) and the reference frequency is called (f).

**Figure 3.12: Sinusoidal Pulse Width Modulation**



*Source*: The Journal of Scientific & Engineering Research, 2012

**Figure 3.13: View of an inverter connected to Load**




*Source*: International Journal of Scientific & Engineering Research, 2012

The different input and output result of AC and DC voltage due to the inverter performances can be found. Up to these resulted input and output, the transfer function is considered. With this selected controller strategy, the transfer function made up with switching functions to show the relationship between the input and output variables. In fact, the result of transfer functions is used to calculate the dependent variables and independent variables. For example, the output voltage of inverter is a dependent variable that can be calculated regards to transfer function, based on input voltage, which is an independent variable.

## 3.7. PWM INVERTER VOLTAGE CONTROL

The methods of output voltage control in PWM inverters are divided into two categories:

I. Input DC voltage control
II. Output AC voltage control by using multi-inverter

### 3.7.1 Input DC Voltage Control

Changing the input DC voltage can control the output voltage. Placing a chopper between source and inverter changes the input DC voltage in the inverter.

### 3.7.2 Output AC Voltage Control By Using Multiple Inverter

Summing output voltages of two six-step inverters can change the main components of the output voltage. If the phase difference between the signals is defined as $\phi$, the phase difference between the output voltages of inverter is also $\phi$. By controlling $\phi$, from zero to 180 degrees, the main components will change from highest value to zero.

## 3.8. PID CONTROLLER

PID controller is defined as a closed loop control system. The system is mostly designed as single-input and single-output (SISO). In this control system, P is a function of proportional to the signal, I is a function of proportional to the integral of the signal and D is a function of proportional to the derivative of the signal.

$K_p$, $K_i$, and $K_d$ are defined as gains of the controller. $K_p$ demonstrates the gain of proportional element. It reduces the rise time but a steady-state error occurs and the proportional element in the controller doesn't eliminate it. $K_i$ shows the gain of integral element. It eliminates the steady-state error but it makes the transient response worse.

$K_d$ represents the gain of the derivative element. It decreases the overshoot, increases the stability of the system and improves the transient response. By implementing proportional and integral elements together, the system response will become more oscillatory but it needs longer settling time to disappear the steady state error. By implementing $K_p$, $K_i$ and $K_d$ controllers all design specifications will be reached.

PID control handles step changes to the set point especially in the bellow situation:

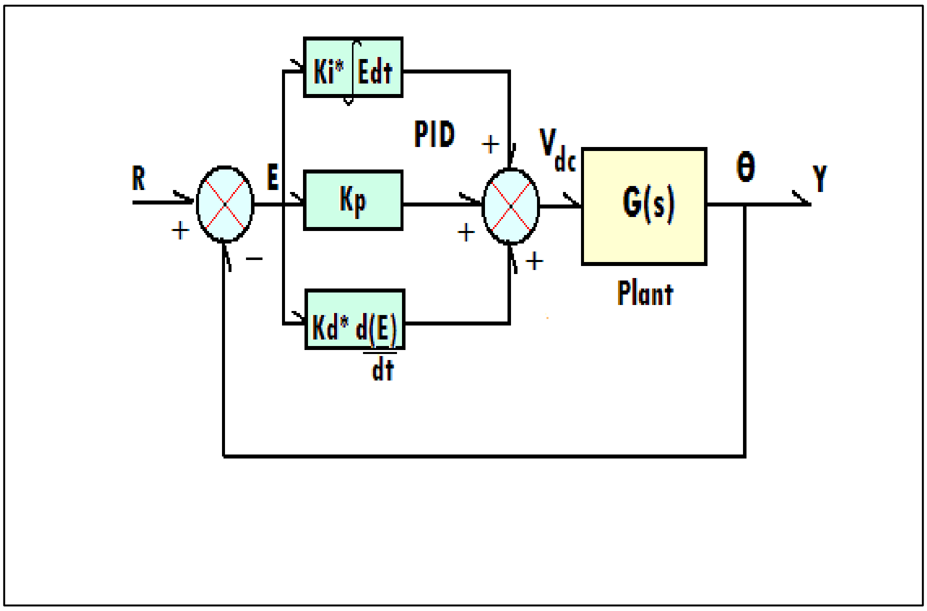
a. Fast Rise Times

b. Little or No Overshoot

c. Fast Settling Time

d. Zero Steady State Error

**Figure 3.14: Schematic of PID controller**




*Source:* Book of Digital Control System Analysis and Design, Phillips & Nagle 1995

The characteristics of PID controller depending on gains are given in table (3.1). $K_d$ has a direct effect on damping and $K_p$ has a direct effect on resonant frequency.

**Table 3.1: Characteristic of a PID controller**

| Closed Loop Response | Rise Time | Over Shoot | Settling Time | Steady State Error |
|---|---|---|---|---|
| $K_p$ | Decrease | Increase | Small Change | Decrease |
| $K_i$ | Decrease | Increase | Increase | Eliminate |
| $K_d$ | Small change | Decrease | Decrease | Small change |

A designing PID controller should be included of these tips:

a. An open-loop response and determine what requires to be improved.
b. A proportional control to improve the rise time.
c. A derivative control to improve the overshoot.
d. An integral control to eliminate the steady-state error.
e. Adjust each of $K_p$, $K_i$, and $K_d$ or catch the desired overall response.

For the single system, implementing all three controllers is not used in all situations, which means if system receives the enough response from PI controller, then derivative controller can be missed.

### 3.8.1 PID Tuning Method

Regulation of control parameters to catch the correct response for the control system is called as tuning. There are many type methods for PID tuning such as:

a. Manual tuning
b. Ziegler
c. Nichols tuning
d. PID tuning software

Manual tuning method is used in this presented system. In this simple method parameters are adjusted by trial and error that means $K_p$, $K_i$ and $K_d$ are changed till to find the desired response for the system. Even working with this simple method should be used by experienced personal.

Firstly, $K_P$ and $K_d$ are set to zero then $K_p$ should be increased up until the output of the loop oscillated. After finding the optimum $K_P$ value, $K_i$ must be set to half of the value in the quarter amplitude decay type response. Then $K_i$ is increased to find any offset correction in specific time. If $K_i$ is increased too much then system will be instable. At the end, $K_d$ will be increased until loop reach to its reference after a load disturbance. Also if $K_d$ is very large number, it causes excessive response and overshoots.

## 3.9. IMPORTANCE OF VOLTAGE CONTROL IN PV SYSTEM

Voltage control as an important topic in all power systems, control the daily changes in load, network and generation. Kundur (1994) shows the important roles of voltage control in a system as: “voltage at the end point of all equipment in the system must be kept within acceptable limits, to keep the malfunction and damaging effect away from the equipment”. The voltage control is totally divided due to its priority into the normal, emergency state and preventive.

There are several methods of voltage control and in all methods; loads change the value of voltage. Some methods of voltage control in an AC power system are defined as bellows:

a. Excitation the control
b. Using tap changing transformers
c. Autotransformer tap changing
d. Booster transformers
e. Induction regulators

Load changing in the system causes the voltage changing in a customer system. For example, lamp is as sensitive equipment with voltage changing. In this case, if the supply voltage is more than the normal range, the operation of system has effects on magnetic circuit and causes the huge magnetic current, heating and low power factor. On the other case, if the voltage is too low, it can decrease the starting rotation in the motor considerably.

Voltage variation in a power system should be standard to minimum level for having the high quality delivery in consumer services. 0.

### 3.10. HARMONIC IN PV SYSTEM

Harmonic is a sinusoidal voltage and current, with frequencies integer multiples of the fundamental frequency. It is combined with main components of current/voltage that cause distortion in the waveform. Harmonic distortion is an effect of nonlinear characteristics of devices and loads in the power system.

In an ideal power grid, the electricity is transmitted as a sinusoidal voltage and current in a constant frequency and specified voltage levels to the consumption center. But in real, the non-linear characteristic elements and equipment like fact devices in different parts of production, transfer and consumption causes some harmonic distortion in sin waves of voltage and current.

The inverters in photovoltaic system during changing the voltage form from DC to AC cause some output harmonics. For this reason reduce and eliminate harmonics in the power system should be considered as an important issue in circuit designing.

Some of the adverse effects of harmonics on power systems classified as below:

a. The failure of capacitor banks due to failure installation or excessive falling reactive power.

b. Interference with distortion control systems and PLC, and in the absence of proper operation of these systems that perform actions such as switching function remote control and time measurement.

c. The additional losses and high heat generation synchronous and induction motors.

d. The insulation fault in the cables for harmonic voltages in the system. Interfere with communication systems.

e. The error in the measurement of electrical energy during the operation in the induction method.

f. Relay performance, especially in static systems and microprocessors.

g. Interference in the large engine control systems and excitation systems in power plants.

h. Mechanical oscillations synchronous and induction motors.

i. Unstable output in a fire circuits, act like the zero point voltage detection in circuits.

# 4. PROPOSED VOLTAGE CONTROL SCHEME IN THE STAND-ALONE SYSTEM

In this chapter, each block of the proposed voltage control scheme in stand-alone PV system and some using functions are explained. The way of how these blocks are connected is shown to understand better of this scheme.

The system consists of the PV array, DC low-pass filter, PWM inverter, AC low-pass filter, loads, switches and the proposed controller scheme. The proposed controller scheme includes some blocks such as park transformation, PID controller and the inverse park transformation.

## 4.1. PARK TRANSFORMATION

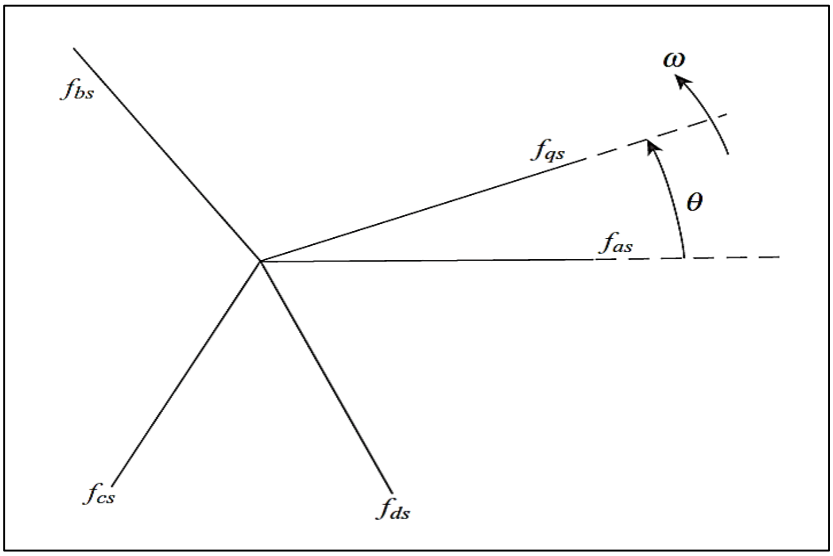
Several mathematical transformations are used to simplify the analysis of the electrical system.

The most useful transformations in the electrical systems are:

a. Fortescue symmetrical components
b. Clarke transformation
c. Concordia transformation
d. Park transformation

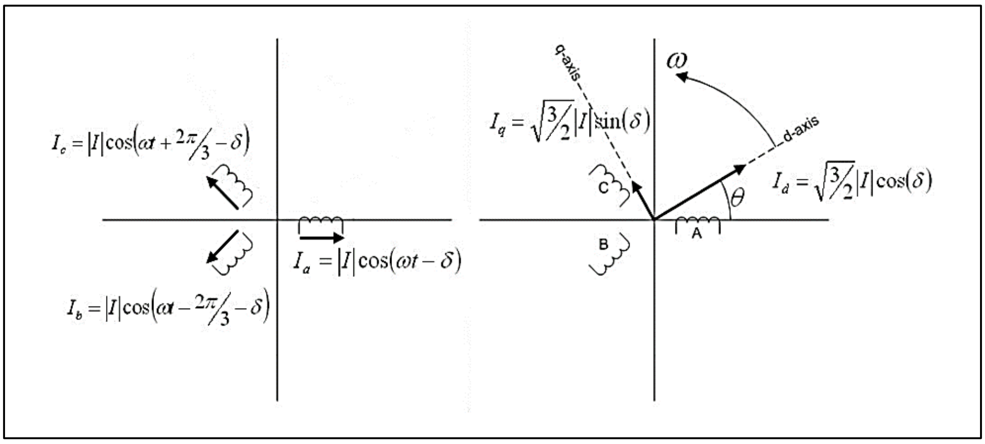
Park or dq0 transformation is a mathematical transformation to make the three-phase circuit analysis simple. In the balanced three-phase circuit, three quantities d, q and 0 will be converted to the two quantities (DC). The calculation processing on the imaginary DC quantities is more simplified and by using the inverse park transformation, the three-phase of AC quantities can be obtained. This method is used to analyze three-phase synchronous machine or simplify the calculation in an inverter. In Park transformation, the components of the (abc) three-phase system rotate on dq axis system by the specified speed (ω). İt is given figure (4.1).

**Figure 4.1: The component of three-phase system in a park transformation**




In this case, the matrix is defined as a function of angle (θ), which is not constant. The speed rotation of the q-axis can be selected arbitrary up to synchronous or non-synchronous machines.

**Figure 4.2: The dq system axis rotation**




Park transformation by regulating the output voltage source of inverter has known as a control method in PV systems. Figure (4.2) is shown the mathematical relation of dq system on the axis rotation

### 4.1.1 Park Transformation Equation

$$\begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad \textbf{(4.1)}$$

$$f_a + f_b + f_c = 0 \quad \textbf{(4.2)}$$

$$\begin{bmatrix} f_d \\ f_q \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} \times \begin{bmatrix} f_\alpha \\ f_\beta \end{bmatrix} \quad \textbf{(4.3)}$$

The equation of park transformation is calculated as follows:

$$[f_{qd0}] = [T_{qd0}(\theta)][f_{abc}] \quad \textbf{(4.4)}$$

$$\begin{bmatrix} f_q \\ f_d \\ f_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin(\theta) & \sin\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad \textbf{(4.5)}$$

The amount of (q, d, 0) component in park transformation is calculated by using equation (4.5). In this proposed scheme the 0 component is equal to zero and just need to find the amount of q and d.

### 4.1.2 The Inverse Park Transformation:

$$\mathrm{f_a} + \mathrm{f_b} + \mathrm{f_c} = 0 \quad \textbf{(4.6)}$$

$$\begin{bmatrix} \mathrm{f}_\alpha \\ \mathrm{f}_\beta \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix} \times \begin{bmatrix} \mathrm{f_d} \\ \mathrm{f_q} \end{bmatrix} \quad \textbf{(4.7)}$$

$$\begin{bmatrix} \mathrm{f_a} \\ \mathrm{f_b} \\ \mathrm{f_c} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \times \begin{bmatrix} \mathrm{f}_\alpha \\ \mathrm{f}_\beta \end{bmatrix} \quad \textbf{(4.8)}$$

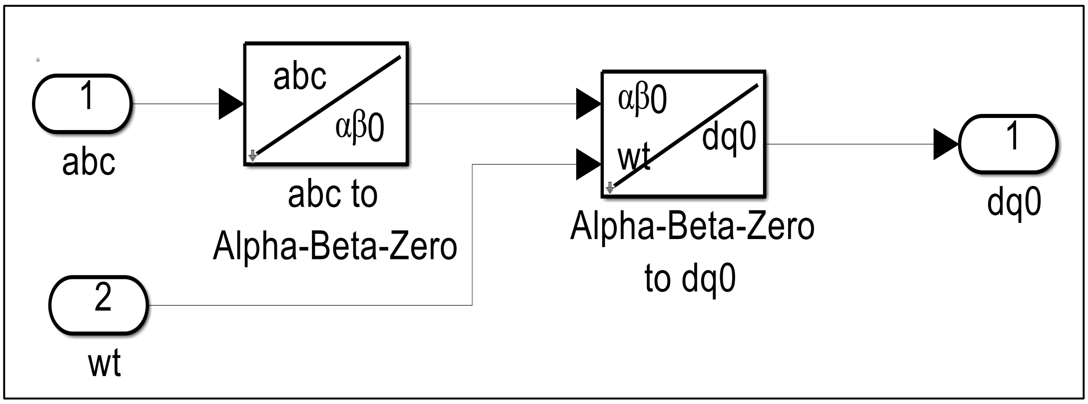
$$\begin{bmatrix} \mathrm{f_a} \\ \mathrm{f_b} \\ \mathrm{f_c} \end{bmatrix} = \begin{bmatrix} \cos\phi & -\sin\phi \\ \cos(\phi - \gamma) & -\sin(\phi - \gamma) \\ \cos(\phi + \gamma) & -\sin(\phi + \gamma) \end{bmatrix} \begin{bmatrix} \mathrm{f_d} \\ \mathrm{f_q} \end{bmatrix}, \gamma = \frac{2\pi}{3} \quad \textbf{(4.9)}$$

$\phi$ : The angle between dq and $\alpha\beta$

The schematic of applied park transformation in a controller system is shown in figure (4.3).

The output result of PI controller is called rotation frequency ($\omega$ in rad/s) with rotation angle $\theta$ in radians.

**Figure 4.3: Schematic of applied Park Transformation in Matlab**

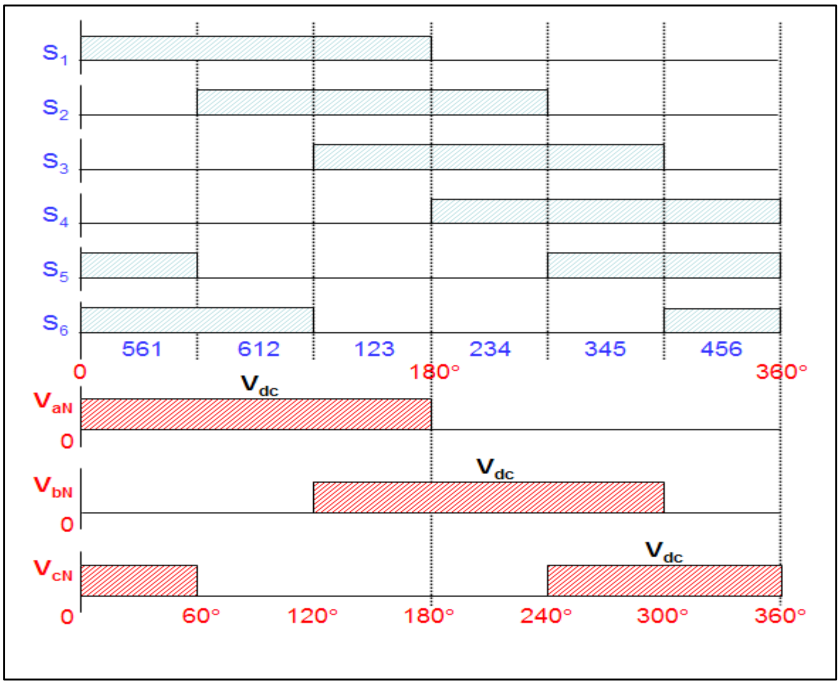



## 4.2. PWM INVERTER

The period of output voltage in the inverter is equal to (2π) radians. The width of each control signal is equal to (π) radian, and control signals with amount of (π/3) radians phase difference apply regularly to the switches. The cycle of the control signal is divided to six same sections. In regular time duration, switches are received the control signal and will be on and off which is shown in Table (4.1).

The switches, are demonstrated with S, start working when they receive a control signal. In this part, six switching cases are happened in the system and the voltages due to the switching case will be provided to the circuit. The occurred voltages depending on switching case are given in Table (4.1). When switches are located in an inverse tendency, the amount of voltage across the switch will equal to amount of voltage across its parallel diode. In any case of presenting control signal, switch or its parallel diode, should conduct the energy.

**Figure 4.4 Three-phase output voltage of the inverter**




*Source*: Phase Voltage Source Inverter book, ali keyhani

**Table 4.1: Table interval command keys**

| Interval | Send the command to switch | Interval | Send the command to switch |
|---|---|---|---|
| *I* | 1.5.6 | IV | 2.3.4 |
| II | 1.2.6 | V | 5.4.3 |
| III | 1.2.3 | VI | 5.4.6 |

Phase A is connected to positive side of DC voltage and phase B is connected to a negative side of DC voltage. Equation (4.10) gives the amount of voltage in this point.

$$V_{ab} = V_{an} - V_{bn}\ ,\quad V_{bc} = V_{bn} - V_{cn}\ ,\quad V_{ca} = V_{cn} - V_{an} \qquad \textbf{(4.10)}$$

By calculating the voltage in the above equation depending on Figure (4.4), the following voltages are obtained. Equation (4.11) shows them.

$$V_{ab} = V_d,\ V_{bc} = -V_d,\ V_{ca} = 0 \quad \textbf{(4.11)}$$

The angle difference between $V_{ab}$ and $V_{bc}$ is equal to 140° and the angle difference between $V_{ab}$ and $V_{ca}$ is equal to 120°.

In this connection, phase voltages can also be achieved like above switch pairs of ($S_1$, $S_4$), ($S_3$, $S_6$) and ($S_5$, $S_2$) which are formed on the three leg of inverter. Each switch in a leg conducts the signal alternatively. In any time, just one switch in a leg is connected to the circuit. Otherwise short-circuit will occur in the circuit and the high current will flow through the circuit. Fast fuses are applied between a pair of switch in a leg to create a delay for the control signal.

Shape of linear voltage or phase in each cycle will be resulted from the below equations. Fourier voltages ($V_{an}$) and ($V_{ab}$) is resulted in equations (4.12), (4.13) and (4.14).

$$V_{ab} = \frac{2\sqrt{V_d\,[\sin(\omega t+{}^{\pi}/_{6})+{}^{1}/_{5}\sin(5\omega t-{}^{\pi}/_{6})+{}^{1}/_{7}\sin(7\omega t+{}^{\pi}/_{6})....]}}{\pi} \quad \textbf{(4.12)}$$

$$V_{an} = {}^{2}/_{\pi}\,V_d[\sin\omega t + {}^{1}/_{5}\sin 5\omega t + {}^{1}/_{7}\sin 7\omega t] \quad \textbf{(4.13)}$$

Fundamental Frequency Component is calculated in equation (4.14).

$$V_1 = \frac{\sqrt{2}}{\pi}V_d \quad \textbf{(4.14)}$$

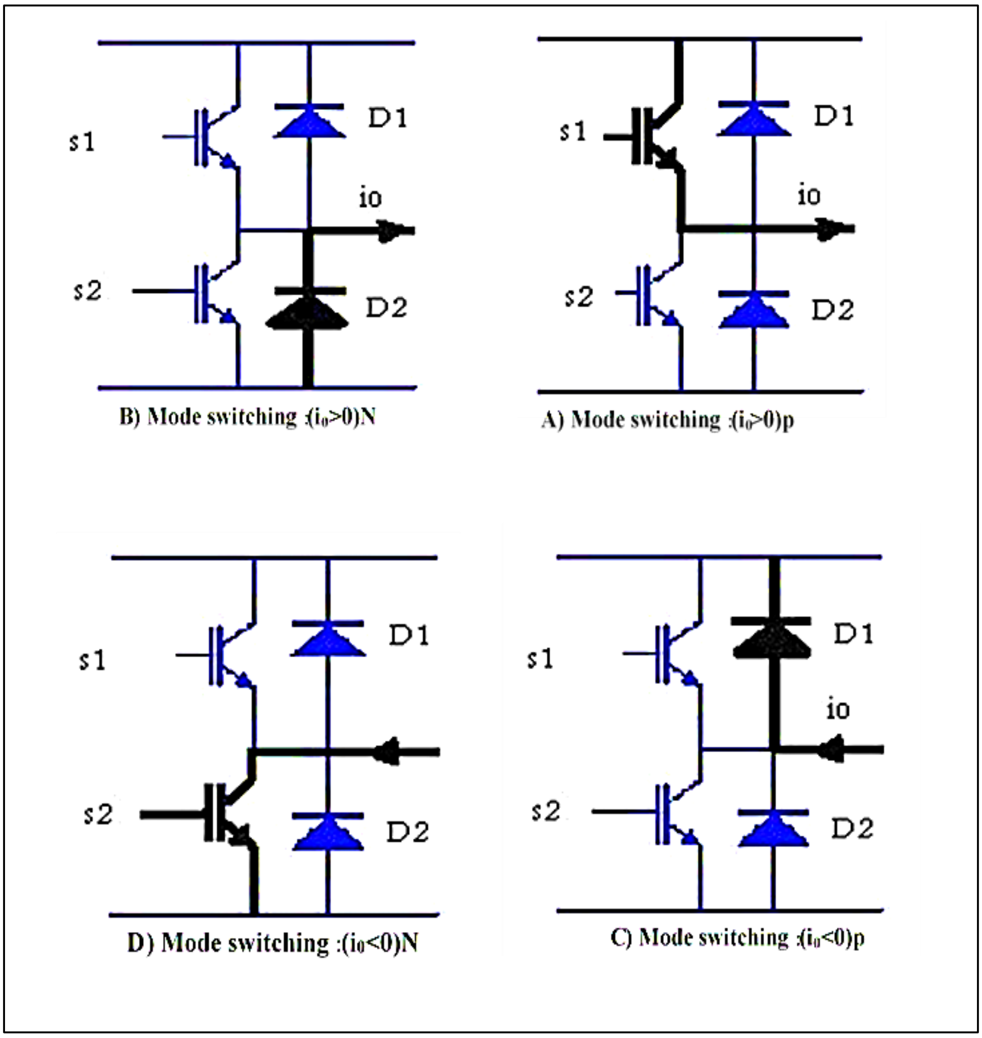
The effective value of voltage is obtained in an equation (4.15).

$$V = [{}^{1}/_{\pi}\{\int_0^{\pi/3}({}^{1}/_{3}\,V_d)^2\,d(\omega t) + \int_{\pi/3}^{2\pi/3}({}^{2}/_{3}\,V_d)^2\,d(\omega t) +$$
$$\int_{2\pi/3}^{\pi}({}^{1}/_{3}\,V_d)^2\,d(\omega t)\}]$$

**(4.15)**

This is an example of switching to better understand the relation between diode and keys in the inverter is shown in figure (4.5). This example is output current ($i_o$), which is following in pairs of key-diode ($S_1$, $D_1$), ($D_2$, $S_2$). During the distances ($0 \leq \omega\ t \leq \pi$) the switch ($S_1$) receives the command signal therefore ($i_o$) flows through the pair ($S_1$, $D_1$), in this position positive current of ($i_o$) is falling to the switch ($S_1$) and negative current of ($i_o$) is falling through the diode ($D_1$). When switch ($S_2$) receives command signal, the positive current ($i_o$) passes cross the switch and diode couples ($D_2$ and $S_2$) and negative current ($i_o$) passes on the switch ($S_2$).

**Figure 4.5: Different Mode Switching in A Three-Phase Inverter**




*Source*: Phase Voltage Source Inverter book, ali keyhani

## 4.3. OUTPUT FILTERS

In the proposed scheme, two filters are used to decrease the output harmonics and distortion as much as possible.

The Low-pass filter is the simplest version of filter that is used in this scheme in a series connection of inductor and a capacitor. DC low-pass filter is directly fed by DC voltage of PV array. Another filter, which is used in this scheme, is a AC low-pass filter in the way of inverter and loads. This kind of filter is called as L network because it looks like L letter. In order to provide what it called low-pass response, the inductor tense to have more and more attenuation as the frequency goes up and for the less attenuation as the frequency goes down. So in discriminate the capacitor tense to favor the higher frequencies it has a higher impinges and tense to the lower frequency at the higher impinges. So by placing the inductor in series, it discriminates against the higher frequencies by placing the capacitor in series, it also discriminates against high frequencies because the frequency goes up impinges and at capacitor goes down.

A DC simple LC low-pass filter converts a pulse width modulation signals to analog signals as cheap D/A converter. The second AC (low – pass) LC filter is used in this system with values information is shown in the figure (4.6) and table (4.2). The input is in connected to PWM inverter and output is connected to load.

**Figure 4.6: The LC low-pass AC filter in this scheme from Matlab**

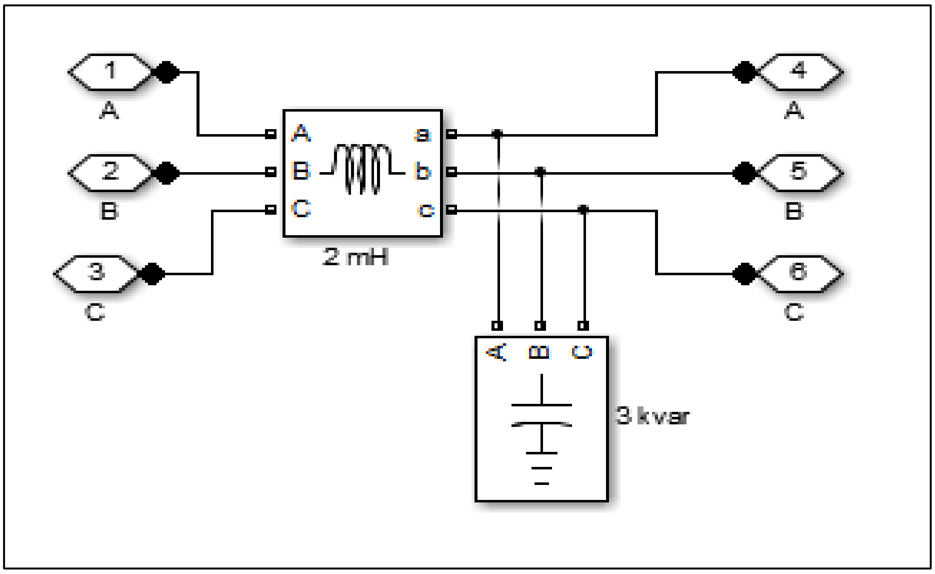


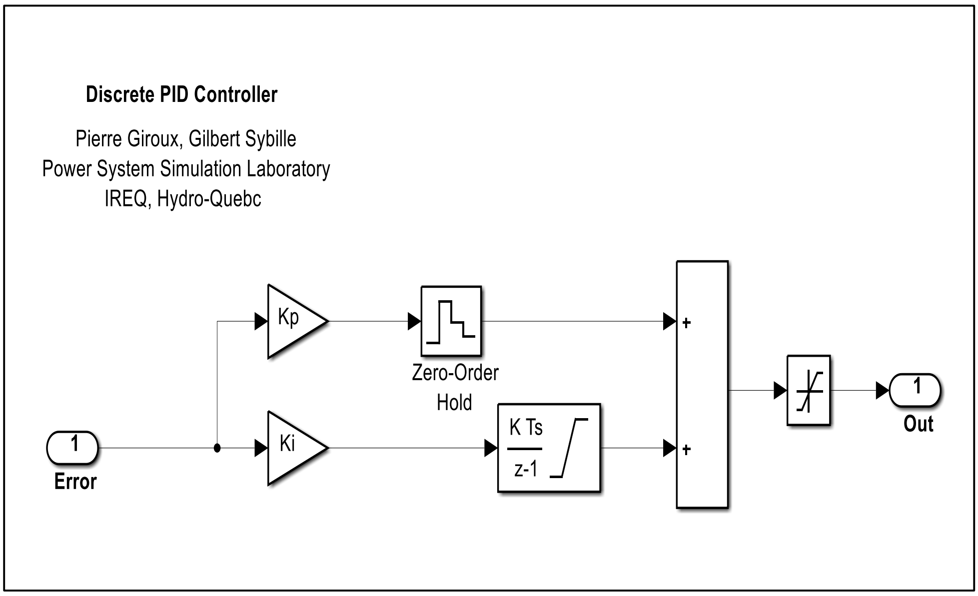

**Table 4.2: Filters in this Proposed System**

| Parameter | Quantity |
|---|---|
| L (for AC) | 2 mH |
| C (for AC) | 38e-6 F |
| L (for DC) | 200e-3 mH |
| C (for DC) | 5000e-06 F |

## 4.4. PID CONTROLLER

The schematic of applied PID controller in the PV system is given in figure (4.7).

**Figure 4.7: The schematic of PID controller in this scheme**




For this scheme, the value of proportional gain parameter is found 0.4, the value of integral gain parameter is 500 and the value of discrete gain parameter is defined zero. The calculation method fo the PID controller in this scheme is manual tuning method. In this controller the $K_p$, $K_i$ and $K_d$ gains should be real and finite.

Figure (4.8) shows the PID controller without applying the control method and figure (4.9) shows the plot with applying controller.

**Figure 4.8: PID plot without controller**

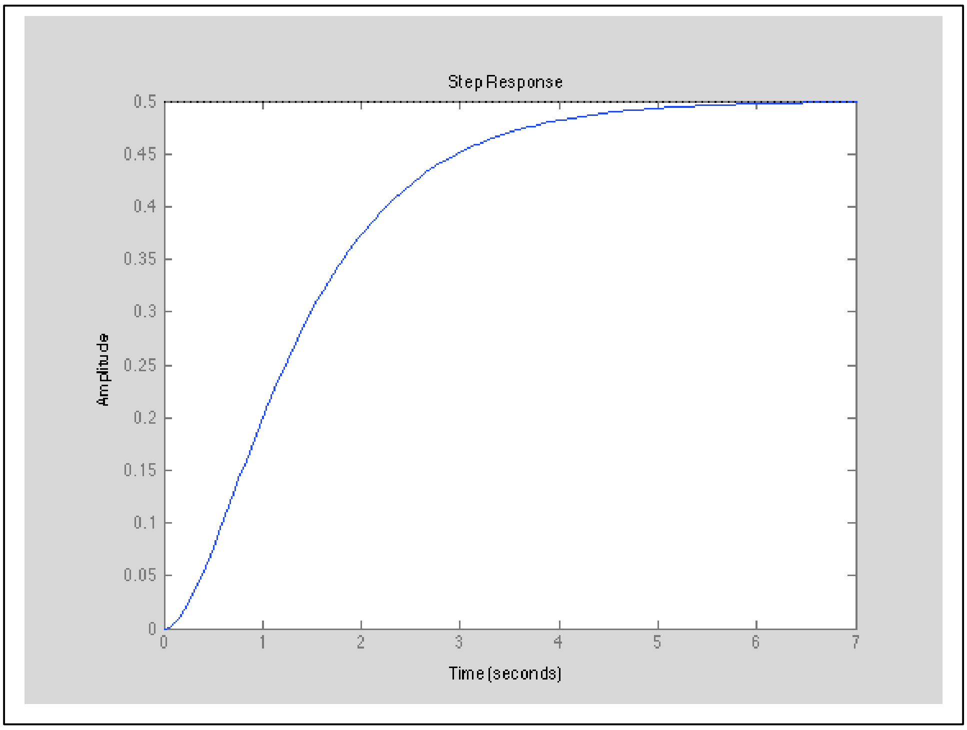
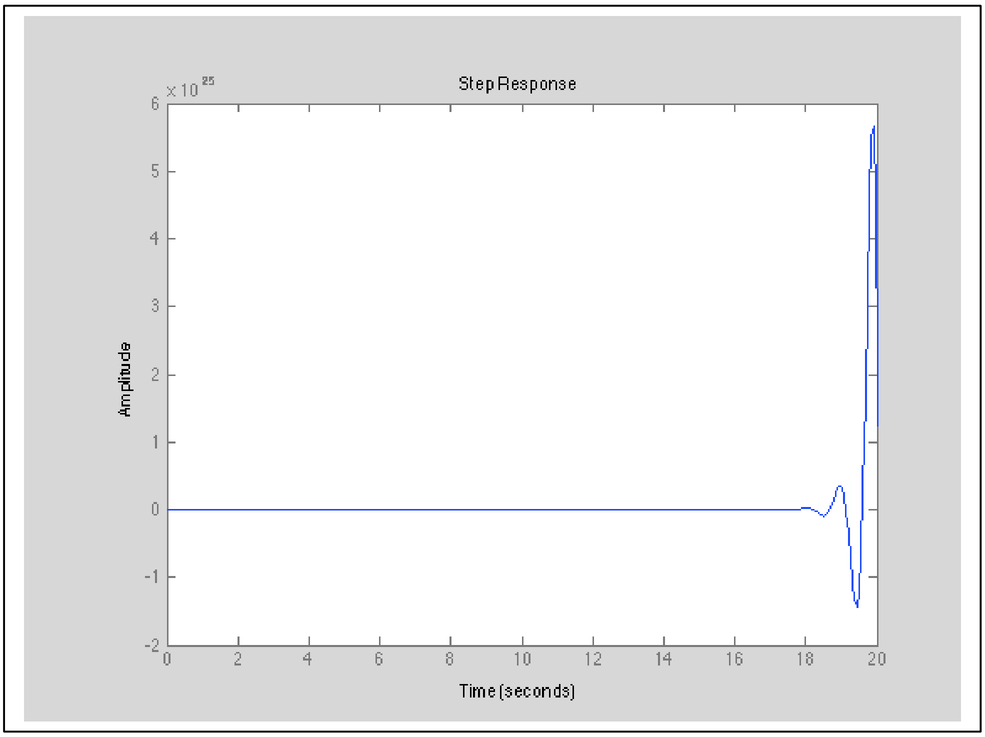



**Figure 4.9: PID plot with controller**



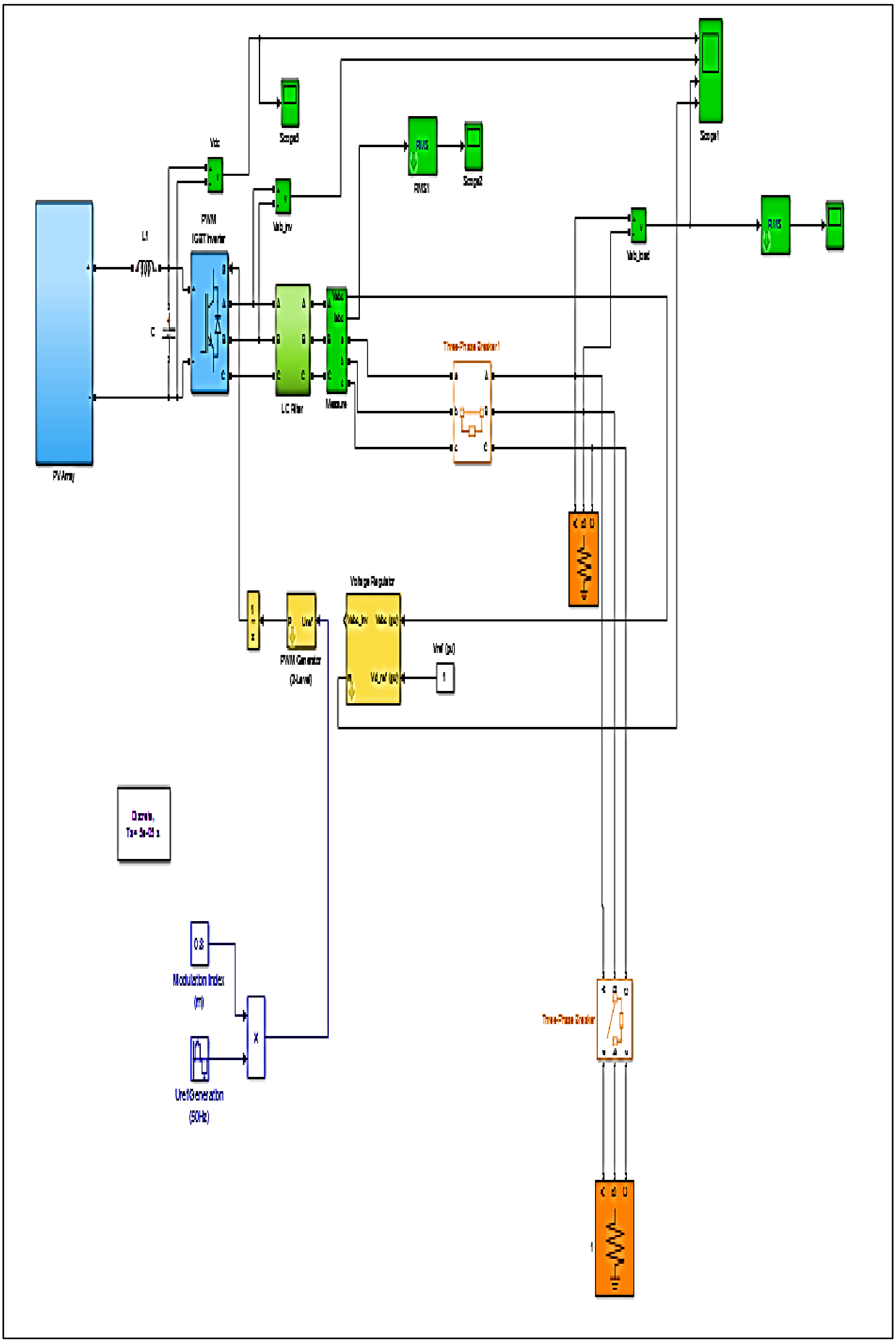
## 4.5. PROPOSED VOLTAGE CONTROL SYSTEM SCHEME

PV array in this system as a function of radiation and angle of sun is applied. It is used to convert sunlight to DC current that should be converted to AC current by an inverter. The DC output voltage of PV array is equal to 48 volts in this study. The DC low-pass filter is connected between PV array and the PWM inverter in order to reduce DC voltage harmonics and distortion. The applied inverter in this scheme changes the DC voltage to AC one and reduces the harmonics. In this PWM inverter, six diodes and six switches are implemented by inverse tendency between each switch and each diode. For this scheme the (IGBT) switches, which are used in all power system design, were chosen. IGBT switch has three legs; two of them connected to the circuit and the third one will send the command by receiving the pulse. At the end of this switches the gates that are working by receiving voltage from the PWM generator are applied.

After the PWM inverter, AC low-pass filter is connected to the system to eliminate or at least decrease the harmonics and distortion of AC voltage. Harmonics emerge in all of non-linear systems. The output of the inverter is connected to the load in a parallel connection with another load. Two breakers are designed in two cases. The first breaker is connected to the system closed by default and the second breaker is closed between different seconds.

The pwm generator is applied after controller in the system to change the signal to pulse. Delayer is placed between generator and inverter to evaluate the performances of the proposed method, consists of a photovoltaic system and a fixed network and a simulated step. The structure of this system is given in figure (4.10).

**Figure 4.10: The structure of proposed PV system**



Schematic of controller in MATLAB, which applied in this scheme, is shown in figure (4.10). This controller system should calculate the difference between two input voltages, if the difference is equal to zero the controller doesn't produce any pulse to the system. When voltage difference is not equal to zero the controller produce the reference voltage as much as the voltage difference amount.

Voltage Vabc (pu)) is in connection with output of inverter coupled to the Park transformation.

$$V_a = V_m \sin\omega t,\ V_b = V_m \sin(\omega t + 120),\ \ V_c = V_m \sin(\omega t - 120) \qquad \textbf{(4.16)}$$

The voltages in the (abc) domain according to equation (4.16) have a (120º) phase difference because of time presentation in the function. To eliminate the time domain, park transformation is used in this part. In this transformation, three-phase quantities of voltage (abc) are converted to $V_q$, $V_d$, $V_0$ components.

In the (dq0) domain, a phase difference equals to (90º) ninety degrees. In the balance system, the (0) component is equal to zero. These quantities pass the selector block to omit the (0) component and indicate the component of ($V_d$ and $V_q$).

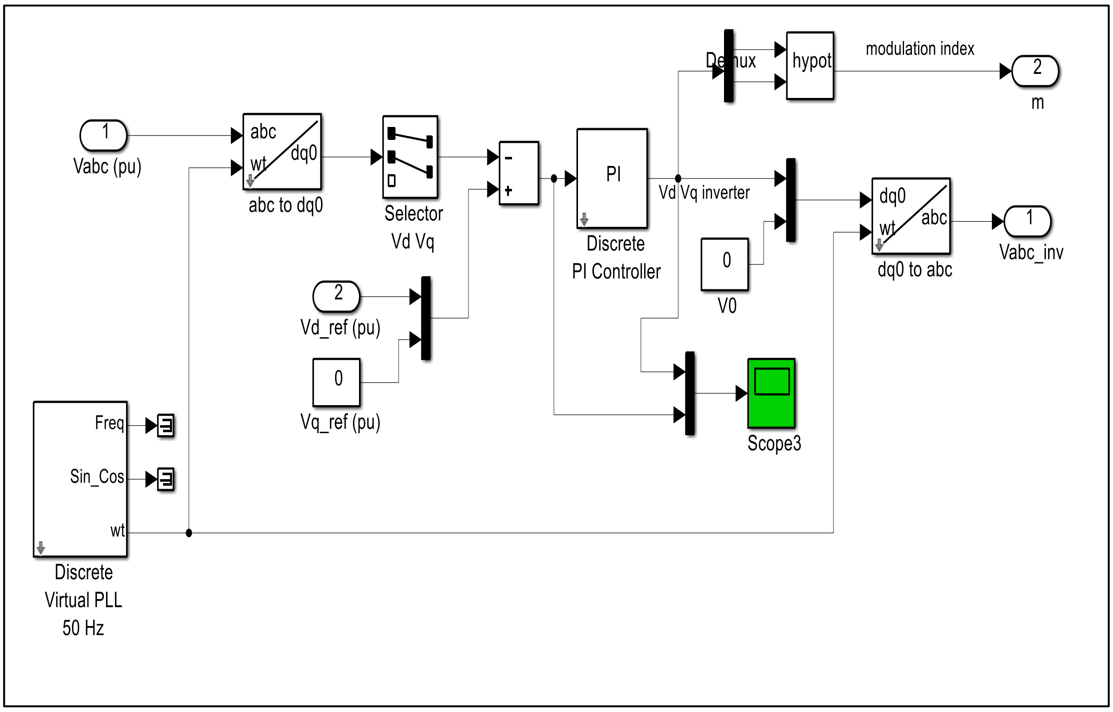
The sum block calculates the differences between input voltages, which shouldn't be more than one.

PID controller by choosing the specific amount that explained in previous part finds the suitable $V_d$ and $V_q$ for the system. The output of inverter, after converting to the component qd0, is compared with an arbitrary reference voltage and after passing through an inverse PID controller, the d, q components are converted to (a, b, c) components. This result is sent as a reference voltage to the PWM inverter, in this case the output voltage will be controlled by high precision.

There is a D multiplexer at the output of PID controller to break up the component for the hypot block to gain the modulation index. Modulation index number is more than 8% and is built by triangle wave with (50 Hz) frequency.

The (wt) block finds the phase difference number between the current and voltage.

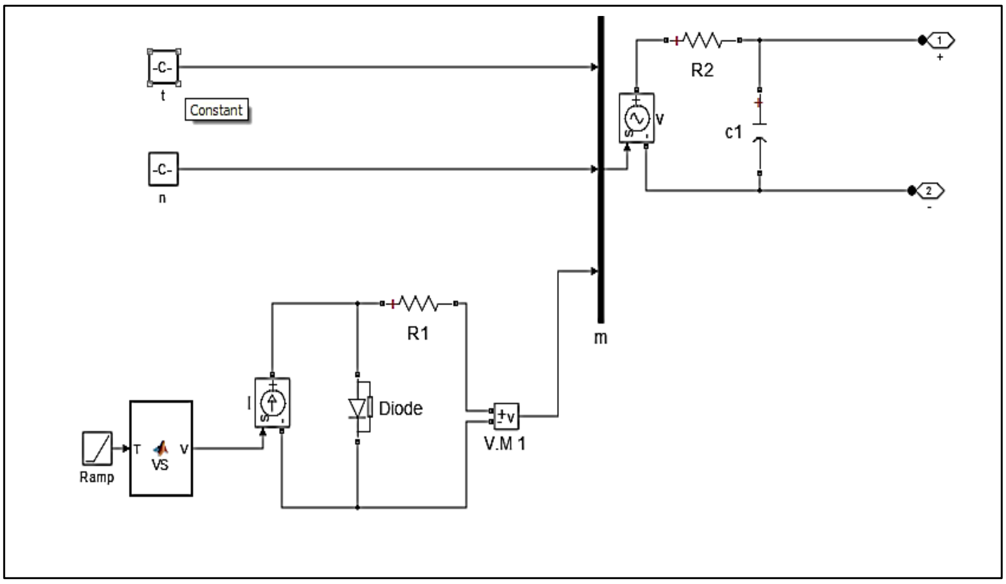
**Figure 4.11: The diagram of voltage control system**




## 4.6. PV ARRAY

Figure (4.11) shows the PV array that is used in this scheme. The influence of sunlight is considered and the output voltage will change due to sunlight changing. Each cell of PV array includes one led diode and resistance element. In this system, the sun radiation is going up with ramp range between zeros to one.

**Figure 4.12: The diagram of PV array**

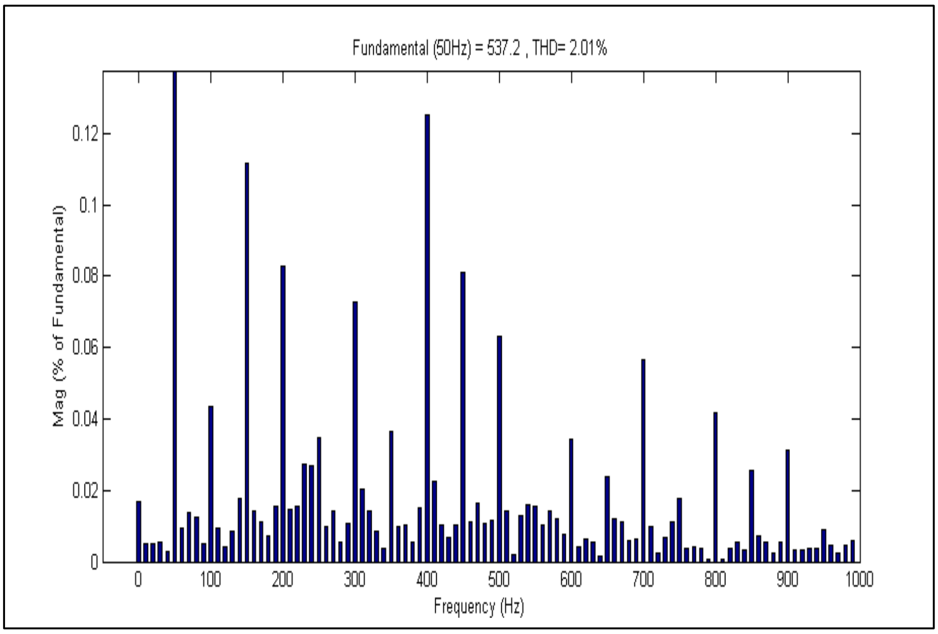


# 5. RESULTS OF SIMULATIONS

## 5.1. HARMONIC ANALYSIS

Power electronic based devices create high harmonics in the system. Harmonics cause some problem in the way of delivered voltage and current. By using filters, they should be decreased in the system. Delivered voltage to the system has some harmonics percentages every time. By comparing three different cases, the effect of harmonic in the system is given. Figure (5.1) shows the harmonic plot under normal condition, figures (5.2) and (5.3) shows the harmonic plot both without and with the controller.

**Figure 5.1: Plot of harmonic for load-1**




Amount of voltage changing during the load connection and step disconnection is very small, but because of using PI controller in the control method, there are high frequency voltage changes in all time of system performance. Figure (5.1) shows the designed filter is appropriate to eliminate the inappropriate harmonic and distortion.

Figures (5.2) and (5.3) show the proposed control scheme has an effect on output harmonics. The control system prevents the sudden change of voltage. It means that only 2% of frequency change will be added to the existing disturbance and this result proves the suitability of the proposed control system.

**Figure 5.2: Plot of harmonic for two loads without controller**

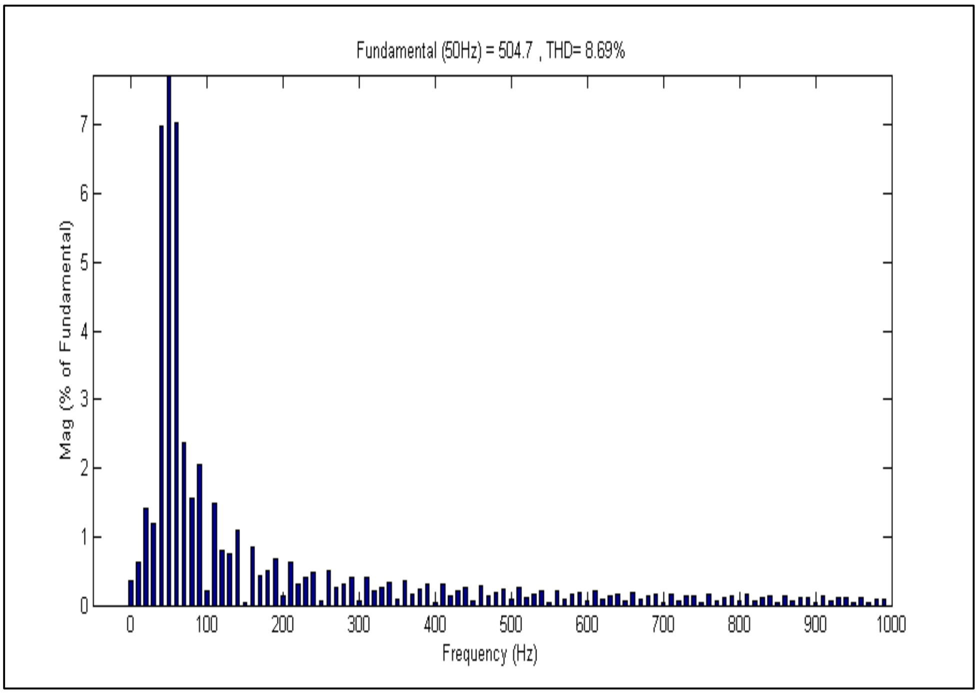
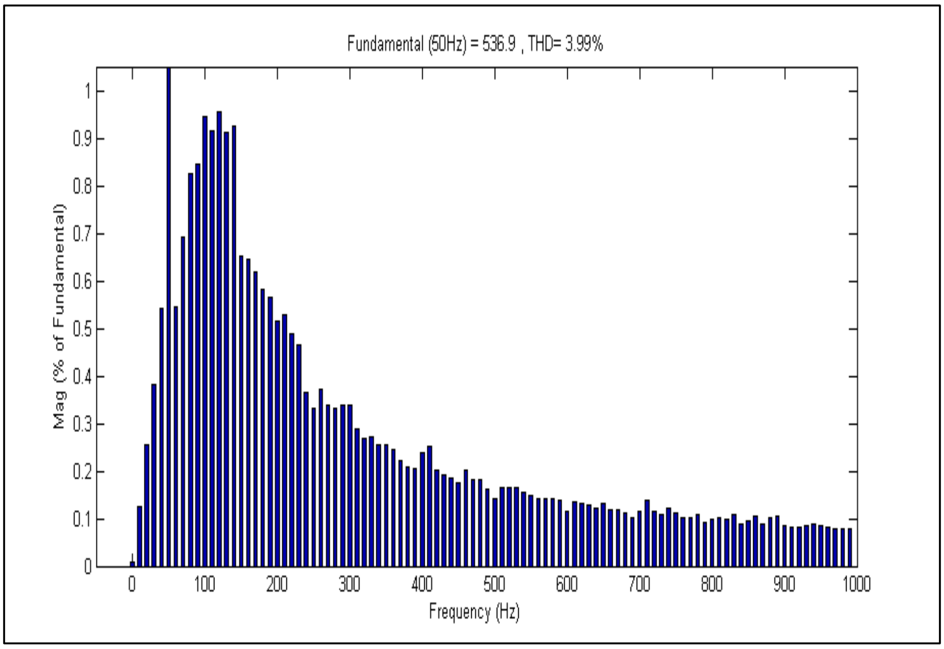


**Figure 5.3: Plot of harmonic for two loads with controller**




## 5.2. OUTPUT PLOTS OF PV PANEL

By using the proposed PV system, the output voltage, power, generated current, sun radiation and absorbed radiation over voltage, that are resulted in MATLAB Simulink, are shown in this part.

The output voltage of PV panel is shown in figure (5.4) under the condition that the first load from zero to five seconds and second load from three to four seconds are connected to the system. The voltage drop occurs in the uncontrolled situation when the second load is applied to the system.

The generated current in PV panel from the sun radiation is shown in figure (5.5) under the same condition the current decreases when second load is connected to system without controller.

**Figure 5.4: The output voltage in PV panel**

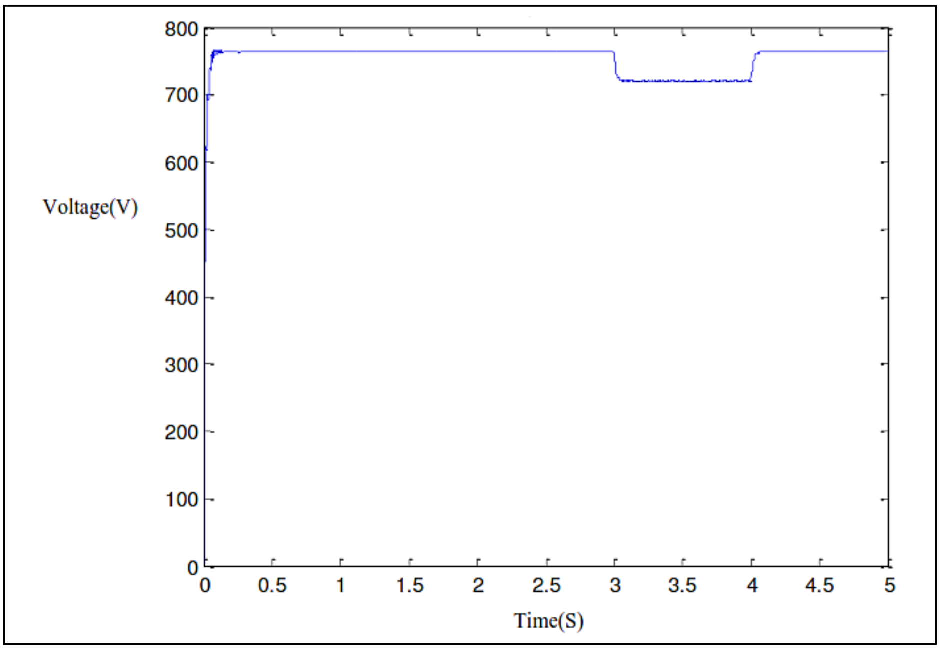
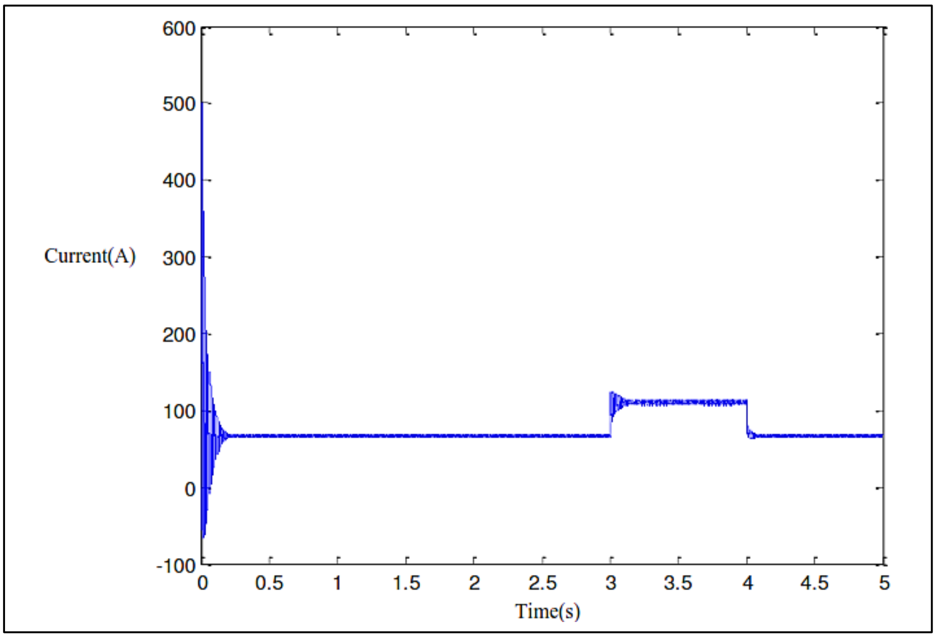
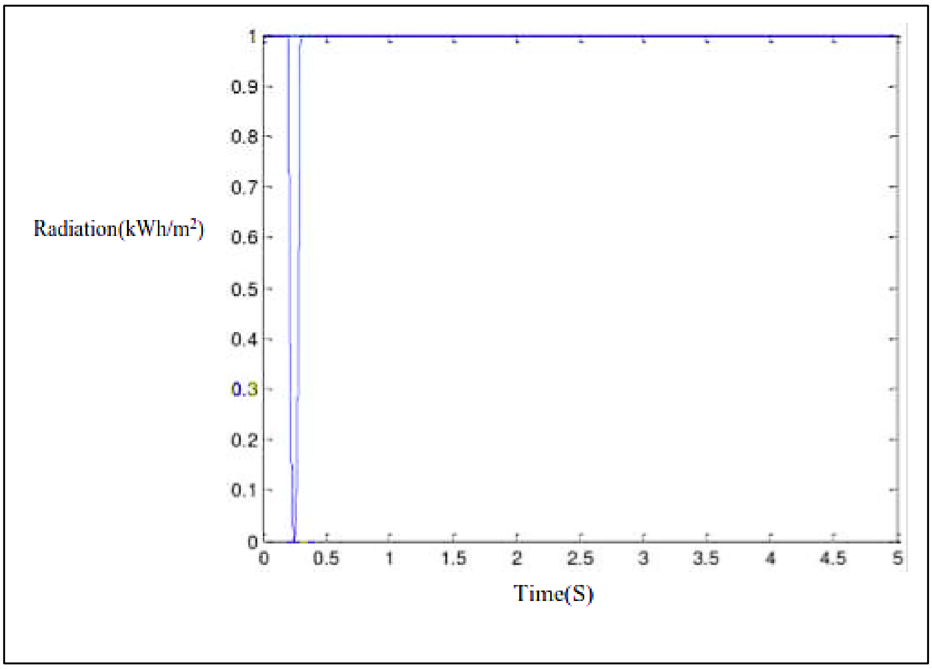



**Figure 5.5: The generated current in PV panel**



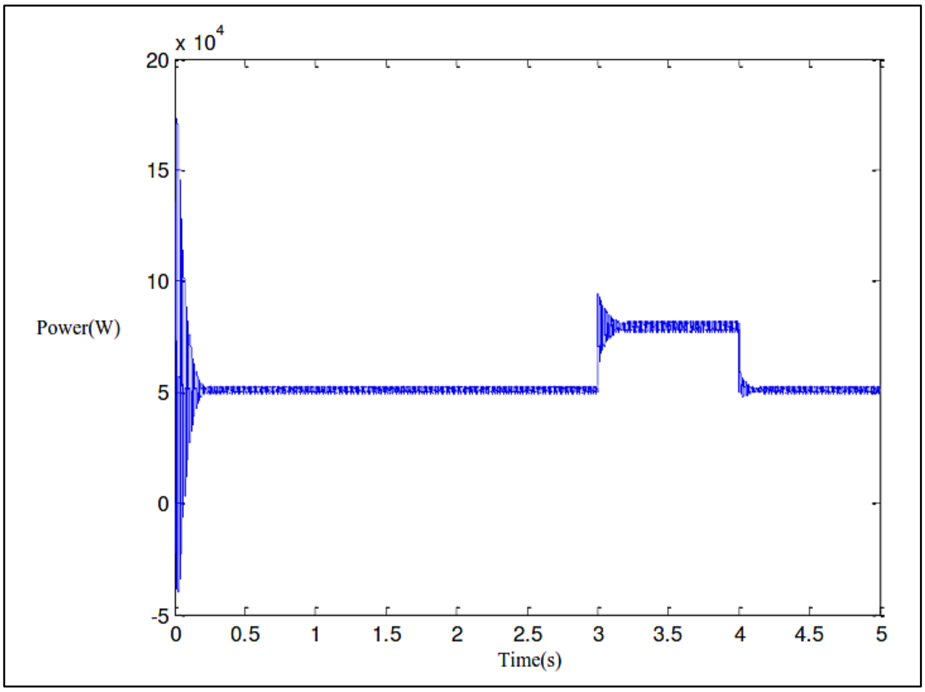

The plot of absorbed solar radiation in a PV panel is shown in figure (5.6).

**Figure 5.6: The absorbed solar radiation in PV panel**




The output power in PV panel is given in figure (5.7) under the same condition the power decreases when second load is connected to the system without the controller.

**Figure 5.7: The output power of PV panel**



## 5.3. PERFORMANCE OF THE VOLTAGE CONTROL SYSTEM

The performance of the voltage control system is investigated in four main cases, which are given in the table (5.1). These cases are:

a. Case (A): Radiation in PV panel is constant. Load-1 is just in the system during all simulation. The type of first load is R in this case. The plots of this case are shown in figure (5.10) and (5.11).
b. Case (B): Radiation in PV panel is constant. There are two loads in the system during the simulation. This case consists of fourteen sub cases. The type of first load is R in all sub cases and is applied from zero to five seconds. R, L, RL, and RLC are used as the second load respectively.. The second load is presented in two different times duration, one of them is from zero to five seconds and the second one is from three to four seconds. .
c. Case (C): Radiation in PV panel is not constant. The amount of radiation is changed during the simulation. . The load-1 is just in the system like Case (A). The type of first load is R in this case.
d. Case (D): Radiation in PV panel is not constant. The amount of radiation is changed during the simulation. There are two loads in the system; the first load is R from zero to five seconds and the second load is R from three to four seconds is applied to the system.

**Table 5.1: Cases for testing the voltage control scheme**

| Cases | No | Radiation ($kWh/m^2$) | Type of Load-1 | Availability Duration of Load-1 (sec) | Type of Load-2 | Availability Duration of Load-2 (sec) | Availability of Voltage Control System | Availability Duration of Radiation (sec) |
|---|---|---|---|---|---|---|---|---|
| A | 1 | 1000 | R | [0 5] | - | - | No | [0 5] |
| | 2 | 1000 | R | [0 5] | - | - | Yes | [0 5] |
| B | 1 | 1000 | R | [0 5] | R | [3 4] | No | [0 5] |
| | 2 | 1000 | R | [0 5] | R | [3 4] | Yes | [0 5] |
| | 3 | 1000 | R | [0 5] | L | [3 4] | No | [0 5] |
| | 4 | 1000 | R | [0 5] | L | [3 4] | Yes | [0 5] |
| | 5 | 1000 | R | [0 5] | RL | [3 4] | No | [0 5] |
| | 6 | 1000 | R | [0 5] | RL | [3 4] | Yes | [0 5] |
| | 7 | 1000 | R | [0 5] | RLC | [3 4] | No | [0 5] |
| | 8 | 1000 | R | [0 5] | RLC | [3 4] | Yes | [0 5] |
| C | 1 | [1000 900 500] | R | [0 5] | - | - | No | [0 2 5] |
| | 2 | [1000 900 500] | R | [0 5] | - | - | Yes | [0 2 5] |
| | 3 | [1000 900 500 700 900] | R | [0 5] | - | - | No | [0 1 2 3 5] |
| | 4 | [1000 900 500 700 900] | R | [0 5] | - | - | Yes | [0 1 2 3 5] |
| D | 1 | [1000 900 500] | R | [0 5] | R | [3 4] | No | [0 2 5] |
| | 2 | [1000 900 500] | R | [0 5] | R | [3 4] | Yes | [0 2 5] |
| | 3 | [1000 700 300 400] | R | [0 5] | R | [3 4] | No | [0 1 3 4] |
| | 4 | [1000 700 300 400] | R | [0 5] | R | [3 4] | Yes | [0 1 3 4] |

Figure (5.8) shows the voltage waveform on the load-1 for case $A_1$

**Figure 5.8: The voltage waveform in case $A_1$**

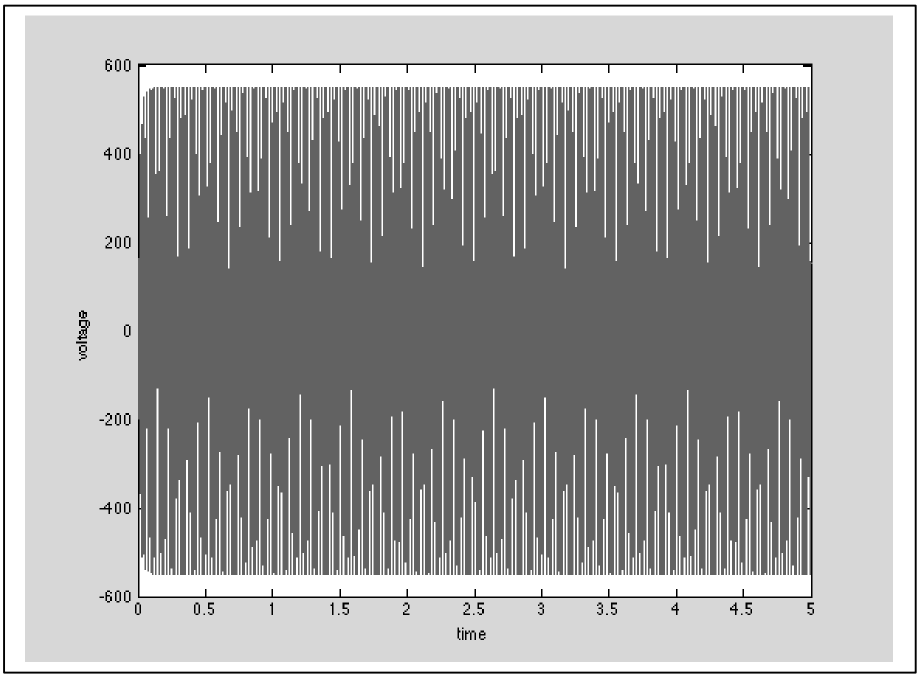
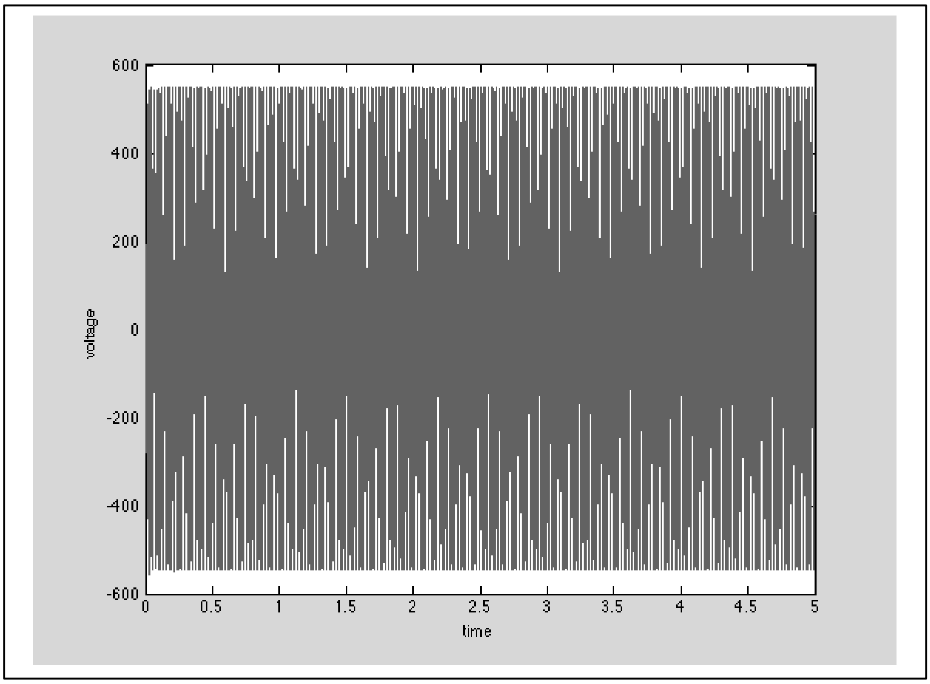



Figure (5.9) represents the voltage waveform on the load-1 by using the voltage controller in the system.

**Figure: 5.9 The voltage waveform in case $A_2$**




When the figure (5.8) and figure (5.9) are compared, there is no voltage drop in both cases. It means that the controller doesn't create any effect on the voltage.

Figure (5.10) shows the system at the presentation of first load-1 is resistor (R) and switched on between [0 5] seconds, load-2 is also resistor (R) and switched on between [3 4] seconds without controller.

**Figure 5.10: The voltage waveform in case B1**

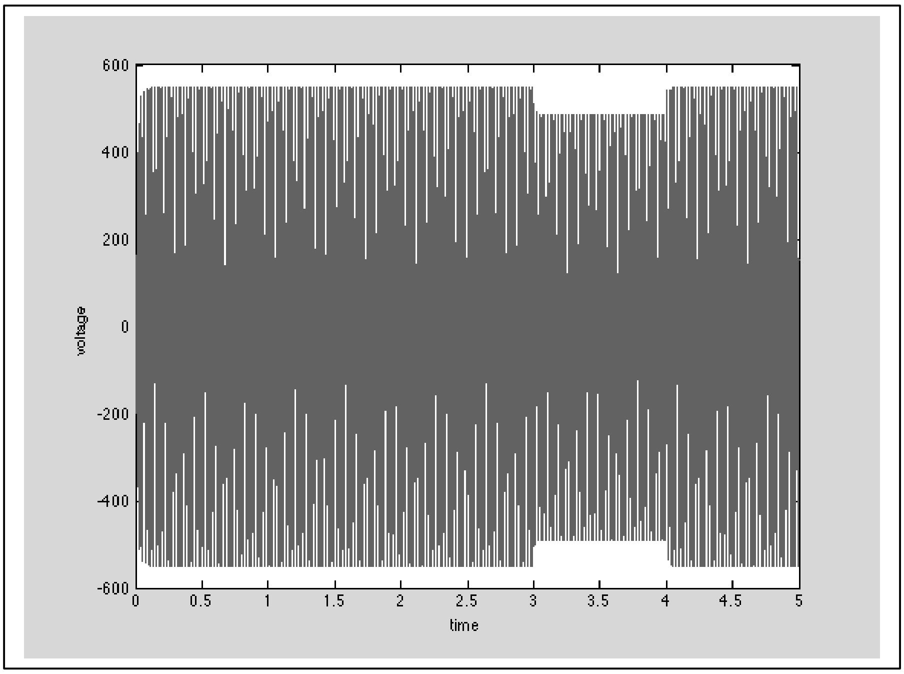



Figure (5.11) shows the system at the presentation on the load when load-1 is resistor (R) and switched on between [0 5] seconds, load-2 is also resistor (R) and switched on between [3 4] with controller. Result between two figures shows without controller during the time [3 4] seconds where the load-2 is switched to the system voltage drop is happened. But in figure (5.11) with controller this voltage change is compensated.

**Figure 5.11: The voltage waveform in case $B_2$**

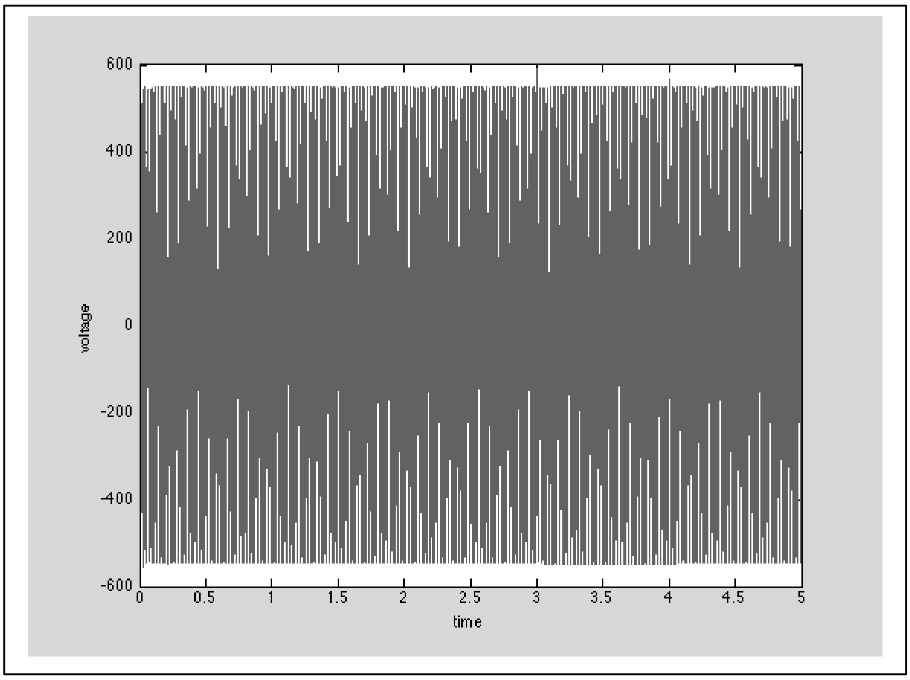



Figure (5.12) shows the Output voltage on the load when load-1 is resistor (R) and switched on between [0 5] seconds and load-2 is inductor (L), switched on between [3 4] seconds without applying the controller to the system.

**Figure 5.12: The voltage waveform in case $B_3$**

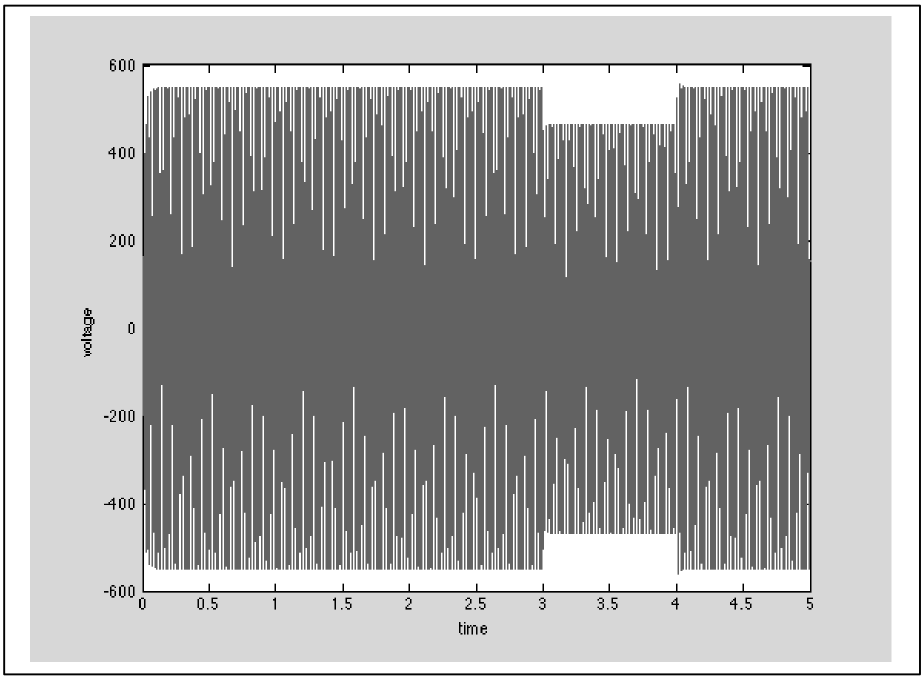


Figure (5.13) shows the Output voltage on the load when load-1 is resistor (R) and switched on between [0 5] seconds and load-2 is inductor (L), switched on between [3 4] seconds by applying the controller to the system. Resulted shows the voltage changes that happened in idle controller will solve totally by using controller in the system.

**Figure 5.13: The voltage waveform in case $B_4$**

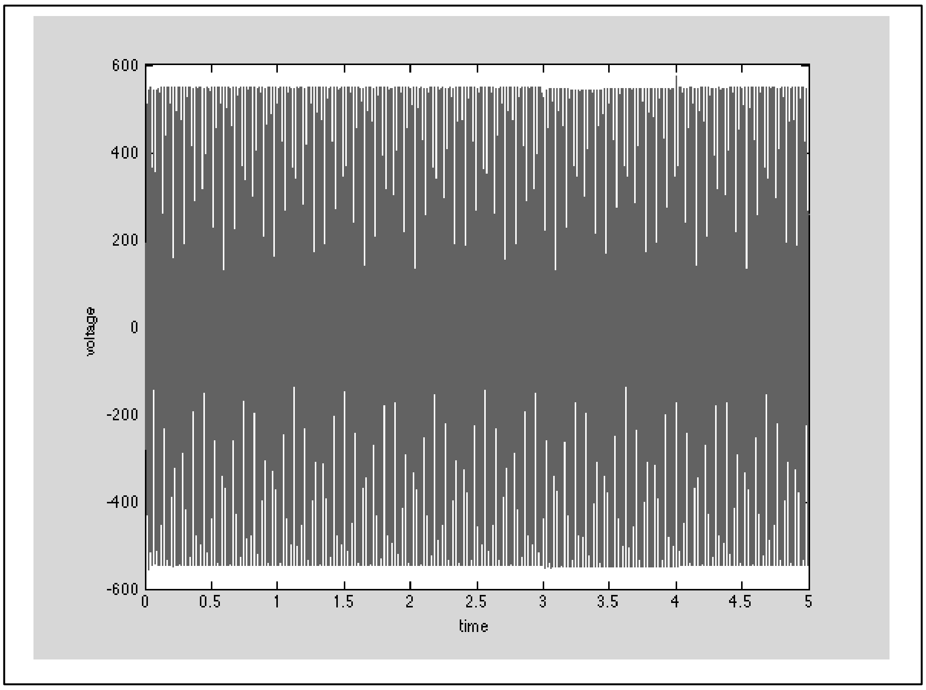



Figure (5.14) shows output voltage on the load when load-1 is resistor (R) and switched on between [0 5] seconds, load-2 is resistor and inductor (R, L), switched on between [3 4] seconds without controller.

**Figure 5.14: The waveform in case $B_5$**

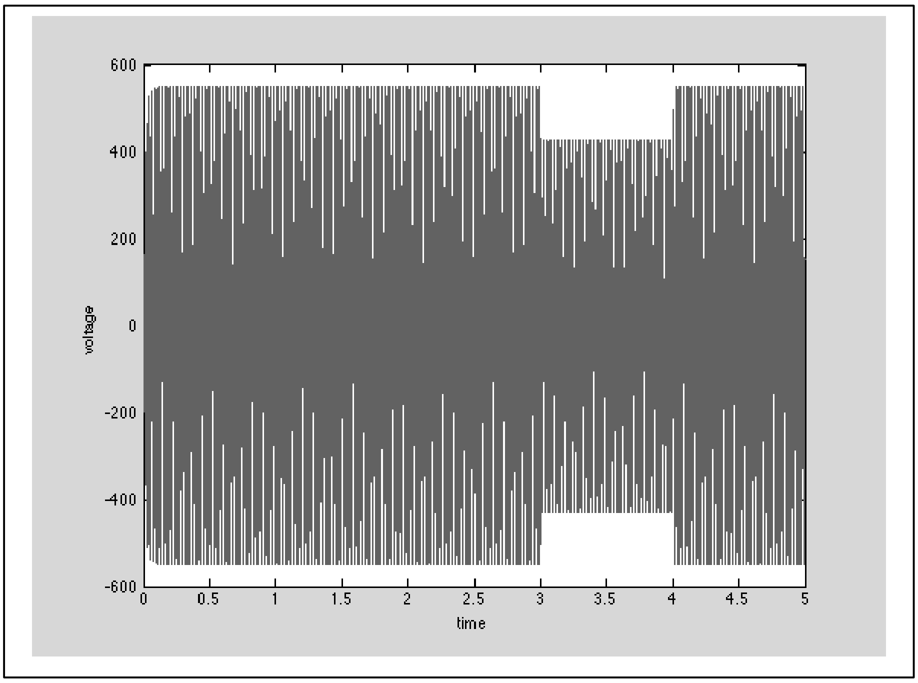



Figure (5.15) shows output voltage on the load when load-1 is resistor (R) and switched on between [0 5] seconds, load-2 is resistor and inductor (R, L), switched on between [3 4] seconds with controller. The result between two figures shows by getting use of controller in the system the voltage drop will compensate totally.

**Figure 5.15: The voltage waveform in case $B_6$**

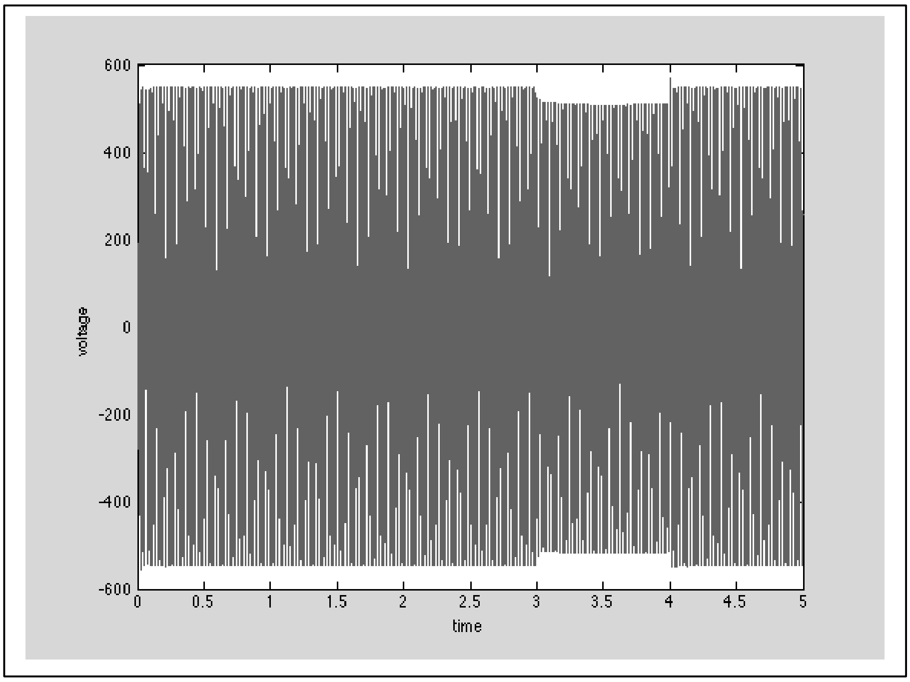



Figure (5.16) shows the output voltage on the load when load-1 is resistor (R), switched on between [0 5] seconds and load-2 is resistor, inductor and capacitor (R and L and C), switched on between [3 4] seconds without applying controller.

**Figure 5.16: The voltage waveform of case $B_7$**

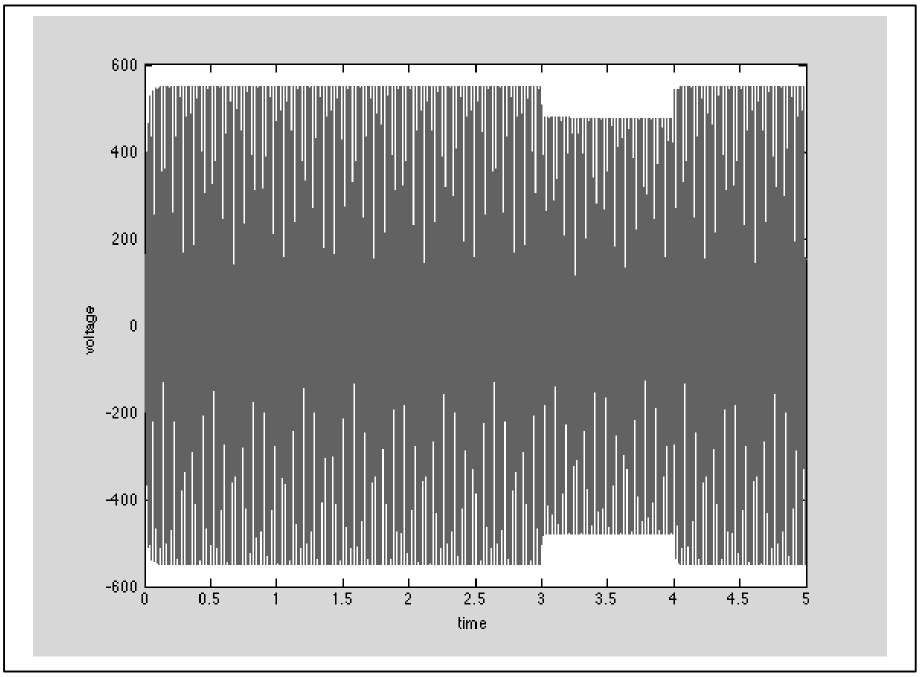


Figure (5.17) shows the output voltage when load-1 is resistor (R), switched on between [0 5] seconds and load-2 is resistor, inductor and capacitor (R and L and C), switched on between [3 4] seconds by imposing a controller. This figure shows due to presentation of capacitor the voltage compensation range is not totally solved but is improved.

**Figure 5.17: The voltage waveform in case $B_8$**

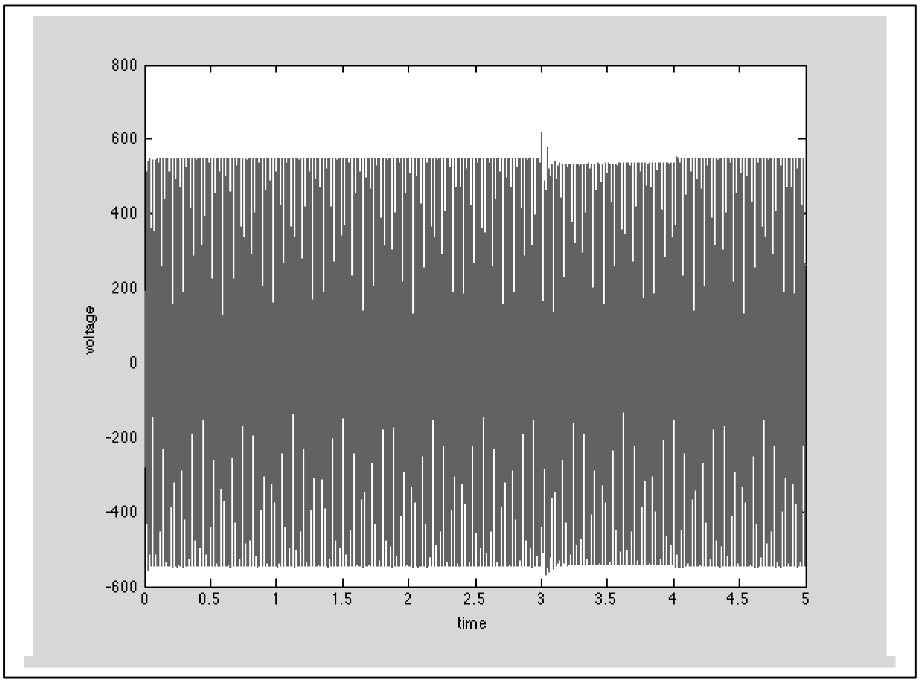



Figure (5.18) shows the waveform on the load without using controller while radiation is changing between [1000 900 500] at time duration of [0 2 5] seconds is shown. In this case just one load is switched on between [0 5] seconds.

**Figure 5.18: The voltage waveform of Case $C_1$**

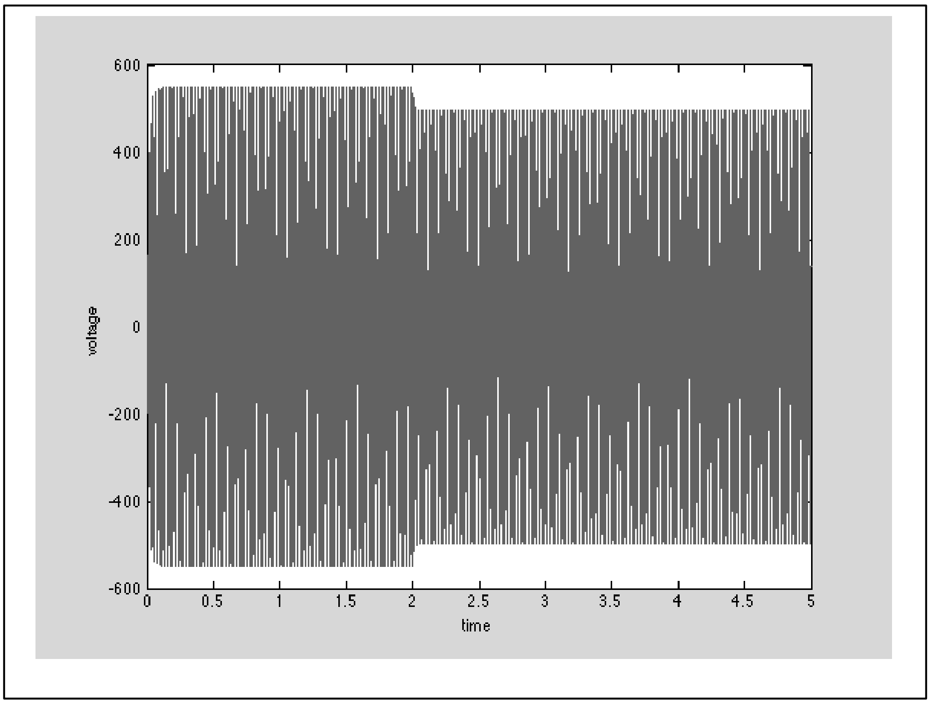



Figure (5.19) shows the waveform on the load when radiation is changing between [1000 900 500] at time duration of [0 2 5] seconds is shown. In this case just one load is switched on between [0 5] seconds and controller is imposed to the system. The controller compensates the part of voltage drop.

**Figure 5.19: The voltage waveform in Case $C_2$**

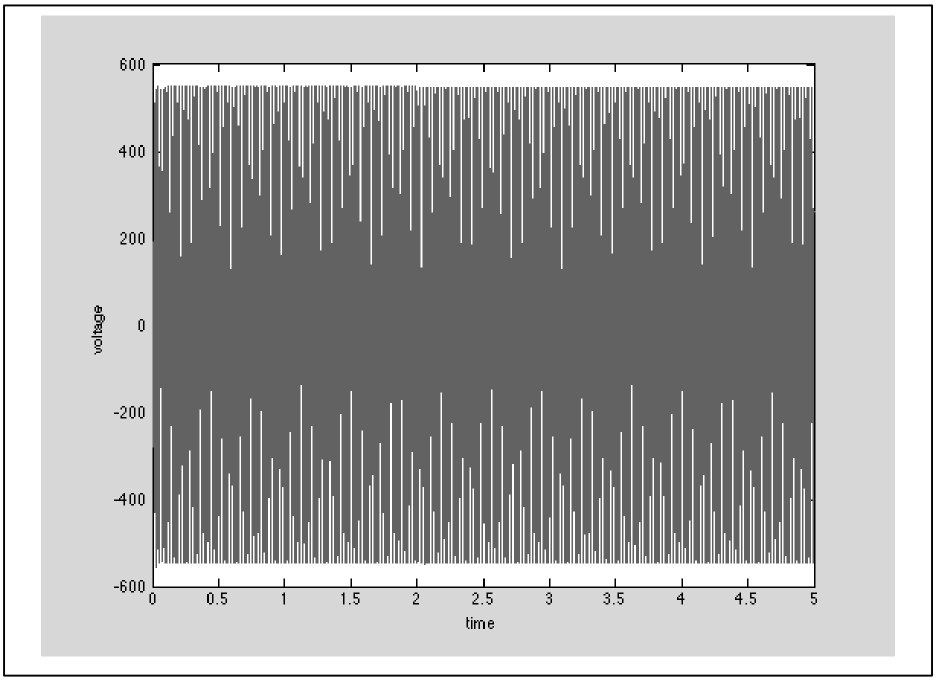



Figure (5.20) shows the waveform on the load without using controller when radiation is changing between [1000 900 500 700 900] at time duration [0 1 2 3 5] seconds, and just first load is switched on between [0 5] seconds is showing.

**Figure 5.20: The voltage waveform in Case $C_3$**

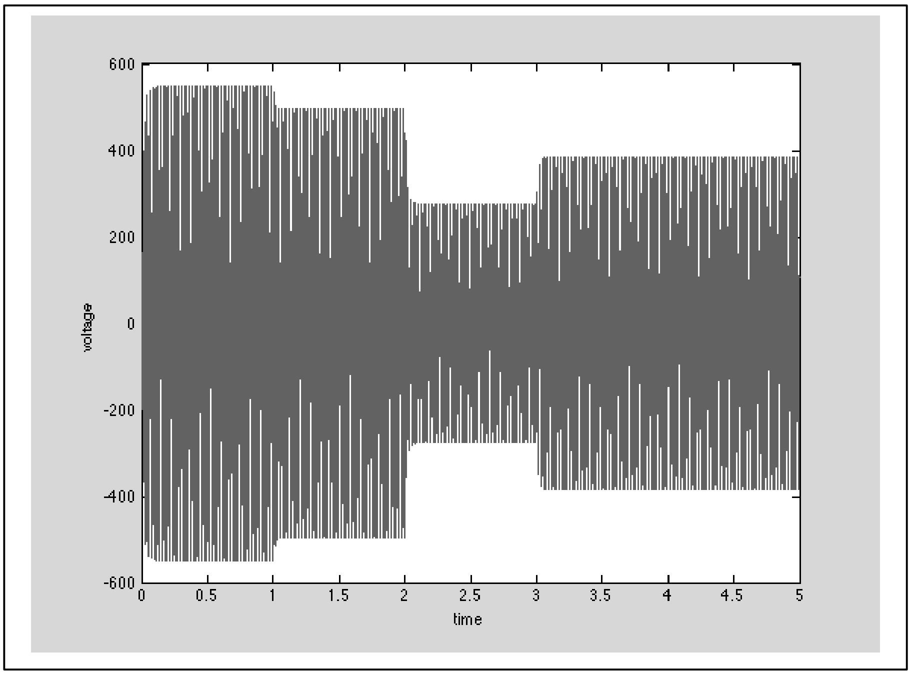


Figure (5.21) shows the waveform on the load when radiation is changing between [1000 900 500 700 900] at time duration [0 1 2 3 5] seconds, and just first load is switched on between [0 5] seconds. In this figure by using controller using controller compensates some amount of voltage drop.

**Figure 5.21: The voltage waveform in Case $C_4$**

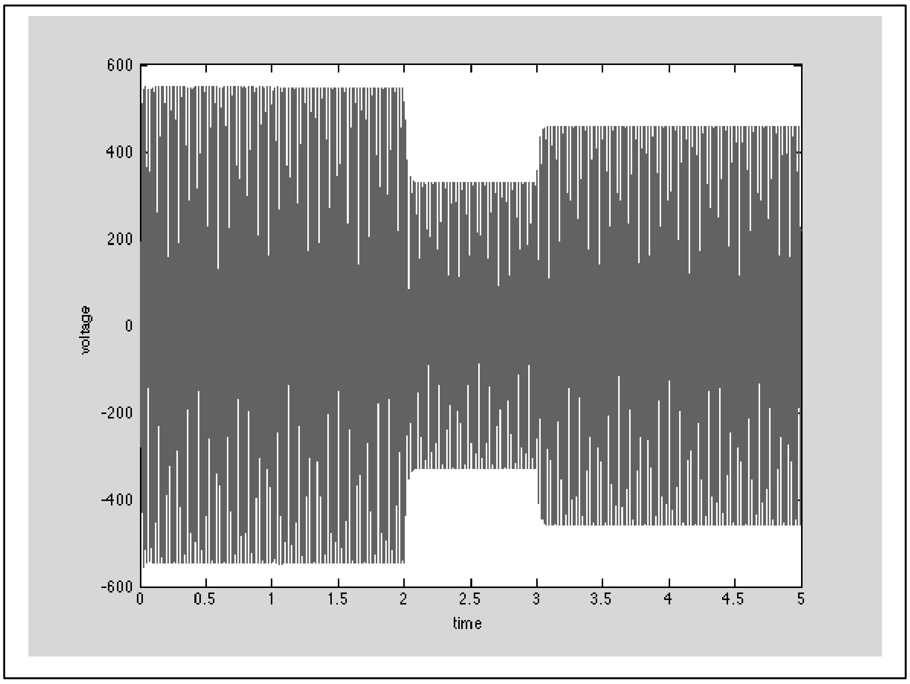
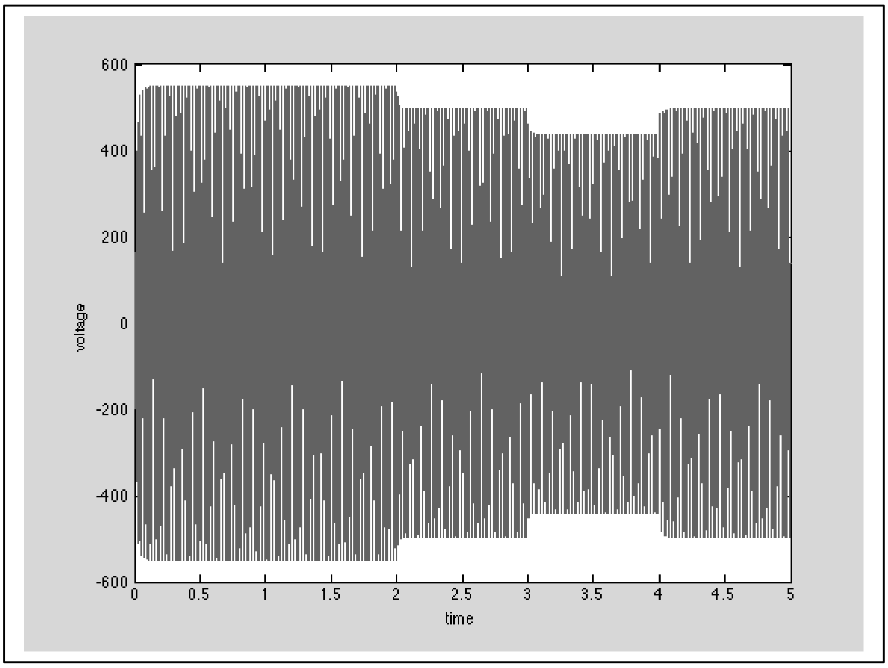



Figure (5.22) shows the waveform on the load without controller while radiation is changing between [1000 900 500] time duration of [0 2 5] seconds and first load is switched on between [0 5] seconds and second load is switched on between [3 4] seconds.

**Figure 5.22: The voltage waveform in Case $D_1$**




Case $D_2$ with controller while radiation is changing between [1000 900 500] time duration of [0 2 5] seconds and first load is switched on between [0 5] seconds and second load is switched on between [3 4] seconds is shown in figure (5.23) the imposed controller compensate the voltage drop in the system.

**Figure 5.23: The voltage waveform in Case $D_2$**

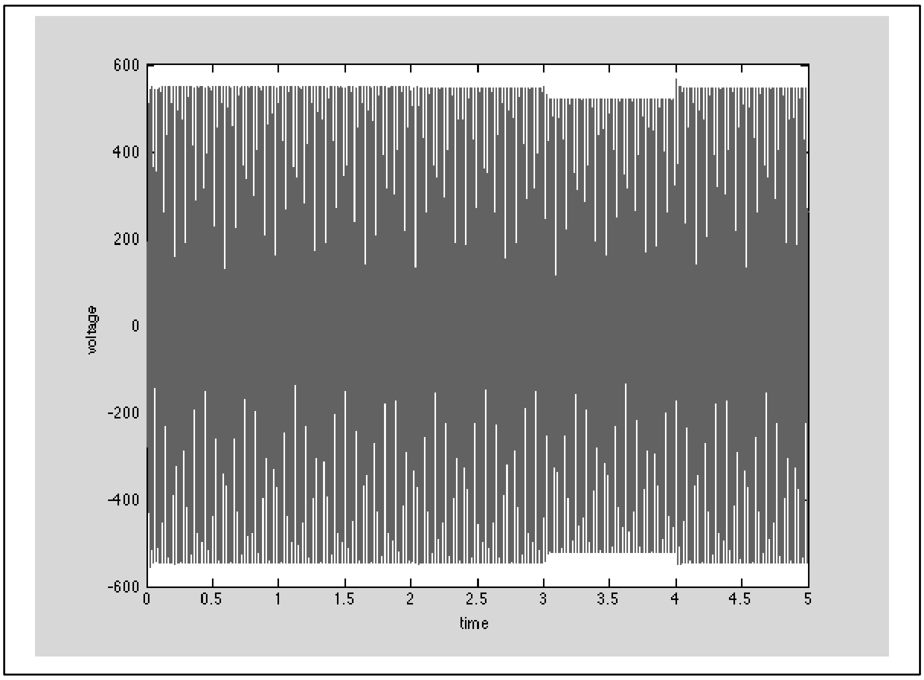
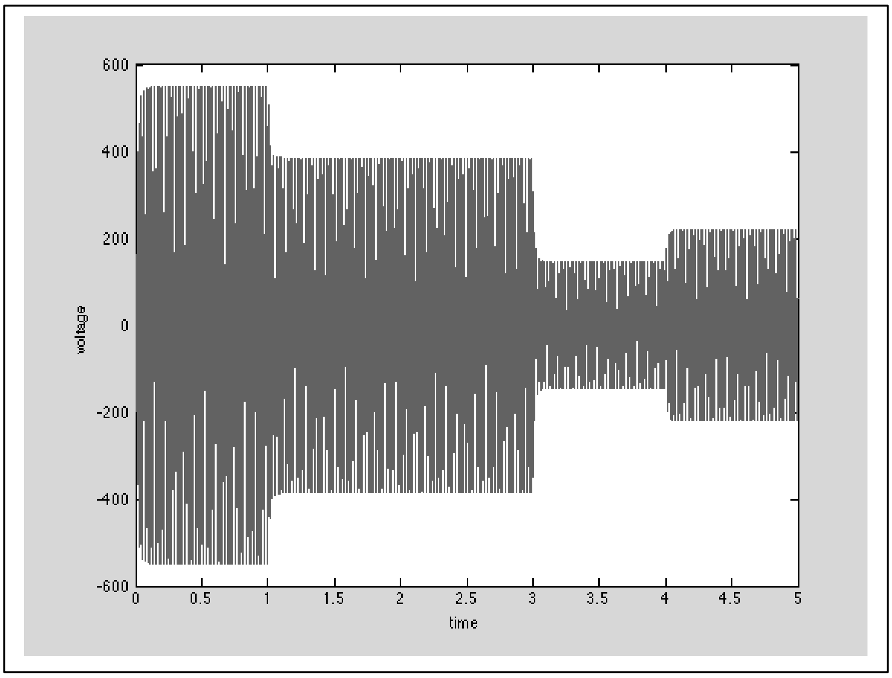


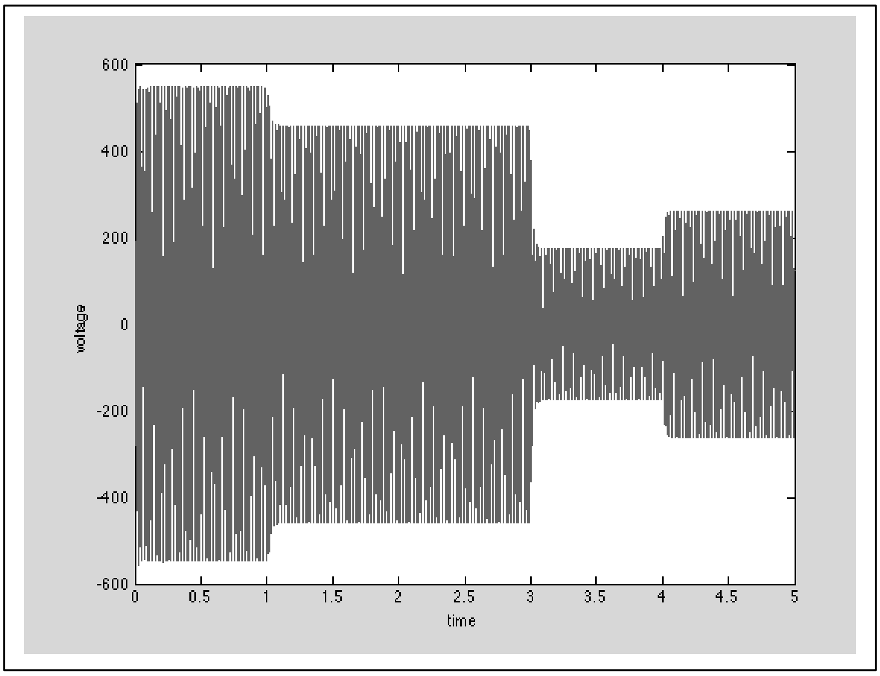
Figure (5.24) shows the waveform on the load without controller while radiation is changing between [1000 700 300 400] time duration of [0 1 3 4] seconds and first load is switched on between [0 5] seconds and second load is switched on between [3 4] seconds.

**Figure 5.24: The voltage waveform in Case $D_3$**




Case $D_4$ with controller while radiation is changing between [1000 700 300 400] time duration of [0 1 3 4] seconds and first load is switched on between [0 5] seconds and second load is switched on between [3 4] seconds is shown in figure (5.25) the imposed controller compensate the voltage drop in the system.

**Figure 5.25: The voltage waveform in Case $D_4$**



# 6. CONCLUSION

In this thesis, the main target is to propose a control system for the stand-alone PV system. A simple and useful controller was designed to control the output AC voltage of PWM inverter. PWM inverter by six keys sends order command to switch on and off the system. Like other electronic systems, the harmonics and distortions occur in the system Using two LC filters eliminates them. One of them is used for DC voltage side and another is used for AC voltage side. These filters improve the efficiency of the system by decreasing the losses, which is caused by THD.

In the proposed controller structure, the park transformation is used for dq0 transmission by converting three phase component such as a, b, c to dq. This method is very useful and simple by applying PI controller but the error percentage because of choosing the $k_p$ and $k_i$ in a trial and error methods will be countable. Filtering the output of the inverter is one of the important steps that must be done to reduce the impact of inappropriate conversion.

For the future plan by imposing some changes such as using some controller instead of PI controller with high accuracy in the operation of PV system, will make this system more effective and useful.

In this study, the PI controller is used for the proposed controller. The parameters of this controller result from trial and error way, which means that they cannot be accurate totally. So these parameters should be optimized to give the better result.

The controller scheme can be more useful by applying battery charging and discharging. In that situation, the system has an ability to regulate the output voltage subjected to the availability of the input power at nighttime or low solar irradiation.

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