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كلية الهندسة  
ماجستير الهندسة الكهربائية  
أنظمة الاتصالات

## **Power Management Device for a Micro Grid Containing a PV System and a Generator**

تصميم جهاز لإدارة شبكة توزيع طاقة صغيرة تحتوي على مولد  
ومصدر للطاقة الشمسية

**Ahmed Yousef Sokkar**

**Supervised by**

**Prof. Dr. Mohamed M. Abdelati**

**Prof. of Electrical Engineering**

**A thesis submitted in partial fulfilment  
of the requirements for the degree of  
Master of Electrical Engineering**

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إقرار

أنا الموقع أدناه مقدم الرسالة التي تحمل العنوان:

## Power Management Device for a Micro Grid Containing a PV System and a Generator

### تصميم جهاز لإدارة شبكة توزيع طاقة صغيرة تحتوي على مولد ومصدر للطاقة الشمسية

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## نتيجة الحكم على أطروحة ماجستير

بناءً على موافقة شئون البحث العلمي والدراسات العليا بالجامعة الإسلامية بغزة على تشكيل لجنة الحكم على أطروحة الباحث/ احمد يوسف عرفات سكر لنيل درجة الماجستير في كلية الهندسة قسم الهندسة الكهربائية - أنظمة الاتصالات وموضوعها:

### تصميم جهاز لإدارة شبكة توزيع طاقة صغيرة تحتوي على مولد ومصدر للطاقة الشمسية Power Management Device for Micro Grid Containing PV System and Power Generator

وبعد المناقشة التي تمت اليوم الاثنين 20 ربيع أول 1438هـ، الموافق 2016/12/19م الساعة العاشرة صباحاً في قاعة المؤتمرات مبنى القدس، اجتمعت لجنة الحكم على الأطروحة والمكونة من:

أ.د. محمد محمد عبد العاطي مشرفاً و رئيساً  
د. أسعد نمر أبو جاسر مناقشاً داخلياً  
د. محمد حاتم مشتهى مناقشاً خارجياً

وبعد المداولة أوصت اللجنة بمنح الباحث درجة الماجستير في كلية الهندسة/ قسم الهندسة الكهربائية -

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واللجنة إذ تمنحه هذه الدرجة فإنها توصيه بتقوى الله ولزوم طاعته وأن يسخر علمه في خدمة دينه ووطنه.

والله ولي التوفيق،،،

نائب الرئيس لشئون البحث العلمي والدراسات العليا

أ.د. عبدالرؤف علي المناعمة

## Abstract

Over the last ten years, Gaza Strip is suffering from inveterate crisis in the electricity sector and since that time experts working in this area to find solutions that contribute to alleviate the problem and commensurate with the available resources. Therefore, Photovoltaic (PV) systems with power generator are used to overcome this crisis. However, one of the biggest challenges of using PV sources with electric generator is reverse power condition. When the volume of the load become less than photovoltaic power systems, reverse power flow from the PV to the generator may cause important problems if it is not considered in the protection system design. One of the objective of this study is to investigate of the reverse power condition of the hybrid power system including 5KVA diesel generator and 3KVA PV. This thesis proposes a power management device (PMD) in order to solve the problem of reverse power flow from PV systems to the generator. The proposed system consists of PIC18F microcontroller, relays, voltage and current sensing component. The proposed power management device constructed at the Islamic University of Gaza to serve the Electrical Engineering Laboratories. the effectiveness of the PMD are evaluated by experimental analyses. The experimental results showed that the amount of reverse power flow from PV power systems is controlled at threshold of 10% of the diesel generator capacity. The result also showed PMD were able prevent the reverse power flow from PV to protect the other power sources.

**Keywords:** Photovoltaic, power distribution system, smart micro-grid system.

## الملخص

تقنية الشبكة الذكية لتوزيع الطاقة منتشرة في البلاد المتحضرة ومشهود لها في دمج مصادر الطاقة المتجددة وتحفيز المواطن على ترشيد استهلاك الطاقة والمساهمة في انتاجها. نظرا لتقطع التيار الكهربائي وغياب التشريعات التي تقفن هذا الموضوع يعزف المستثمرون للطاقة الشمسية عن بناء الأنظمة المجهزة للتكامل مع الشبكة (On-Grid) ويتجهون للأنظمة المعزولة (Off-Grid) رغم ان الأولى تمتاز بعدم احتياجها للبطاريات وبالتالي قلة تكلفتها وصدقتها للبيئة. غياب الخبرة التقنية في بناء وإدارة الشبكات الذكية لدى صناعات القرار في البلد ولدي مستثمري القطاع الخاص في مجال الطاقة المتجددة يساهم سلبا في الابتعاد عن الشبكة الذكية كحل استراتيجي لأزمة الطاقة في غزة. ولهذا نقوم في هذه الرسالة في بناء شبكة ذكية خاصة بقدرة ابتدائية 8 كيلو وات وقابلة للتوسع والربط مع اي شبكة ذكية مستقبلية. ويتم تركيب النظام في الجامعة الإسلامية ليخدم مختبرات قسم الهندسة الكهربائية بتغطية احتياجاتها من الطاقة والمساهمة في اغراض البحث والتدريس وتوجيه البوصلة نحو الحلول الاستراتيجية لأزمة الطاقة. النظام المقترح يحتوي على مصدرين للطاقة مولد ديزل بقدرة 5 كيلو فولت امبير ونظام خلايا شمسية بقدرة 3 كيلو فولت امبير. الى جانب المصدر الرئيسي في حال توفره. نظام التحكم والإدارة المنوي بناؤه يقوم بإدخال المصادر المتاحة حسب الأحمال المطلوبة مراعيًا التزامن وأولويات المصادر وأولويات الأحمال والعمل على حماية مصادر الطاقة من الأعطال الناتجة عن تشغيل النظام.

قال تعالى:

وَيَسْأَلُونَكَ عَنِ الرُّوحِ قُلِ الرُّوحُ مِنْ  
أَمْرِ رَبِّي وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا  
قَلِيلًا

صدق الله العظيم  
[الاسراء:85]

## **Dedication**

This thesis is firstly dedicated to God almighty and to my parents, who were immense sources of support throughout my education, I thank you. Thanks for all your love and support through the end.

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## List of Abbreviations

<b>A/B</b>	Analog-to-Binary
<b>AC</b>	Alternating Current
<b>CB</b>	Circuit Breaker
<b>CG</b>	Contacto Generator
<b>CM</b>	Contacto Main
<b>CT</b>	Current Transformer
<b>DC</b>	Direct Current
<b>DERs</b>	Distributed Energy Resources
<b>DG</b>	Distributed Generation
<b>DPCA</b>	Distributed Power Coalition of America
<b>DS</b>	Duty Cycle
<b>ELCB</b>	Earth Leakage Circuit Breaker
<b>GCB</b>	Generator Circuit Breaker
<b>HPF</b>	High Pass Filter
<b>KVA</b>	Kilo Volt Ampere
<b>KWh</b>	Kilo Watt hour
<b>MCB</b>	Miniature Circuit Breaker
<b>MPPT</b>	Maximum Power Point Tracking
<b>MTS</b>	Manual Transfer Switch
<b>PV</b>	Photovoltaic
<b>PWM</b>	Pulse Width Modulated
<b>RMS</b>	Root Mean Square
<b>RPR</b>	Reverse Power Relay
<b>SCADA</b>	Supervisory Control and Data Acquisition
<b>STC</b>	Standard Test Conditions
<b>SWG</b>	Switch Generator
<b>SWM</b>	Switch Main
<b>VT</b>	Voltage Transformer
<b>WTG</b>	wind Turbine Generators

# **Chapter 1**

## **Introduction**

# Chapter 1

## Introduction

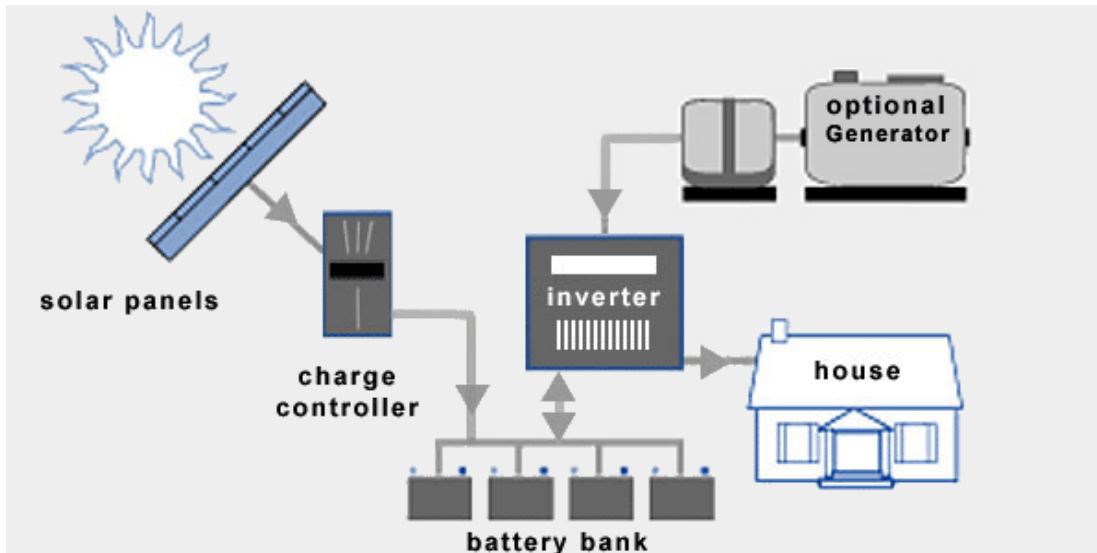
### 1.1 Background

Micro-grid technology for energy distribution is widely used in developed countries. It is recognized for integration of renewable energy sources and motivation of citizens to rationalize energy consumption while contribution to energy production. Any small scale electrical power generation technology that provides electric power near a load site, with or without interconnection to any distribution system is known as Distributed Energy Resources (DERs) or Distributed Generation (DG) (Bernal, Dufo, Dom and Yusta, 2008). They can be operated according to customer's demand and facilities during peak hours as an auxiliary power source, thus emphasizing on much greener sources of power supply. Of all the alternative resources, available, photovoltaic system, wind turbines, synchronous generators driven by turbines and fuel cells are amongst the most popular sources. Photovoltaic systems derive power from the sun, which depends on many factors such as solar irradiation and light intensity. These factors in turn affect the efficiency, voltage and output of the system (Das, Esmaili, L. Xu, and Nichols, 2005).

Since most of these factors cannot be controlled individually, renewable energy based DGs are usually composed of two or more systems to compensate one system for other. In residential homes and small businesses facility people are used to store electric power provided by the power distribution company by the use of batteries and inverter system to use the stored energy during power outages. Although the use of inverter system is considered better than electric generators, this solution involves several disadvantages including changing the batteries periodically due to limited life span. Also, due to the high price of the batteries and their large size, the energy that can be stored is limited. Furthermore, the stored electric power can only be used in small devices such as lighting and computers.

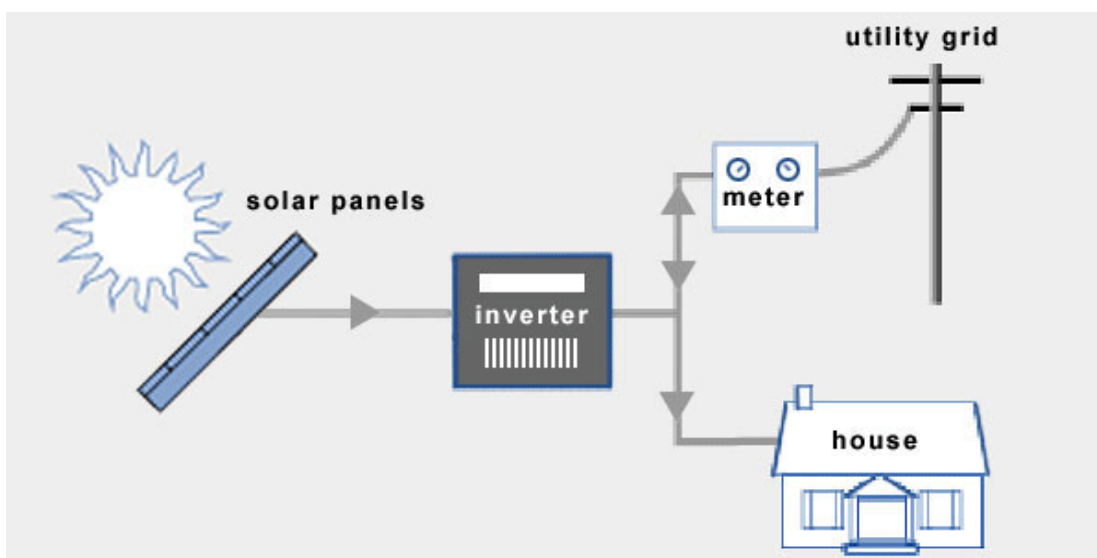
Over time the solar energy systems appeared on the market, this technology enabled the user to run most of the loads during the day and store limited amounts of energy

in the system batteries to be used at night. This system is called (Off-Grid) as shown in Figure 1.1.

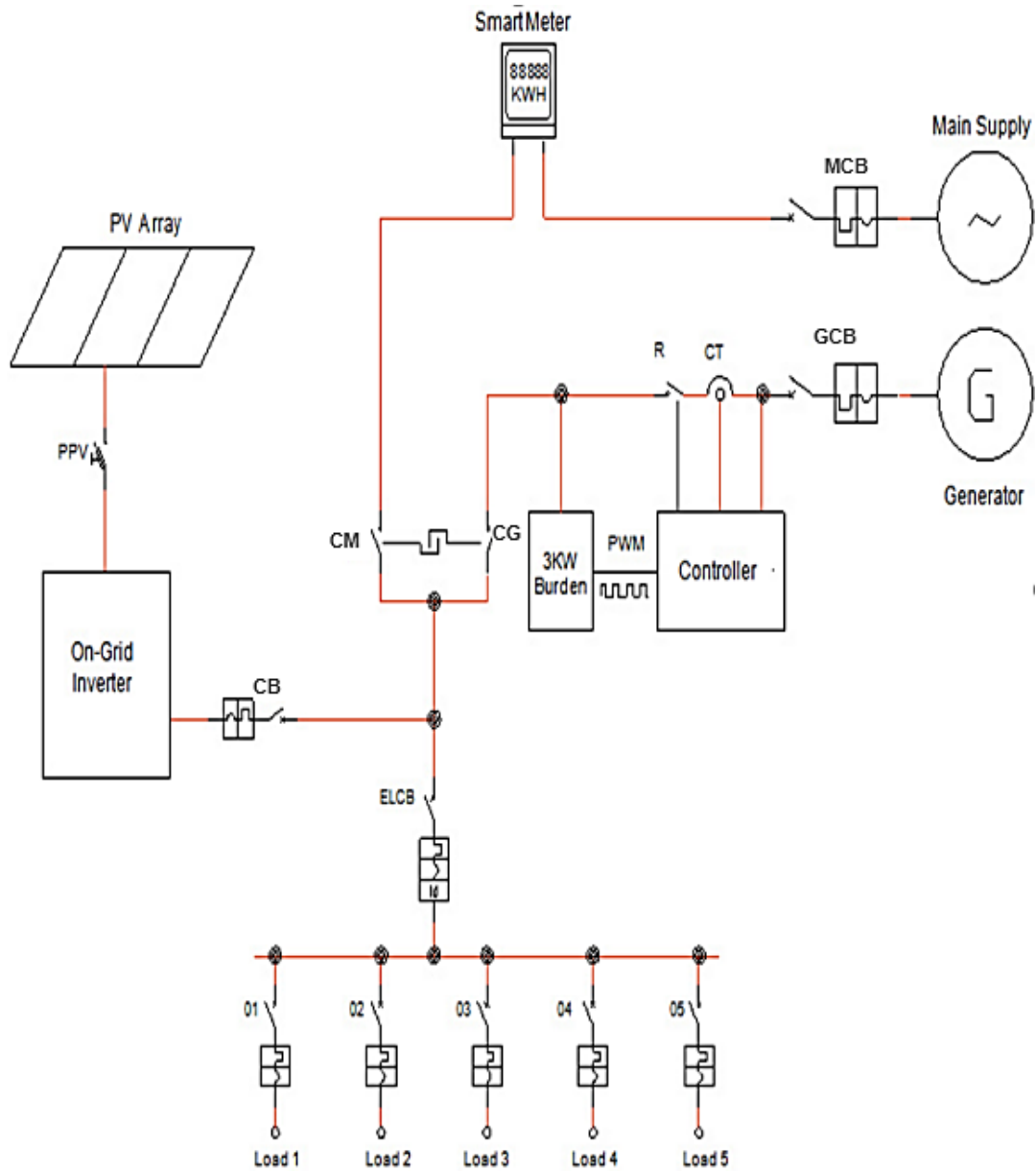


**Figure (1.1):** off-grid system.

The disadvantage of this system is the high cost and also the manually split of loads. In developed countries, they had developed less expensive and more efficient system which is called (On-Grid) as shown in Figure 1.2.



**Figure (1.2):** on-grid system.



**Figure (1.3):** Circuit diagram of the main distribution board.

This system does not require batteries, but the users consume the demanded power quantity and pump the overflowing energy to the distributor rather than storing it. Of course, the main source of electricity is available around the 24 (Das et al 2005& Zhu, D. Xu, PWu, Shen, and Chen, 2008). Such technology is unsuitable for Gaza because of the frequent interruption (disconnect of the energy) of the main source of power. Therefore, we strongly believe we need a combination of those sources as shown in Figure 1.3.



## **1.2 Synchronous Generator Protection**

Synchronous generators supply almost all the electric power we consume today. The rotor of a synchronous generator needs to be driven by a source of mechanical power or prime mover and the field winding needs to be fed by a source of DC power in order to provide active and reactive power to the power system. These exclusive combinations of electrical and mechanical equipment need to be protected against different kinds of faults. Generator faults are always considered to be serious since they can cause severe and costly damage to insulation, windings, core, shafts and couplings. Protective relays using variety of signals are meant to monitor and provide proper signals to alarm or remove the generator from the system under faulty conditions. Such abnormal conditions and associated protective devices will be discussed in chapter three.

## **1.3 Problem Statement**

The objective this work is to use distributed energy sources consisting of photovoltaic and synchronous generator. The use of renewable sources in conjunction with the utility grid has some problems. One of the biggest problems using renewable sources is its interconnection with the grid. Without any proper control strategy to interconnect the individual systems together, the output power of the distribution system cannot be regulated to meet the power demand. This would also give rise to deficiency in the power quality and also stability problems in the system. Thus, a proper control strategy is required to control one of the renewable sources in order to meet the load demand while maintaining power quality. Modelling a standalone system is a challenge, and connecting different renewable sources together with the utility grid is the main focus of this research.

## **1.4 Research application**

Distributed generators located at various places in the micro grid require protective relays in order to change their protection and control settings. For example, when distributed generators are placed at no identical place, power system improves

because of the resulting increased number of circuit paths to feed users in case of equipment (utility source, breakers and/or power lines) failure or maintenance operations. In certain circuit paths with distributed generators, currents along power lines could flow in different directions depending on what type of distributed generator was connected to end users the details regarding distributed generator are explained in chapter two section 2.1.

# **Chapter 2**

## **PV Fundamental**

## Chapter 2

### PV Fundamental

#### 2.1 Distributed Generation

Distributed Generation (DG) also known as decentralized generation is the future trend of the present-day utility system due to its ability to accommodate various alternative/ renewable energy sources. Distributed Generation will revolutionize the world of power system as the internet did the world of computing. As the internet, DG evolved from need for survivability with large mesh networks that would re-route the outages and yet could sustain failures and maintain its stability. In the same way, Distributed Generation, referred to as DG, is essentially known as the “Internet of Energy,” by producing energy from very small generation sources, sustaining the faults and yet supplying unlimited power (Ron and Wilder, 2007).

With the introduction of Distributed Generation, the energy sector has undergone major changes in many countries. These changes created a very competitive network driven by liberalization of market and decentralized power generation continues to compete with the centralized generation market (Zobaa and Cecati, 2006). Different countries use different definitions for DG to familiarize with the overall concept of DG as discussed by (Zobaa and Cecati 2006). One such general definition suggested is:

*“Distributed generation is an electric power source connected directly to the distribution network or on the customer side of the meter”* (Ackerman et al, 2000).

Distributed Generation, when implemented, provides reliable, high quality, low-cost electric power and offers savings in grid expansions and line losses. DGs, if connected to the power grid, provide bidirectional power flow between the grid and local generation unit, which enhances the total generation capacity, providing uninterrupted power supply with optimum energy cost (Zobaa and Cecati 2006).

According to the Distributed Power Coalition of America (DPCA), DGs have the potential to capture up to 20% of the entire power of the total generation capacity (Borbely and Kreider, 2001). In today's environment where issues such as blackouts due to voltage instability, reliability and electricity costs are at its peak (Kurita and Sakurai, 1988; US-Canada, 2003). Distributed Generation plays an important role.

The customers had to pay nearly double that of the usual price per kWh and such kinds of power failures have become frequent in recent times. All these blackouts clearly serve as a warning for the future scenario where Distributed Generation could very well be a solution to all the above problems. From renewable to non-renewable energy, Distributed Generation covers a wide spectrum of sources for electricity generation. Distributed Generation should not be confused with renewable generation; it may or may not be renewable sources. DG power sources also known as Distributed Energy Resources (DERs) are of many types, namely photovoltaic cells (PV), fuel cells, synchronous generators driven diesel engines, gas turbines or micro turbines, wind turbine generators (WTG), and internal combustion engines to name some of them. These DER capacities may range from 3kW to 10MW, which is less than 500 MW capacity of centralized generation (Jin and Jimenez, 2010). Distributed sources being green and environmental friendly, seldom contribute to air pollution which is very minimal (Puttgen et al, 2003).

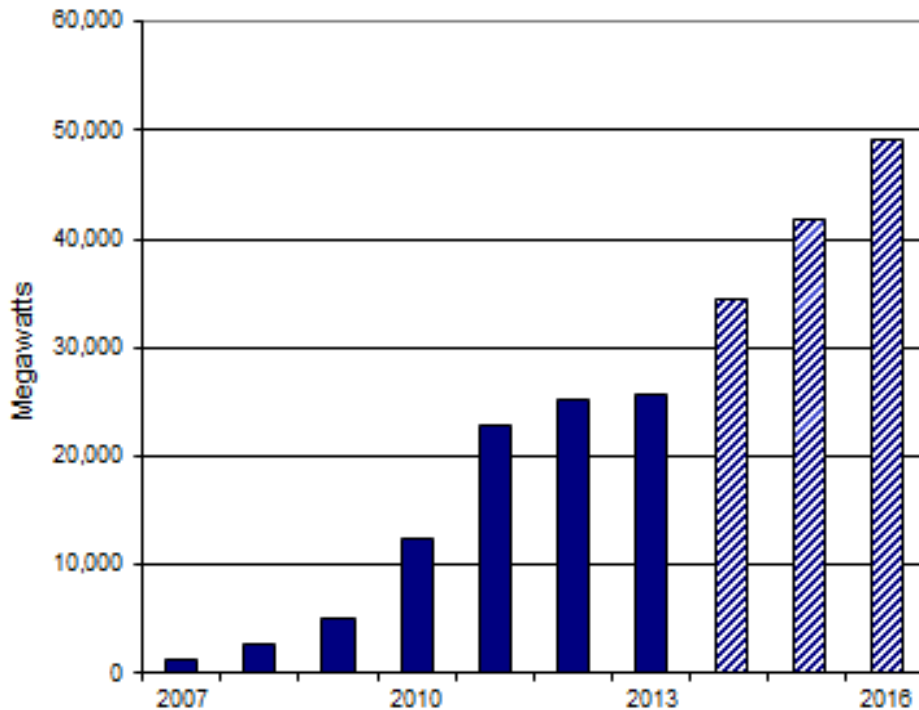
## **2.2 Photovoltaic System**

The history of photovoltaic cells dates back to 1839 when a French physicist Alexander Edmund Becquerel discovered that certain materials when exposed to sunlight produced small electric currents. This discovery led towards an active research interest for electricity generating materials, thus coining the term "*photovoltaic effect*". According to photovoltaic effect, when light falls on a semiconductor material of the PV cell it absorbs light energy in the form of photons which penetrates into the atoms of semiconductor.

This process frees the electrons in the negative layer to flow through an external circuit and then back to the positive layer, thus producing a flow of electric current (Williams, 1960). In 1957, Hoffman electronics produced solar cell with 9% efficiency, the first radiation proof silicon solar cell was produced in the same year too. On 17th March of the same year, the first satellite powered by solar cells, Vanguard I, was launched (Perlin,1999). In 1963, Bell laboratories in the USA launched the first commercial telecommunications satellite, Telstar. The usage of solar cells in this expedition has brought a revolutionary interest in application of solar cells in space programs. This major event even marked a great interest in use of solar cells as a major source of power supply in communication and satellite industry. After Telstar space expedition, the solar cells were in demand due to their efficiency. (Figure 2.1) clearly shows the world-wide increase in the production of PV power in megawatts, annual solar photovoltaics module production in china from 2007-2016. The demand started depreciating as the production cost per watt was higher when compared to fossil fuels.

Even though solar cell' efficiencies were increasing, its cost per watt was still too high when compared to fossil fuels, thus making it only viable to use in places connected to small utility grids and lines. Lately the production costs of solar cells are declining rapidly making these available for use in simple daily products like calculators and watches. This has also pushed solar cells to be economically more viable to be used not only in standalone applications but also with power system.

annual solar photovoltaics module capacity in china from 2007-2016.



**Figure (2.1):** Annual solar PV Capacity

The arrangement of photovoltaic cells in arrays is a notable process. A set of modules are aligned together to form arrays. These arrays are known as solar panels and are prominently used in households. A few important points about PV arrays:

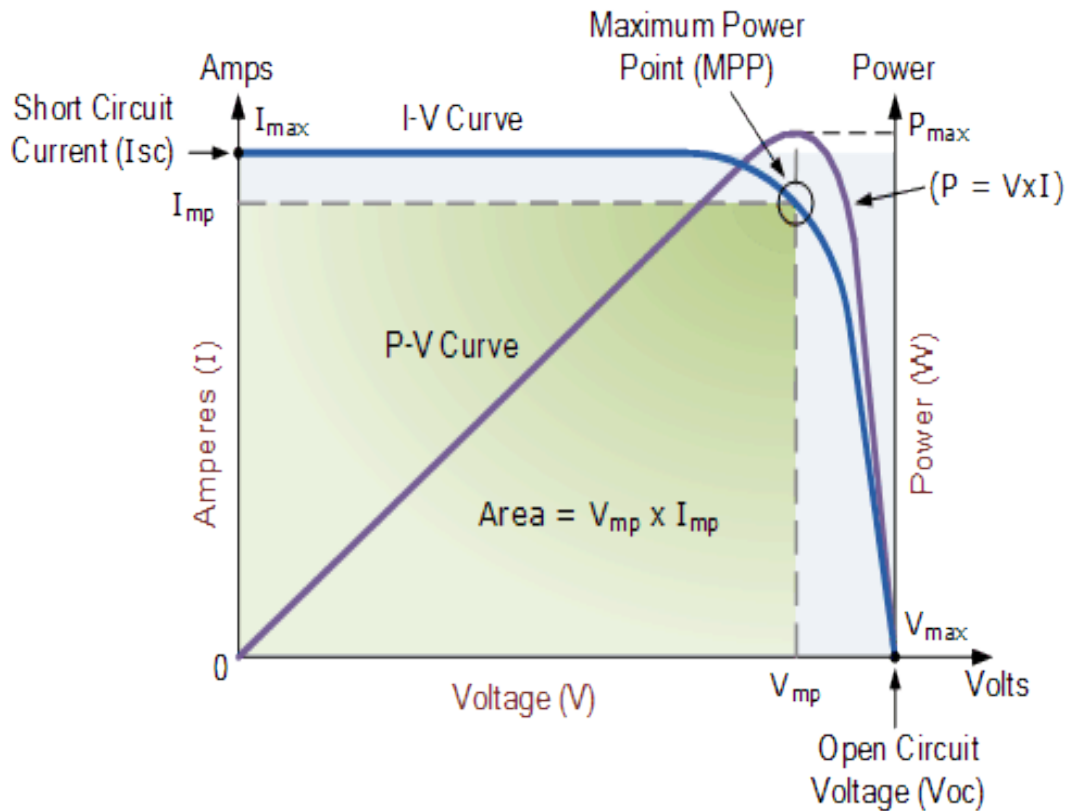
- To increase the utility and efficiency, PV cells are interconnected together using a sealed, waterproof package to form “Modules”. When two modules are interconnected together in series, their voltage doubles and the current stays constant.
- When two modules are wired together in parallel, the current is doubled keeping the voltage constant and giving maximum power. To get the maximum desired voltage, modules are wired together in series and parallel, to form PV arrays. This arrangement can produce power anywhere in the presence of direct sunlight.

### 2.2.1 Electrical Characteristics of Photovoltaic Cells

Electrical characteristics of PV cells are defined as the behaviour of cell under different conditions, that are best determined using the current and voltage levels at different irradiance levels or when connected with different loads. When the PV cell has, no load connected to it, the voltage across it reaches maximum. This is known as “open circuit voltage.” When a load is connected across the PV cell, the current reaches its maximum and the voltage decreases. This current is referred to as “short circuit current.” A nonlinear relation exists between the PV cell's current and voltage.

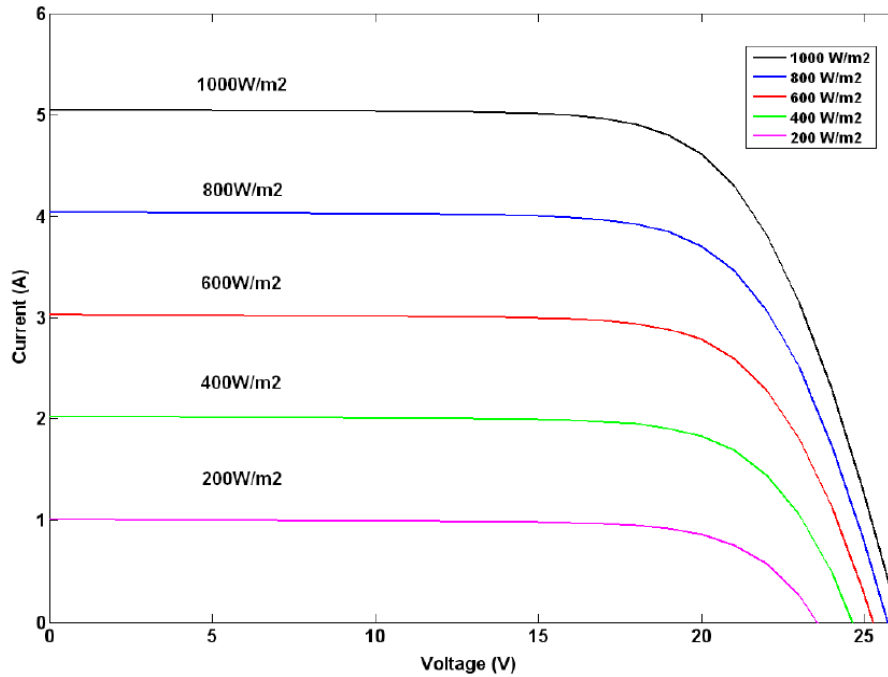
This relation indicates that there is a variation in voltage and current of PV cell with any change in the load. Figure 2.2 shows the I-V curve of a PV cell, this I-V curve is used to determine the characteristics of the PV cell used in solar modules. At Standard Test Conditions (STC), comparisons between performances of different PV cells are made. STC is defined as the light intensity at  $1000 \text{ W/m}^2$  of solar irradiation and  $25^\circ\text{C}$  temperature of PV cell. The  $P_{\text{max}}$  on the figure below represents the maximum power of the PV; at this point the power (product of output voltage and current of PV) reaches its maximum point. It is also known as “Maximum power point”. The solar cell has a maximum output current called short circuit current ( $I_{\text{sc}}$ ), open circuit voltage ( $V_{\text{oc}}$ ), and a maximum output voltage. PV modules usually supply power in peak watts ( $W_{\text{p}}$ ) measured at STC.





**Figure (2.2):** I-V curve showing the maximum power point of PV

The characteristics and efficiency of a PV cell depends on many factors such as the size and material, irradiance, temperature, and light intensity. The current is directly proportional to light intensity, unlike voltage which varies slightly by changing light intensity. Figure 2.3 shows the change in current voltage curve under changing irradiation levels at 25°C and light intensity at 1000 W/m<sup>2</sup> (Brea, 2009); the short circuit current is significantly affected by change in irradiation.



**Figure (2.3):** Current voltage characteristics

Figure 2.3 Current voltage characteristics of PV the performance of the Photovoltaic cell also depend upon the temperature. Voltage mainly is affected by change in temperature. An increase in temperature decreases the voltage and the current increases by small amounts.

### 2.2.2 Advances in Photovoltaic Technology and Its Application

Photovoltaic energy has been substantially beneficial due to less air pollution and zero emissions into the environment. One disadvantage with PV is its high cost of installation. But, with the ongoing improvements in PV technology and from the experiences gained by installing thousands of systems, PV energy and its performance have increased by leaps and bounds (Barker and Bing, 2005). The costs of PV cells have also dropped in the past few decades, thus making it more accessible to customers (Akihiro, 2005). Other than the space satellites and household applications, photovoltaic systems are being used in rural areas, such as in rural health clinics for refrigeration, water pumps for irrigation, and small scale

power generations (Zobaa and Cecati, 2006). PV sources have become popular for off-grid and on-grid market, making it more economical (Barker and Bing, 2005). The output power of the PV system depends on many variable factors such as the solar insolation levels, light intensity and temperatures. This is one drawback of a photovoltaic generation system, as the insolation level is not always constant to produce the expected energy and lowers the reliability of the generation system (Billinton, 2001; Liang et al, 2001). Many methods are developed to locate and obtain the maximum power from the cells (Kim et al, 2001).

The photovoltaic system can be connected to the grid which can act as pool of energy from which the power can be taken and also given back depending upon the insolation level and local energy demand (Zobaa and Cecati, 2006). Maximum Power Point Technique (MPPT) is one such technique used to extract the maximum power from the PV cells at any given point of solar insolation. The output of PV is DC and it must be converted to AC using DC/AC converter and this AC output can be interfaced with the utility grid of large or small scale. On the other hand, super capacitors or batteries can be used to store energy for standalone PV systems (Jamehbozorg, et al, 2011).

### **2.3 PV module and maximum power point tracking.**

A photovoltaic module consists of interconnected solar cells to form a single unit. A non-linear relation exists between voltage and current of a solar cell, shown in Figure 2.2, are plotted by simulating the simple PV module/equivalent circuit of photovoltaic module (Durgadevi, et al, 2011). The output of photovoltaic cell depends on the solar insolation at specific levels; at a particular operating point the output of the PV system is maximum. This maximum efficiency helps in extracting the maximum power. It is difficult to achieve an optimum insolation value. This maximum output can be extracted using the Maximum power point tracking (MPPT). MPPT is used in many applications in connection with PV system like in PV water pumps systems (Yoo, 2010) and low cost household applications (Brea,

2007). Hence, it is desirable to obtain maximum power point output at minimum cost under various operating conditions. Due to the importance of MPPT, several studies have been published (Esrām and Chapman, 2007; Faranda, and Maugeri, 2008) comparing the different methods of working, namely, (i) Perturb and Observe, (ii) incremental conductance, (iii) constant voltage, and (iv) Fuzzy logic control.

## **2.4 Converter and integration of PV to the grid.**

A conventional two stage conversion unit is generally required for a photovoltaic system to be interfaced with electric power system. The first stage would be the DC/DC converter, which in turn is to track the maximum power point from the PV system. The DC output from the MPPT is converted to AC output such that the voltage level of the photovoltaic system is adjusted to the grid level. This is the second stage which involves the DC/AC converter (Durgadevi, et al, 2011). This converter is controlled to produce the output voltage to match with the grid quality during standalone mode. During the grid connected mode the output current is matched in phase with the electric grid such that power is transferred to the grid at unity power factor (Zobaa and Cecati, 2006). The controllers are designed based on control goals and depending upon the DC/DC and DC/AC converters. The efficiency of the conversion system depends on various factors and individual devices connected like converters, batteries, and switches (Liang, Kuo and Chen, 2001). The DC to AC conversion efficiency of modern day converters has proven to exceed 90%. The most recent converters use the maximum power point technology for extracting the power from the photovoltaic system by dynamically adjusting the DC bus voltage of the PV system to its optimum value of changing insolation level and temperature.

# **Chapter3**

## **Protective Relaying**

### **Fundamentals**

## **Chapter3**

### **Protective Relaying Fundamentals**

#### **3.1 Power system protection**

The primary purpose of power system protection is to ensure safe operation of power systems. Furthermore, the tasks are to minimize the impact of unavoidable faults in the system most protective relays use digital processors to deploy a wide range of functions, and are programmable to allow more sophisticated criteria for initiating interrupt procedures to be applied. Modern digital relays have also started to fulfill a monitoring function since they can record the voltages and currents they measure for a period before and after any fault (Power System Relaying Committee, 2007). Power plant generators are important components of an electrical energy system, they should be constantly monitored and protected in order to maintain the quality and reliability of the power supply, otherwise, generators may occur in case of faults or incorrect operation. One of them is reverse power condition, reverse power flow causes problems if it is not considered in the protection system design. One of the objective of this study is to investigate the reverse power condition of the generators for this purpose, reverse power data are collected from cogeneration power plant generators (Power System Relaying Committee, 2007).

#### **3.2 Relaying**

The principal task of a protection system is to detect abnormal conditions, including faults in power system equipment such as generators, transformers, transmission lines, substations, and distribution systems. In doing so, the protection system should also initiate action to limit to a minimum the damage caused by the fault or abnormal condition and shorten, as far as possible, the duration of the power supply interruption. Immediate isolation of the fault not only restricts damage to the equipment, but also contributes to maintaining the stability of the system.

The isolation of a fault and protection of the equipment is usually the responsibility of a protection scheme based on relaying devices. The designers consider normal

systems operations and expected malfunctions, but base their protection designs mostly on the worst possible scenario. A protective relay is a sensing device which, when energized by suitable currents, voltages, or both, responds to the magnitudes and relationships of those currents and voltages by sending (relaying) a signal which will activate appropriate isolation equipment.

### **3.2.1 Sensing Sources, Current and Voltage Transformers**

Since the protective relays operate from currents and voltages supplied by current transformers (CTs) and voltage transformers (VTs), their operative function cannot be any better than their associated transducers. (Current and potential transformers do not "sense" in the strict use of the term. They serve to transform currents and voltages accurately to convenient amplitudes and to provide electrical isolation). It is therefore necessary that the outputs of the instrument transformers present a realistic picture to the relays of the conditions in the primary circuit during faults, as well as during normal operations.

### **3.2.2 Relay Characteristics**

A relay may be activated by a single quantity, such as a current or voltage, or by two quantities (same or mixed). In the latter case the relay may be made to respond to the phase angle between the two quantities, or to the relative magnitude of the two quantities or to a combination of the magnitude and the phase angle. The relation between the quantities that will cause the relay to operate may be shown graphically by what is called the operating characteristic. When the relay is activated by a single quantity, its response is purely a function of time as in Figure 3.1. When the relay is activated by two quantities, the characteristics may be shown in terms of the magnitude of one quantity and the phase angle between the two quantities as in Figure 3.2.

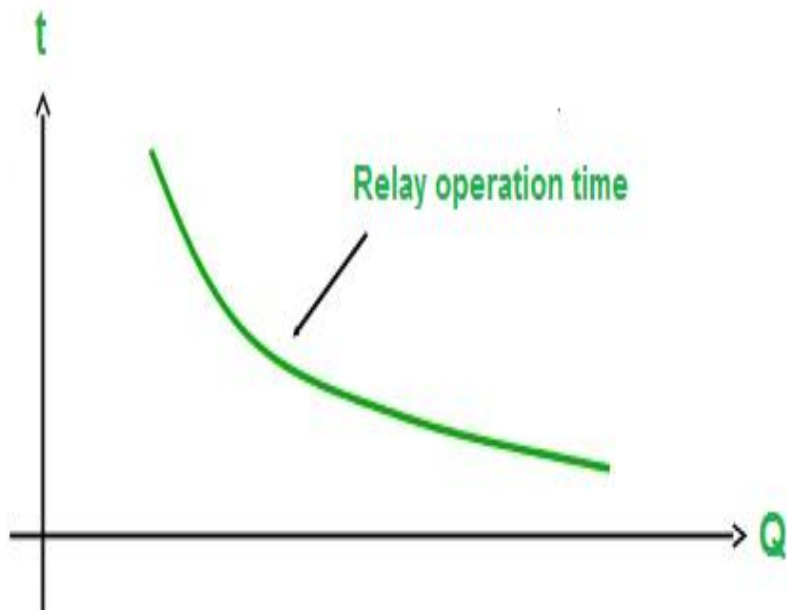


Figure (3.1): Quantity vs. Time

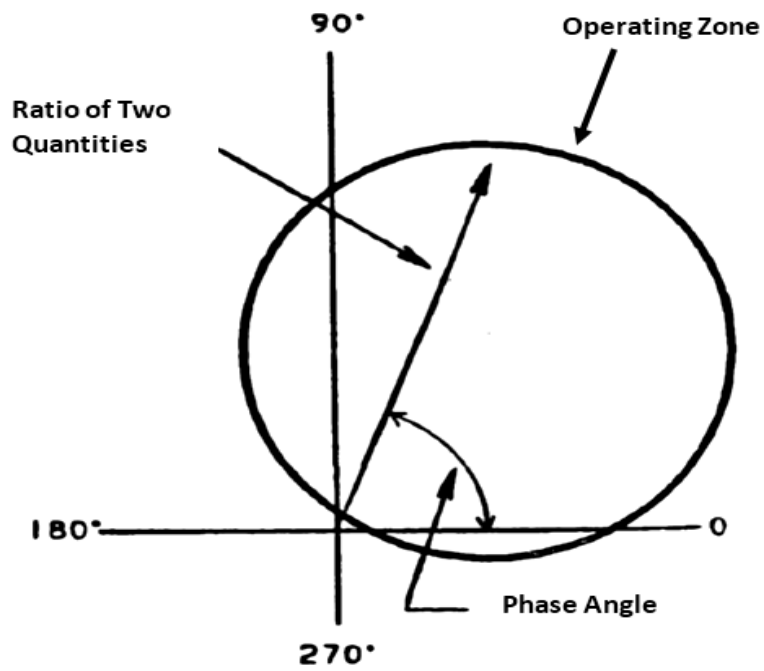


Figure (3.2): Quantities vs. Phase Angle



### **3.2.3 Electromechanical to Electronic Relays**

Over seventy percent of the existing protective systems in our present-day power systems are based on electromechanical relays. The schemes in use depend on the characteristics of induction disc or cup, moving coil or moving ferro-magnetic element often termed as armature elements. Several issues and considerations have influenced the pace of development in electronic relays:

1. Better performance and characteristics, e.g., higher speed with greater accuracy and sensitivity.
2. Greater standardization in manufacturing.
3. Easier manufacturing and reduction in maintenance time. Initially, electronic relays were designed using thermionic tubes, but the drawbacks of providing special power supplies for cathode heating and the provision of special voltages for anodes and electrode bias led researchers to solid state components, and recently to the microprocessor.

### **3.2.4 Advantages of Electronic Relays Over Electromechanical Relays**

Electronic relays in general possess the following advantages:

1. Low burden on current and voltage transformers when the power is operated.
2. Absence of mechanical inertia and burning contacts; high resistance to shock and vibration.
3. Very fast operation and long life.
4. Low maintenance owing to the absence of moving parts and bearing friction.
5. Quick reset action and absence of overshoot.
6. Ease of providing high amplification factors to provide increased sensitivity.
7. A greater degree of selectivity in the shaping of operations characteristics, enabling the practical utilization of relays with operating characteristics more closely approaching the ideal requirements.
8. Miniaturization of the relay modules due to low energy requirements.

The electronic relays with solid state components have certain limitations, but these can be overcome as indicated.

1. Temperature: sensitivity temperature compensation circuits have been developed and new solid state devices are less sensitive to temperature variations.
2. Aging: this is eliminated by presoaking of components for several hours at a relatively high temperature.
3. Sensitivity to voltage spikes: this can be reduced by filters and shielding.
4. Damage due to overloading: this can be reduced by careful circuit design.
5. Limited reliability: this can be reduced by utilizing redundant circuits and logic.

Electronic relays may be single or multiple-input devices. Individual modules are now on the market to provide critical measuring as well as non-critical switching functions. Timing and connection requirements are much better satisfied by solid-state circuits than with electromagnetic elements.

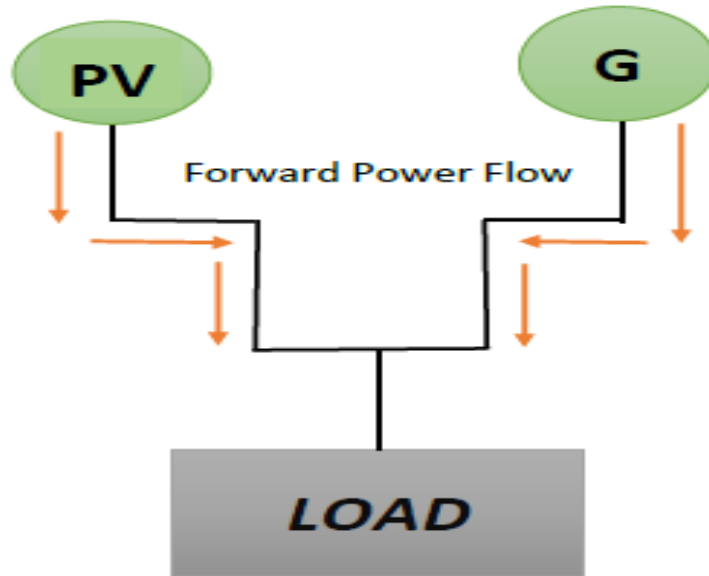
### **3.2.5 Basic Construction of Electronic Relay**

Basically, electronic protective relays based on current or voltage comparison are Analog to binary (A/D) signal converters with square wave output which can be supplied to a comparator circuit in such a way that a triggering signal is obtained only when both the observed and comparison signals are present the duration of the loop or cycle time is based on a timer circuit which can be adjusted accordingly with the type of application.

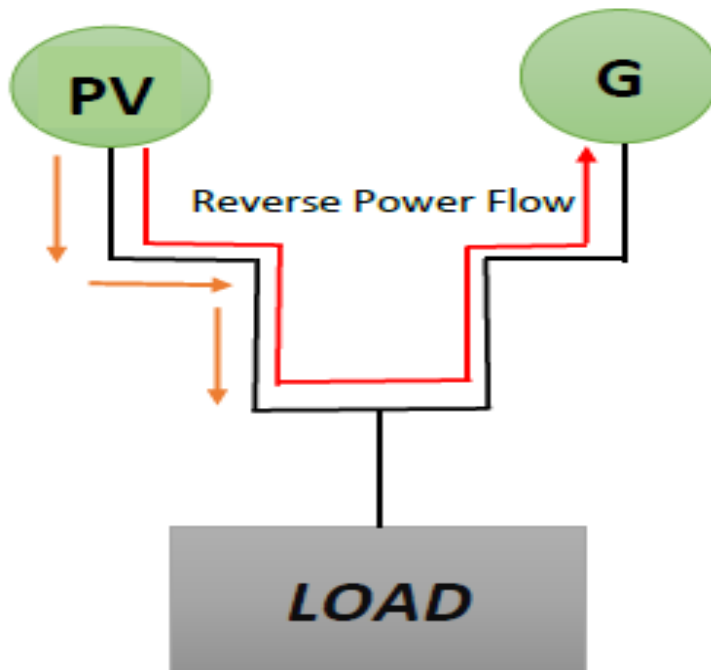
### **3.3 Reverse Power Flow Mechanism**

Radial distribution networks are usually designed for unidirectional power flow, from the in feed downstream to the loads. This assumption is reflected in standard protection schemes with directional over current relays. With a generator on the

distribution feeder, the load flow situation may be changed. The generator used is a synchronous machine which can either run as generator or motor depending upon the form of input energy. The definition of motor and generator operation relates to the sign of the average power. During the motoring action of the generator the power flows from the bus-bars to the machine. This condition is called as reverse power flow (Contino, Iannone, Leva, and Zani, 2006).



**Figure (3.3):** Forward power flow



**Figure (3.4):** Reverse power flow

### **3.4 Microprocessor Based Relays**

A microprocessor or a computer is inherently programmable and has basically simple logic and large memory capability, because whenever it strikes a limit another processor can be added to extend it further. Also, computer technology has the inherent capability for data transfer, mathematical or logic analysis, communication between modules both local and remote, data compression and reporting any exception. The capability of "reporting by exception" is ideal for relaying functions as during normal power system operation the microprocessor is gathering and "processing" the data collected, but it is the data during the instability period, when it is needed most and a tripping decision is made, which is reported under this rule of exception capability and stored in the memory.

These capabilities make adaptive functions much more feasible with the microprocessor technology. That is, the protection control and monitoring functions can automatically adjust their performance to match the ever-changing requirements of a dynamic power system and can also handle and optimize the changing system configuration. With the trend setting breakthroughs in the microprocessor based technology of the past decade, the implementation of more elaborate protection schemes with adaptive features are becoming practical. The use of these adaptive features in combination with the microprocessor's self-diagnostic capability, make it possible to further enhance protective schemes for the substations. A trend is developing to make it a part of a general Supervisory Control and Data Acquisition System (SCADA), but still capable of making a tripping decision at a module level for the sake of information and cost savings on hardware involved.

# **Chapter 4**

## **System Design and Components**

## **Chapter 4**

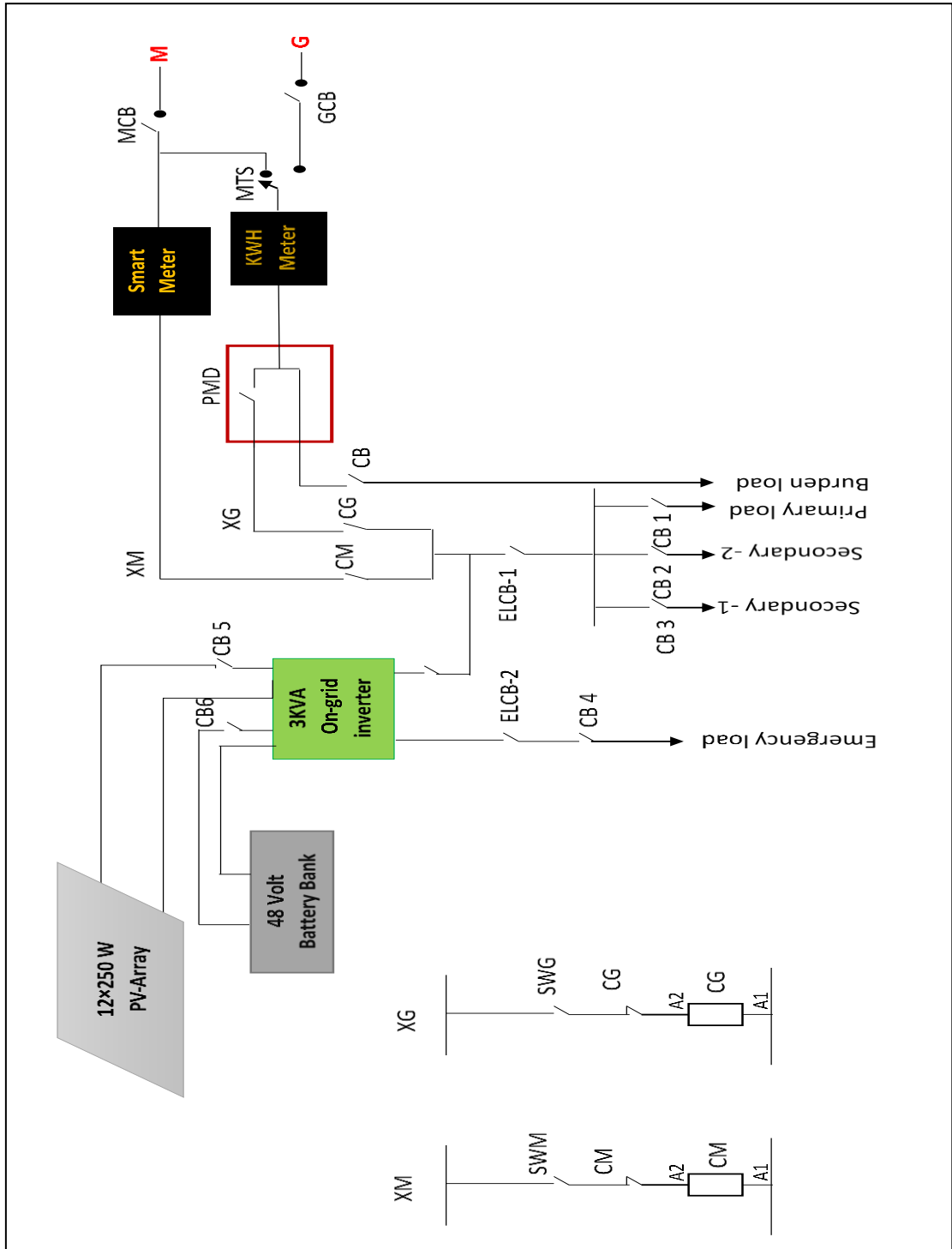
### **System Design and Components**

This chapter introduces the design of the system and experiments by using the main power sources. It gives a general understanding of how to design experiments. Refer to subsequent chapters in this thesis.

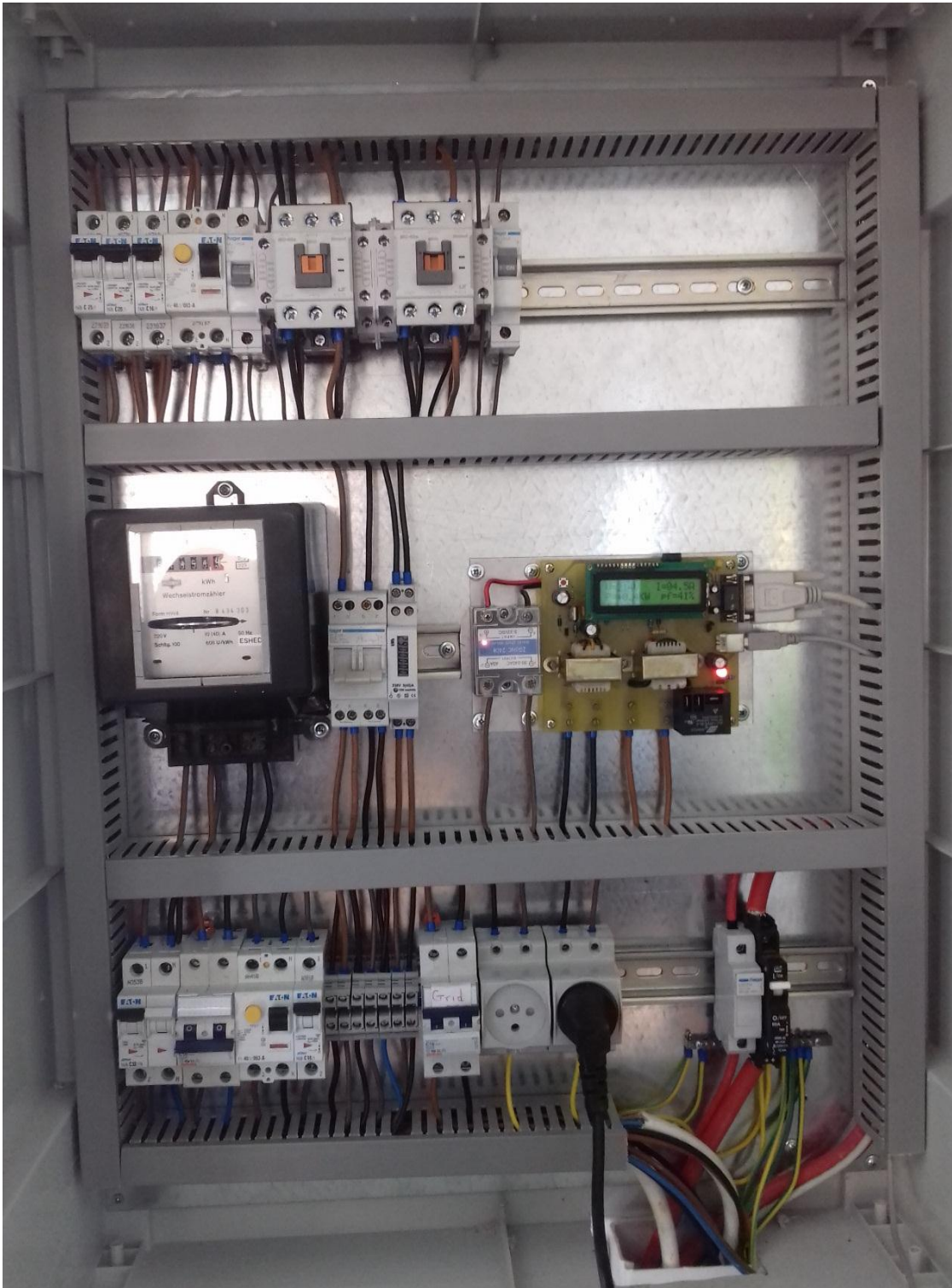
#### **4.1 System Requirements**

The system was constructed at the Islamic university of Gaza to serve the Electrical Engineering Laboratories. It will help in meeting its energy needs while being valuable tool for teaching and research purposes. Moreover, it will help attracting attention to the strategic solutions of the energy crisis. The system includes two sources of power. 5KVA diesel generator and a 3KVA PV system along with the main power supply. It is enough resources of power to run the renewable laboratory in our department and test the proposed device. The control and management system helps synchronizing the On-Grid inverter with the diesel generator while keeping the generator loaded above a specified threshold (about 20%). In this study, we plan to analyse all possible scenarios and configure the controller to act properly.

The aim of the system is to help interconnect a different of power resources as well as reduction of the power crisis in Gaza. Therefore, the components used to build this system were selected according to available component in local markets. However, the complete system shown in Figure 4.1 and Figure 4.2.



**Figure (4.1):** complete power and control circuit diagram.

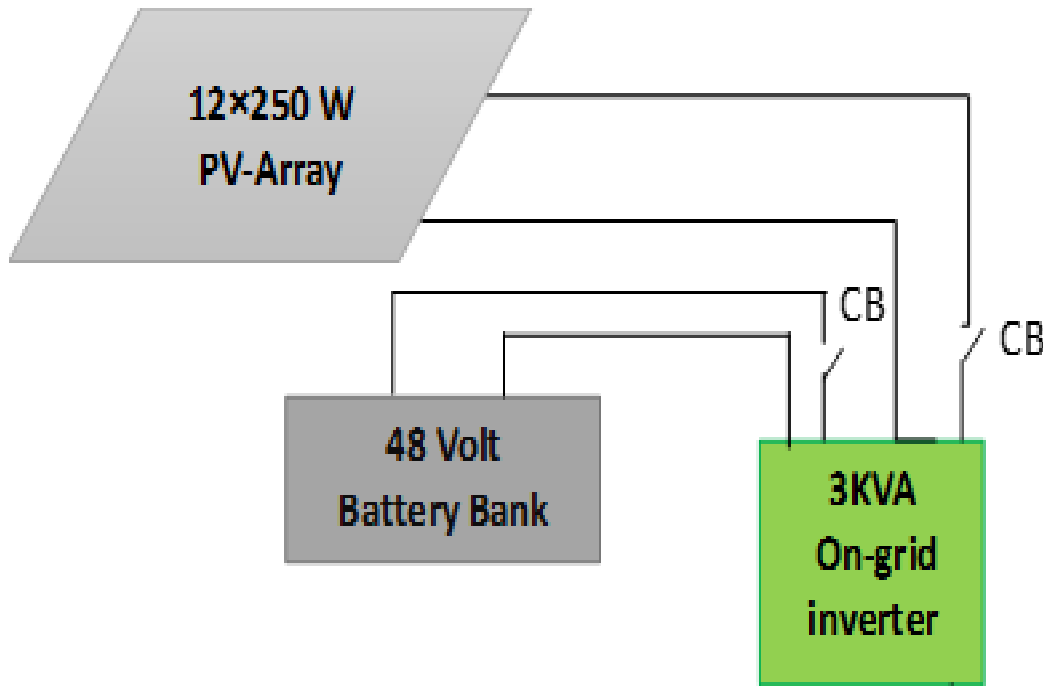


**Figure (4.2):** complete power and control circuit board.



## 4.2 PV Source

The use of PV source of operate with on-grid technology with 3 KVA capacity as shown in figure 4.3.



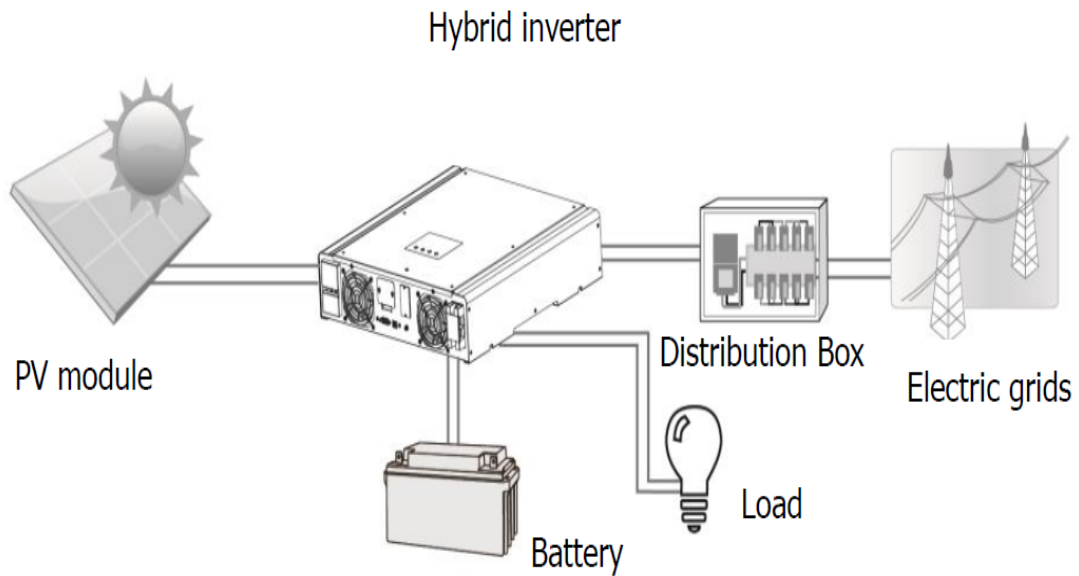
**Figure (4.3):** 3KVA on-grid PV system.

### 4.2.1 PV panels

Canadian Solar cell new modules have significantly raised the standard of module efficiency in the solar industry. They introduced innovative four bus-bar cell technology, which demonstrates higher power output and higher system reliability.

### 4.2.2 on-grid 3KVA inverter

We used 3KVA on-grid InfiniSolar inverter, this hybrid PV inverter can provide power to connected loads by utilizing PV power, utility power and battery power as shown in figure 4.4.



**Figure (4.4):** Hybrid PV system.

Depending on different power situations, this hybrid inverter is designed to generate continuous power from PV solar modules (solar panels), battery, and the utility. When MPP input voltage of PV modules is within acceptable range, this inverter is able to generate power to feed the grid (utility) and charge battery. This inverter is only compatible with PV module types of single crystalline and poly crystalline.

# **Chapter 5**

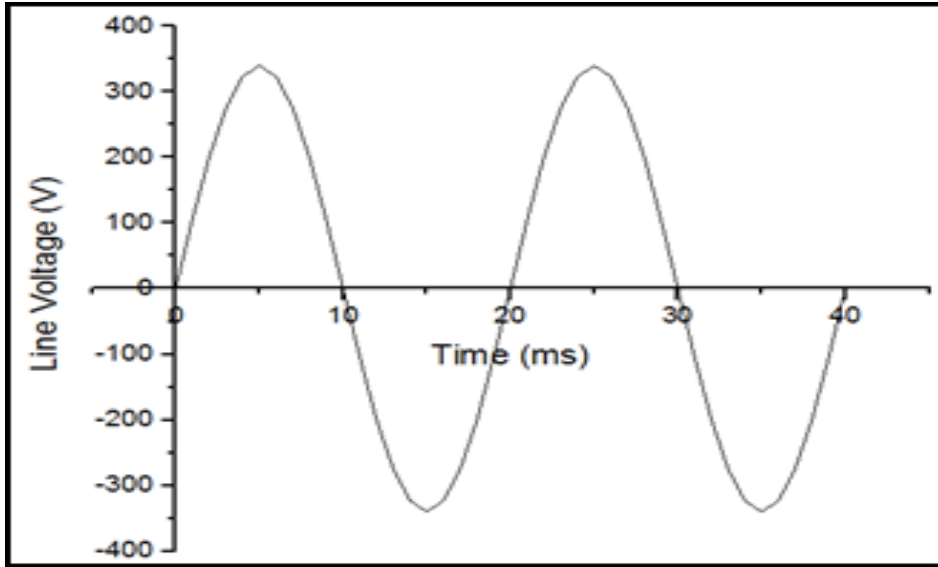
## **System Design and Experimental Results**

## Chapter 5

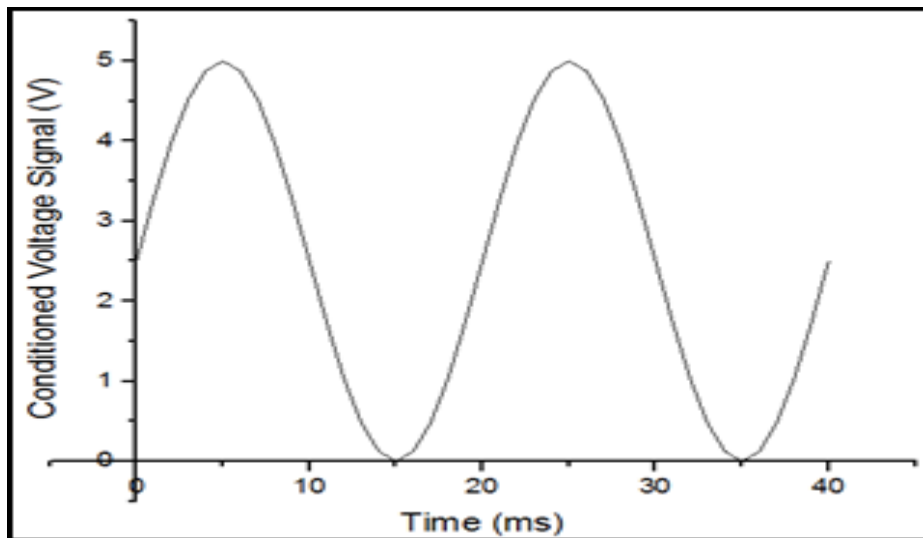
### System Design and Experimental Results

#### 5.1 Voltage and Current sensors

The voltage signal will be fed to one of the analog input channels of the microcontroller. The range of the analog input is from 0 to 5 volts for the targeted PIC18F microcontroller family. Therefore, a signal conditioning circuit is necessary to match the line voltage whose nominal root mean square (rms) value is 220V to fit within the allowable analog input range of the microcontroller as illustrated in Figure 4.1 Utilizing the full dynamic range of the analog channel helps in achieving the best possible resolution of the analog to digital conversion process. To this end, the AC voltage signal will be converted to have a peak to peak value of 5V (1.768 V rms) and then shifted 2.5V. Conversion could be done by a simple voltage divider. However, this approach leads to common ground between the microcontroller circuit and the line input which has many safety and disturbance concerns. Therefore, a transformer will be utilized insuring galvanic isolation between the controller circuit and the line voltage. A standard transformer 220V to 12x2V rated 300 mA is modified to have an additional winding which produce a maximum of 1.768 V rms for the maximum expected line voltage which is about 240V rms. The original secondary windings of this transformer will be used to generate a 12V along with a regulated 5V power sources necessary for the controller circuit.



(a)



(b)

**Figure (5.1):** Voltage sensing. (a) AC input. (b) Conditioned signal

As the number of primary winding is unknown to us, the required number of turns of the voltage sensing windings is determined experimentally and found to be 37. Now the primary number of turns may be calculated for future use as  $N_p = 37 \times 240 \div 1.768 = 5023$ . The resulted signal is clamped over a 2.5V DC so that the conditioned signal always lay within the analog input range of the microcontroller which is 0-5 volts.

For AC, current sensing, there are many techniques used in the industry. One may use a small series resistor and measure the voltage drop across it. This method is not proper here as it does not provide galvanic isolation. Another method is to use Hall Effect current sensor integrated circuits such as Allegro ACS712. Such chip senses the magnetic field generated by the current flowing through the sensors legs, which in turn outputs an analog voltage proportional to the current it senses. While being efficient and have small footprint, they are unavailable in the local market unfortunately. The last common method is to use the current transformer (CT) technique. Although not available in the sieged Gaza, we found a way to build it locally using a standard 220V to 12x2V 300 mA transformers. The low voltage winding has been totally removed and replaced by 2 turn winding of an insulated copper cable whose cross-sectional area is 4 mm<sup>2</sup>.

This 2-turn winding is now the primary winding of the current transformer. Using a low value burden resistor across the 5023 turn secondary winding, one may estimate the primary current by measuring the voltage drop on the burden resistor. In order to calculate the value of the burden resistor, the maximum current that will be measured should be specified. In our case this value is 20A rms. The turn's ratio of the CT is 2 to 5023. Therefore, the maximum current in the secondary winding is

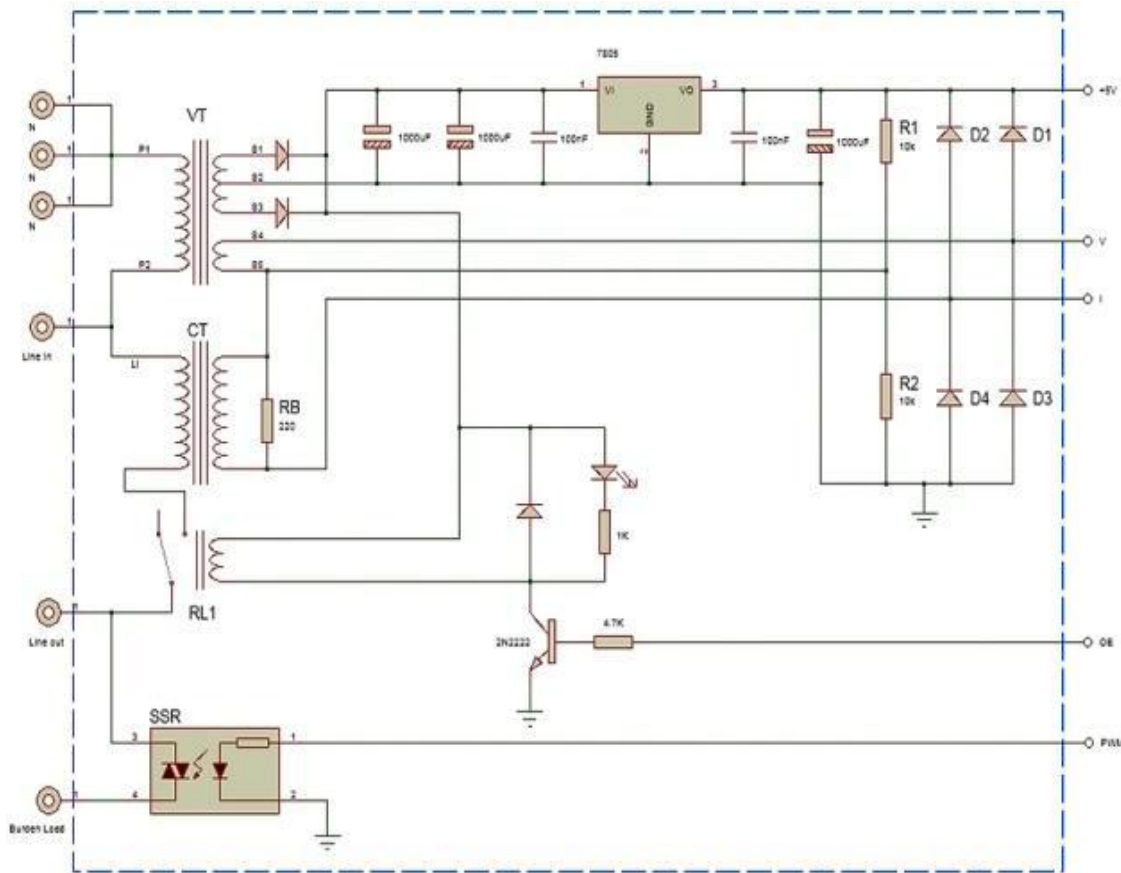
$$I_s = I_p \frac{N_p}{N_s} = 8 \text{ mA} \quad (1)$$

To maximize measurement resolution, the voltage across the burden resistor at peak-current ( $8\sqrt{2}$  mA) should be equal to one-half of the analog reference voltage (5V). Therefore, the ideal burden resistor is

$$R = \frac{2.5 \times 10^3}{8\sqrt{2}} = 221 \Omega \quad (2)$$

In our implementation, we used the nearest standard resistor which is 220  $\Omega \pm 1\%$ . The voltage across the burden resistor is clamped over a 2.5 V DC to keep the signal within the analog input range of the microcontroller. Figure 3 shows the complete

circuit used for voltage and current sensing along with the power supply unit. Resistors R1 and R2 form a voltage divider to obtain the required 2.5 V DC shift source and the diodes D1 to D4 are used to clip any possible spikes that may damage the controller. The relay (RL1) allows the controller to disconnect the generator from the grid in case of faults. The solid-state relay will be excited by a pulse width modulated (PWM) control signal to operate a burden load that keeps the generator load above a specified threshold.



**Figure (5.2):** AC current and voltage sensing circuit along with the power supply unit.

## 5.2 Hardware Design

The device is required to read the instantaneous voltage and current signals and use them to compute and display the standard electrical measurements such as rms voltage, rms current, power, and power factor. The device should be able to keep the power above a preset value through controlling a burden load. Moreover, it should be





200 nF capacitor at pin 14. The switch SW1 allows the device to be powered through the host USB port. This option is valuable during software developing and firmware uploading.

### 5.3 Software Algorithm

The voltage wave of the generator output is sinusoidal with frequency  $f$  and peak value of  $V_p$ . It may be expressed as.

$$v_l(t) = V_p \cos(2\pi ft) \quad (3)$$

The voltage signal at the analog to digital converter input ( $V_a(t)$ ) is a shifted scaled version of the line voltage. The DC shift is half the analog to digital reference voltage  $V_r$  and the scaling factor ( $k_v$ ) is the voltage transformer turns ratio. For our specific case  $V_r$  is 5V and  $k_v$  is 37/5023. Therefore, the signal at the analog to digital converter input is expressed as follows:

$$v_a(t) = k_v V_p \cos(2\pi ft) + \frac{V_r}{2} \quad (4)$$

The analog to digital converter has a resolution of 10 bit (1024 levels). Assuming a sampling period of  $T_s$  and neglecting the quantization error, the  $n^{\text{th}}$  digital samples will equal:

$$v_d(nT_s) = \frac{2^m - 1}{V_r} (k_v V_p \cos(2\pi f n T_s) + \frac{V_r}{2}) \quad (5)$$

The scaling number comes from the fact that when the analog input equals the reference value, it is converted to the maximum 10-bit digital number which is  $2^m - 1$ . In order to obtain a digital value equals the line voltage along with some DC offset that will be removed later; the converted signal must be multiplied by the scaling factor  $\frac{V_r}{k_v(2^m - 1)}$ . The resultant signal will equal:

$$v_s(nT_s) = V_p \cos(2\pi f n T_s) + \frac{V_r}{2k_v} \quad (6)$$

Using a High Pass Filter (HPF) the DC content of the signal is eliminated producing a clean digital version of the line voltage signal:

$$v(nT_s) = V_p \cos(2\pi f n T_s) \quad (7)$$

The line current waveform will be also sinusoidal having the same frequency but with peak value of  $I_p$  and a phase shift  $\theta$  that depend on the applied load. The current may be expressed as:

$$I_l(t) = I_p \cos(2\pi f t + \theta) \quad (8)$$

Using the same procedure carried for the voltage, we will obtain a clean digital version of the line current signal which equals:

$$I(nT_s) = I_p \cos(2\pi f n T_s + \theta) \quad (9)$$

The extracted voltage and current signals are multiplied to give the instantaneous power signal:

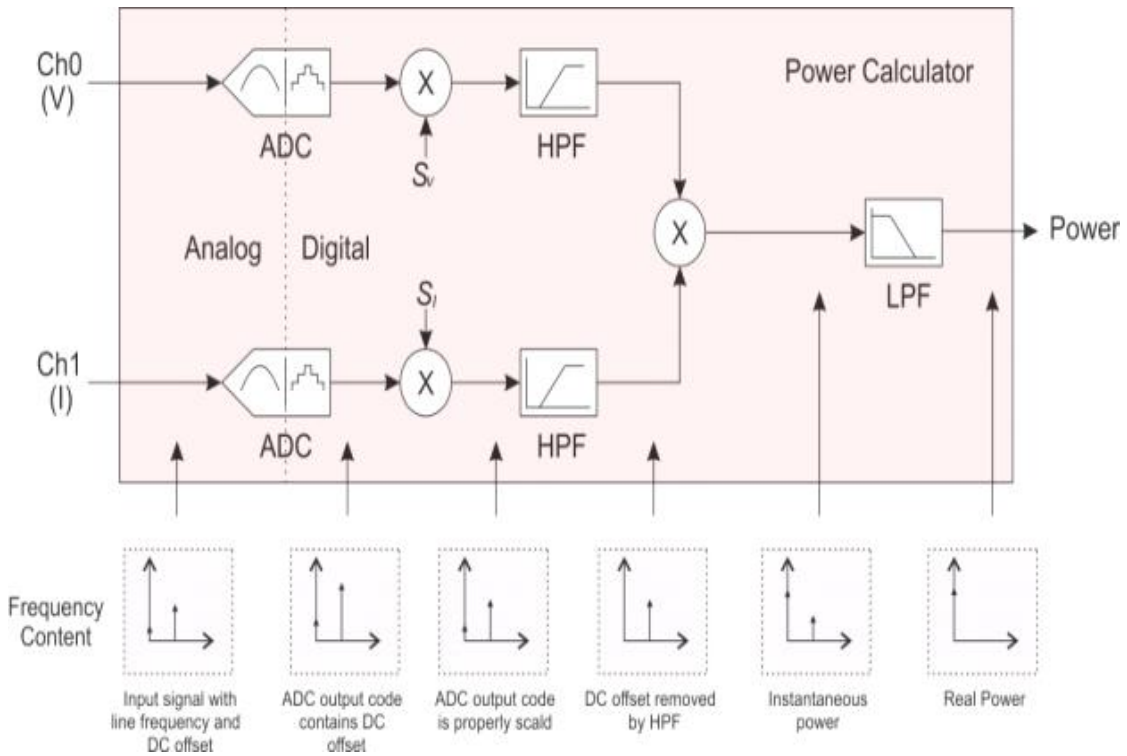
$$\begin{aligned} P(nT_s) &= V_p I_p \cos(2\pi f n T_s) \cos(2\pi f n T_s + \theta) \\ &= V_p I_p \cos(2\pi f n T_s) [\cos \theta \cos(2\pi f n T_s) - \sin \theta \sin(2\pi f n T_s)] \\ &= V_p I_p \cos \theta \cos^2(2\pi f n T_s) - \frac{1}{2} V_p I_p \sin \theta \sin(4\pi f n T_s) \\ &= \frac{1}{2} V_p I_p \cos \theta [1 + \cos(4\pi f n T_s)] - \frac{1}{2} V_p I_p \sin \theta \sin(4\pi f n T_s) \\ &= \frac{1}{2} V_p I_p \cos \theta + \frac{1}{2} V_p I_p [\cos \theta \cos(4\pi f n T_s) - \sin \theta \sin(4\pi f n T_s)] \end{aligned}$$

$$= \frac{1}{2} V_p I_p \cos \theta + \frac{1}{2} V_p I_p \cos(4\pi f n T_s + \theta) \quad (10)$$

Substituting  $V_p = \sqrt{2}V_{rms}$  and  $I_p = \sqrt{2}I_{rms}$  into previous equation, the instantaneous power formula becomes:

$$P(nT_s) = V_{rms} I_{rms} \cos \theta + V_{rms} I_{rms} \cos(4\pi f n T_s + \theta) \quad (11)$$

The first term is constant and known as real or active power while the other term is oscillating between the source and load. It is known as the reactive power. In order to extract the active power component, the instantaneous power is filtered with a low pass filter (LPF). A block diagram that illustrates the signal processing for power calculation is shown in Figure 5.4.



**Figure (5.4):** Signal processing for power calculation.

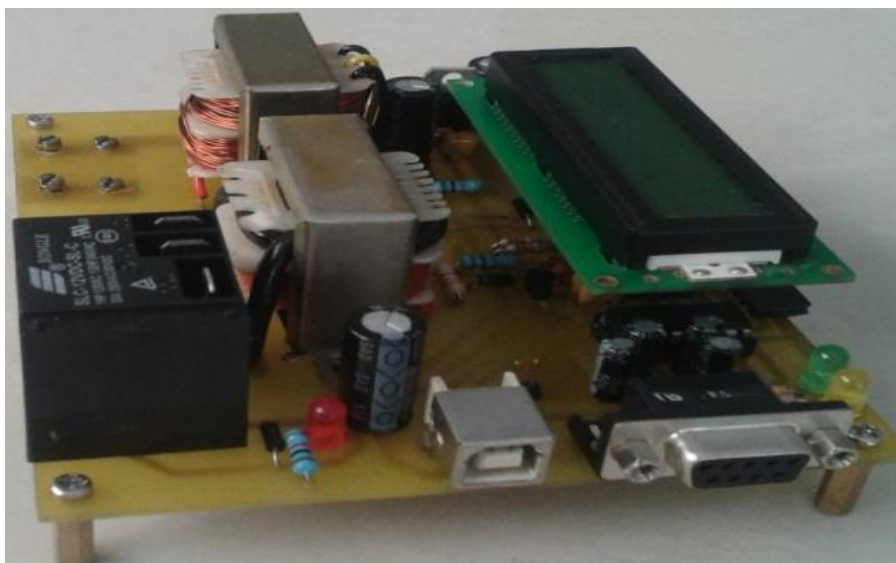
For the control process the calculated power is compared to a preset threshold (about 20% of the generator rating) the error signal is used to set the duty cycle of the PWM control signal that activates the burden load. The duty cycle may range from 0 to 255. If not reached its maximum and the power is still less than the threshold, the

duty cycle is increased quickly. On the other hand, if not reached its minimum and the power is above the threshold, the duty cycle is decreased slowly until it reaches 10% after which the decrement is performed in a much slower rate. Defining a long integer variable DSL that is 100 times the duty cycle DS, the proposed algorithm is easily implemented using integer arithmetic as follows:

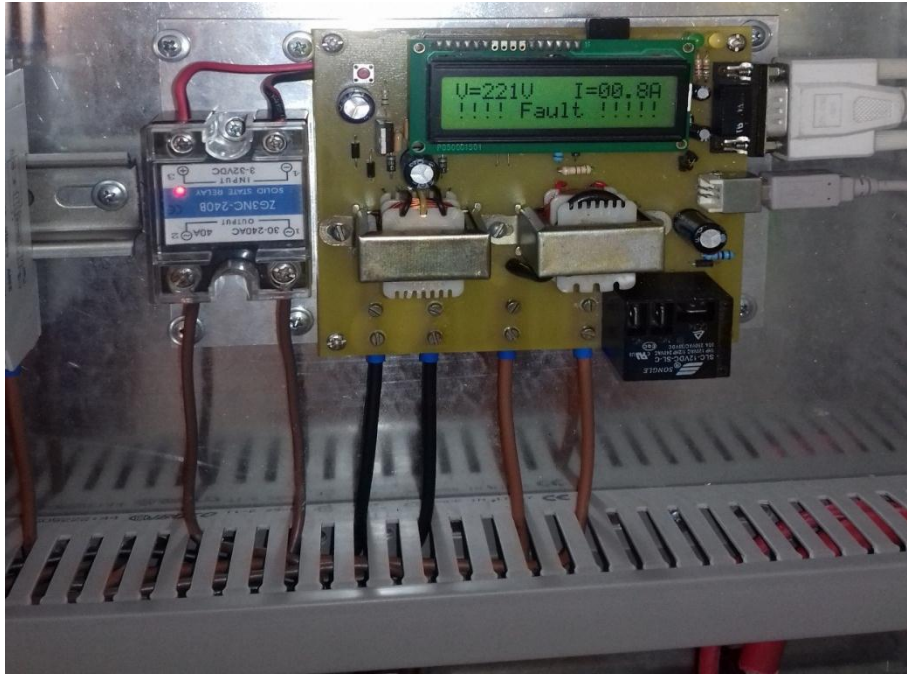
```
if (P<Pth && DSL<25420) DSL+=80 ;  
if (P>Pth && DSL>2500 ) DSL-=40 ;  
if (P>Pth && DSL<2501 && DSL>0 ) DSL-=1 ;  
if (P<0) {RA4_bit=0; Lcd_Out (2, 1,"!!!! Fault !!!!!");}  
DS=(DSL+50)/100,  
PWM1_Set_Duty(DS);
```

#### 5.4 Experimental results

The device is implemented on an 11x13 cm printed circuit board as illustrated in Figure 5.5. The Mikroelektronika USB boot loader is downloaded on the microcontroller using a chip programmer for once. Later, the USB port is used to download the controller software. We started by simple software routines to test the hardware functionality such as the display, the relay, the solid-state relay, and the line measurements. Doing this successfully, the controller code is installed and the device is connected with the inverter as illustrated in Figure 5.6.

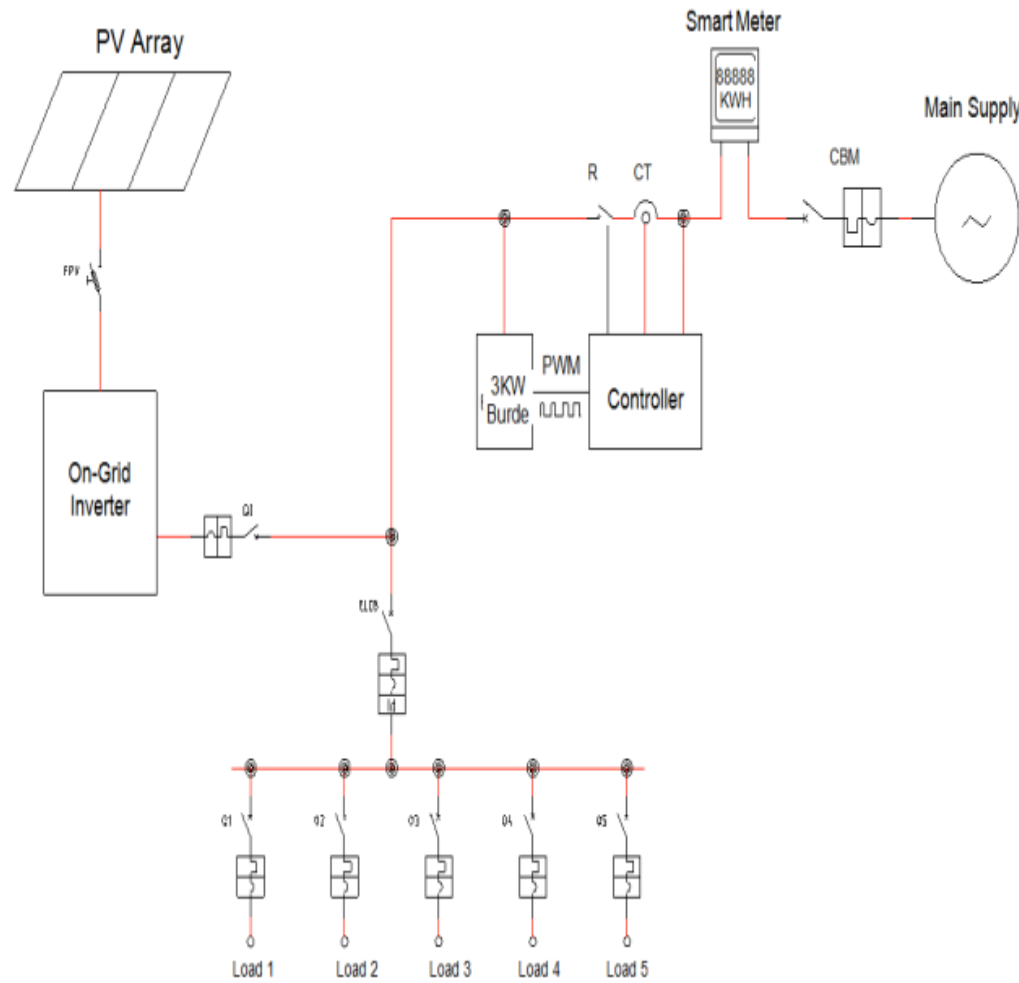


**Figure (5.5):** The power management device.



**Figure (5.6):** The power management device after connection.

For the sake of the generator safety, we preferred to test the device first with the mains supply.



**Figure (5.7):** Device testing first experiment.

The power threshold is set to 300W and the experiment is conducted at noon time when the inverter was able to inject up to 2400 W into the grid. A variable load is used while running connection and disconnection of the inverter and the mains circuit breakers. All scenarios are successfully conducted and the controller was able to keep the power drawn from the grid positive.

The second experiment was to test the device for generator protection. Therefore, it's integrated with our experimental platform illustrated in Figure 1.3. The first run of the experiment did not go as expected. The generator we are using is small size rated 5 KVA. There was a significant tolerance of its frequency especially on load variation. Under no load its frequency was 51.6 Hz and this lays outside the

allowable frequency range for the inverter which is from 47.5 Hz to 51.5 Hz. Once loaded its frequency drops to about 49 Hz. To fix the situation we preferred to adjust the generator governor so that it has a frequency of 50.5 Hz at no load. Moreover, the power threshold is raised to 500 W instead of 300 W. It is about 10% of the generator rating and secures a wide margin for transients. Having done these modifications, the system operated properly without any complications.



**Figure (5.8):** Second experiment

# **Chapter 6**

## **Conclusion and Future work**



## **Chapter 6**

### **Conclusion and Future work**

#### **6.1 conclusion**

When connecting an on-grid PV system with a power generator, it is expected to share the load and help reducing the consumption of generator fuel. However, if the load is lower than the injected PV power, energy will flow in the generator disturbing its operation and risking its safety. The main objective of this research was to design and implement a device that regulates such a situation. The device is based on PIC18F2550 microcontroller and programmed to keep the generator running above 10% of its rating. The device is tested successfully on an experimental platform at the Islamic university of Gaza.

The implemented device will enable institutions which has backup generator to integrate renewable systems in their power grid. However, a complementary research is expected to integrate this device with a higher-level controller for the institution.

#### **6.2 Future work**

Its recommended to perform this type of work with wider power demand and building whether in IUG or other organization.

Other researcher may proceed to perform an automatic control to connect and disconnect between the power resources.

Another future work suggested to use a telecommunication and mobile technology to control the load type that will be easier to the users.

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## The Reference List

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## Appendix 1



# Power Management Device for a Micro Grid Containing a PV System and a Generator

Ahmed Y. Sokkar, Mohamed M. Abdelati.

**Abstract**— over the last seven years, Gaza Strip is suffering from inveterate crisis in the electricity sector and since that time experts working in this area to find solutions that contribute to alleviate the problem and commensurate with the available resources. Therefore, Photovoltaic (PV) systems are used to overcome this crisis. However, one of the biggest challenges of using PV sources is its interconnection with the grid. Without any proper control strategy to interconnect the individual systems together, the output power of the distribution system cannot be regulated to meet the power demand. This paper proposes a power management device in order to synchronize two power resources namely; PV and generator in order to meet the load demand while maintaining power quality. Modeling a standalone system is a challenge, and connecting different renewable sources together with the utility grid is the main focus of this research. The proposed power management device constructed at the Islamic University of Gaza to serve the Electrical Engineering Laboratories includes two sources of power; a 5KVA diesel generator and 3KVA PV system along with the mains power supply. The proposed control and management system will be able to synchronize these sources to the distribution bus according to the instantaneous load taking on consideration supply priorities and load priorities.

**Index Terms**— Photovoltaic, power distribution system, smart micro-grid system.

## I. INTRODUCTION

Smart grid technology for energy distribution is widely used in the developed countries. It is recognized for integration of renewable energy sources and motivation of citizens to rationalize energy consumption while contribution to energy production. Any small scale electrical power generation technology that provides electric power near a load site, with or without interconnection to any distribution system is known as Distributed Energy Resources (DERs) or Distributed Generation (DG). They can be operated according to customer's demand and facilities during peak hours as an auxiliary power source, thus emphasizing on much greener sources of power supply [1]. Of all the alternative resources, available, photovoltaic system, wind turbines, synchronous generators driven by turbines and fuel cells are amongst the most popular sources. Photovoltaic systems derive power from the sun, which depends on many factors such as solar irradiation and light intensity. These factors in turn affect the efficiency, voltage and output of the system [1,2].

Furthermore, the stored electric power can only be used in small devices such as lighting and computers. Over time the solar energy systems appeared on market, this technology enabled the user to run most of the loads during the day and store limited amounts of energy in the system batteries to be used

at night. This system is called (Off-Grid). The disadvantage of earlier mentioned system is the high cost and also the manually split of loads [3].

In developed countries, they had developed less expensive and more efficient system which is called (On-Grid), this system does not require batteries, but the user consume the demanded power quantity and pump the overflowing energy to the distributor rather than storing it [3]. Of course, the main source of electricity is available around the 24. Such technology is unsuitable for Gaza because of the frequent interruption (disconnect of the energy) of the main source of power. Therefore, we strongly believe we need a combination of those solutions in a smart small network to be installed at home as shown in Figure 1.

The generator uses a synchronous machine which can either run as generator or motor depending upon the form of input energy. The definition of motor and generator operation relates to the sign of the average power. During the motoring action of the generator the power flows from the bus-bars to the machine. This condition is called as reverse power flow [4]. The aim of this research is to design and implement a device that help generators to stay in the forward power flow mode. The device has current and voltage sensors and able to calculate the active power along with many other electrical quantities such as reactive power, power factor, rms voltage, and rms current [5].

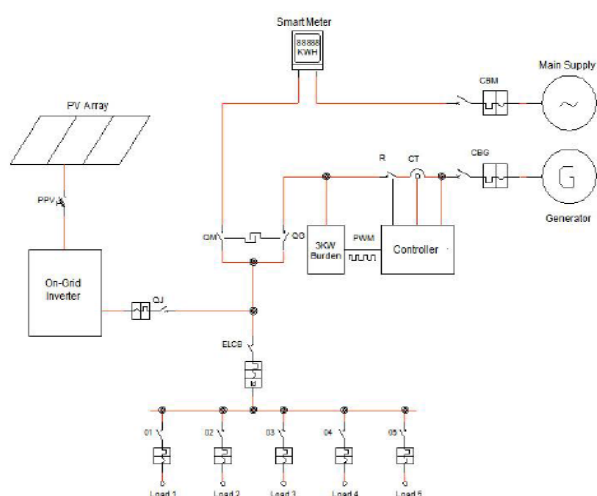


Figure 1: Circuit diagram of the main distribution board.

The rest of this paper is organized as follows: In section II, the current and voltage sensors are designed. In section III, the sensors are interfaced to a proper microcontroller. The software algorithm is described in Section IV and the experimental results are detailed in Section V. Finally, in Section VI, Conclusions and suggestions for future work are outlined.

## II. VOLTAGE AND CURRENT SENSORS

The voltage signal will be fed to one of the analog input channels of the microcontroller. The range of the analog input is from 0 to 5 volts for the targeted PIC18F microcontroller family [6]. Therefore, a signal conditioning circuit is necessary to match the line voltage whose nominal root mean square (rms) value is 220V to fit within the allowable analog input range of the microcontroller as illustrated in Figure 2. Utilizing the full dynamic range of the analog channel helps in achieving the best possible resolution of the analog to digital conversion process. To this end, the AC voltage signal will be converted to have a peak to peak value of 5V (1.768 V rms) and then shifted 2.5V. Conversion could be done by a simple voltage divider. However, this approach leads to common ground between the microcontroller circuit and the line input which has many safety and disturbance concerns. Therefore, a transformer will be utilized insuring galvanic isolation between the controller circuit and the line voltage. A standard transformer 220V to 12x2V rated 300 mA is modified to have an additional winding which produce a maximum of 1.768 V rms for the maximum expected line voltage which is about 240V rms. The original secondary windings of this transformer will be used to generate a 12V along with a regulated 5V power sources necessary for the controller circuit.

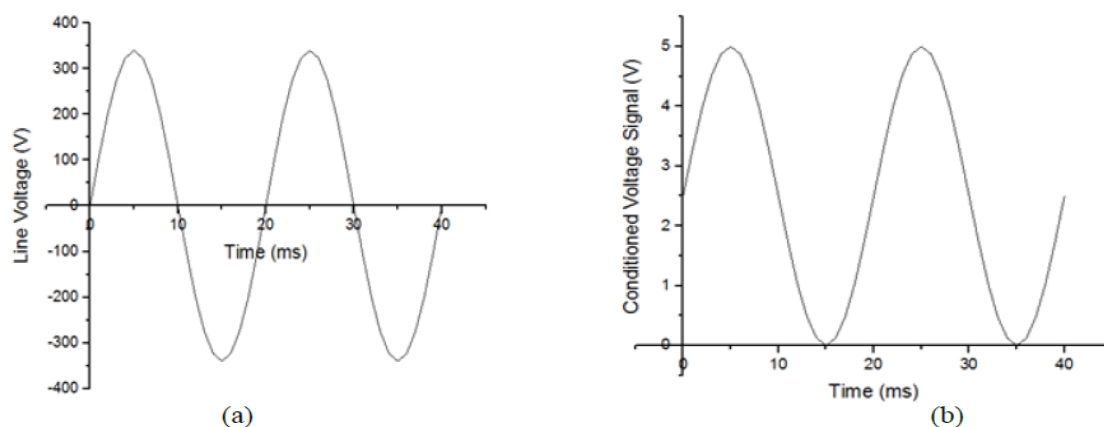


Figure 2: Voltage sensing. (a) AC input. (b) Conditioned signal

As the number of primary winding is unknown to us, the required number of turns of the voltage sensing windings is determined experimentally and found to be 37. Now the primary number of turns may be calculated for future use as  $N_p = 37 \times 240 \div 1.768 = 5023$ . The resulted signal is clamped over a 2.5V DC so that the conditioned signal always lay within the analog input range of the microcontroller which is 0-5 volts.

For AC, current sensing, there are many techniques used in the industry. One may use a small series resistor and measure the voltage drop across it. This method is not proper here as it does not provide galvanic isolation. Another method is to use Hall Effect current sensor integrated circuits such as Allegro ACS712. Such chip senses the magnetic field generated by the current flowing through the sensors legs, which in turn outputs an analog voltage proportional to the current it senses. While being efficient and have small footprint, they are unavailable in the local market unfortunately. The last common method is to use the current transformer (CT) technique. Although not available in the siege Gaza, we found a way to build it locally using a standard 220V to 12x2V 300 mA transformers. The low voltage winding has been totally removed and replaced by 2 turn winding of an insulated copper cable whose cross-sectional area is  $4 \text{ mm}^2$ .

This 2-turn winding is now the primary winding of the current transformer. Using a low-value burden resistor across the 5023 turn secondary winding, one may estimate the primary current by measuring the voltage drop on the burden resistor. In order to calculate the value of the burden resistor, the maximum current that will be measured should be specified. In our case this value is 20A<sub>rms</sub>. The turn's ratio of the CT is 2 to 5023. Therefore, the maximum current in the secondary winding is

$$I_s = I_p \frac{N_s}{N_p} = 8 \text{ mA} \quad (1)$$

To maximize measurement resolution, the voltage across the burden resistor at peak-current ( $8\sqrt{2} \text{ mA}$ ) should be equal to one-half of the analog reference voltage (5V). Therefore, the ideal burden resistor is

$$R = \frac{2.5}{8\sqrt{2}} = 221 \Omega \quad (2)$$

In our implementation, we used the nearest standard resistor which is  $220 \Omega \pm 1\%$ . The voltage across the burden resistor is clamped over a 2.5 V DC to keep the signal within the analog input range of the microcontroller. Figure 3 shows the complete circuit used for voltage and current sensing along with the power supply unit. Resistors R1 and R2 form a voltage divider to obtain the required 2.5 V DC shift source and the diodes D1 to D4 are used to clip any possible spikes that may damage the controller. The relay (RL1) allows the controller to disconnect the generator from the grid in case of faults. The solid-state relay will be excited by a pulse width modulated (PWM) control signal to operate a burden load that keeps the generator load above a specified threshold.

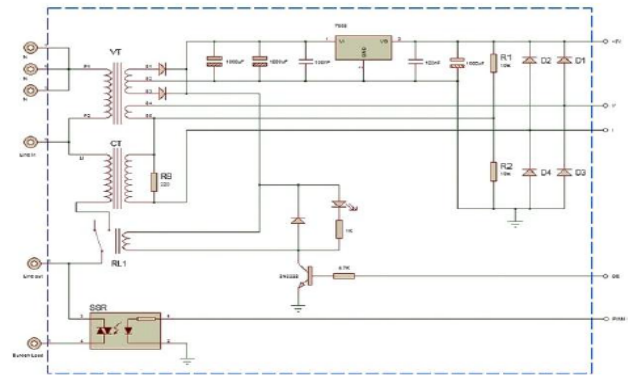


Figure 3: AC current and voltage sensing circuit along with the power supply unit.

### III. HARDWARE DESIGN

The device is required to read the instantaneous voltage and current signals and use them to compute and display the standard electrical measurements such as rms voltage, rms current, power, and power factor. The device should be able to keep the power above a preset value through controlling a burden load. Moreover, it should be able to disconnect the generator from the grid in case of any fault. The device is better featured with communication channels for possible interconnection with other devices in the grid such as the power inverter or a grid management controller. In addition, these channels may facilitate uploading the expected device firmware updates. To meet these requirements, a PIC18F2550 microcontroller is selected. It is ideal for low power and connectivity applications that benefit from the



availability of a USB port and an asynchronous serial port (EUSART). Has 2 pulse width modulation (PWM) outputs, rich of analog and digital channels, possess large amounts of RAM memory for buffering and Enhanced FLASH program memory make

it suitable for embedded control and monitoring applications. The circuit diagram of the controller unit is shown in Figure 4.

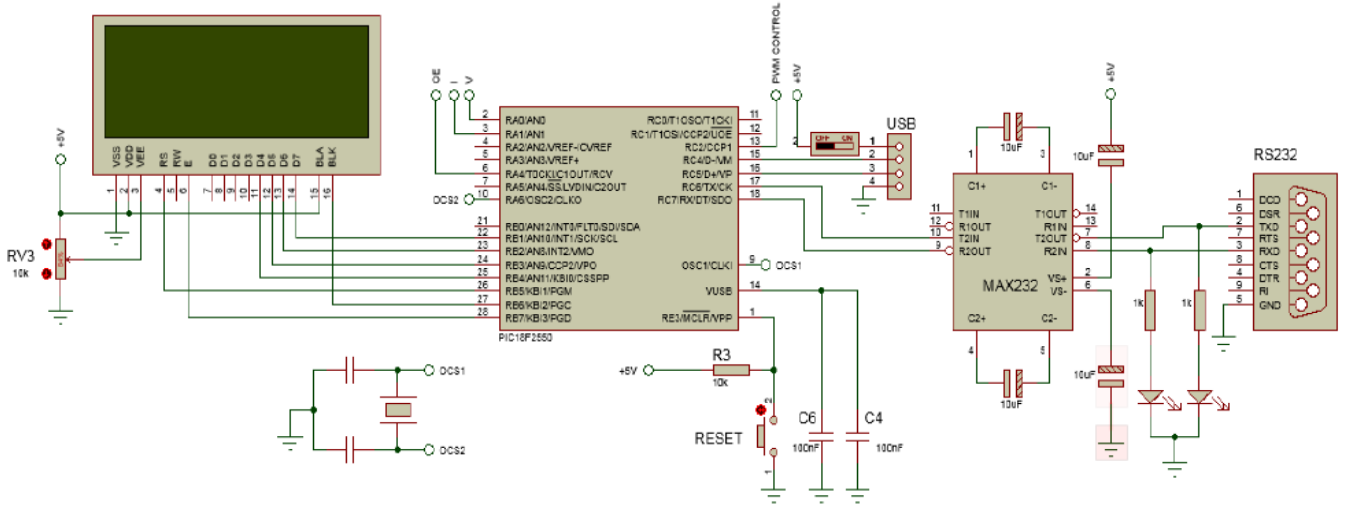


Figure 4: the microcontroller section of the device.

Along with the microcontroller chip, a Max232 integrated circuit is added to convert signals from a RS-232 serial port to the TTL signals of the microcontroller's USART serial port. The USB port of the microcontroller is ready to use after connecting the 200 nF capacitor at pin 14. The switch SW1 allows the device to be powered through the host USB port. This option is valuable during software developing and firmware uploading.

#### IV. SOFTWARE ALGORITHM

The voltage wave form of the generator output is sinusoidal with frequency  $f$  and peak value of  $V_p$ . It may be expressed as.

$$v_l(t) = V_p \cos(2\pi ft) \quad (3)$$

The voltage signal at the analog to digital converter input ( $V_a(t)$ ) is a shifted scaled version of the line voltage. The DC shift is half the analog to digital reference voltage  $V_r$ , and the scaling factor ( $k_v$ ) is the voltage transformer turns ratio. For our specific case  $V_r$  is 5V and  $k_v$  is 37/5023. Therefore, the signal at the analog to digital converter input is expressed as

follows:

$$v_a(t) = k_v V_p \cos(2\pi ft) + \frac{V_r}{2} \quad (4)$$

The analog to digital converter has a resolution of 10 bit (1024 levels). Assuming a sampling period of  $T_s$  and neglecting the quantization error, the  $n^{\text{th}}$  digital samples will equal:

$$v_a(nT_s) = \frac{2^m - 1}{V_r} (k_v V_p \cos(2\pi f n T_s) + \frac{V_r}{2}) \quad (5)$$

The scaling number comes from the fact that when the analog input equals the reference value, it is converted to the maximum 10-bit digital number which is  $2^m - 1$ . In order to obtain a digital value equals the line voltage along with some DC offset that will be removed later; the converted signal must be multiplied by the scaling factor  $\frac{V_r}{k_v(2^m - 1)}$ . The resultant signal will equal:

$$v_s(nT_s) = V_p \cos(2\pi f n T_s) + \frac{V_r}{2k_v} \quad (6)$$

Using a High Pass Filter (HPF) the DC content of the signal is eliminated producing a clean digital version of the line voltage signal:

$$v(nT_s) = V_p \cos(2\pi f n T_s) \quad (7)$$

The line current waveform will be also sinusoidal having the same frequency but with peak value of  $I_p$  and a phase shift  $\theta$  that depend on the applied load. The current may be expressed as:

$$I_l(t) = I_p \cos(2\pi f t + \theta) \quad (8)$$

Using the same procedure carried for the voltage, we will obtain a clean digital version of the line current signal which equals:

$$I(nT_s) = I_p \cos(2\pi f n T_s + \theta) \quad (9)$$

The extracted voltage and current signals are multiplied to give the instantaneous power signal:

$$\begin{aligned} P(nT_s) &= V_p I_p \cos(2\pi f n T_s) \cos(2\pi f n T_s + \theta) \\ &= V_p I_p \cos(2\pi f n T_s) [\cos \theta \cos(2\pi f n T_s) \\ &\quad - \sin \theta \sin(2\pi f n T_s)] \\ &= V_p I_p \cos \theta \cos^2(2\pi f n T_s) \\ &\quad - \frac{1}{2} V_p I_p \sin \theta \sin(4\pi f n T_s) \\ &= \frac{1}{2} V_p I_p \cos \theta [1 + \cos(4\pi f n T_s)] \\ &\quad - \frac{1}{2} V_p I_p \sin \theta \sin(4\pi f n T_s) \\ &= \frac{1}{2} V_p I_p \cos \theta + \frac{1}{2} V_p I_p [\cos \theta \cos(4\pi f n T_s) \\ &\quad - \sin \theta \sin(4\pi f n T_s)] \\ &= \frac{1}{2} V_p I_p \cos \theta + \frac{1}{2} V_p I_p \cos(4\pi f n T_s + \theta) \end{aligned} \quad (10)$$

Substituting  $V_p = \sqrt{2}V_{rms}$  and  $I_p = \sqrt{2}I_{rms}$  into equation 10, the instantaneous power formula becomes:

$$P(nT_s) = V_{rms} I_{rms} \cos \theta + V_{rms} I_{rms} \cos(4\pi f n T_s + \theta) \quad (11)$$

The first term is constant and known as real or active power while the other term is oscillating between the source and load. It is known as the reactive power. In order to extract the active power component, the instantaneous power is filtered with a low pass filter (LPF). A block diagram that illustrates the signal processing for power calculation is shown in Figure 5.

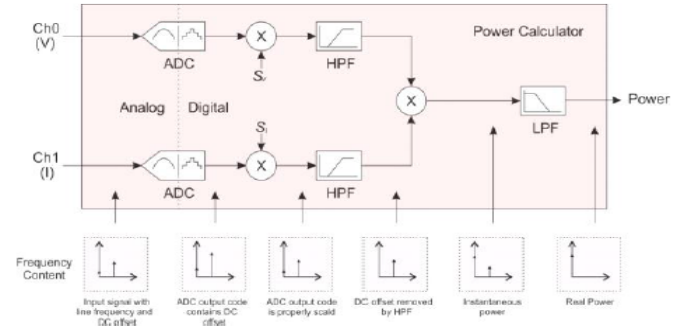


Figure 5: Signal processing for power calculation.

For the control process the calculated power is compared to a preset threshold (about 20% of the generator rating) the error signal is used to set the duty cycle of the PWM control signal that activates the burden load. The duty cycle may range from 0 to 255. If not reached its maximum and the power is still less than the threshold, the duty cycle is increased quickly. On the other hand, if not reached its minimum and the power is above the threshold, the duty cycle is decreased slowly until it reaches 10% after which the decrement is performed in a much slower rate. Defining a long integer variable DSL that is 100 times the duty cycle DS, the proposed algorithm is easily implemented using integer arithmetic as follows:

```

if (P < Pth && DSL < 25420) DSL += 80 ;
if (P > Pth && DSL > 2500) DSL -= 40 ;
if (P > Pth && DSL < 2501 && DSL > 0) DSL -= 1 ;
if (P < 0) {RA4_bit = 0; Lcd_Out(2, 1, "!!!! Fault !!!!!");}
DS = (DSL + 50) / 100;
PWM1_Set_Duty(DS);
    
```

## V. EXPERIMENTAL RESULTS

The device is implemented on an 11x13 cm printed circuit board as illustrated in Figure 6. The Mikroelektronika USB boot loader is downloaded on the microcontroller using a chip programmer for once. Later, the USB port is used to download the controller software. We started by simple software routines to test the hardware functionality such as the display, the relay, the solid-state relay, and the line measurements. Doing this successfully, the controller code is installed and the device is connected with the inverter as illustrated in Figure 7.

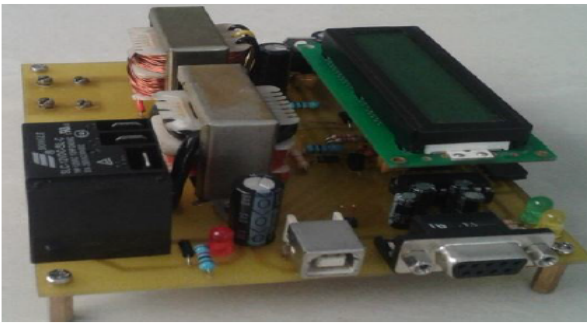


Figure 6: The power management device.

For the sake of the generator safety, we preferred to test the device first with the mains supply.

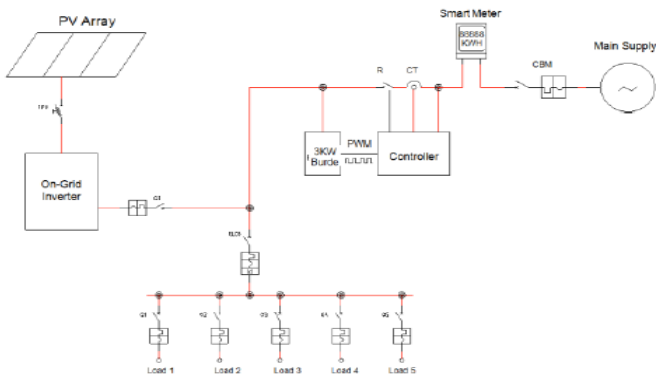


Figure 7: Device testing first experiment.

The power threshold is set to 300W and the experiment is conducted at noon time when the inverter was able to inject up to 2400 W into the grid. A variable load is used while running connection and disconnection of the inverter and the mains circuit breakers. All scenarios are successfully conducted and the controller was able to keep the power drawn from the grid positive.

The second experiment was to test the device for generator protection. Therefore, it's integrated with our experimental platform illustrated in Figure 1. The first run of the experiment did not go as expected. The generator we are using is small size rated 5 KVA. There was a significant tolerance of its frequency especially on load variation. Under no load its frequency was 51.6 Hz and this lays outside the allowable frequency range for the inverter which is from 47.5 Hz to 51.5 Hz. Once loaded its frequency drops to about 49 Hz. To fix the situation we preferred to adjust the generator governor so that it has a frequency of 50.5 Hz at no load. Moreover, the power threshold is raised to 500 W instead of 300 W. It is about 10% of the generator rating and secures a wide margin for transients. Having done these modifications, the system operated properly without any complications.

## VI. CONCLUSION

When connecting an on-grid PV system with a power generator, it is expected to share the load and help reducing the consumption of generator fuel. However, if the load is lower than the injected PV power, energy will flow in the generator disturbing its operation and risking its safety. The main objective of this research was to design and implement a device that regulates such a situation. The device is based on PIC18F2550 microcontroller and programmed to keep the generator running above 10% of its rating. The device is tested successfully on an experimental platform at the Islamic university of Gaza.

The implemented device will enable institutions which has backup generator to integrate renewable systems in their power grid. However, a complementary research is expected to integrate this device with a higher-level controller for the institution.

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**Ahmed Y Sokkar.** Is a master candidate at Islamic University Gaza, college of engineering, department of electrical engineering. He earned his BE of mechatronics from Misr University for science and Technology. He interested on area of electric power and control.

**Mohamed M. Abdelati** He got the B.Sc. degree in the Power Systems and the M.Sc. in the communication Systems in 1990 and 1992 respectively from METU. He got his Ph.D. degree from Bilkent University in ATM networks in 1997. Abdelati worked as an instructor and then Assistant Professor at the East Mediterranean University/North Cyprus during the academic year 1996/7. Afterwards, he joined the Electrical & Computer Engineering department of IUG/Palestine. His research was directed toward Industrial Automation where he addressed many practical problems which concern the local community. He is a fellow of Fulbright, DAAD, and Alexander von Humboldt foundations. His current research interests include SCADA, SMPS, and embedded systems.