An-Najah National University Faculty of Graduate Studies

# An Iterative Method for Optimally Sizing Solar Inverter in Grid Connected System: A Case Study of Palestine

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This Thesis is Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Engineering in Clean Energy and Conservation Strategy, Faculty of Graduate Studies, An-Najah National University, Nablus, Palestine

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# **Dedication**

# To my parents

To my wife

To my son Anas

To my daughters Sara, Danya and Jana

To all of them,

I dedicate this work

III

# Acknowledgments

It is an honor for me to have the opportunity to thank all people who helped me to conduct this study. All appreciations go to my supervisor, Dr. Tamer Khatib for his exceptional guidance and insightful comments and observations throughout the duration of this project.My thanks and appreciations go to the staff of Clean Energy and Conservation Strategy Engineering Master Program in An-Najah National University, especially Prof. Dr. Marwan Mahmoud for his assistance.

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الاقرار

أنا الموقع أدناه مقدم الرسالة التى تحمل عنوان

# An Iterative Method for Optimally Sizing Solar Inverter in Grid Connected System: A Case Study of **Palestine**

أقر بأن ما اشتملت عليه هذه الرسالة إنما هو نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، وأن هذه الرسالة كاملة، أو أي جزء منها لم يقدم من قبل لنيل أي درجة أو لقب علمي أو بحثى لدى أي مؤسسة تعليمية أو بحثية أخرى.

#### **Declaration**

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

**Student's name:** اسم الطالب: Signature: التوقيع: التاريخ: **Date:** 

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## An Inverter Method for Optimally Sizing Solar Inverter in Grid Connected System: A Case Study of Palestine By Ali ahmad ali mohamad Supervisor Dr. Tamer khatib

#### Abstract

Optimizing the size of grid connected inverters in photovoltaic system in Palestine is presented in this thesis. The sizing ratio which is the ratio of the rated power of PV and the rated power of inverter is optimized using inverter model for three different loads and three locations . A MATLAB model is develop for a PV array and inverter to estimate the annual average inverter's efficiency using hourly solar radiation and ambient temperature data. The simulation shows that the average optimum sizing ratio for the three loads is 1.5.

A comparison between a conventional inverter (its capacity matches to PV array capacity) and a second system where the inverter is optimally installed considering the sizing ratio is considered and simulate the two system for one year time using MATLAB. it is observed that the total energy produced and the losses from first case are 24893kwh and 1550kwh respectively whereas in second case are 25135 kWh and 1309 kWh respectively for 50kWp PV system.

In addition the annual yield factor for optimum sizing system is 502.7  $kWh/kW_p/year$  whereas the annual yield factor for conventionally sized inverter is 497.86 kWh/kW\_p/year.

## **Chapter One**

#### Introduction

#### 1.1 Background

The increasing use of renewable energy is attributed not only to global warming but also the ease of the free resource available from nature. Since fossil fuel is the most commonly used source of energy to meet the energy demands of the world for a long time, there has been a fast reduction of fossil fuel deposits in the world and consequently in the near future a big shortage of energy is expected to happen if the trend continues this way. Therefore, there is a need to find better sustainable energy solutions to preserve the earth for the future generations in the world [Santra,2012].

Solar energy is free energy from the sun and it is renewable, unlimited and friendly to environment. Photovoltaic (PV) energy generation is one of the applications of direct solar energy utilization. These systems have been spread lately due to the increase in energy consumption and the resulting environmental pollution. PV systems can be classified into three systems, standalone, grid connected and hybrid PV systems. Grid connected PV systems are directly connected to the grid and inject their production directly to the grid. These systems are usually called distribution generation units. A distribution generation unit is an electric power generator which produces electricity at a location close to the loads and can be tied to electrical utility. Thus it can be used to generate a part of electricity demanded by consumers to reduce electricity that purchased from utility grid especially at peak demands and at emergency situation. Distribution generation has many benefits such as it has less initial cost than conventional sources, does not need large area as in large power plant, reduce loading on transmission lines, produces less pollutant emissions, increases power system's reliability since it can act as backup power source.

However, the obstacle of using grid connected PV system is the high initial cost and low overall efficiency. Moreover, there are some challenges to such systems in terms of power systems such as the negative impact on the electrical network in terms of power quality, system's voltage levels due to the injected power and system protection.

A typical grid connected PV system is shown in figure (1.1). In this system the photovoltaic are designed to be connected to the utility grid through a grid tied inverter (GTI) which is used to convert the direct current that comes from the PV array to an alternating current so as to ensure that the shape of the output wave is matching the voltage and frequency of the electrical network (pure sine wave, THD<3%). Many factors should be considered for GTI such as the input voltage that must be matched with the nominal voltage of the PV array. Moreover, the

nominal power of inverter should also be matched with the DC power of the array as well as GTI conversion efficiency.

GTIs are usually sized according to the rated power of the PV array, rather than the load requirements. Also GTIs usually include maximum power point tracking to ensure maximum power injection [Yasin,2008].



Figure (1.1): Grid-connected PV power system

#### **1.3 Problem statement :**

Since the solar resource is not always stable, the output power from PV panels is also not always stable. To maximize the output power from photovoltaic array, many previous researches were carried out in the field of PV systems so as to have the PV panels of the system optimally matched to the inverter's rated power [Khatib,2012]. At low solar radiation levels, PV array generates less power than its rated power and accordingly the inverter is operated with lower inverter efficiency [Keller,1995.Coppye, 1995]. Thus, finding the optimal size of a grid connected inverter acts an important role in increasing total energy produced by the PV system. To optimize the inverter size, local solar

radiation, ambient temperature and inverter efficiency curve are needed [Macagnan,1992. Jantsch, 1992]. Thus, it must be taken in to account that the optimization of the inverter's size of in PV system is a location dependent process. In the meanwhile, such an optimization was not conducted in Palestine considering Palestinian climate.

#### **1.4 Objectives:**

- 1- To optimally size a grid connected solar inverter using a numerical algorithm.
- 2- To conduct a comparison between the proposal of this thesis and a PV system with conventionally sized inverter.

#### **1.5 Methodology**

The research work in this thesis is divided into work packages and tasks as described below:

WP.1 Literature review

T.1 A review of current optimization methods for calculating the optimum size of grid inverter in PV System.

WP.2 Data collection and analysis

T.1 Collection of solar radiation and ambient temperature data for Palestine.

T.2 Frequency distribution analysis of these data.

WP.3 Modeling of grid connected PV system.

T.1 Modeling of PV array output power

T.2 Modeling of grid connected inverter efficiency

WP.4 Optimal sizing of the solar inverter

T.1 optimal sizing of PV inverter considering solar radiation and ambient temperature data as well inverter's efficiency model for three inverters types using MATLAB

T.2 Conduct between the cases of having a normally installed inverter and an optimally installed inverter using MATLAB to validate the proposal of this thesis.

WP.5 Thesis writing

T.1 Thesis writing

T.2 Research paper writing and submission

## **Chapter Two**

#### Literature review

Many research works have been done on the optimization of inverter size in grid connected systems. Most of these researches focused on finding the optimum sizing ratio of the inverter so as to ensure a maximum efficiency operation through the year time. Sizing ratio can be defined as the ratio of the PV array rated power to the inverter rated power. In [Velasco,2010] factors like the location of photovoltaic system and the efficiency of grid connected inverter have been simulated to maximize the annual energy produced from PV grid connected system. The simulation procedure is applied taking into account different inverter efficiencies and meteorological variables such as ambient temperature and solar radiation records study the effect of these variables on the optimal value of the sizing factor. In this paper the sizing ratio is defined as the ratio between the rated power of the inverter and the peak power of PV system at standard testing condition. The proposed system was modeled using MATLAB. The annual output energy is computed for different values of sizing factor by changing the rated power of the inverter and then the optimal value of the sizing ratio which gives the maximum annual energy yield was found. The results showed that the optimal value of the sizing ratio increased when PV location latitude was decreased as shown in figure (2.1).



Figure (2.1): Annual energy produced versus sizing factor[Velasco,2010]

In [Velasco,2010] the size of inverter is optimized by using different commercial inverter models for many locations in Malaysia considering low, medium and high loads. A Matlab model is developed for the photovoltaic system and for the inverter by taking the influence of hourly temperature and radiation data to find best size of inverter and highest overall efficiency using iterative method. In the simulation, different values of the sizing ratio are used. After that, the result of this simulation was used to calculate the annual efficiency of the inverter and consequently the optimal sizing ratio of the inverter. The conducted simulation has considered three different loads for different sites in Malaysia. The result shows that the value of the optimum sizing ratio are nearly the same for low, medium and high loads as shown in figure (2.2). Also it is noted that the smallest value of sizing ratio is obtained in Kuala Lumpur since it has high potential of solar radiation as compared to other adapted regions.



Figure (2.2): Searching for the optimum inverter size for Kuala Lumpur

#### [Khatib,2012]

In [Stetz,1992] one of the major influencing factors on the size of inverter which is the reactive power is analyzed economically. Models of PV module and inverter were done using Matlab in order to simulate the performance of PV system considering different conditions such as location, module technology and orientation. The results showed that the size of PV inverters should be modified to reactive power provision. A comparison of the annual total cost of the inverter with reactive power provision and the inverter without reactive power provision is done. The results show that providing reactive power with 0.9 power factor increases the inverter size by 12 percent as shown in figure (2.3).



Figure (2.3): Additional sizing, due to reactive power supply[Stetz, 1992].

Also it was concluded that the influence of the orientation and the location of the PV system on the size of inverter due to reactive power is insignificant. Further simulations showed that decreasing reimbursement rates for PV energy lower the economically optimized inverter sizing while decreasing investment costs lead to the opposite effect.

In [Keller,1995] a simulation is conducted to study the influence of the area of PV according to nominal power of the inverter on the total energy produced and system's efficiency has been done for two locations. For this purpose, the data is actually measured and used to calculate AC production in kWh/kWp and the capture losses as shown in figure (2.5). It was concluded that it is necessary to optimally size the inverter when the PV module area is oversized because the modules rarely produced power in reality above its nominal power at standard conditions. Moreover, the results showed that energy production will be higher if the rated power of PV array is in the range of (40% - 80%) above the nominal power of inverter.



**Figure (2.5):**Recapitulation of monthly production (Lausanne/Switzerland), in kWh/kWp per day[Keller,1995].

In [Burger,2006] a discussion on the impact of solar radiation on the size of inverter is conducted. A comparison between two systems based on solar radiation input is done. One of these systems depends on hourly average of solar radiation and inverter's efficiency model to calculate the annual efficiency. In the meanwhile the other is based on the average reading for one minute of solar radiation and inverter efficiency model to calculate the annual efficiency of the inverter and the losses. This comparison shows that the second system has higher losses because of the under sizing of inverter as shown in figure (2.7). That leads to the fact that important radiation peaks are hidden in the average hourly records that must be taken when sizing the inverter.



**Figure (2.7):** Energy content distribution in percentage of total incident energy of 1min average values (left bar) and hourly average values (right bar) [Burger,2006].

In [Macedo,2007] The performance of roof mounted PV system was analyzed for three years in Northern Ireland. A PV monitoring was set up for this system as shown in figure (2.6) to records the DC and AC outputs of the system which were used to calculate the monthly energy of PV system. It was noted that low radiation conditions have bad influence on the efficiency of the overall system.



**Figure (2.6):** Schematic diagram of the ECOS PV monitoring system [Macedo,2007]. In [Demoulias,2010] many ratios between the rated power of inverter and the rated power of photovoltaic array are taken for a grid connected PV system with capacity of 11 kWp. This capacity is divided by 8 subsystems and each subsystem is connected to an inverter with capacity of 1 kW with sizing ratios. Each subsystem was monitored for a one-year time. After that, the annual energy produced, the annual yield, the performance ratio and the capture losses were computed for each group .The result shows that the annual array yield does not affected with ratio between 55 and 102%.

In [Mondol ,2006] the optimum size of grid connected inverter is calculated in any location using mathematical expression derived from the curve of the inverter efficiency to estimate the annual energy produced from PV system. The mathematical expression which takes into consideration that the DC power for any PV system is expressed by a straight line as shown in figure (2.8). The proposed model has been compared with measured data and simulation results and the results are nearly the same.



**Figure (2.8):** Typical dc-power duration curve. (a) Actual curve, (b) straight-line fitting [Mondol ,2006].

In [Notton,2010] the ratio of the photovoltaic rated power to inverter rated power is analyzed based on different factors such as the annual output of the inverter to the rated output power of photovoltaic system, the characteristic of inverter and the solar radiation in many location in Europe .The results of this study are shown in figure(2.8).



**Figure (2.9):**Correlation between optimum sizing ratio and cost ratio[Notton,2010]. The sizing ratio was simulated based on different parameters such as the yearly output of inverter to the rated output of PV, the yearly output of inverter to the cost of PV system for three type of inverter. The result

show that if the rated power of PV array is higher than the rated power of inverter, the optimum performance is achieved when the cost of inverter is increased in relation to the cost of PV. Also it was concluded that the influence of sizing ratio on the performance of PV system is important for inverter having low efficiency rather inverter having high efficiency.

In[Korneakis,2010] an optimal sizing methodology for grid-connected PV is described taking the influence of many parameters such as the inclination, the location of PV system and the type of inverter. The hourly energy produced from PV system for many technologies for PV module and the inverter efficiency are computed using a model for PV module and for inverter.



Figure (2.10): Average monthly mean values of the PV system

#### efficiencies[Korneakis,2010].

The result shows that the efficiency curve of the chosen inverter is the most affecting parameter on the optimum size of the inverter.

In [Rampinelli,2014] optimization of different parameters of grid connected PV system is suggested in order to maximize the benefits economically and environmentally among the lifecycle of the component of the system. These parameters include number and type of photovoltaic modules, tilt angle and other parameters. The methodology used for optimum sizing of the parameters of PV grid connected system is shown in figure (2.10).



Figure (2.11): Flowchart of the proposed optimization

methodology[Rampinelli,2014].

# **Chapter Three**

#### **Optimal Sizing of inverter using iterative numerical method**

#### **3.1 Introduction**

Based on the conducted literature review, a solar inverter should be optimally sized so as to achieve maximum energy conversion efficiency of the system. In the meanwhile, the optimization of the grid connected inverter is a location dependent process and it strongly depends on the solar radiation profile of the adapted area. Thus, in this chapter optimal sizing of inverter considering Palestine weather for three sites is conducted.

#### 3.2 Frequency distribution analysis for adapted solar radiation data

Figure (3.1) shows the distribution frequency analysis of the solar radiation records in Palestine.

From the figure, the largest number of hours which is 1020 hours in the year contains low solar radiation records (less than 100 w/m<sup>2</sup>) which represents approximately 23.3% of the total readings while approximately 70.9% of the total readings (2795 hours) contain solar radiation records in the range (100-800) w/m<sup>2</sup>. In the meanwhile, approximately about 12.4% of the total readings (543hours) contain solar radiation records in the range of (700-1000 w/m<sup>2</sup>) while, the lowest number of hours (12 hours) contain solar radiation records above 1000 w/m<sup>2</sup> which represent 0.27% of the total readings.



Figure (3.1): most frequent solar radiation.

This analysis shows that the most frequent reading are below standard testing conditions which means that the PV array will mostly generate power less than its rated power.

In general, if the PV array generates power less than its rated power the inverter will operate under part loading conditions and the efficiency will be decreased as shown in figure (3.2). As a result of that, the energy produced by the PV system will be lowered causing considerable energy losses and reduction in the performance of the overall system.

Figure (3.2) describes the efficiency of an inverter in terms of power generated from the PV and the rated power of inverter. This curve is divided into three zones A, B and C. From the figure it is very clear that with loading ratio less than 0.3, the conversion efficiency will be not the maximum. Anyway the development of the inverter model in this thesis was based on this curve using MATLAB curve fitting tool [Khatib,2012].



Figure (3.2): Typical efficiency curve for an inverter[Khatib,2012]

# **3.3 Proposed numerical iterative method for calculating the optimum size of inverter.**

Figures 3.3, 3.4, 3.5 show average solar radiation in Palestine in general and in two cities in Palestine namely Nablus and Jerico respectively. In the meanwhile figure 3.6 shows the hourly solar radiation in Nablus city.



Figure(3.3): Monthly average of solar irradiation in Palistine in general.



Figure(3.4) : Monthly average of solar irradiation in Nablus.



Figure (3.5) : Monthly average of solar irradiation in Jericho.



Figure (3.6) : Daily solar radiation for Nablus.

In the general optimal sizing of PV inverter plays a significant role in achieving maximum output energy from the PV system. In order to maximize the annual average inverter efficiency, the rated power of a PV array must be corresponding to the rated power of the inverter.

To determine the best size of the inverter in grid connected PV system, a model of PV grid connected systems is developed using MATLAB. This model predicts the performance of the system including all of its parts under different conditions of loading and weather. Hourly solar radiation and ambient temperature data are obtained first as shown in the figures (3.7) and (3.8) respectively.



Figure (3.7: A sample of solar radiation data in Palestine.

Figure (3.7) shows the variation of solar radiation among five days which is approximately like sinusoid. The peak of solar radiation happens at noon and it differs from month to other but the average of solar radiation in Palestine is 456.7w/m<sup>2</sup>.



Figure (3.8): A sample ambient temperature data in Palestine.

In the meanwhile, Figure (3.8) shows the records of ambient temperature among five days .As we see there no significant difference in these values and the average value of ambient temperature in Palestine is 25.3C<sup>o</sup>.

A model of PV array is developed to estimate the power delivered from it depending on the solar radiation and ambient temperature records as shown in equation (1) [Khatib,2012].

$$P_{PV}(t) = P_{PV(rated)} \left[ \frac{G(t)}{1000} \right] - \alpha_{T} \left[ T(t) - 25 \right]$$
(1)

Where  $\propto_T$ : represents temperature coefficient of the PV module . On the other hand, to estimate the inverters output power and efficiency, two models of an inverter is used. According to literature models have been developed in the literature. A model based on weighting of the efficiency of inverter for different power Equation (2) [Hajiah,2012]:

$$\eta_{inv} = (0.03 \eta_{5\%}) + (0.06 \eta_{10\%}) + (0.13 \eta_{20\%}) + (0.1 \eta_{30\%}) + (0.48 \eta_{50\%}) + (0.2 \eta_{100\%})$$
(2)

Where  $\eta_{5\%}$ ,  $\eta_{10\%}$ ,  $\eta_{20\%}$ ,  $\eta_{30\%}$ ,  $\eta_{50\%}$  and  $\eta_{100\%}$  are the values of conversion efficiency, respectively 5%, 10%, 20%, 30%, 50%, and 100% rated power of the inverter.

Another model as shown in equation (3) [Hajiah,2012].

$$\eta_{inv} = \frac{(P_{AC} / P_{NOM})}{(P_{AC} / P_{NOM}) + (K_{0} + K_{1}(P_{AC} / P_{NOM}) + K_{2}(P_{AC} / P_{NOM})^{2})}$$
(3)

Where  $K_0$ ,  $K_1$  and  $K_2$  are mathematical coefficients ,  $P_{AC}$  is the output power of the inverter, and  $P_{NOM}$  is the nominal power of the inverter . In this thesis, two models are selected. The first model was developed by [Khatib,2012]. The efficiency of an inverter is calculated in terms of PV power and inverter rated power as shown in equation (4) .

$$\eta_{inverter} = C1 - (P_{Ratio} * C2) - \left(\frac{C3}{P_{Ratio}}\right)$$
(4)

Where:

$$P_{Ratio} = \frac{P_{PV(rated)} * \left(\frac{G(t)}{1000}\right)}{P_{inverter}}$$
(5)

While C1, C2 and C3 are the model coefficients.

	C1	C2	C3
5kW	97.644	1.995	0.455
50kW	100.583	3.611	0.972
100kW	99.967	3.222	0.644

 Table (3. 1) : Inverter models coefficients

The optimum size of an inverter is represented by the ratio Rs which represents the rated power of the PV array to the rated power of inverter used as follows.

$$R_{s} = \frac{P_{PV (rated)}}{P_{inv (rated)}}$$
(6)

The second model which is considered is shown in equation (7)

$$f(x) = p1 * x^{9} + p2 * x^{8} + p3 * x^{7} + p4 * x^{6} + p5 * x^{5} + p6 * x^{4} + \dots$$
  

$$p7 * x^{3} + p8 * x^{2} + p9 * x + p10$$
(7)

Where p1,p2,p3, p4,p5,p6,p7,p8,p9 and p10 are Coefficients values p1 = 0.8744, p2 = -13.11, p3 = 83.94, p4 = -299.9, p5 = 655.2p6 = -902.6, p7 = 781, p8 = -410.3, p9 = 118.4, p10 = 82.6

and x is the  $P_{Ratio}$ 

Figure (3.9) shows the optimization algorithm for inverter size in a grid connected PV system. At the beginning, the PV system parameters such as the rated power of the PV array and the temperature coefficient of the PV module and the inverter model coefficients are obtained. The solar radiation and ambient temperature records are used. In the iteration loop a set of  $R_S$  (from 0.5 to 5 at step equal to .01) values is proposed. The rated power of inverter can be obtained by dividing the rated power of the PV to each value of  $R_S$ . Then the hourly PV array output is calculated using the PV model in equation (1). Then by using the inverter model described in equation (4) and (7), the hourly inverter efficiency is calculated.

After that, the average yearly efficiency is calculated by dividing the summation of the hourly inverter efficiency among the year to the number of records and stored it in an array. The loop will be repeated until Rs reaches its maximum value. Finally, when Rs reaches its maximum value, a search for the maximum efficiency and its optimum Rs is found. A curve shows the relation between Rs values and the average efficiency is plotted and the optimum value of Rs and its maximum efficiency are shown on this curve.

The following flowchart presents the proposed iteration method used for determining the optimal inverter size. The iterative method which has been described above is done using the model described in equation (4) for an inverter with different sizes .



Figure (3.9): iterative method for calculating the inverter size

#### **3.4 Validation of thesis's proposal :**

To see the benefits of optimally sizing the inverter in grid connected system , a comparison between having a normally select inverter (its capacity matches to the PV array capacity) and a second system where the inverter is optimally installed considering the sizing ratio is considered and simulate the two system for one year time using MATLAB for three different sizes of inverter (5 kW,50kW and 100kW). The two systems are simulated to calculate the total energy produced, the average yearly efficiency and the losses.

The flow chart described in figure (3.10) shows the methodology of calculating the energy yield of the system considering a normally installed inverter. At the beginning, PV parameters such as the rated power of PV array is obtained. The hourly solar radiation and ambient temperature records are also obtained to calculate the hourly power of PV array using equation (1). In this case avoid set the rated power of an inverter equal to the rated power of PV . Then equation (4) and (5) are used to calculate the hourly efficiency for the inverter. The hourly output power from the inverter can be calculated by multiplying the hourly efficiency of it with the hourly power of PV. The average efficiency can then be calculated by dividing the summation of the hourly efficiency to length of these values. The total energy produced from the PV system and the inverter are calculated by summation the hourly power for each of them. The losses for the whole year of this system can be calculated by

subtracting the total energy from the inverter from the total energy produced from PV as shown in equation (8):

$$\Sigma P_{losses} = \Sigma P_{PV (hourly)} - \Sigma P_{inv (hourly)}$$
(8)



Figure (3.10): the capacity of inverter equals the PV array capacity.

a simulation of the PV system with optimization have been done where the in the second system, the inverter is optimally installed considering the sizing ratio is simulated among one year. In this case the power of photovoltaic ( $P_{pv}$ ) will be greater than the power of inverter ( $P_{inv}$ ), so an MPPT control with power limitation control is proposed to prevent overloading of inverter in this case. This control can avoid the overloading with an acceptable reduction of the excess power and make shift to the maximum power point [Yang,2014].

The flow chart described in figure (3.6) shows the methodology in case of having an optimally installed inverter.

At the beginning, the PV parameters such as the rated power of PV array is obtained. The hourly solar radiation and ambient temperature records are also obtained to calculate the hourly power of PV array using equation (1). In this case we set the rated power of an inverter equal to 60 percent of the rated power of PV. A controller that is based on if statement must be done to avoid overloading the inverter. For that reason we set the rated power of an inverter to be equal to the rated power of PV array when the power produced by the PV is greater than the rated power of inverter. Then equation (4) and (5) are used to calculate the hourly efficiency for the inverter. The hourly output power from the inverter can be calculated by multiplying the hourly efficiency of it with the hourly power of PV. The average efficiency can then be calculated by dividing the summation of the hourly efficiency to the length of these values. The total energy produced from the PV system and the inverter are calculated by summation the hourly power for each of them. At the end the losses for the whole year of this system can be calculated by subtracting the total energy from the inverter from the total energy produced from PV as shown in equation (7).



**Figure (3.11):** the inverter is optimally installed according to the sizing ratio (Pinv is 60% of Ppv).

In addition, the annual yield factor and the capacity factor are used to compare both systems. The annual yield factor (YF) in kWh/kWp is defined as the ratio between the annual energy output produced from the PV system to the rated power of the PV array as shown in equation (8) [Rampinelli,2014].

$$Y_{F} = \frac{E_{PV} (KWh / year)}{P_{PV (rated)} (KWp)}$$
(8)

In the meanwhile, the capacity factor (CF) is defined as the ratio of the annual yield factor to number of hours in a year. The capacity factor evaluates the usage of the PV array:

$$C_{F} = \frac{Y_{F}}{8760}$$
 (9)

## **Chapter Four**

#### **Results and discussion**

#### **4.1 Introduction**

An optimal sizing of inverter in grid connected PV system has been done. The optimum size of inverter in grid tie PV system for Palestine is searched using the iterative method described in chapter three by taking three different loads. As we see from figure (4.1) when the rated power of the PV equals the rated power of an inverter (Rs=1), the average efficiency is not maximized.

The optimum ratio between the rated power of PV to the rated power of an inverter for the three loads were 1.5, 1.66 and 1.4 respectively. It is noted that the optimum ratio Rs values are almost the same for different loads. Considering this sizing ratio the results show that the overall efficiency of the inverter reaches 94.91%, 95.16% and 95.79% respectively. Also it can be concluded that at sizing ratio less than and above the optimum ratio, the average efficiency is lowered. At low solar radiation levels, PV array generates less power than its rated power and accordingly the inverter is operated with lower inverter efficiency. While at high solar radiation, the inverter will be overloaded and operated with lower efficiency also. Thus, it must be taken in to account that the optimization of the inverter's size in PV system is a location dependent process (see figures 4.1-4.3).



5kW)







Figure (4. 3): searching for the optimum inverter size at R<sub>s</sub>=1.4(for inverter size 100kW) .

The average value of the sizing ratio for three different sizes of inverter is approximately 1.5 using the first model described in equation (4).

For the second model of an inverter in equation (7), the sizing ratio was 1.64 as shown in figure (4.4) which is almost matches with the result of the first model.



Figure (4.4): Optimum inverter size for Nablus

Table (4.1) shows the optimum inverter size at different locations.

Table (4.1) : Optimum inverter sizes (Rs) for different locations.

	Nablus	Jericho
Rs	1.64	1.58
Max_efficiency	93.71	94.26

The following table show the optimum sizing ratio for every month for Nablus , we can conclude that in June we have the smallest sizing ratio (Rs=1.01) since the solar radiation is the highest in this month , while the sizing ratio is the biggest in December (Rs=2.95) since the solar radiation is the lowest in this month for Nablus, for medium solar radiation (in

September )the sizing ratio was (Rs=1.36) and the average sizing ratio for Nablus was 1.64

Month	Rs	Max_ eff
January	2.75	92.9
February	2.19	93.5
March	1.71	93.7
April	1.27	94.5
May	1.07	94.6
June	1.01	94.82
July	1.03	94.63
August	1.11	94.56
September	1.36	94.25
October	1.88	93.91
November	2.31	93.18
December	2.95	93.35
Average	1.64	94.2

Table (4. 2) : Monthly (Rs) and maximum efficiency.

#### 4.2 Results for the validation of the proposed methods

In order to validate the proposal of the thesis, a comparison between having a normally inverter (its capacity equals to the PV array capacity) and a second system where the inverter is optimally installed considering the sizing ratio will be considered and simulate the two system for one year time to see the total energy produced.

#### Case1: the capacity of inverter matches the PV array capacity

In this case a simulation of the PV system without optimization is made

(the capacity of the PV array is equal power of inverter) to calculate the total energy produced, the average yearly efficiency and the losses.

Figure (4.5) shows the hourly power of PV, efficiency and power of inverter for five days.



Figure (4.5): the solar radiation , hourly power of PV , efficiency and power of inverter.

The hourly PV power is vary among the year since the hourly solar radiation and temperature is changed; The output power of a PV array increases linearly as the solar radiation increases, and therefore the hourly efficiency will be changed since it depends on power generated from the PV, the average yearly efficiency for this case is 94.465% .the hourly output power of the inverter is changed accordingly. The total energy from the inverter is 24893kwh and total losses is 1550 kWh among one year.

**Case2: the inverter is optimally installed according to the sizing ratio** In this case a simulation of the PV system with optimization have been done where the inverter, is optimally installed considering the sizing ratio (Rs=1.5) that means the rated capacity of the inverter is approximately 66% of the capacity of PV array.



Figure (4.6): The solar radiation , hourly power of PV , efficiency and power of inverter.

The hourly efficiency in case2 of optimally sized is higher than in case 1 and therefore the hourly output power of the inverter increase as shown in figure (4.6).

The result show that the average yearly efficiency for case one is 94.465% and total losses is 1550 kWh among one year for inverter size 50kW. In the meanwhile, the average yearly efficiency in case two is 95.16%, and total loses is 1309 kwh among one year. The following table summarizes the difference between two case for three different sizes.

	Case 1			Case2		
	(Without optimization)			(With optimization)		
<b>Ppv_rated</b> ( <b>kW</b> <sub>p</sub> )	5	5 50 100			50	100
Pinv_rated /	100	100	100	66	60	70
Ppv_rated						
Rs	1	1	1	1.5	1.6	1.4
Ppv_tot	2644	2644	52889	2472	26444	50278
Average efficiency	94.68	94.46%	95.53	94.91	95.16%	95.79
Pinv_tot	2500	24893	50422	2345	25135	48115
Total Losses( kwh )	277	2927	4716	246	1309	4186
$Y_F (kWh / kW_p)$	500	497.86	504	469	502.7	481
CF (%)	5.7	5.6	5.7	5.3	5.7	5.4

Table (4. 3) : Comparison between tow cases.

From the table, it can be concluded that case 2 is better than case 1 in terms of efficiency and energy losses. The total output of inverter in case2 of optimally sized inverter is greater than case 1 since the efficiency is higher and therefore the losses is lower. The annual yield factor for optimally sized system for 50 Kw is 502.7 kWh/kWp per year, meanwhile, the annual yield factor for normally installed inverter is 497.86 kWh/kWp per year for inverter size of 50kw. This proves that the optimal sizing of the PV inverter has better performance when it compared to normal installed one, since the losses is less and the average maximum efficiency is greater .

## **Chapter Five**

#### **5.1 Conclusion**

In this thesis optimal sizing of grid connected inverter of the PV systems was carried out . solar radiation and ambient temperature for Palestine are also obtained to develop models for photovoltaic array and inverter. The results show that the average optimum inverter size ratio is 1.5 for three different loads and the average maximum efficiency reaches 95.29%. A comparison between having a normally inverter (its capacity equals to the PV array capacity ) and a second system where the inverter is optimally installed considering the sizing ratio is considered and simulate the two system for one year time using matlab.it is observed that the total energy produced and the losses from case one are 24893kwh and 1550kwh respectively whereas in case 2 are 25135 kWh and 1309 kWh respectively. From the results, it is noted that optimum sizing of PV inverter increases the efficiency and the total energy produced and reduce the losses. The annual yield factor for optimum sizing system is 502.7 kWh/kW<sub>p</sub>/year whereas the annual yield factor for normally installed inverter is 497.86 kWh/kW<sub>p</sub>/year. This proves that sizing the PV inverter has almost the best performance when compared to normal installed one.

#### **5.2 Future work:**

- 1- Simulate different models of inverter to make comparison of the inverter efficiency performance .
- 2- Design a GUI in Matlab which describe mathematical modeling and analysis of a PV system to be used as evaluating tool.
- 3- Making the comparison between the cases of having a normally installed inverter and an optimally installed inverter experimentally.

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#### **APPENDIX** A

Code for optimal sizing of inverter in grid connected system

```
filename='AbedProject';
sheetname='1';
G=xlsread(filename, sheetname, 'N10:N1168');
string='city';
AV InvEff=[];
Rs=[];
for Rsi=.5:.01:5;
Rs=[Rs;Rsi];
Pm=45;
InvC=Pm/Rsi;
P Ratio=(Pm*(G/1000))/InvC;
InvEffi=100.583-(P Ratio.*3.611)- (0.972./P Ratio);
%50KW
N=[];
P=[];
for j=1:length(InvEffi)
if (InvEffi(j) == NaN);
N=[N;InvEffi(j)];
else
    P=[P;InvEffi(j)];
end
end
Ν;
P(isnan(P)) = 0;
Av=sum(P)/length(P);
AV InvEff=[AV InvEff;Av];
end
Rs;
AV InvEff;
plot(Rs,AV InvEff,'-k','LineWidth',2.5)
hold on
[MAX MAX INDEX] = max(AV InvEff);
Maximum EFF=MAX
OPT Rs=(MAX INDEX*0.01)+.5
plot(OPT Rs,Maximum EFF,'dred','MarkerFaceColor','red','M
arkerEdgeColor','red', 'MarkerSize',8)
xlabel('R S', 'FontSize', 14, 'FontName', 'Times new roman')
ylabel('Conversion
efficiency', 'FontSize', 14, 'FontName', 'Times new roman')
title(string,'FontSize',14,'FontName','Times new roman')
legend('Inverter performance','Optimum R S
', 'FontSize', 14, 'FontName', 'Times new roman')
```

#### **APPENDIX B**

```
Code for simulation of inverter in grid connected system Case I (P_{PV} = P_{inv})
filename='AbedProject';
sheetname='1';
G=xlsread(filename, sheetname, 'N10:N3000');
T=xlsread(filename, sheetname, 'M10:M3000');
Pm=50;
InvC=Pm;
Ppv=[];
P Ratio=[];
InvEff=[];
for i=1:1:length(G)
Ppvi=Pm*(G(i)/1000);
P Ratioi=(Pm*(G(i)/1000))/InvC;
Ppv=[Ppvi;Ppv];
P Ratio=[P Ratioi; P Ratio];
end
Ppv;
P Ratio;
for j=1:1:length(P Ratio)
    InvEffi=100.583-(P Ratio(j).*3.611)-
(0.972./P Ratio(j));
                       %50KW
    InvEff=[InvEffi; InvEff];
end
InvEff;
Ppv tot=sum(Ppv)
Pinv out= Ppv.*(InvEff/100);
Pinv tot=sum(Pinv out)
avg InvEff=sum(InvEff)/length(InvEff)
Loss=Ppv tot-(Pinv tot*(avg InvEff/100))
%Loss=Ppv tot-Pinv tot
%subplot(2,1,1)
%plot(G)
%grid on
%xlable 'Sample number ';
%ylable 'Solar radiation (W/m2)';
%subplot(2,1,2)
%plot(T)
%grid on
%xlable 'Sample number ';
%ylable 'Ambient temperatuer (C)';
subplot(3,1,1)
plot(Ppv)
grid on
subplot(3,1,2)
plot(InvEff)
grid on
```

#### **APPENDIX C**

Code for simulation of inverter in grid connected system Case I

```
(P_{PV}=1.66P_{inv})
filename='AbedProject';
sheetname='1';
G=xlsread(filename, sheetname, 'N10:N1168');
Pm=50;
InvC=Pm/1.66;
Ppv=[];
P Ratio=[];
InvEff=[];
for i=1:1:length(G)
Ppvi=Pm*(G(i)/1000);
if Ppvi>InvC
    Ppvi=InvC;
end
P Ratioi=(Pm*(G(i)/1000))/InvC;
Ppv=[Ppvi;Ppv];
P Ratio=[P Ratioi; P Ratio];
end
Ppv;
P Ratio;
for j=1:1:length(P Ratio)
InvEffi=100.583-(P Ratio(j).*3.611)- (0.972./P Ratio(j));
%50KW
 InvEff=[InvEffi; InvEff];
end
InvEff;
Ppv tot=sum(Ppv)
Pinv out= Ppv.*(InvEff/100);
Pinv tot=sum(Pinv out)
avg InvEff=sum(InvEff)/length(InvEff)
Loss=(Ppv tot-(Pinv tot*(avg InvEff/100)))
subplot(3,1,1)
plot(Ppv)
grid on
subplot(3,1,2)
plot(InvEff)
grid on
%xlable 'Sample number' ;
%ylable 'efficiency';
subplot(3,1,3)
plot(Pinv out)
grid on
```

جامعة النجاح الوطنية كلية الدر إسات العليا

# تصميم العواكس في أنظمة الخلايا الكهروضوئية المرتبطة بالشبكة بطريقة مثلى/ دراسة حالة لفلسطين

إعداد على أحمد على محمد

> إشراف د. تامر خطيب

قدمت هذه الأطروحة استكمالا لمتطلبات الحصول على درجة الماجستير في هندسة الطاقة النظيفة وترشيد افستهلاك بكلية الدراسات العليا، جامعة النجاح الوطنية، نابلس، فلسطين. 2017

# تصميم العواكس في أنظمة الخلايا الكهروضوئية المرتبطة بالشبكة بطريقة مثلى/ دراسة حالة لفلسطين إعداد علي أحمد علي محمد إشراف د. تامر خطيب

الملخص

في هذه الرسالة تم اختيار الحجم الامثل للعاكس الموصول على الشبكة في انظمة الخلايا الشمسية في فلسطين ، حيث تم اختيار نسبة التحجيم الامثل للعاكس والذي يمثل نسبة القدرة الاسمية للخلايا الشمسية الى القدرة الاسمية للعاكس لثلاثة أحمال مختلفة ولثلاثة مواقع مختلفة ، وتم عمل محاكاة باستخدام برنامج الماتلاب لمصفوفة الخلايا الشمسية والعاكس لحساب معدل كفاءة العاكس باستخدام بيانات الاشعاع الشمسي ودرجة الحرارة في فلسطين ، حيث أظهرت نتائج المحاكاة ان نسبة التحجيم الامثل للعاكس هي 1.5

وكذلك تم عمل مقارنة بين نظام مساواة القدرة الاسمية للعاكس مع القدرة الاسمية للخلايا الشمسية ونظام اخر تم فيه استخدام الحجم الامثل للعاكس حسب نسبة التحجيم التي تم الحصول عليها ، وتم عمل محاكاة للنظامين على مدار سنة باستخدام برنامج الماتلاب وتم الحصول على النتائج التالية : للنظام الاول كانت الطاقة المنتجة والخسائر 24893 كيلوواط في الساعة و5505 كيلوواط في الساعة على التوالي . بينما للنظام الثاني كانت الطاقة المنتجة والخسائر 1309 كيلوواط في السائر 1309 كيلوواط في الساعة و1300 كيلوواط في الساعة و1309 كيلوواط في الساعة و1309 كيلوواط في الساعة و1309 كيلوواط في الساعة و1309 كيلوواط في الساعة و1300 كيلوواط في الساعة و1309 كيلوواط في الساعة و1300 كيلوواط في الساعة على التوالي .

وتم حساب عامل العائد السنوي للنظامين فكانت قيمته للنظام الاول 497.86 كيلو واط في الساعة لكل كيلو واط من قدرة لكل كيلو واط من قدرة الخلايا في السنة وللنظام الثاني كانت قيمة العائد 502.7 كيلو واط من قدرة الخلايا في السنة .