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Determination of Harmonics for Modeling Integration of Solar Generation to The Electric Grid

Ramu Gokarapu
University of New Orleans

Determination of Harmonics for Modeling Integration of Solar Generation to The Electric Grid

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Ramu Gokarapu

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Dedication

To my parents, my brother, sai, my friends and all the teachers for their support, encouragement and the corvette they're giving me for graduation.

Acknowledgement

It is indeed a great pleasure to thank all those who have, directly or indirectly, helped me in successfully completing thesis.

At the outset I wish to thank my advisor Dr.Parviz Rastgoufard who was by my side always, patiently and constantly inspiring, encouraging and guiding me throughout my Master's program. I have learnt a lot from his meticulous planning and implementation, dedication and hard work. My association with him for over two years was a rewarding experience. Special thanks are extended to Dr.Ittiphong Leevongwat for his technical advice throughout my Master's research work and also for the constructive and valuable comments on the thesis.

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Abstract

The purpose of this study is to determine a model for analysis of integrating solar generation to the electric grid .The model is then used in determining Harmonics of Integrating solar panels to the electric grid that are based on parallel or series combination of solar cells. To study integration of solar generation to the grid, we have used solar series and solar parallel models in EMTP (Electro Magnetic Transient Program) real time simulation software. When integrating solar generation models to the grid, due to DC to AC conversion and due to variation of solar energy intensity, the electric utility shall experience undesired harmonics that may impact quality of service to other customers in the grid. This study identifies one method of analysis for determining harmonic content of solar panels before solar generation can be integrated in to the electric grid.

KEY WORDS: Solar generation model, EMTP, solar series model, solar parallel model, harmonics.

CHAPTER 1

1.1 Introduction

Renewable energy resources will be an increasingly important part of the power systems in the new era. These resources assist in the reduction of the emission of green house gases and also add much flexibility by decreasing our dependence on fossil fuels. These renewable [12] energy resources include solar, wind and hydro energies. This thesis discusses the integration of solar energy resources to the grid by using reduced harmonics as measuring criteria.

The electrical potential developed between two dissimilar materials when their common junction is illuminated with radiation of photons converts the light directly into the electricity. This phenomenon is called photo voltaic effect [1]. Semi-conductor materials have two energy bands, namely Conduction and Valence bands. They are separated by a small margin called the band gap or the energy gap. Photovoltaic effect takes place when an electron goes from one band to another band, leaving behind a hole in its place. This hole is a positive energy and when we apply the voltage to the semiconductor device, the electrons and their holes generate the electric current. Hence we get the solar current and the solar irradiance (the amount of solar radiant energy falling on the surface per unit area per unit time) [2].

A solar panel is a collection of solar cells. Each solar cell provides a relatively small amount of power. Many solar cells that are spread over a large area can provide enough power to be useful[3]. The main goal is to achieve the higher power photovoltaic modules by interconnecting solar cells which helps us in the construction and production of Mega Watt (MW) size photo voltaic energy. Solar panels collect free power from the sun, and convert the sunlight into electricity with no moving parts, zero emissions and no maintenance. More power can be generated by pointing the solar panels directly towards the sun.

1.2 Discussion for a Basic Solar Model

There are four basic components in a solar model, namely, Solar Panels, Charge Controller, Power Inverter, and the Storage Batteries [4].

Solar Panels convert light into electricity. As proper charging will prevent damage and increase the life and performance of the batteries, a Charge Controller plays important role in preventing overcharging of the batteries. The Power Inverter is the main component of the system. It produces 120 volts AC from the 12 volts DC stored in the batteries. Storage Batteries store the electrical power in the form of a chemical reaction. Power is generated either when there is sunshine, or by the generator, so that the storage batteries will return the power when there is no sun.

In order to get more sun power, we change the solar panel direction in every season (fall, summer and spring) [24].When collecting solar energy we can reap our biggest yield by positioning array as close to perpendicular to the sun's rays as possible.

1.3 Types of Solar Electric Systems

1.3.1 Grid Tie Solar Systems

A Grid-tie solar system is useful for homes, and is now integrated with the Grid utility. This system is cost effective. The grid-tie solar system unit should be connected to an inverter that produces electricity, which is necessary for connecting it to the utility grid [1,5]. The availability of various tax incentives and rebates from different state and local agencies is a great advantage to this type of system. The disadvantage, however, with this type of system is that most of the units do not have the battery storage that allows for power to be returned when the utility fails.

1.3.2 Stand-Alone Solar System

A stand-alone solar system unit involves just the solar panel configuration and it is unlike the traditional systems which are based on fossil fuels and movable utilities. The system is a self power producible unit and does not depend on utility grid. A complete stand-alone home solar system needs two inverters to supply the required AC house current enough to power large loads such as air conditioners. A second inverter helps to ensure that power is available when one of the inverters eventually requires servicing. These systems need a sizable battery storage capacity because these are the batteries that act as power sources when solar power is unavailable due to bad weather conditions. A complete stand-alone solar system will usually require at least 20 solar panels to keep the batteries at a safe and proper state of charge [5]. Typically this type of system is most cost effective when the system is located away from the utility grid.

The solar power is used by many users from different communities such as, industrial, residential or commercial. As a lot of diversity persists in the usage of power in these communities, we need to implement different types of technologies to have efficient power utilization and to satisfy the customers. There are several types of solar panels but crystalline solar panels and thin film solar panels [2] are the most popular ones.

In the recent years, the increase in the research and development of photo voltaic power generators is the alternative energy resource in hybrid energy system. The photo voltaic generators can be grid connected or stand alone and can be used for two types. The main issues of photo voltaic generation are - efficiency and the power quality. To improve the power, there are methods in Maximum Power Point Tracking (MPPT) techniques.

1.4 Scope of this Work

This work focuses on integrating the solar generation model with the utility grid model and studies the impacts, by analyzing the harmonics in the solar generation model. Two models based on parallel or series combination of solar cells have been developed using EMTP (Electro Magnetic Transient Program) real time simulation software. The two EMTP models include solar panels, DC-AC inverters, and transformer models to increase voltage for integrating to electric grids. Once the models had been developed in EMTP software environment, they are used to study harmonic contents like Total Harmonic Distortion (THD) of voltage and current waveforms for both parallel and series connected solar cell panels. The model is then used to determine the THD of two test cases.

1.5 Remaining Chapters

Chapter 2 focuses on studying importance, differences, advantages and disadvantages of different types of solar technologies such as crystalline solar panels and the thin film solar panels. Chapter 3 deals with analyzing the solar cell electric circuit models productivity, characteristics in several configuration, either series or parallel and also the harmonics of the model. Chapter 4 involves the design and simulation of the variants of the solar cell model and understanding its harmonics in every configuration using EMTP (Electro Magnetic Transient Program). Chapter 5 compares and contrasts solar cell models configurations by total harmonic distortion (THD) which stands as evaluation criteria for harmonic analysis in each case. In chapter 6, the concluding remarks are made and possible future works are discussed.

Chapter 2:

2.1 Technologies in Solar Energy

Solar technologies are form on the basis of three key elements in the solar cell. First one is the semiconductor, which absorbs the light energy and converts into electron-hole pairs. Second one is the semi conductor junction which separates the electrons and holes. And third one is the contacts on the front and back of the cell which allows current flow to the external circuit. The two main technologies of solar modules are :

1. Crystalline solar panels
2. Thin film solar panels

Crystalline solar panels are further divided in to two types [1, 2]. They are: Mono crystalline solar panels and Poly crystalline solar panels. Different solar modules are described in the fallowing sections.

Crystalline silicon (c-Si) has been used as a light-absorbing semiconductor material in most solar cells, even though it is a relatively poor absorber of light and requires a considerable thickness (several hundred microns) of material. Nevertheless, it is proved to be very effective because it yields stable solar cells with good efficiencies. Crystalline solar panels are classified into two types - mono crystalline and poly crystalline.

Mono crystalline solar panels are made from a large crystal of silicon. These solar panels are the most efficient in absorbing sunlight and converting it into electricity. Crystalline silicon is used as the light absorbing semiconductor material in most of the crystalline solar panels. These solar panels are most expensive and work better than the other solar panels in lower light conditions. The percentage of sunlight converted by electricity by using these panels is 15% [7].

Poly crystalline solar panels are the most common type of solar panels used in the market. They look like shattered glass, are slightly less efficient than the mono crystalline solar panels and are less expensive to produce. Instead of one large crystal, this type of solar panel consists of multiple amounts of smaller silicon crystals [7] .The percentage of sunlight converted by electricity using this panels is 14%.

2.2 Thin Film Solar Panels

Thin Film Solar Panels are further classified in to two types

1. Amorphous solar panels.
2. Copper Indium Diselenide solar panels.

Amorphous silicon solar panels are the most developed solar panels of the thin film solar technologies. In its simplest form, the solar cell structure has a single sequence of p-i-n layers. Amorphous solar panels consist of a thin-like film made from molten silicon that is spread directly across large plates of stainless steel or similar material. They have a relatively low efficiency when compared to the other two types of solar panels, but are the cheapest to produce [8] .The advantage of these solar panels over the other panels is that these are shadow protected. The percentage of sunlight converted to electricity using these panels usually range between 5-7%. These solar panels continue to charge even while part of the solar panel cells is in a shadow [7]. Amorphous solar panels work great on boats and other types of transportation.

Copper Indium Diselenide Solar Panels are one of the newest and the most promising. It is a new proprietary multi-junction device made of Copper Indium Gallium diSelenide (CIGS). These panels are capable of higher photovoltaic efficiency than standard amorphous silicon and the panel doesn't have to be quite as large to produce the same power output as others[7, 8]. The only disadvantage with this type of Panels is that the power drops off more (compared to multi-junction amorphous silicon) in partially sunny conditions. The percentage of sunlight converted by electricity by using these panels is 10%.

Amorphous silicon solar panel technology is the most well-developed thin film solar technology to-date and has an interesting avenue of further development through the use of "microcrystalline" silicon which seeks to combine the stable high efficiencies of crystalline Si technology with the simpler and cheaper large area deposition technology of amorphous silicon. However, conventional crystalline silicon manufacturing technology has continued its steady improvement year by year and its production costs are still falling too.

Table 2.1 [7] provides a summary of the differences between Crystalline and Thin film solar panels. The values recorded are in terms of cost, sun light conversion efficiency, space and applications.

Crystalline	Thin Films
Types of Crystalline Panels • Mono Crystalline (15%) • Poly Crystalline (14%) (% Sun light converted to electricity)	**Types of Thin Film Panels** • Amorphous Silicon (5-7%) • Copper Indium Diselenide(10%) • Cadmium Telluride (7%) (% Sun light converted to electricity)
Positive Factors ❖ Efficient ❖ Requires less space ❖ Long track record	**Positive Factors** ❖ Less Expensive ❖ Less temperature sensitive ❖ Very versatile
Negative Factors ➢ Costly ➢ Temperature Sensitive ➢ Limited Applications	**Negative Factors** ➢ Shorter track record ➢ Low Efficiency ➢ Requires more space

Table 2.1: Difference between the two modules [7]

Group III-V technologies solar panels have 25% high photovoltaic efficiency as they use a variety of materials with very high conversion efficiencies. These materials are categorized as

Group III and Group V elements in the Periodic Table. A typical material used in this technology is gallium arsenide, which can be combined with other materials to create semiconductors that can respond to different types of solar energy [7]. Though these technologies are very effective, their current use is limited due to their costs. They are currently employed in space applications and continue to be researched for new applications

String Ribbon Silicon solar panels have variation on the polycrystalline production process, using the same molten silicon but slowly drawing a thin strip of crystalline silicon out of the molten form. These strips of photovoltaic material are then assembled in a panel with the same metal conductor strips, attaching each strip to the electrical current. This technology saves on cost when compared to the standard polycrystalline panels as it eliminates the sawing process for producing wafers.

In this chapter, we discussed the solar panel technologies by focusing on studying the importance of different types of solar panel models. Emphasis has been made on highlighting the differences, advantages and disadvantages of various types of solar technologies such as crystalline solar panels and the thin film solar panels. The basis for all the solar cell technologies, can however be attributed to the standard solar cell model. Chapter 3 discusses the solar electric cell model, characteristics of that electric cell, connection of solar cells in series, connection of solar cells in parallel and about the harmonics.

CHAPTER 3

3.1 Solar electric cell model

Sunlight can be converted to electricity by using solar panels comprising many photovoltaic solar cells .These Photovoltaic cells are manufactured from fine films .These films are semiconductor devices which convert solar energy into dc current, the conversion efficiencies ranging from 3 to 31%. The conversion efficiency changes with the type of technology, temperature, sun intensity and the material of the solar cell used. The parallel and the series connections of the solar cells give high voltages and currents [14]. So the emphasis of a solar panel design is based on providing parallel or series connections of the solar cells. The implementation of a full electric power system needs power electronic equipment, energy storage and also protection equipment.

3.2 Electricity Generation by Photovoltaic Effect

Semi conductor materials have two energy bands, namely Conduction and Valence bands. They are separated by a small margin called the band gap or the energy gap. Photovoltaic effect takes place when an electron goes from one band to another band, leaving behind a hole in its place [14]. This hole is a positive energy and when we apply the voltage to the semiconductor device the electrons and their holes will generate the electric current [13]. Hence electricity is generated. The Solar cell equivalent circuit is shown below in fig. 3.1. The fallowing equation is delivered from the circuit

$$I_0 = I_\lambda - I_d - I_p \tag{3.1}$$

In the equation 3.1,

I_λ is the photon current that will depends on light intensity and its wave length

. I_d is the Shockley temperature depends upon the diode current

I_P is the PV cell leakage current

The photon current is proportional to the light intensity and it depends on the light intensity λ

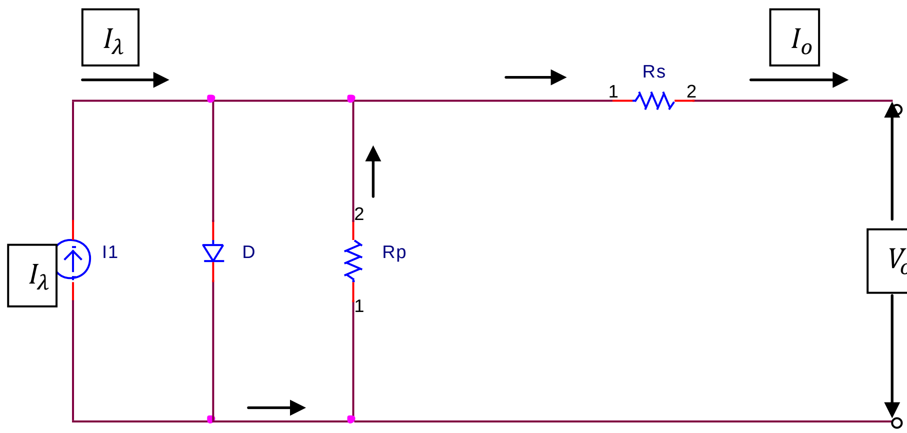

Figure: 3.1: Solar cell circuit

The photon current parameters are related to the short circuit current I_{sc} and to the cell open circuit voltage V_{oc}. From the I-V characteristics, circuit current may be obtained for the given solar cell. When the output voltage is $V_0 = 0$ the open circuit voltage is obtained. For zero output current $I_0 = 0$ photon current is known for standard illumination intensity L_S=1.0 sun and a prescribed value of $I_{\lambda o}$. The expression below can be used to obtain the photo current for every level L.

$$I_\lambda = \frac{L}{L_s} I_{\lambda_0} \tag{3.2}$$

The Shockley diode current expression is given below

$$I_d = I_s(e^{qv_d/\eta kT} - 1) \tag{3.3}$$

Where in Equation 3.3,

I_S is the reversed saturated current of the diode. 100pa typically for a silicon cell k is the Boltzmann constant 1.38047×10^{-23}J/K

q is the electron charge 1.60210×10^{-19} C

V_d is the diode voltage

η is the empirical constant

T is the absolute temperature 273.2+t_c

q/kT = 38.94452 C/J for any temperature q/k=11605.4677C

The internal losses or the leakage current can be represented by the parallel resistance R_P across the Shockley diode. Normally the range is 200 to 300ohms. Like parallel resistance, there is series resistance R_s between the photon current source and the load across photo voltaic terminals. This value is between 0.05 to 0.10ohms. With the above specifications, the equation 3.1 becomes

$$I_0 = I_\lambda - I_s(e^{qv_d/kT} - 1) - \frac{V_d}{R_p} \tag{3.4}$$

$V_d = I_o(R_s + R_L) = V_o(1+R_s/R_L)$ substituting the diode voltage V_d in the equation (3.4) we get

$$I_0 = \frac{R_p}{R_p + R_s + R_L}[I_\lambda - I_s(e^{qv_d/kT} - 1)] \tag{3.5}$$

If there are large values for the load resistance R_L with respect to the parallel resistance R_p of the solar cell, it results in a difference in the output current values. For this reason, we have to use an empirical factor η in the exponential term in the equations (3.4) or (3.5). Then they can be adjusted to the practical data. The two equations are given (3.6) and (3.7)

$$I_0 = I_\lambda - I_s(e^{qv_d/\eta kT} - 1) - \frac{V_d}{R_p} \tag{3.6}$$

(Or)

$$I_0 = \frac{R_p}{R_p + R_s + R_L}[I_\lambda - I_s(e^{qv_d/\eta kT} - 1)] \tag{3.7}$$

From the I-V characteristic curve, it is clear that the diode and the open circuit voltage both change with the load current. When I_o=0 in the illuminated panel then the cell open circuit voltage is obtained from the equation (3.6) as

$$V_{oc} = V_d \mid_{I_0=0} = (I_\lambda - I_d)R_p = [I_\lambda - I_s(e^{\eta q v_{oc}/kT} - 1)]R_p \tag{3.8}$$

The simplified form is

$$V_{oc} = \frac{kT}{\eta q}\ln(1 + \frac{I_\lambda}{I_s} - \frac{V_{oc}}{I_s R_p}) \tag{3.9}$$

If the open circuit voltage and the parallel resistance changes in order of 0.6v and 300ohms then the equation 3.9 becomes

$$V_{oc} \cong \frac{kT}{\eta q}\ln\frac{I_\lambda}{I_s} \tag{3.10}$$

The series resistance of the cell is very small so when there is short circuit occurred to the PV cell practically the opposition to the current through is R_S [14]. The short circuit current can be written as

$$I_{sc} \cong I_\lambda \tag{3.11}$$

The output power is the product of output voltage and the output current. The corresponding equation is

$$P_o = \frac{V_o R_p}{R_p + R_s + R_L}[I_\lambda - I_s(e^{qV_o(1+R_s/R_L)/\eta kT} - 1] \tag{3.12}$$

To get the maximum power, differentiate the equation (3.12) with respect to the output voltage V_o and the total derivative equals to zero .To find the external load voltage V_{om} for the maximum power it will satisfy the equation below:

$$I_s e^{qV_{om}(1+R_s/R_L)/\eta kT} = \frac{I_\lambda + I_s}{1+V_{om}^{q(1+R_s/R_L)/\eta kT}} \tag{3.13}$$

Another way is by plotting the equation (3.12) and obtains its maximum graphically. The maximum power is given as

$$P_m = \frac{V_{om}(I_s + I_\lambda)}{1+\eta kT/qV_{om}(1+R_s/R_L)} \tag{3.14}$$

The incident flux power P_i is known on the cell. The conversion efficiency now becomes

$$\eta_m = \frac{P_m}{P_i} = \frac{V_{om}(I_s + I_\lambda)}{P_i(1+kT/\eta qV_{om})(1+R_s/R_L)} \tag{3.15}$$

3.3 PV Cell Characteristic on Temperature

Temperature influences Solar cell in two ways. With the illumination of the sun gaining of the current varies and also the reverse biased diode current and voltage are also affected [14]. For the saturation current, the expression is given as

$$I_s(T) = KT^m e^{-V_{GO}/\eta V_T} \tag{3.16}$$

K is a constant independent on temperature

m value is 2 for germanium and1 for silicon

η value 1 for germanium, 2 for silicon

V_{GO} value is 0.785v for germanium and 1.21v for silicon V_T=kT/q

T value is $298^o C$

Taking the derivative to the 3.16 saturation current expression in the logarithm form will give the below expression

$$\frac{d(\ln I_s)}{dT} = \frac{dI_s / I_s}{dT} = \frac{m}{T} + \frac{V_{GO}}{\eta T V_T} \tag{3.17}$$

The standard conditions with the parameters, given the logarithm per unit variation dI_s/I_s with the temperature is about 8% per^oC for the silicon and it is 11% per^oC for the germanium .The variation is small in the commercial diodes because the surface leakage for those diodes is not that much important effect for the photovoltaic cells. With respect to the I_s, if the diode saturation current I_{so} changes for the temperature T_o at another temperature T.

$$I_s(T) \cong I_{s0} \times 2^{(T-T_0)/10} \tag{3.18}$$

The more practical way for this issue is to use the temperature coefficients. Positive temperature coefficients are used for the current and the negative temperature coefficients are used for the voltage. For the short circuit current given in equation 3.19.

$$I_{sc} = I_{sc0}(1+\alpha\Delta T) \tag{3.19}$$

α is the temperature coefficient of the current. For a crystal silicon PV cell α value is about 500μunits /K. Table 3.1 [14] gives the information about standard conditions and normal conditions of the PV panel.

Parameter	**Standard Conditions**	**Normal Conditions**
Solar Illumination(W/m^2)	1000	800
Cell Temperature(^oC)	25	42
Solar Spectral Irradiance	ASTM E-892	ASTM E-892

Table: 3.1: PV panel parameters [14]

If the voltage is fixed and the temperature is increased, the diode current increases. Taking the derivative from the Shockley's equation, gives an expression for the variation of the diode voltage is possible with its saturation current the variation with the temperature as a difference of two terms by balancing these two terms by reducing the voltage and increase of current may be kept a constant current for both silicon and germanium diodes [14].

$$\frac{dV_d}{dT} \cong -2.5mV/^oC \tag{3.20}$$

With increase in temperature will decrease the relationship so we need a perfect expression for this variation that one given in equation 3.21.

$$\frac{dV_d}{dT} = \frac{V_d - (V_{GO} + m\eta V_T)}{T} \tag{3.21}$$

The usual values are $\frac{dV_d}{dT} \cong -2.1mV/^oC$ for germanium and $\frac{dV_d}{dT} \cong -2.3mV/^oC$ for silicon. The practical approach suggests that $\beta = 5\mu$units/K for the open circuit voltage of the PV cell. The temperature corrected to the open circuit voltage can be written as equation 3.22

$$V_{oc} = V_{oc0}(1 - \beta\Delta T) \tag{3.22}$$

Where β is a negative temperature coefficient

3.3.1 PV Cell Output Characteristics

The PV cell output characteristics used for power electronic system control design which is connected to photovoltaic arrays. It describes the output power versus the load voltage and the output power versus the load current at different sun illumination and temperature levels. Voltage-based power control is better as showed in the next figure. On the efficiency of solar panel cell, temperature also plays important role. In the figure, it shows that for a cell illuminated by 0.6 under two different temperatures $t_1 = 50^oC$ and $t_2 = -25^o$C the cell short circuit current decreases whereas the open circuit voltage increases.

The equation (3.2) tells that when the output power of a PV cell increases with the level of illumination generating a locus of maximum power below figure (the output voltage vs. the output current) will show the maximum output power locus for an individual PV cell. The maximum voltage or the maximum power in these two is also not same for different illumination levels at the maximum power point in the below figure and the previous sun illumination characteristics figure. The output power is given as below

$$P_o = V_o I_o \tag{3.23}$$

The peak power given as differentiation of equation 3.23 equals to zero and hence the expression becomes

$$\frac{dP_o}{dV_o} = V_o + I_o \frac{dV_o}{dI_o} = 0 \text{ From this}$$

$$\frac{dV_o}{dI_o} = -\frac{V_o}{I_o} \tag{3.24}$$

The equation 3.24 tells that the dynamical internal resistance of the source should match the external load resistance.

3.4 Equivalent Model and Parameters for Photovoltaic Panels

Figure 3.2 represents the detailed model of a PV cell. The value of the capacitor is very low (10 PF) so it won't taken into account because of the very low value in the dc current analysis.

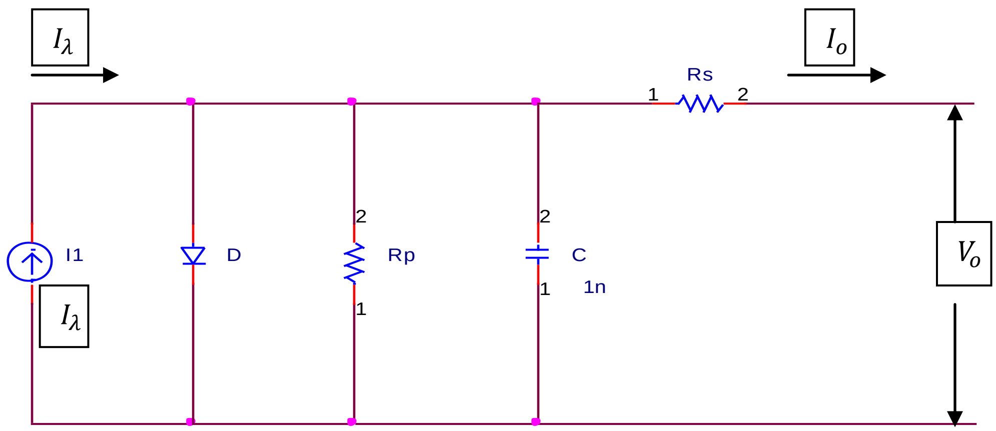

Figure: 3.2: Equivalent model and parameters for PV panel

The parameters values in the circuit are R_s is from 0.01 to 1.0 Ω and R_p is in the range 200 to 800 Ω the illumination current depends on the sun luminous intensity in lumens or photo candles where 1lumen=1.496exp(-10)W;1lumen/ft^2 =1footcanle=1.609exp(-12)W/m^2.

3.5 Dark-Current Electric Parameters of a Photovoltaic Panel

Three parameters are selected from the PV characteristics curve, representing three points on the curve as shown in the below figure .To obtain the parameters in equivalent circuit of a PV cell also called as dark current, electric parameters may be established from panel in a moderately dark condition, that means deactivating the internal source current of the circuit [14]. With an external voltage source, we can measure the points $(V_{01}I_{o1})$, $(V_{02}I_{o2})$ and $(V_{03}I_{o3})$ as shown in the equation 3.25.

$$
\begin{aligned}
V_{d1} &= V_{o1} - I_{o1}R_s \\
V_{d2} &= V_{o2} - I_{o2}R_s \\
V_{d3} &= V_{o3} - I_{o3}R_s
\end{aligned} \tag{3.25}
$$

The selected three points in the equation 3.25 will cover the most portion of the Shockley's equation.

Point 1 is close to the maximum reverse voltage of the cell .Point 2 is close to the rated current of the cell. Point 3 is close to the tenth of the rated current cell. From the equation 3.25,

$$
R_s = \frac{V_{d1}}{I_{o1} - I_{d1}} = \frac{V_{d2}}{I_{o2} - I_{d2}} = \frac{V_{d3}}{I_{o3} - I_{d3}} \tag{3.26}
$$

With equation (3.3) we obtain

$$
I_s = \frac{(V_{d2}/V_{d1})(I_{o1} - I_{o2})}{(V_{d2}/V_{d1})[\exp(qv_{d1}/\eta kT) - 1] - [\exp(qv_{d2}/\eta kT) - 1]} \tag{3.27a}
$$

$$
I_s = \frac{(V_{d3}/V_{d1})(I_{o1} - I_{o3})}{(V_{d3}/V_{d1})[\exp(qv_{d1}/\eta kT) - 1] - [\exp(qv_{d3}/\eta kT) - 1]} \tag{3.27b}
$$

All the right side terms in the two equations (3.26) and (3.27a) are the functions of R_s of the measured pairs of values. So from the equation (3.27), we define the function of R_s as

$$
f(R_s) = \frac{(V_{d2}/V_{d1})(I_{o1} - I_{o2})}{(V_{d2}/V_{d1})[\exp(qv_{d1}/\eta kT) - 1] - [\exp(qv_{d2}/\eta kT) - 1]} \tag{3.28a}
$$

$$
f(R_s) = \frac{(V_{d3}/V_{d1})(I_{o1} - I_{o3})}{(V_{d3}/V_{d1})[\exp(qv_{d1}/\eta kT) - 1] - [\exp(qv_{d3}/\eta kT) - 1]} \tag{3.28b}
$$

The solution f (R_s)=0 gives two different values for R_s. One of the values is discarded for the physical reasons. When R_s is back substituted in to the equation (3.26) it may give negative solution and distinct values for R_p with large different values of I_s. Once we get the right solution for $R_s$and R_p, the values are replaced in equation (3.27) to give two similar solutions for I_s.

The limitations of this method are the correct knowledge of the empirical constant η. When there are a number of PV cells in series or parallel arrangement in a PV panel, the number has to be included in the equation of the foregoing method as discussed.

3.6 Model of a PV Panel Consisting n Cells in Series

We will next develop the model of a PV panel consisting of n cells in series using Mathematical Induction. We know that the model of photovoltaic panel when there is only one cell; n=1 is:

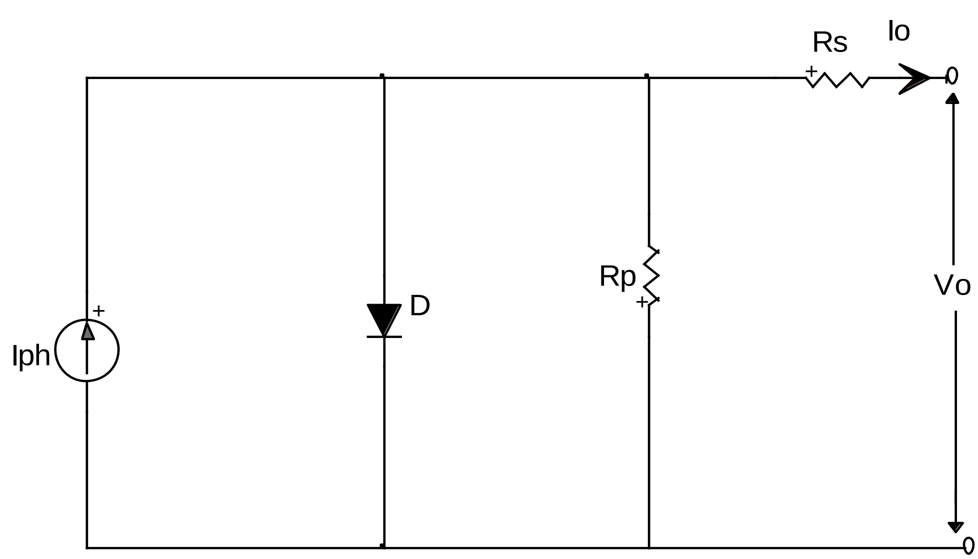

Figure 3.3: Single Solar cell circuit

Similarly Figure3.3 now represented as Figure 3.4 that is a more suitable representation for integrating PV cells in series.

Representing Figure 3.3 in Figure 3.4.

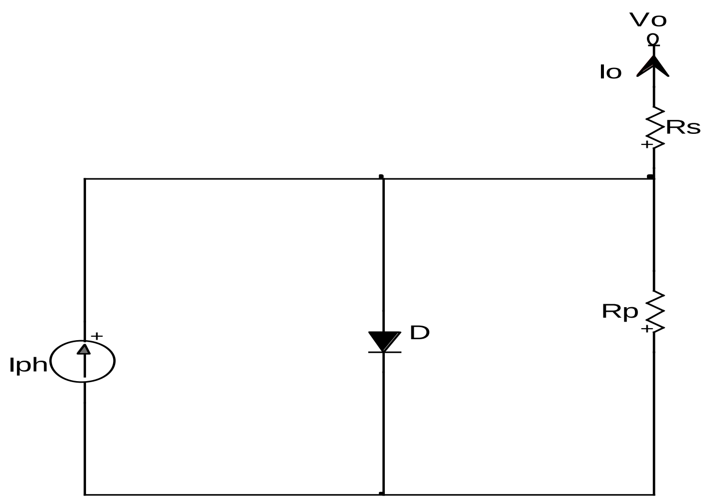

Figure 3.4: Modified Single Solar cell circuit

We know that when there are two cells in series in the PV panel; n=z, the model is:

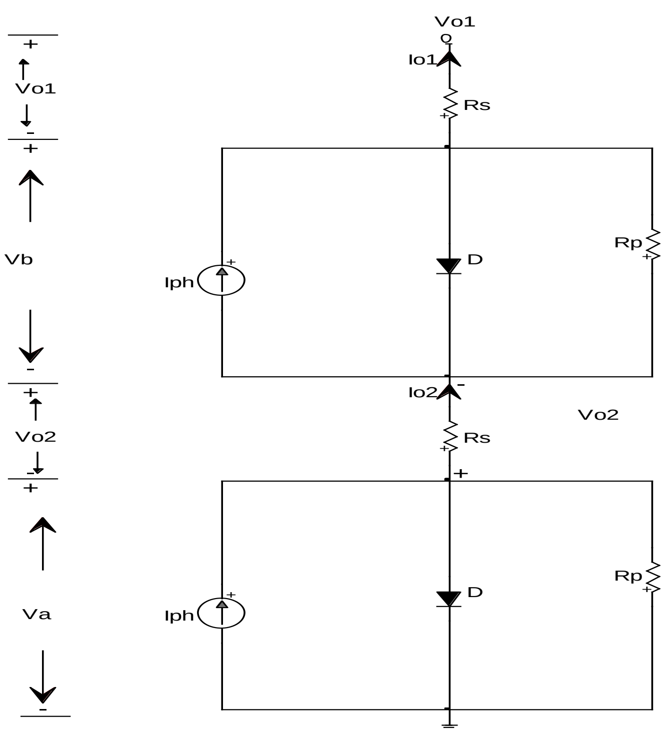

Figure 3.5: Two Solar cells connected in series

Figure 3.5 can be represented as Figure 3.6 by combining resistances and focusing on the total Vo of the 2-cell panel with respect to the ground.

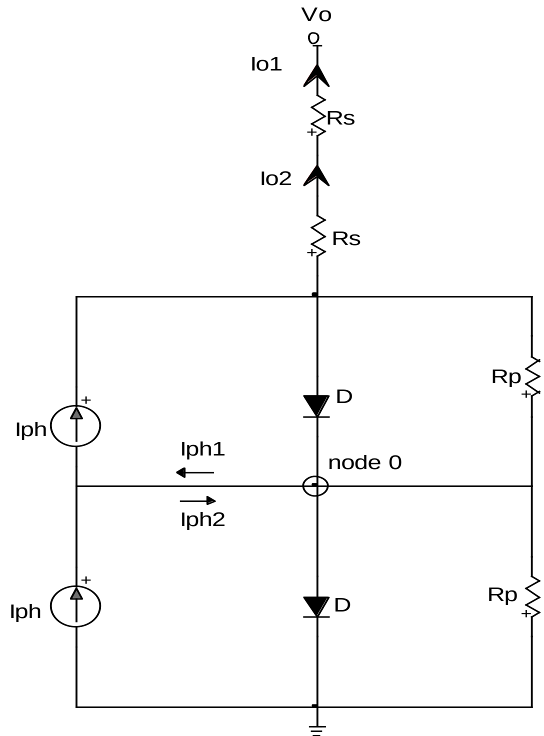

Figure 3.6: Modified Two Solar cells circuit

From Figure 3.6, Iph1 = -Iph2 so we can remove node 0 and the modified Figure 3.6 can be represented in Figure 3.7.

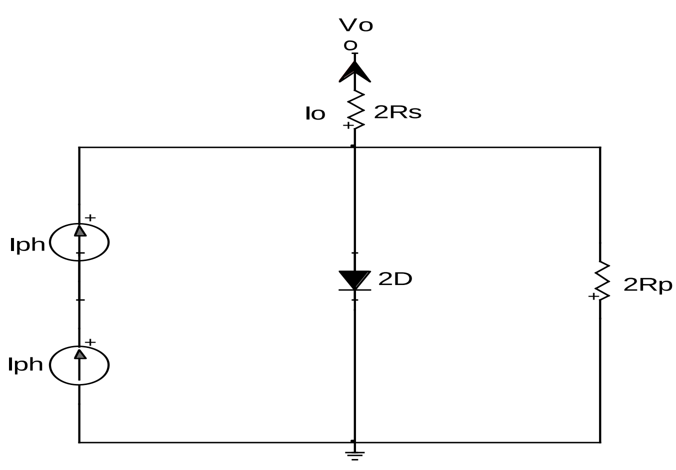

Figure 3.7: Modified Two Solar cells circuit

To prove the model of the photovoltaic panel when there are n cells in the panel, we use Mathematical Induction.

We know the model when n=1 is the model represented b Figure 3.4.We showed that when n=2, the model is represented by Figure 3.5. We assume that when n=k, then the model is according to Figure 3.8.

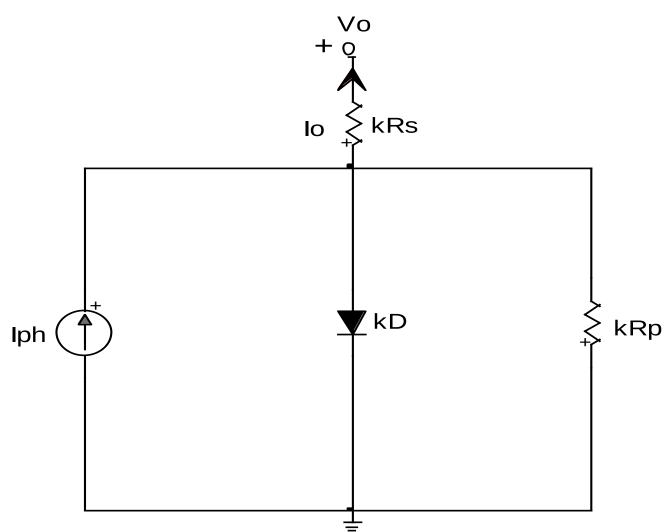

Figure 3.8: Model for k solar cells connected in series

We prove that when n= k+1, the model of the PV panel is according to Figure 3.9.

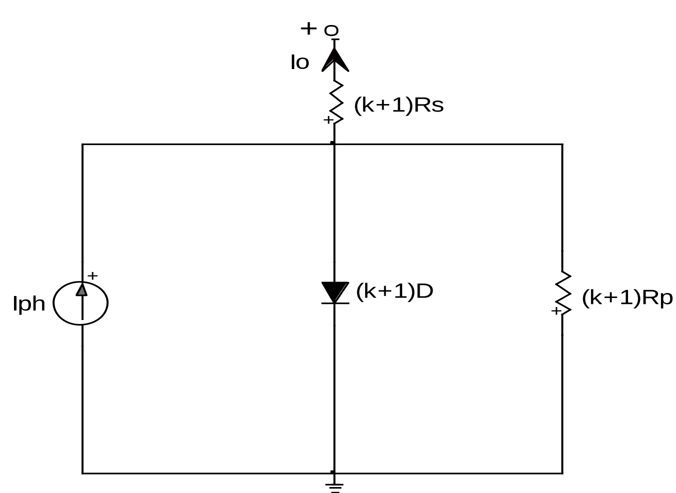

Figure 3.9: Model for (k+1) solar cells connected in series

Figure 3.9 is redrawn according to Figure 3.10.

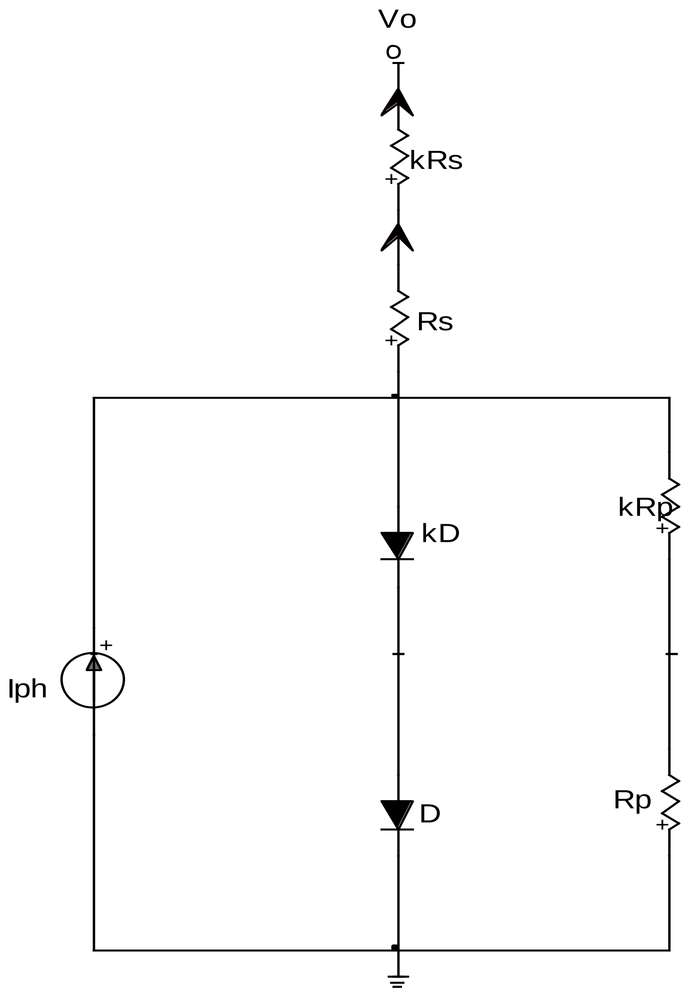

Figure 3.10: Modified model for Figure 3.9

Figure 3.10 is now represented as Figure 3.11.

Figure 3.11 which is a decomposed version of Figure 3.10 represents the model for a photovoltaic panel consisting of two panels, one including **k** cells and the other including **1** cell. Using our assumption for the model of PV panel consisting of k cells as one cell that has series and parallel resistances of kRs and kRp and the diode of kD. Now we have two cells in series that we have already shown to have the model of Figure3.5. Therefore we showed that Figure 3.9

is an accurate model representing PV panel consisting of n=k+1.

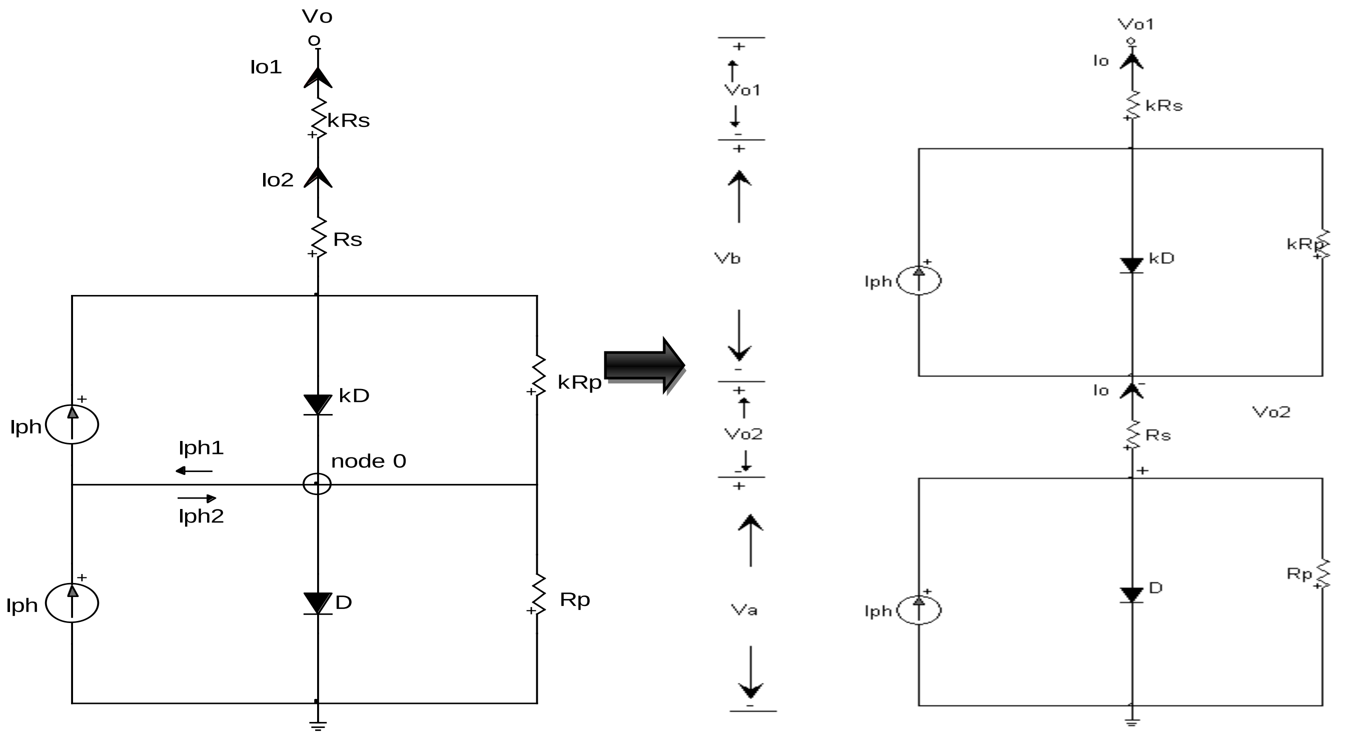

Figure 3.11: PV panel connected with k solar cells and 1 solar cell

Because k could vary to our choice, the model of PV panel consisting of n cells using Mathematical Induction is depicted by Figure 3.12

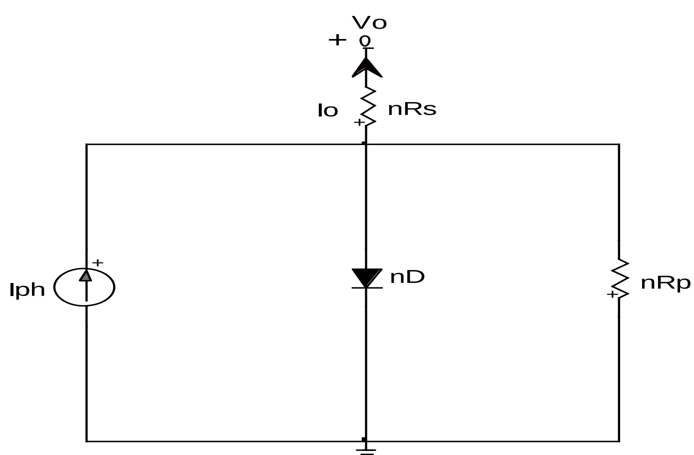

Figure 3.12: Equivalent model of a PV panel with identical n cells in series.

3.7 Model of a PV panel consisting of n cells in Parallel

The model for PV panel when there is only one solar cell; n=1 is:

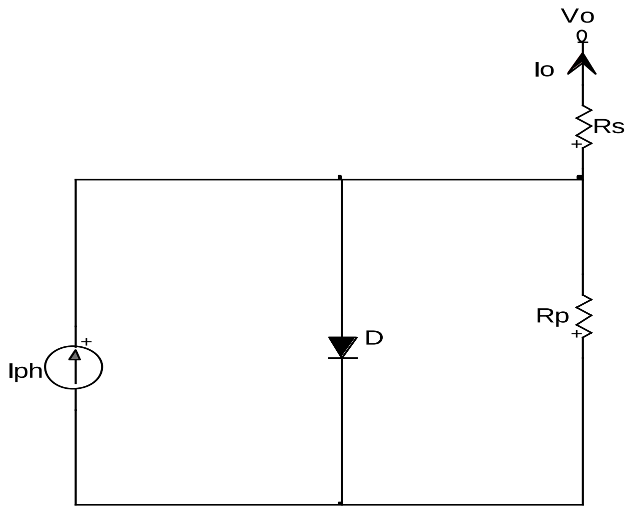

Figure 3.13: Model for single solar cell

We show that when there are two cells in parallel connection in the PV panel; n=2 then the model is:

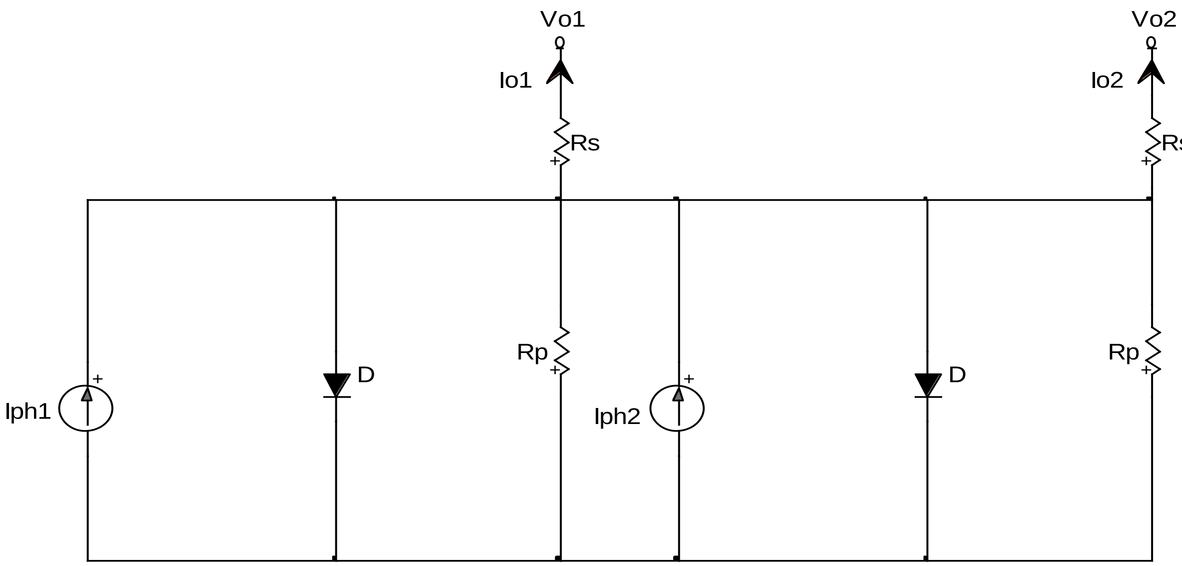

Figure 3.14: Model for two solar cells connected in parallel

Figure 3.14 is redrawn according to Figure 3.15

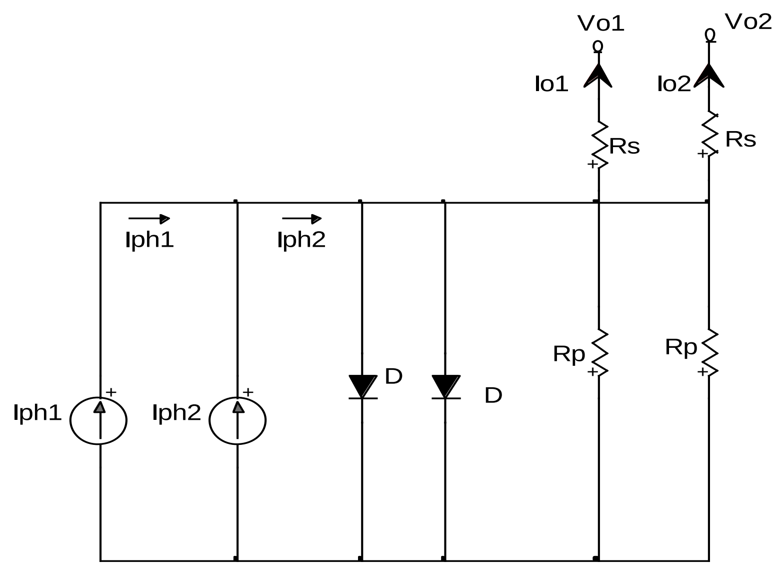

Figure 3.15: Modified model for two solar cells connected in parallel.

From Figure 3.15, because Iph1=Iph2 we can add two current sources. Figure 3.15 is now represented as 3.16.

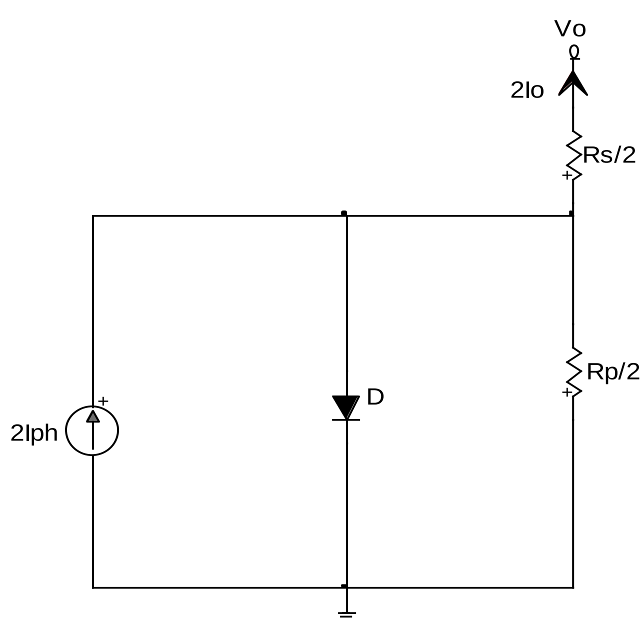

Figure 3.16: Model for Two solar cells connected in parallel.

To prove the model of photo voltaic panel when there are n cells in the parallel, we use Mathematical Induction.

We know the model when n=1 the model is represented by Figure 3.13. We showed that when n=2 the model is according to Figure 3.16 we assume that when n=r, the model is according to Figure 3.17.

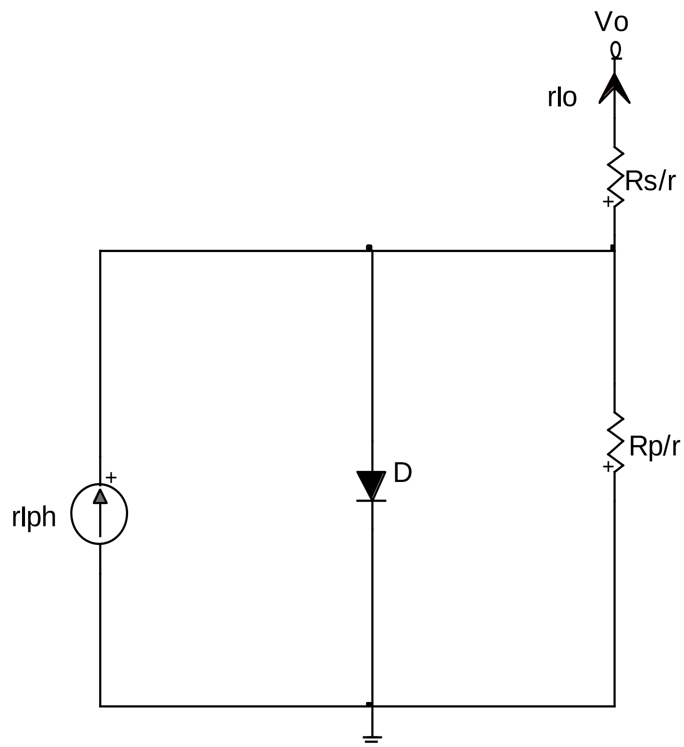

Figure 3.17: Model of a PV panel with r cells in parallel

We prove that when n=r+1, the model of the PV panel is according to Figure 3.18

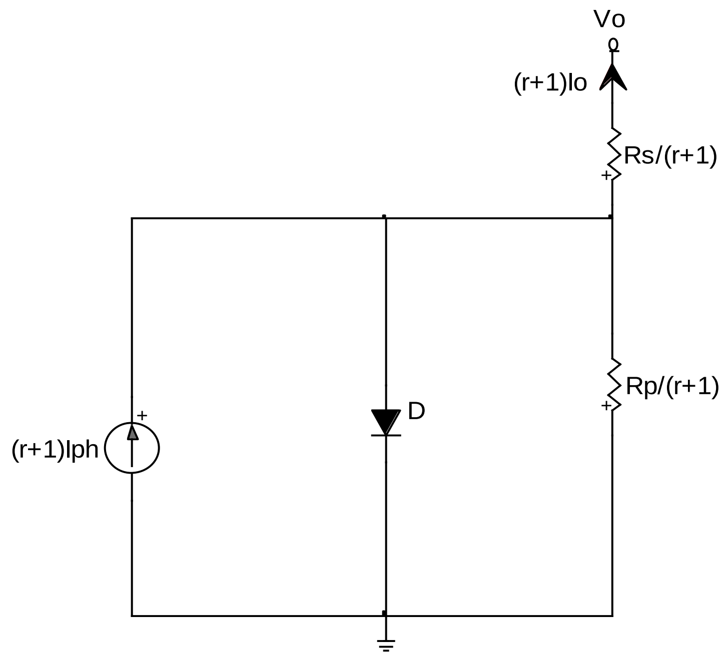

Figure 3.18: Model of a PV panel with (r+1) cells in parallel

Figure 3.18 is redrawn according to Figure 3.19

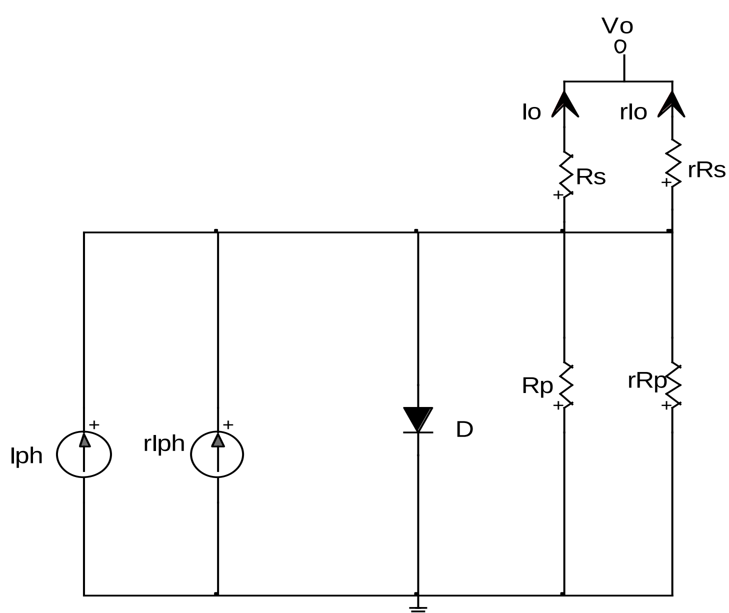

Figure 3.19: Model of a PV panel with r cells and 1 cell.

Figure 3.19 is next represented as Figure 3.20

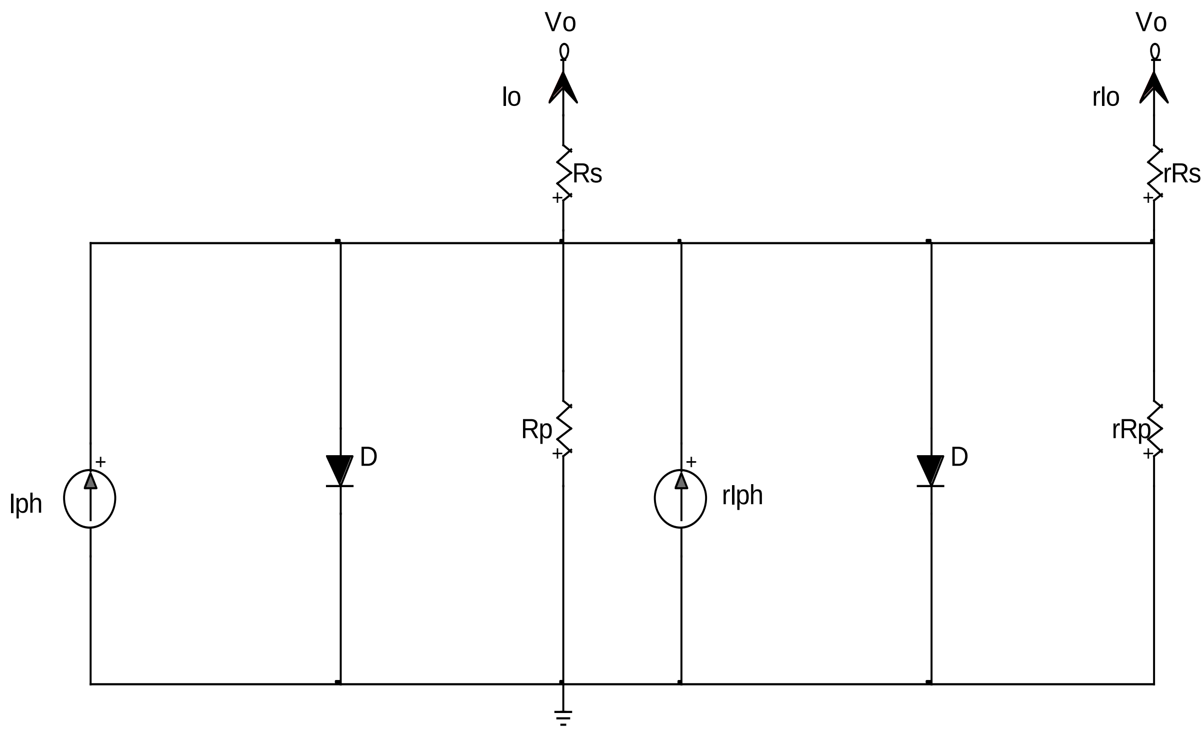

Figure 3.20: Model of a PV panel with r cells and 1 cell.

Figure 3.20 represents a model for a PV panel consisting of two panels in parallel connection, one including **r** cells and the other including **1** cell. Consider the panel consisting of r cells as one cell that has series and parallel resistances of rRs and rRp and the diode of D. Now we have two cells in parallel that we have already shown to have the model of Figure3.16. Therefore we showed that Figure 3.18 is an accurate model representing PV panel consisting of n=k+1.

The model of PV panel consisting of n cells is depicted by Figure 3.21.

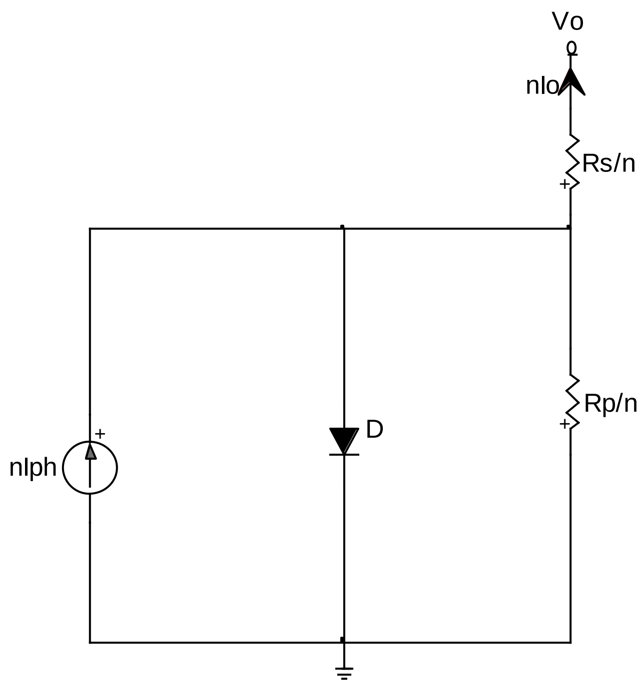

Figure 3.21 Equivalent model of PV panel with n cells in parallel.

3.8 Harmonics

Harmonics are the byproducts of the modern electronics. They occur frequently when there are power supplies, variable frequency devices or any electronic device using solid state power switching supplies to convert DC to AC. Nonlinear loads creates harmonics by drawing current in abrupt pulses, rather than in a smooth sinusoidal manner [23].

Harmonics are the integral multiples of the fundamental frequency involving non linear loads or control devices, including electromagnetic devices like transformers, lighting ballasts and also solid state devices like rectifiers, thyristors, and phase controlled switching devices [21].

Harmonics can effect or increase electromagnetic interference in sensitive electronic systems also there is abnormal heating of cables, motors, transformers and the other electromagnetic equipment [19]. because of the harmonics in the system there is excessive capacitor currents and because of system resonance at harmonic frequencies cause to excessive voltages. High level of harmonic distortion in the system can effects transformers ,capacitors ,motor or generator heating ,miss operations of equipment and other problems which will decrease the system reliability .By decreasing harmonics we can improve power system reliability

Using the development of [23] Fourier series of the function can be represented as equation 3.29

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos nt + \sum_{n=1}^{\infty} b_n \sin nt \tag{3.29}$$

$$= \frac{a_0}{2} + a_1 \cos t + a_2 \cos 2t + a_3 \cos 3t + \ldots\ldots\ldots\ldots$$

$$+ b_1 \sin t + b_2 \sin 2t + b_3 \sin 3t + \ldots\ldots\ldots$$

We can write equation 3.29 as:

$$f(t) = \frac{a_0}{2} + (a_1 \cos t + b_1 \sin t) + (a_2 \cos 2t + b_2 \sin 2t) + (a_3 \cos 3t + b_3 \sin 3t) + \ldots\ldots\ldots\ldots \tag{3.30}$$

$(a_1 \cos t + b_1 \sin t)$ is known as the fundamental harmonic

$(a_2 \cos 2t + b_2 \sin 2t)$ is known as the second harmonic

$(a_3 \cos 3t + b_3 \sin 3t)$ is known as third harmonic, etc.

Fourier series will contain odd harmonics if $f(t+\pi) = -f(t)$

Fourier series will contain even harmonics if $f(t+\pi) = f(t)$

Even and Odd harmonics also related to the number of pulses, or paths of conduction. The general equation for the harmonic number is given in equation 3.31

$$h = (n * p) \pm 1 \tag{3.31}$$

In equation 3.31, h is the harmonic number, n is any integer, and p is the number of pulses in the circuit. For the full wave inverter number of pulses is two, so only odd harmonics will exist in full wave rectifiers.

Odd harmonics are present in the signal when the negative half cycle is to be same as positive half cycle but in the negative direction. Alternatively, odd harmonics are present in the signal when the first and third quarters are similar, and the second and the fourth quarters are similar. Odd harmonics occurs with the rectifier bridges where the positive and negative half cycles are similar.

Even harmonics present when the negative half cycle in the signal is not similar to the positive half cycle. Even harmonics is that in the signal first and fourth quarters are similar, and the second and third quarters are similar. Even harmonics are not common in industrial power systems.

3.8.1Total Harmonic Distortion

Total Harmonic Distortion is a measure of closeness in a shape between the output voltage waveform and its fundamental component [21]. It is defined as the ratio of the rms of its total harmonic component of the output voltage and the rms value of the fundamental component.

The main purpose that we use the inverter is to convert a dc input source to requiring ac output .It is very useful to describe the quality of the ac output either in terms of voltage or current THD .The quality of the output (non sinusoidal wave) can be expressed as Total Harmonic Distortion (THD)

Harmonics work together in distorting the fundamental waveform .The representation of the harmonic current (or) voltage with respect to the fundamental waveform is called total harmonic distortion. It is specified for both current and voltage.

Total Harmonic Distortion for voltage is given by equation 3.32 [20]

.
$$THD = \frac{\sqrt{\sum_{n=2}^{\infty}(V_{n,rms})^2}}{(V_{1,rms})} = \frac{\sqrt{V_{rms}^2 - V_{1,rms}^2}}{V_{1,rms}} \tag{3.32}$$

The equation 3.32 represents the total harmonic distortion of voltage. The THD of the current is determined by substituting the current for voltage in the equation 3.32. The THD of the load current demands more interest than the voltage [21].The THD of the current is calculated by taking square root of the addition of the squares of the harmonic currents, and dividing those harmonic currents with the fundamental current as given below.

Total Harmonic Distortion for current given below [20]

$$I_{THD} = \frac{\sqrt{(I_3^2 + I_5^2 + I_7^2 + I_7^2 + I_9^2 + I_{11}^2 + ...)}}{I_1} \tag{3.33}$$

The definitions for the THD (voltage and current) are based on Fourier series. There are few benefits if we do harmonic analysis by using Fourier series method. By using Fourier series method, we can determine not only THD but also the distortion factor. This can also be applied to describe the inverter's output waveform.

Distortion factor indicates the amount of harmonics that remain in the output voltage waveform after the waveform has been subjected to second order attenuation.

Harmonic currents travel on the outer edge of the conductors creating heat. This is called skin effect [15].The created heat causes the circuit breakers to trip, neutral and phase conductors to heat up and motors and transformers to fail prematurely.

In this chapter, we studied the standard electric circuit model for the solar cell. Using the model, we analyzed the production of dc current when the photon current (sun energy) falls on the semi-conductor photo voltaic panel. The chapter also discussed the behavior of the solar panels when connected in series and in parallel. Harmonics and their effects have been studied in detail along with the equations for calculating Total Harmonic Distortion of voltage and current, for solar series and parallel connection models. Chapter 4 explains the design implementation of the solar cell electric models discussed in chapter 3. The design implementation is done using EMTP (Electro Magnetic Transient Program) real time simulation software.

Chapter 4

4.1 Overview of EMTP

EMTP-RV is the end result of the "Electro Magnetic Transient Program Restructuring Project". It was undertaken by the Development Coordination Group (DCG) in 1998 for modernizing the EMTP96 software. EMTP-RV is the enhanced computational engine and EMTPWorks is its new Graphical User Interface (GUI). This software is a sophisticated computer program for the simulation of electromagnetic, electromechanical and control system transients in multiphase electric power systems. It features variety of modeling capabilities encompassing electromagnetic and electromechanical oscillations ranging in duration from microseconds to seconds [22]. It is used in power electronic applications in power systems. EMTP-RV computational engine is driven by EMTPWorks. The data transmission from EMTPWorks to EMTP-RV is by using a nelist file. EMTP-RV reads the file, decodes the simulated network topology, required models and computation functions, builds the system matrix and performs the simulation. The simulation results are saved into binary ASCII files. The binary files which, used for showing the simulations waveforms from a stand-alone waveform visualization application is called Scope view.

4.1.1 Scope View

Scope View is a data acquisition and signal processing software adapted very well for the visualization of waveforms and analysis of EMTP-RV results. Scope view is also used to simultaneously load, view and process data from applications such as EMTP-RV, MATLAB and Comtrade format files [22].

4.2 Single solar cell model in EMTP

From Chapter 3, we take the solar cell circuit model and test that model by designing it in EMTP (Electro Magnetic Transient Program) software.

EMTP is the real-time simulation software used in this approach to build the solar cell model and to simulate the model. All the parameter values of solar cell are recorded from the standard reference.

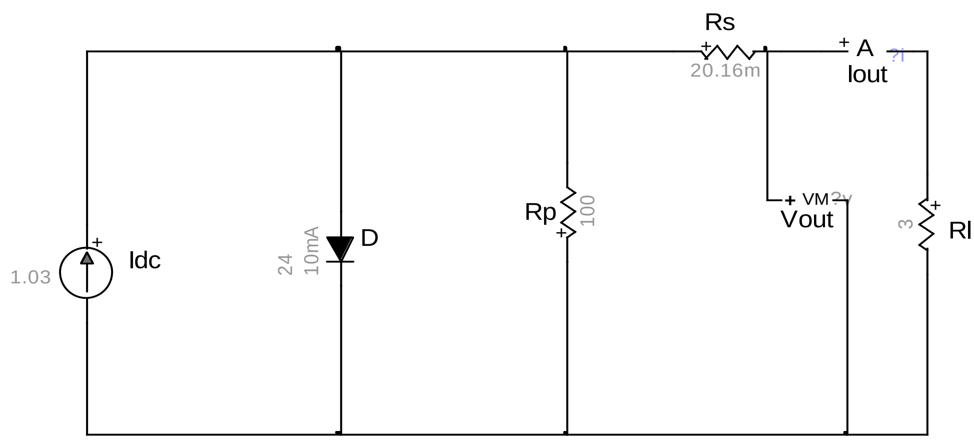

Figure 4.1: Single solar cell circuit

In Figure 4.1, we built the model for single solar cell by supplying 1.03A of photon current, diode voltage of 24v and 10mA of diode current, with parallel and series resistances of 100ohms and 20.16 m ohms respectively.

After simulating the solar cell circuit shown in Figure 4.1, we have obtained the values of V_{out} and I_{out} as shown in Figure 4.2

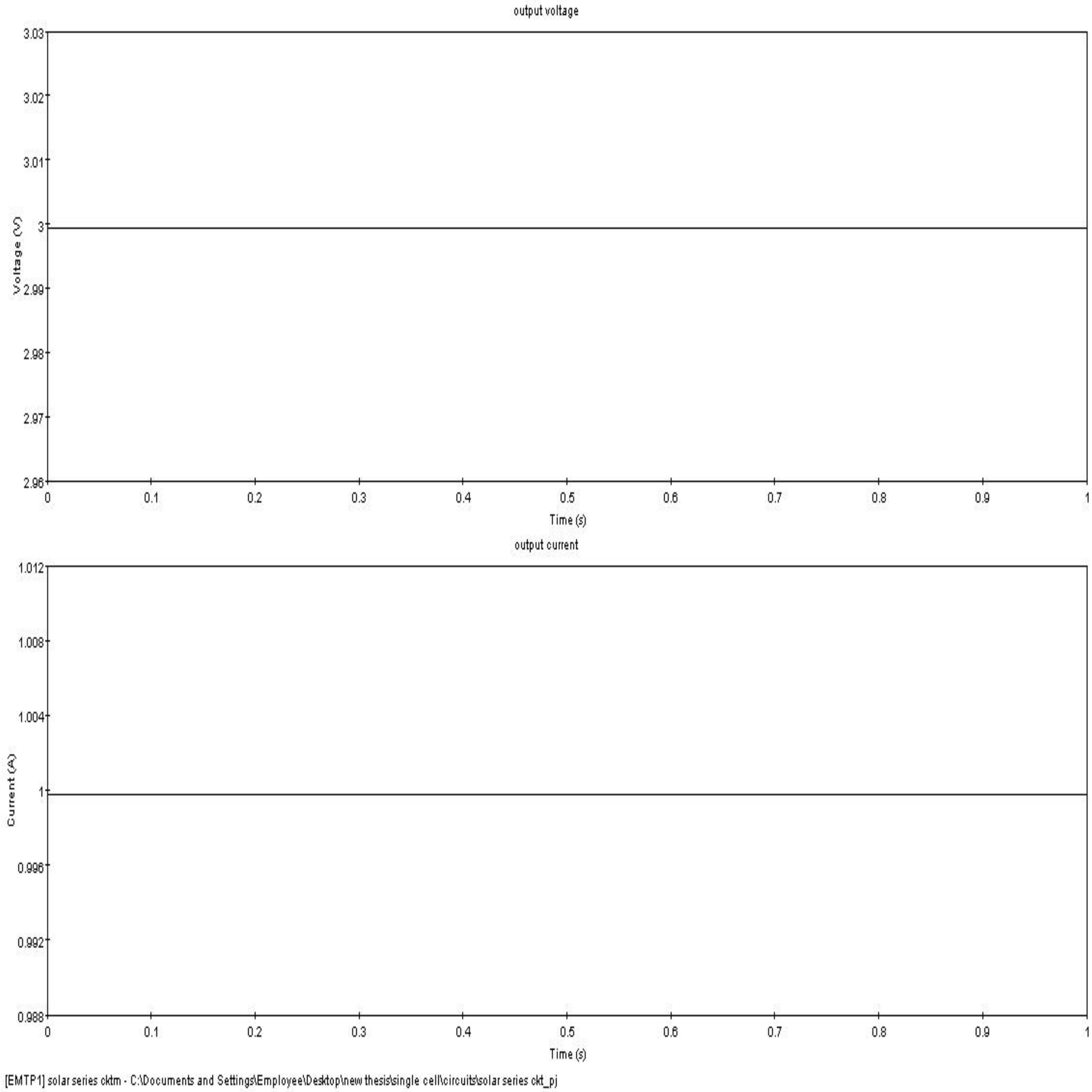

Figure 4.2: Output voltage and output current wave forms of single solar cell from EMTP

From Figure 4.2, the dc values of output voltage and output current have been obtained. However, we had to increase the values since the recorded values are very low. Hence dc values are converted into ac values by using inverter. Then we connected a transformer to the inverter to step up the voltage and current values. The Figure 4.3 depicts an inverter which is used to convert the dc values obtained from the solar cell to AC values.

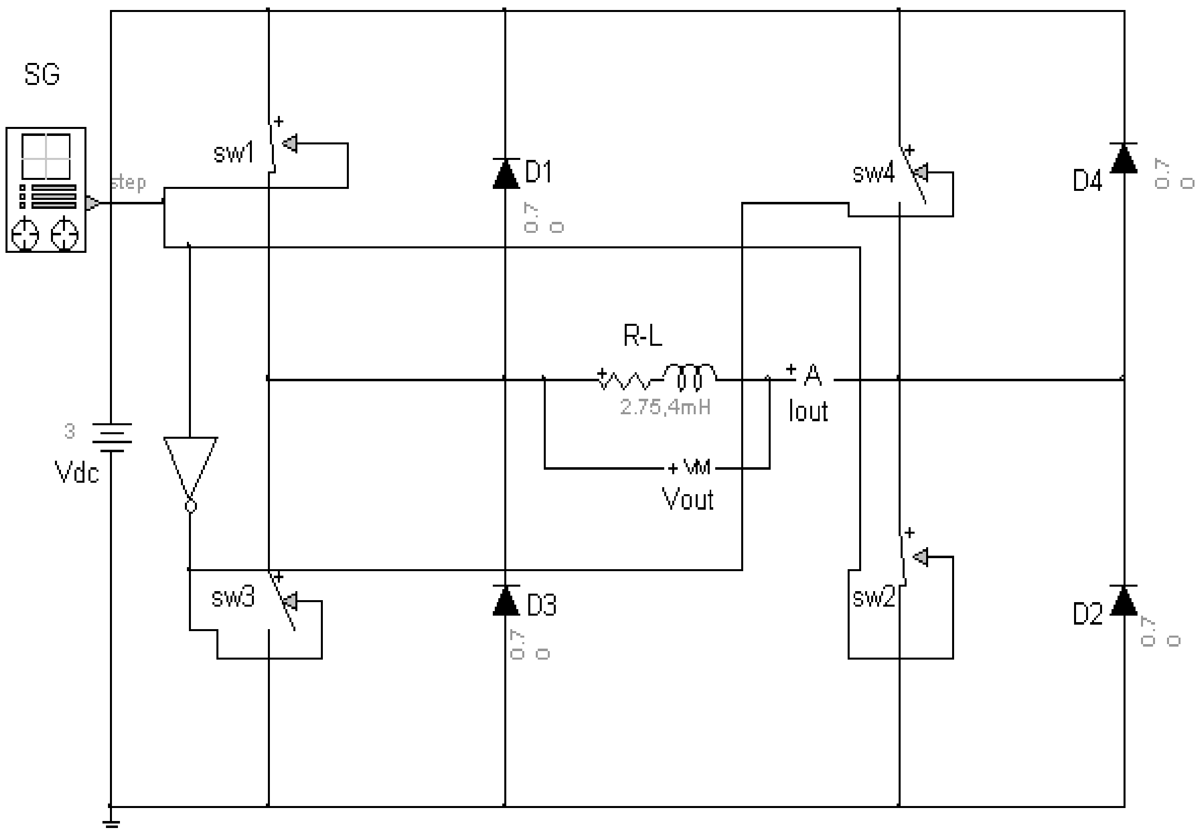

Figure 4.3: Solar cell connected to inverter

The output of the inverter is an ac value. The input values given are dc voltage and current that would be converted to ac by using the inverter. The obtained ac values for the voltage and the current are given in Figure 4.4.

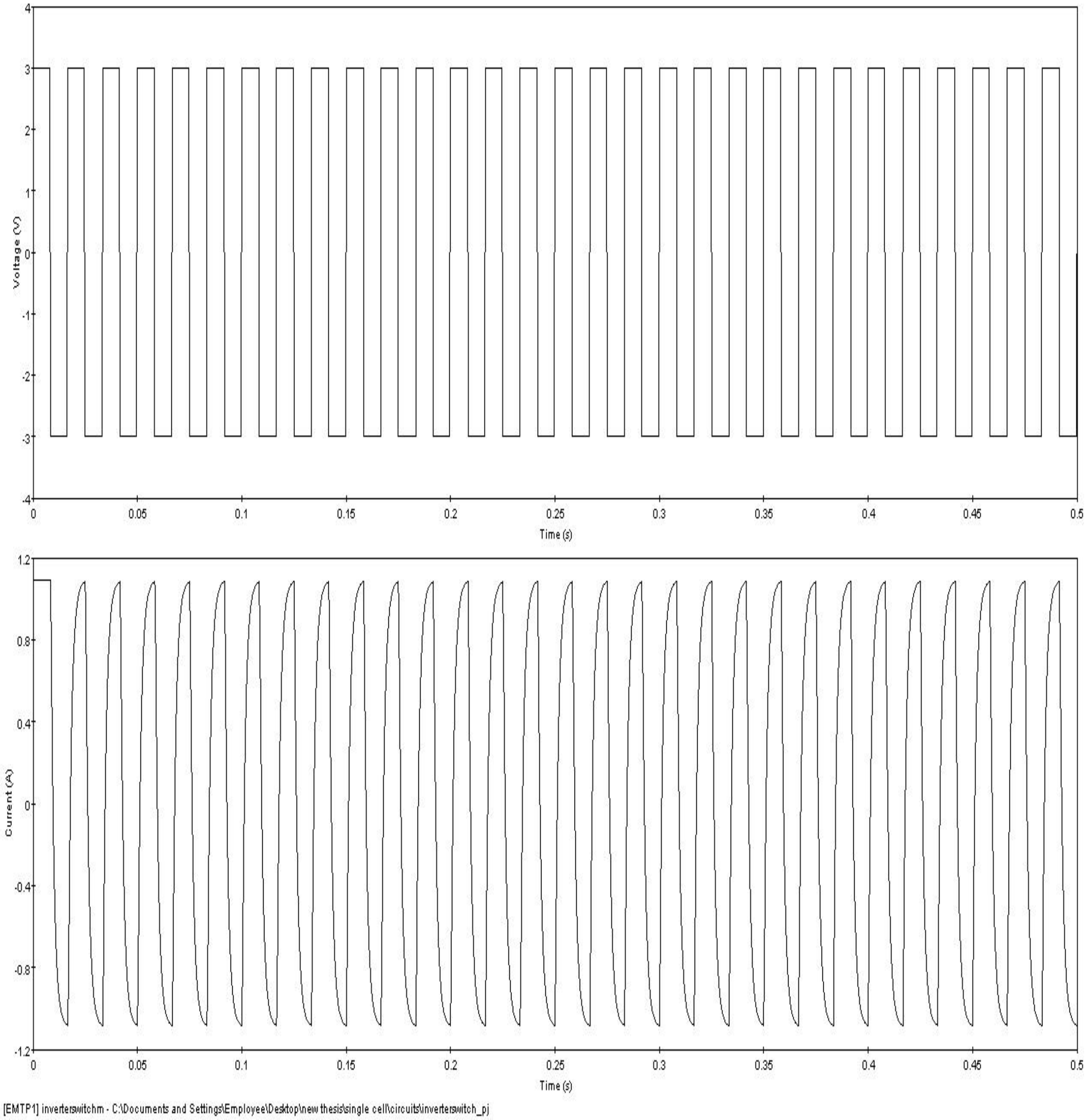

Figure 4.4: Output voltage and output current from the inverter

The output values obtained from the inverter are ac values but still those are quite low values. So to increase the output power, the inverter is connected to the transformer so that the transformer could step-up the voltage. Figure 4.5 shows the inverter connected to the transformer, whose turn's ratio is 20. Figure 4.5 is then developed in EMTP for obtaining the voltage and current outputs of the transformer.

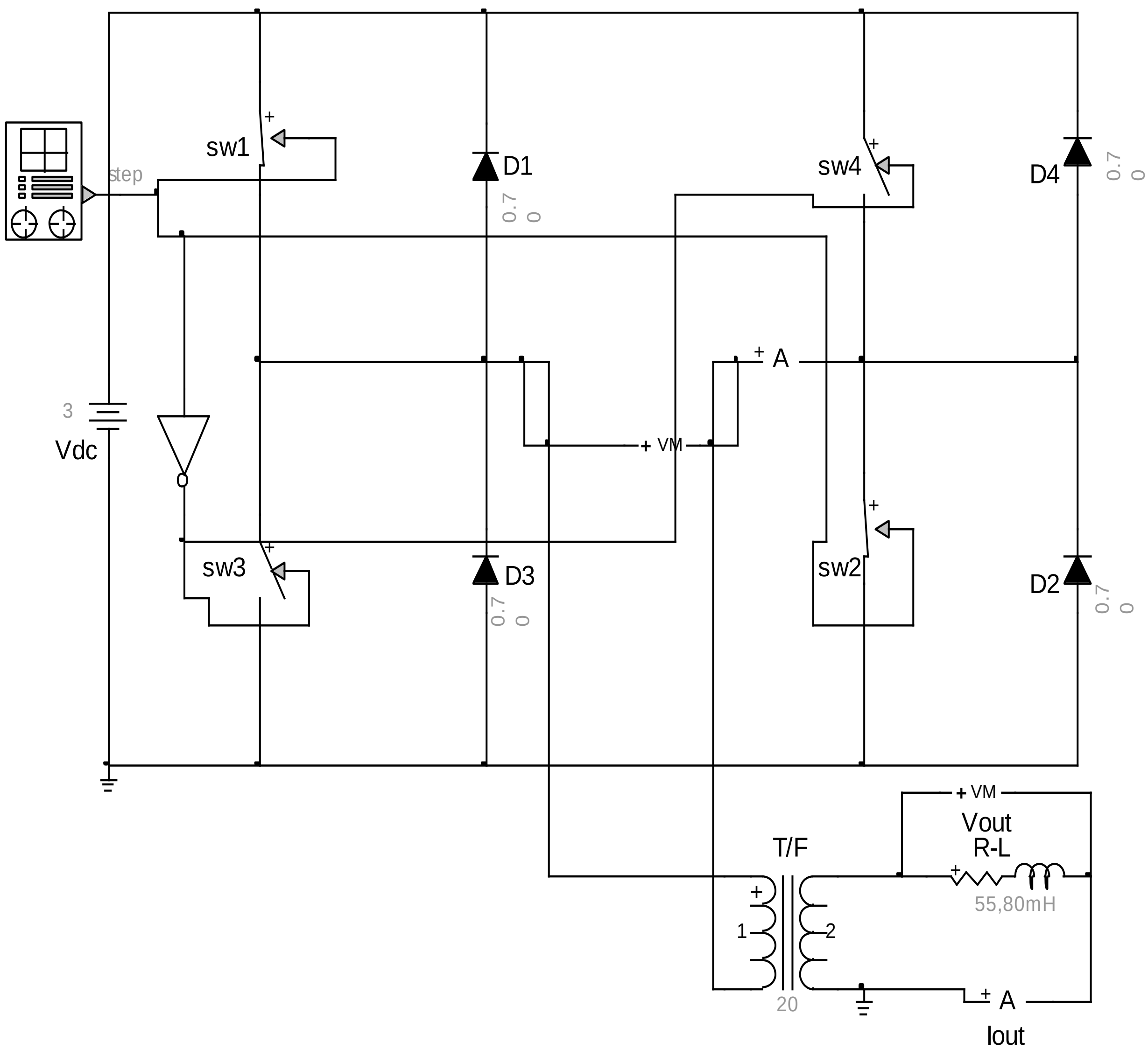

Figure 4.5: Inverter connected to Transformer

In Figure 4.5, the inverter is connected to the transformer to step up the voltage to improve the power for integrating into the electric grid. Figure 4.6 shows the output voltage and output current at the transformer secondary side.

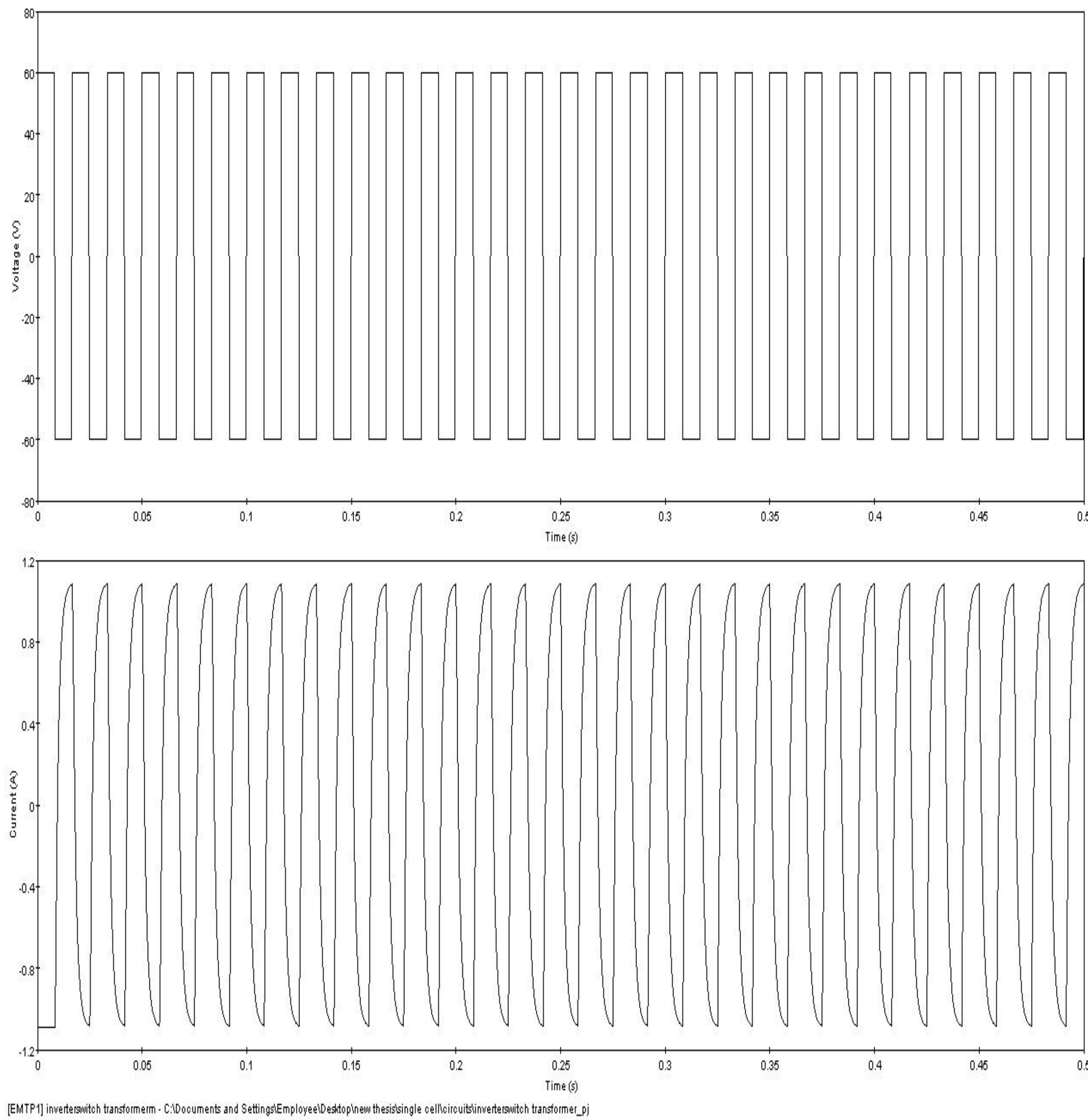

Figure 4.6: Voltage and current at transformer secondary side

From Figure 4.1 to Figure 4.6, our approach is first built the single solar cell and simulated the solar cell to get the dc output. To convert the output dc values into ac values, an inverter was connected using the dc inputs. To step up the values of the obtained ac voltage and current, the inverter was connected to a transformer to get the improved output values from the transformer second end.

The results are recorded when a single solar cell is connected to the model. Results vary when multiple solar cells are connected in series and parallel by using the same procedure from Figure 4.1 to Figure 4.6.

4.3 Solar series model in EMTP

To examine the results with many cells connected, 5 solar cells are connected in series. With 5 cells connected, every parameter in the solar cell increases fivefold. However the current value remains the same because current would not change when cells are connected in series. The equivalent circuit diagram of the solar cells connected in series is shown in Figure 4.7.

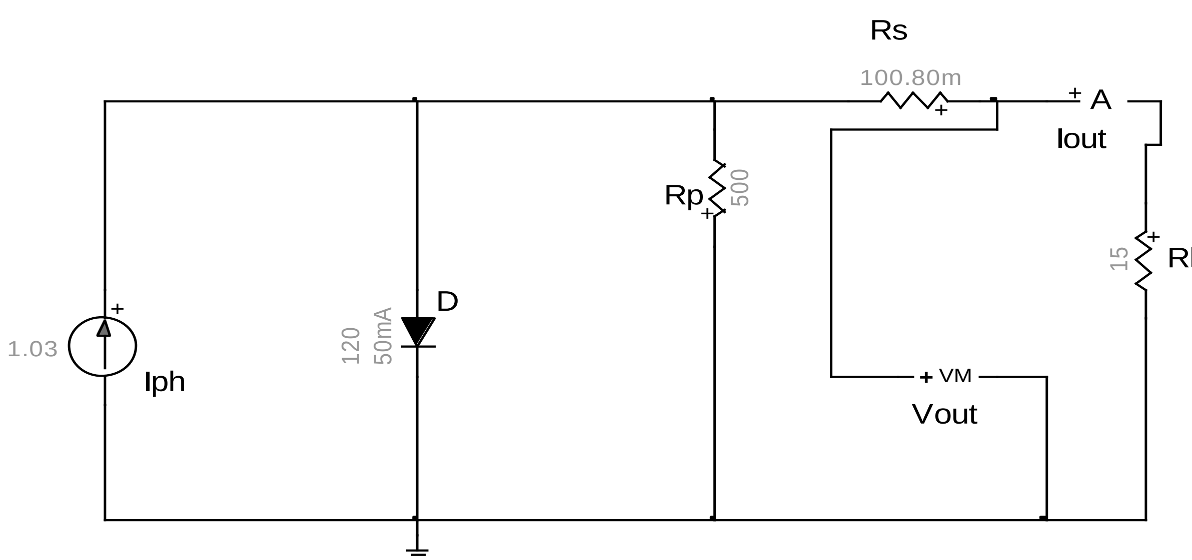

Figure 4.7: Solar cells connected in series

Theoretically, if we connect the solar cells in series then the improvement is on output voltage but the output current remains the same. After simulating the model in Figure 4.7 we obtained the output voltage and the output current in Figure 4.8 .

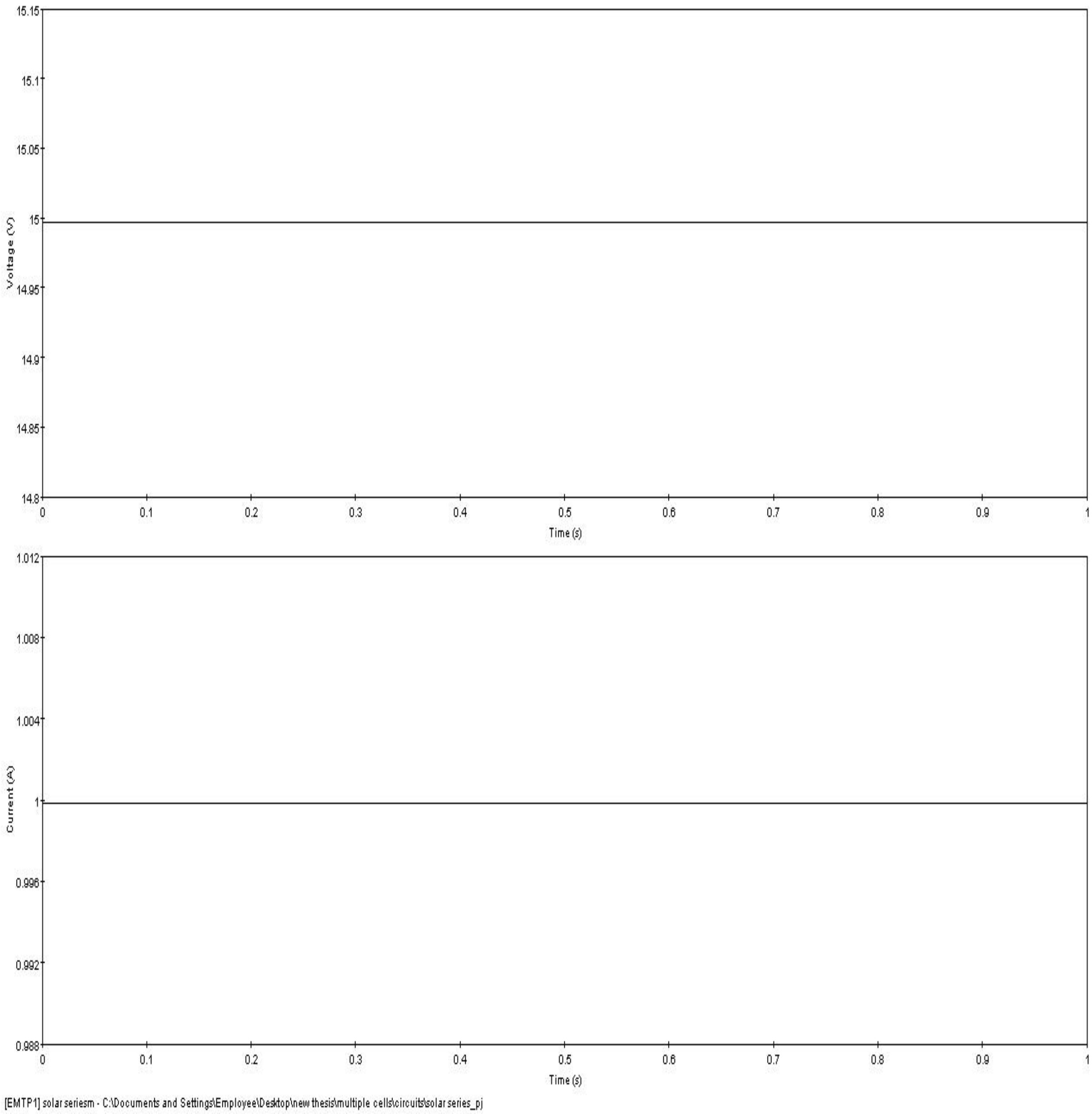

Figure 4.8: Output voltage and output current when solar cells are connected in series

Like mentioned in Figure 4.8, the output voltage is improved nearly five times as compared to the previous voltage but the current value is the same. The dc values are then needed to be converted into ac in a similar way as described in the previous section. The inverter is built and the values from the series of solar cells are given to the inverter to convert the DC values into AC.

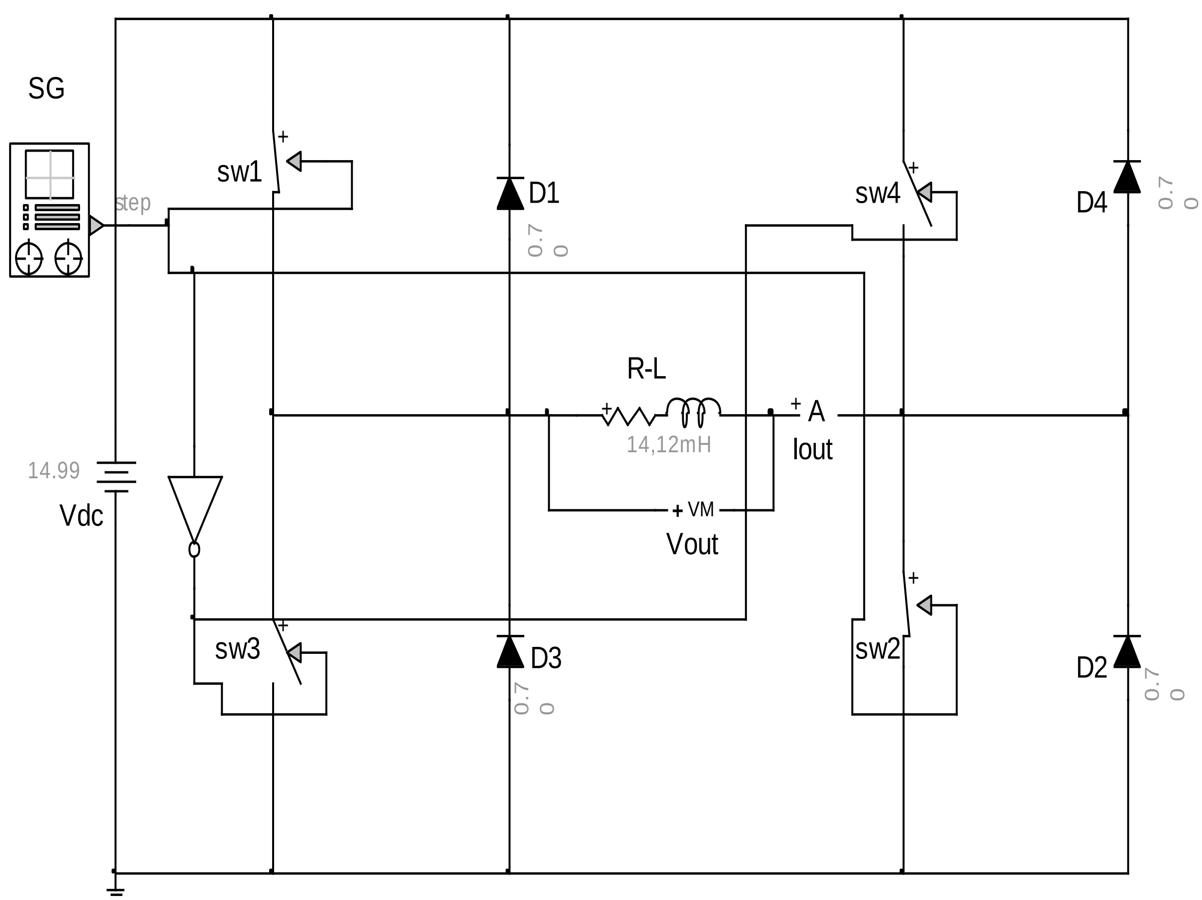

Figure 4.9: Series of solar cells connected to Inverter

After simulating the model in Figure 4.9, the output voltage and the output current values are recorded. Figure 4.10 shows the output voltage and output current after the inverter converts the dc values to the ac values.

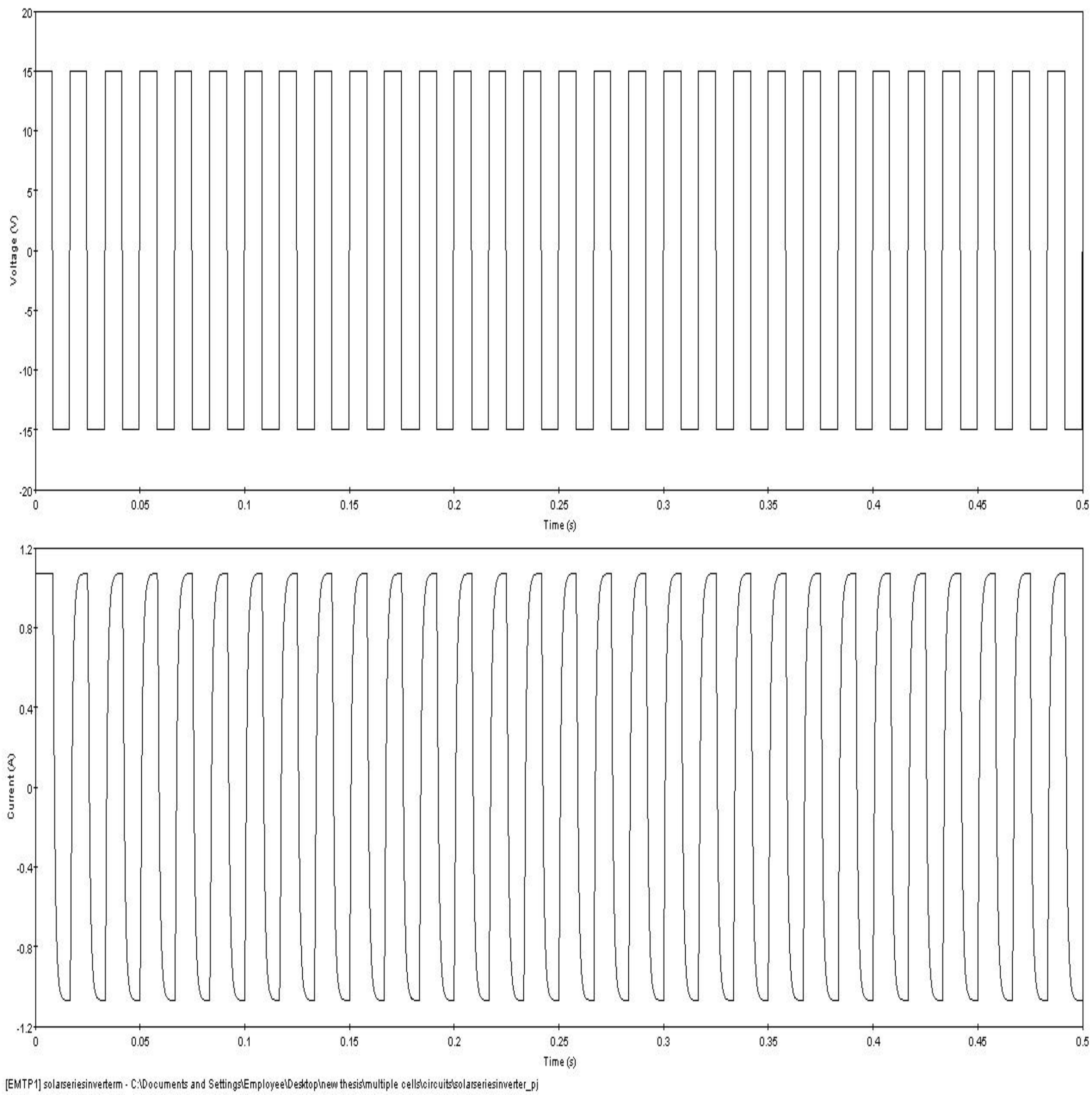

Figure 4.10: Output voltage and current with solar series cells connected to inverter

To increase the voltage and current, the output from the inverter is supplied as the input to the transformer. This setup will increase the voltage or current values on the transformer's secondary side. The Figure 4.11 shows the circuit connection from inverter to the transformer.

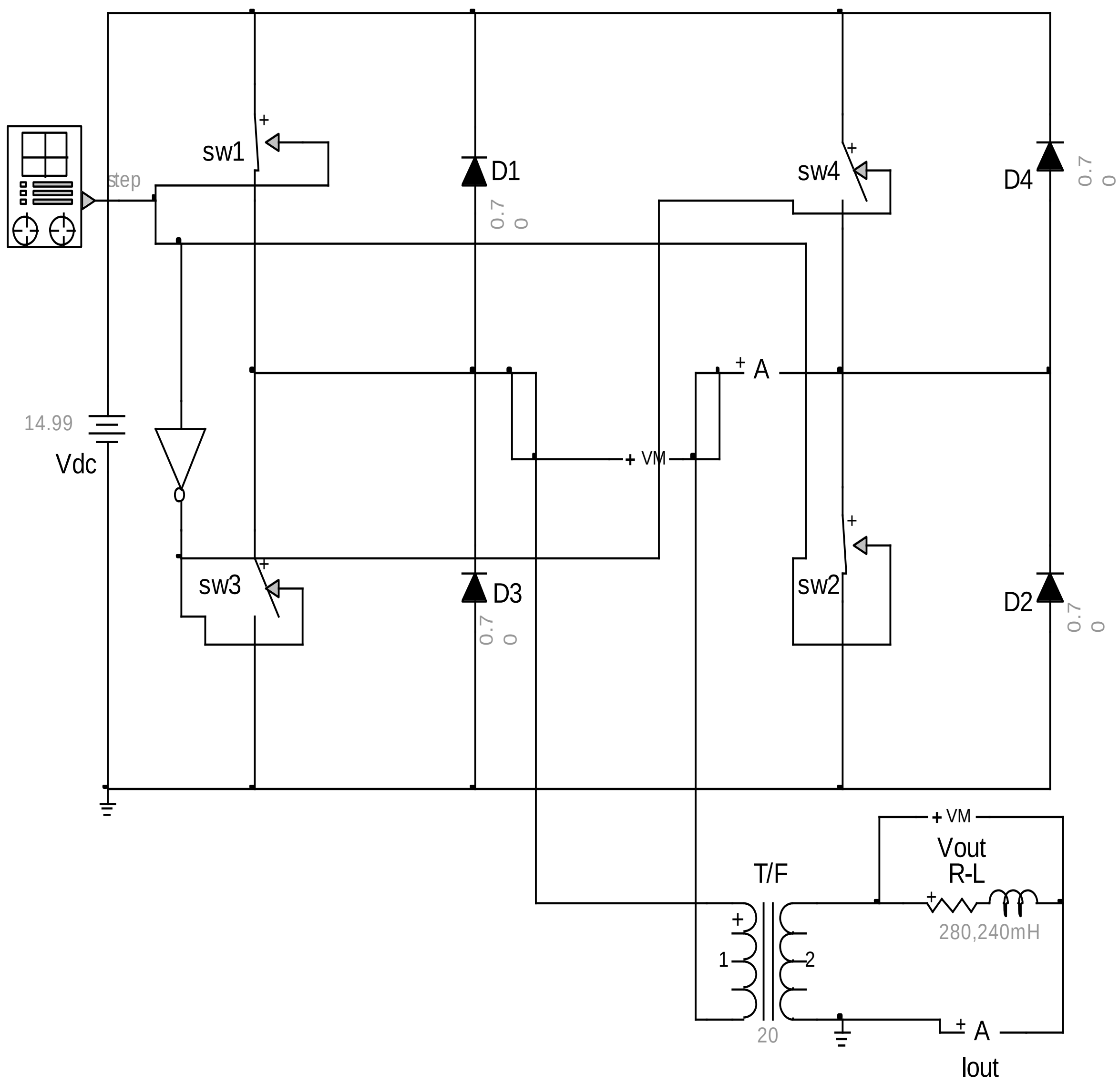

Figure 4.11: Solar series inverter connected to transformer

The resulting waveforms of output voltage and the output current on the transformer secondary side can be graphed as Figure 4.12.

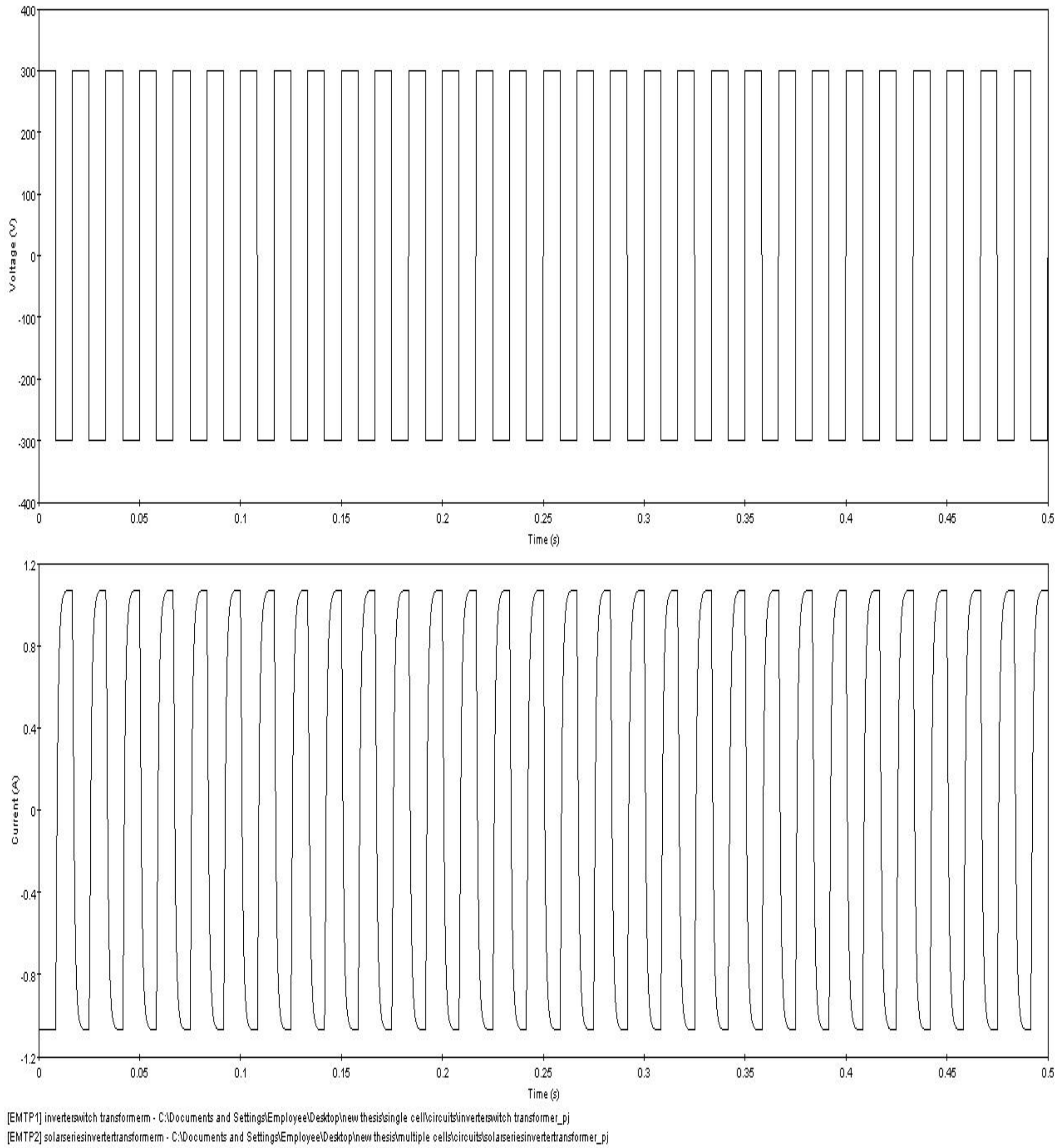

Figure 4.12: Output voltage and current on the secondary side of the transformer

We built the model for solar cells connected in series. Similar sequence of steps has been followed to obtain the results from the solar cells connected in parallel. We then were able to realistically compare the results from both scenarios (Series and Parallel) for determining the Harmonic Distortion using Harmonic Analysis.

4.4 Solar parallel model in EMTP

To determine the results when the solar cells are connected in parallel, we connected five solar cells in parallel. Unlike the series connection, in the parallel connection, every parameter remains the same as actual value except for the current. Current value will increase because we are connecting the solar cells in parallel. The parallel connection of the solar cells in the circuit is shown in Figure 4.13.

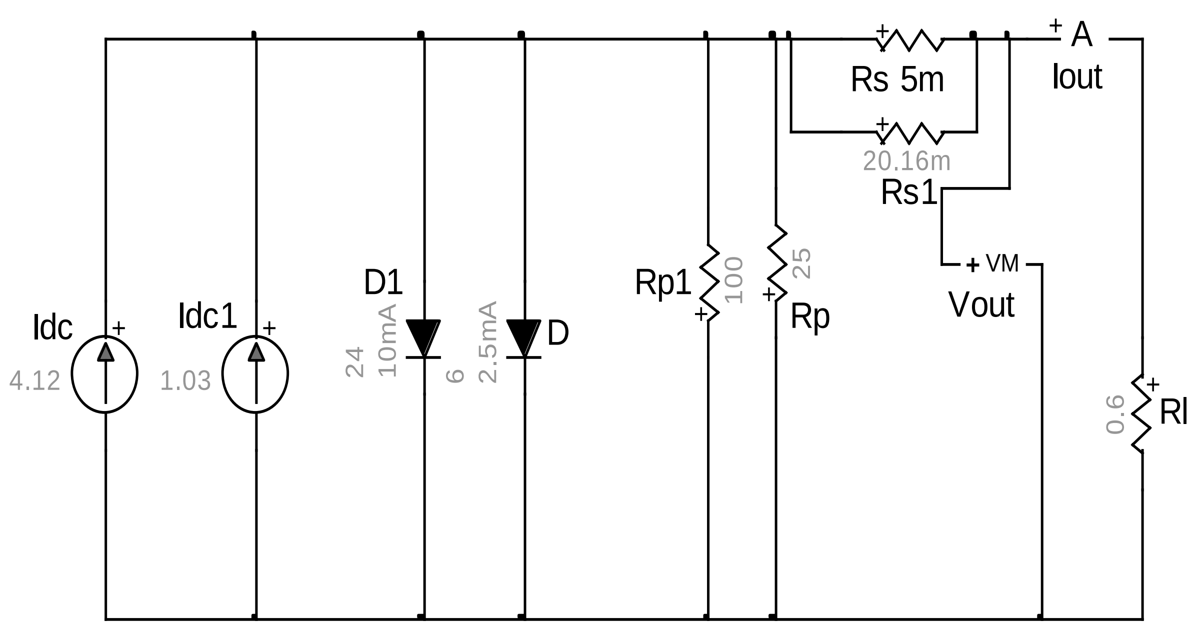

Figure 4.13: Parallel connection of solar cell model

After Simulating Figure 4.13, in the output we will get output current and the output voltage. Output current will increase in the parallel connection. The Figure 4.14 shows the waveforms of output current and output voltage obtained from simulation of the model in Figure. 4.13.

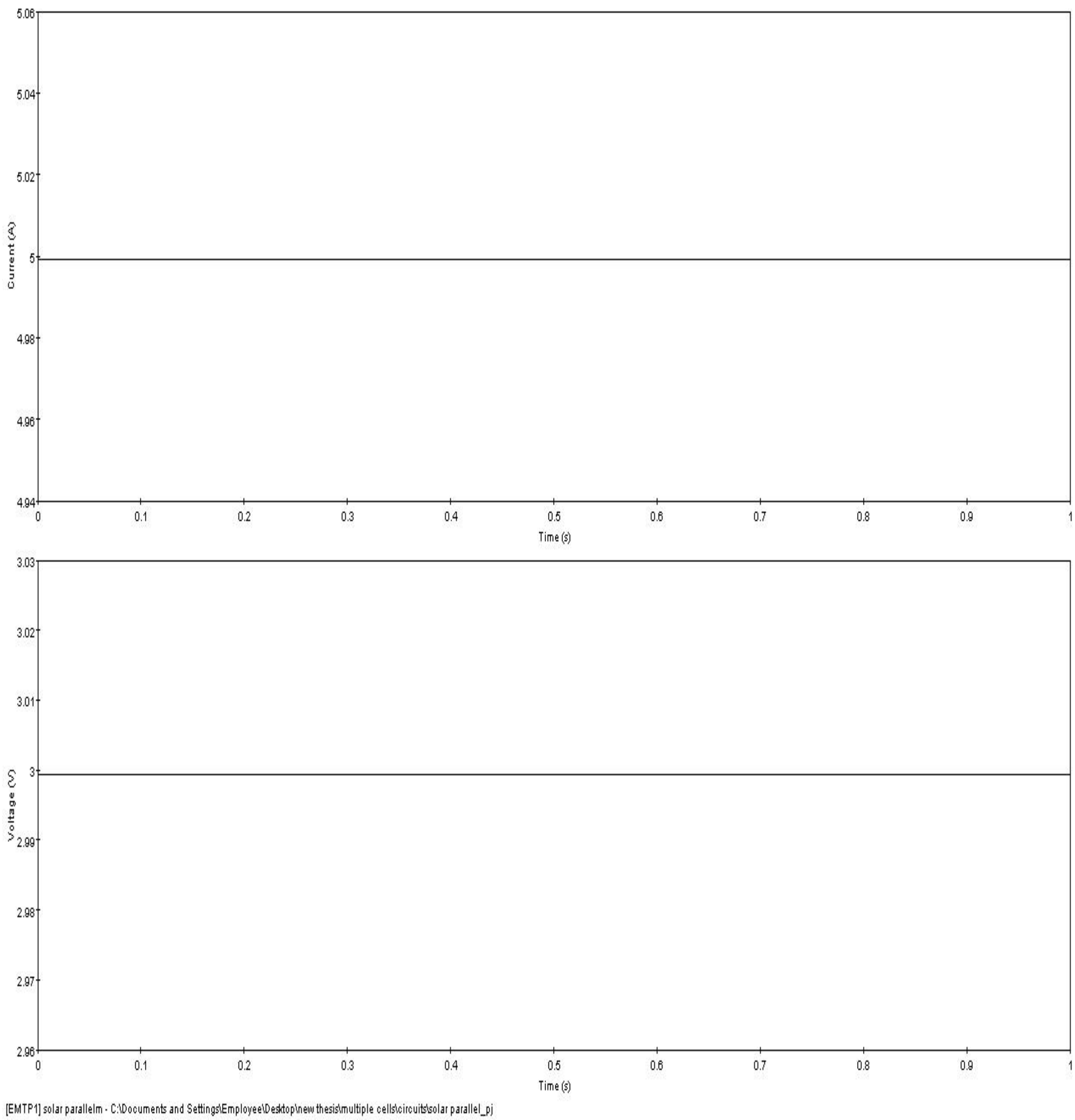

Figure 4.14: output current and voltage of parallel connection of solar cell

In Figure 4.14 we can see the current is increased nearly five times than the actual single solar cell current. Connection of the parallel solar cells to the inverter can be seen in the figure 4.15.

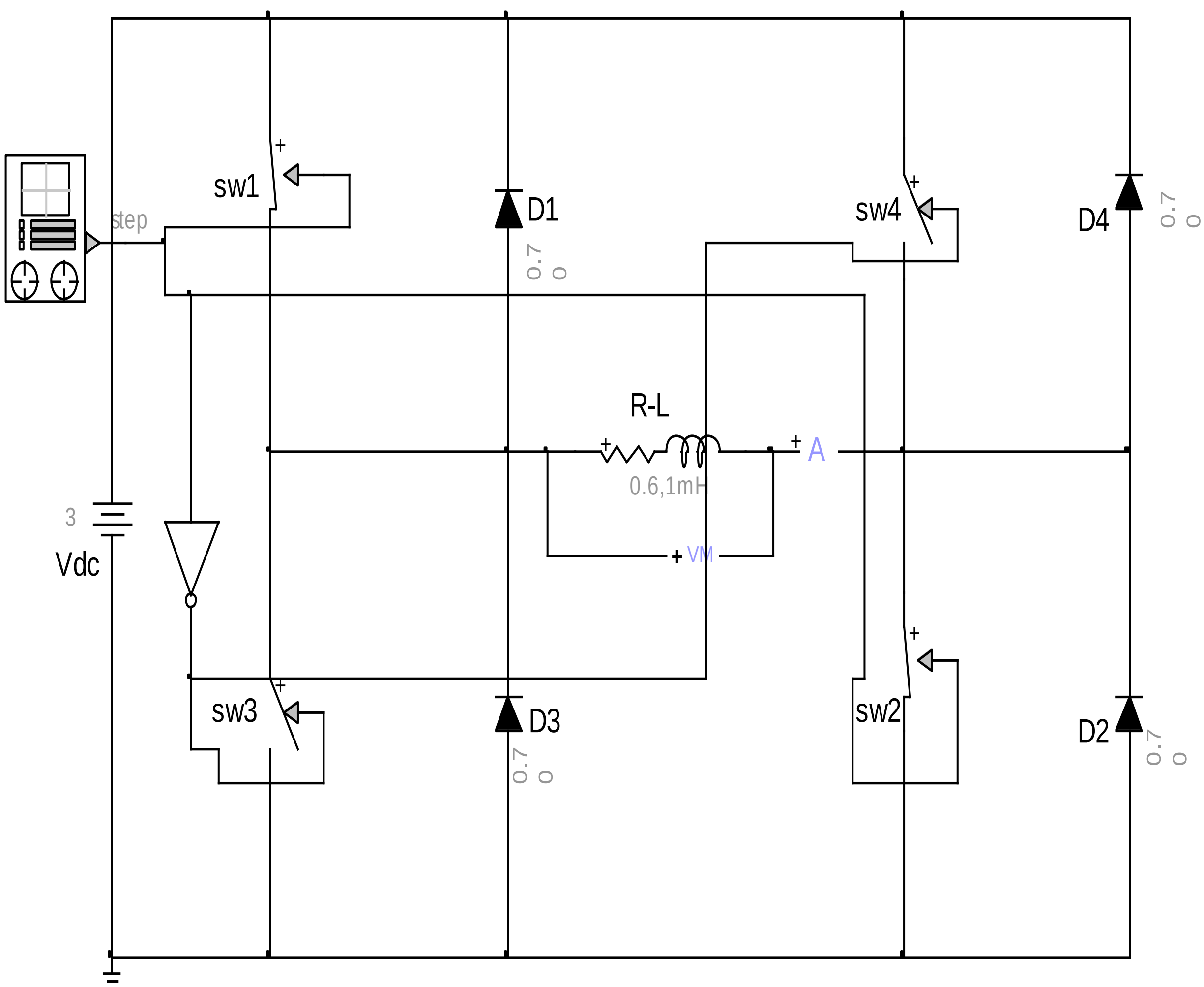

Figure 4.15: Parallel solar cells connected to Inverter

After simulating the model in Figure 4.15, the resulting output voltage and the output current values are shown in Figure 4.16. To increase the voltage or current, the inverter is in turn connected to the transformer.

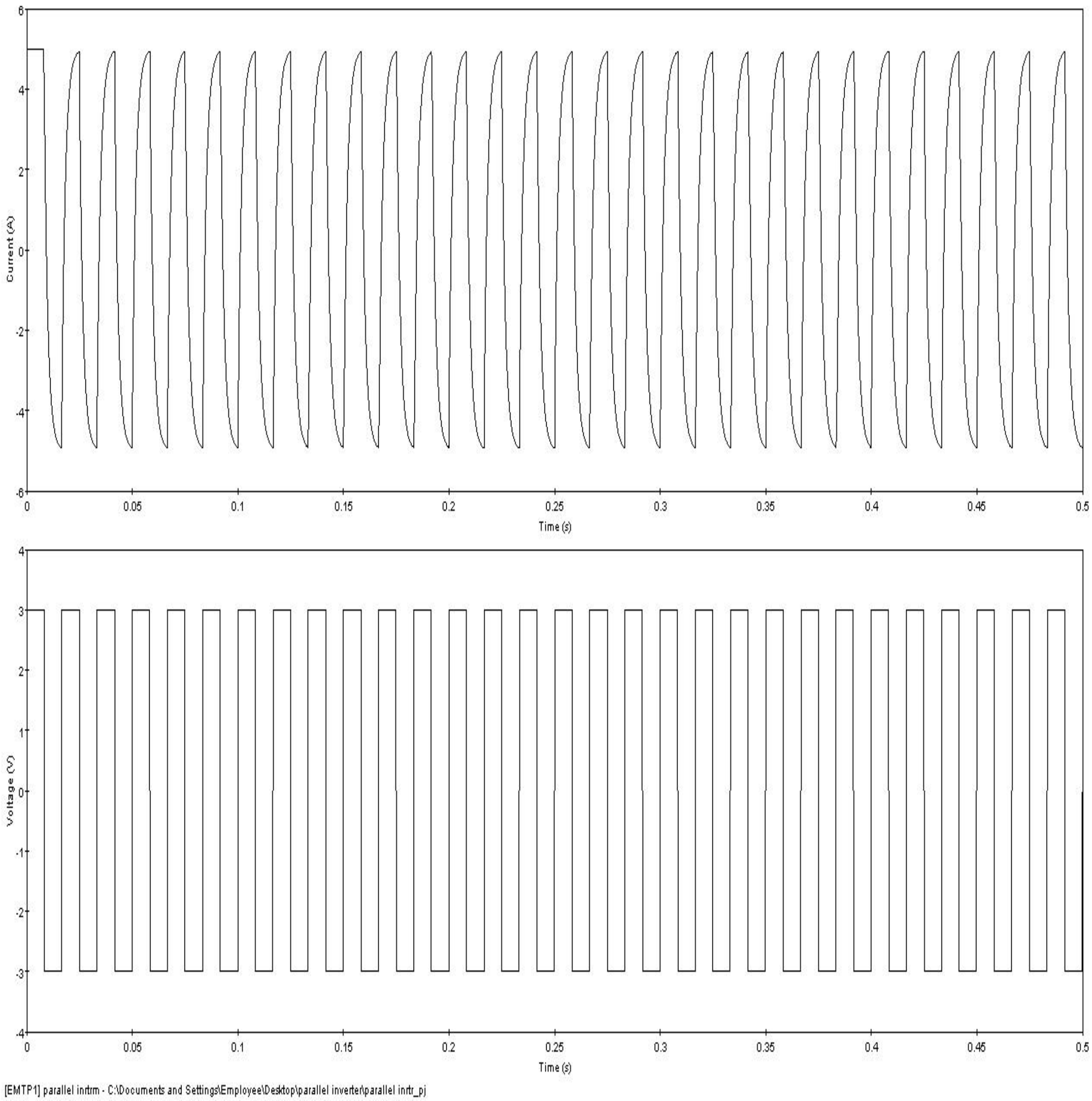

Figure 4.16: Output current and voltage of the parallel connected solar cell inverter

When the inverter is connected to the transformer, the output voltage and the output current rise in their magnitude from the transformer's secondary side. Figure 4.17 shows the inverter connection to the transformer.

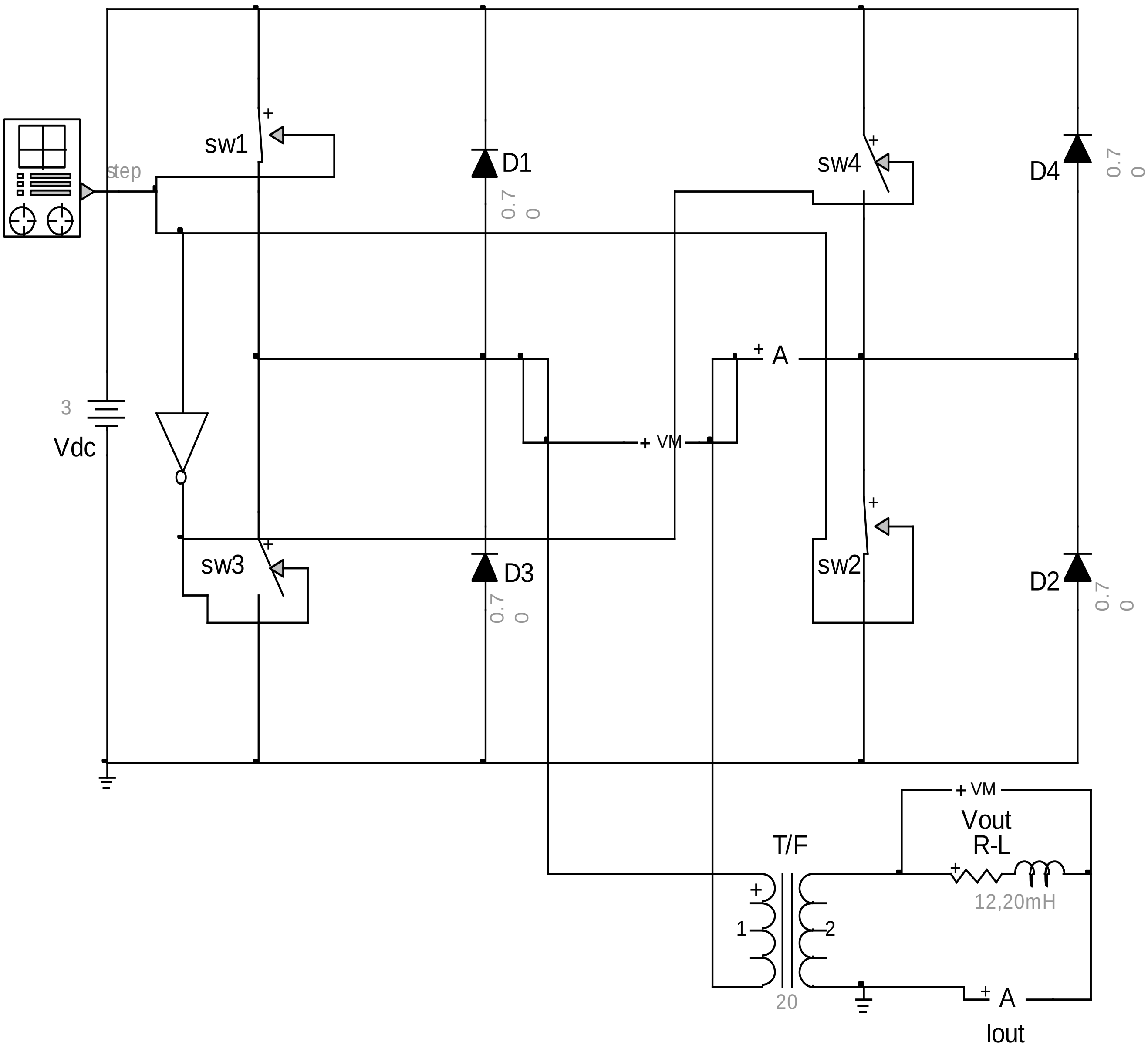

Figure 4.17 Solar parallel inverter connected to the transformer

After simulating model in Figure 4.17, the waveforms of output voltage and the output current on the transformer secondary side were found to show readings as in Figure 4.18.

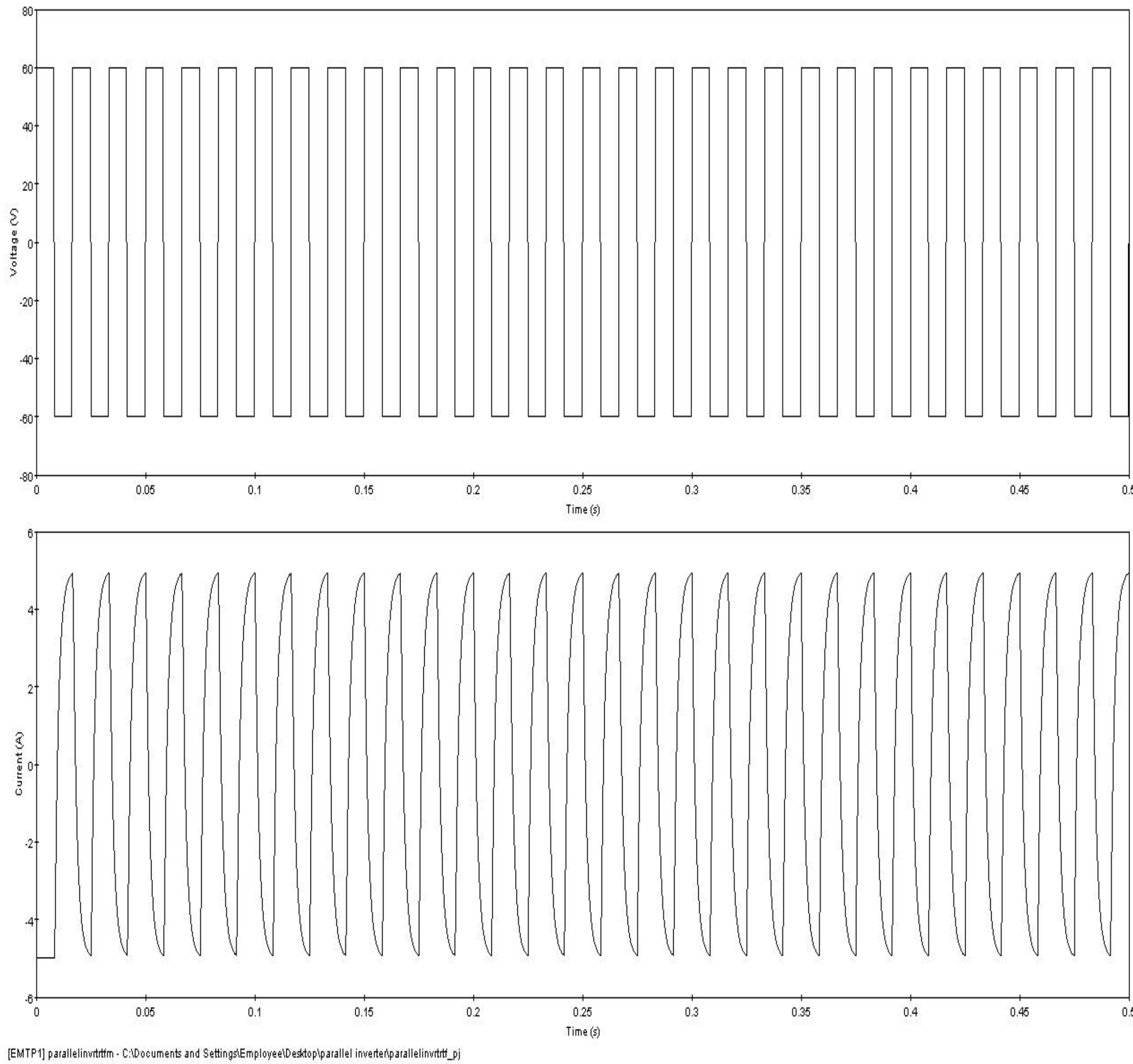

Figure 4.18: Output current and voltage on the secondary side of the transformer.

From Figures 4.13 to 4.18, codes for simulating the solar models were developed in EMTP. In chapter 5, we extend the study of solar models through harmonic analysis by calculating the Total Harmonic Distortion (THD) for both the developed solar series model and solar parallel model.

Chapter 5

5.1 Results

The results from chapter 4 have provided us the required details for further analysis in the comparison between solar series connection model and solar parallel connection model. The results obtained can be used to perform Harmonic Analysis for both models. Harmonic Analysis determines the Total Harmonic Distortion (THD) for the respective models. THD in turn helps us identify the better model prospect to connect to the utility. Figure 5.1 shows the solar series connection model taken from chapter 4 to do harmonic analysis.

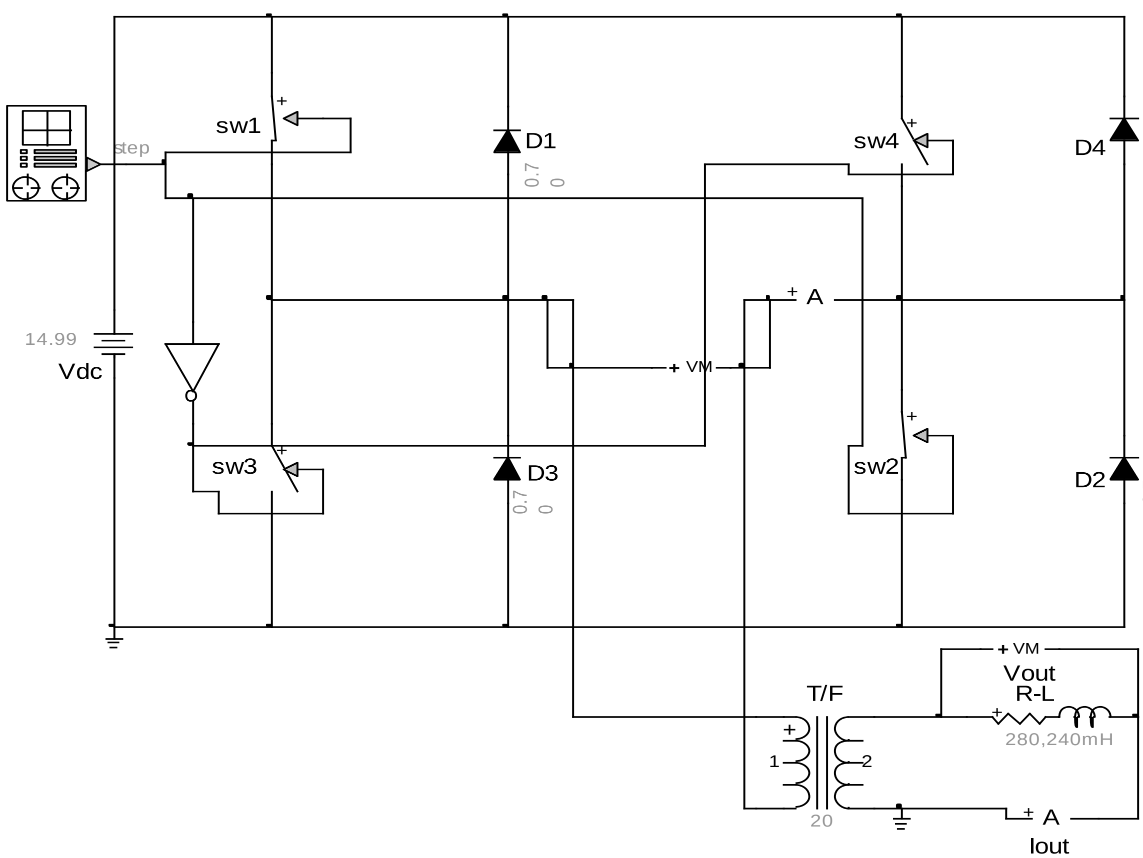

Figure 5.1: Solar series connection model

5.2 Harmonic Analysis of solar series model

Harmonic analysis for the model in Figure 5.1 is done using EMTP software to calculate the voltage at the fundamental frequency, RMS values of the output current and voltage of solar series connection model. The current and voltage harmonics at different harmonic frequencies can also be obtained through Harmonic analysis.

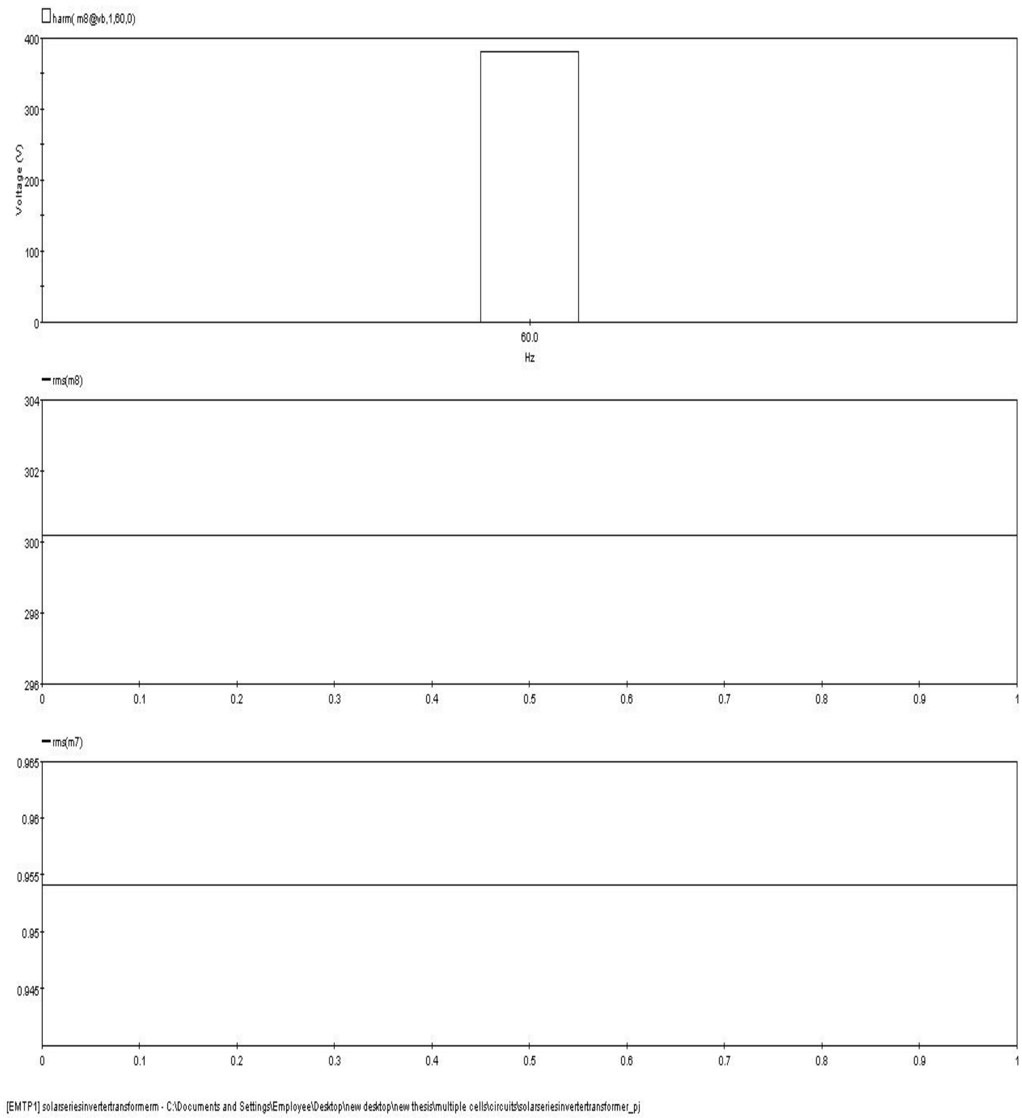

Figure 5.2: Harmonic analysis of the solar series connection model

Figure 5.2 shows the output voltage at the fundamental frequency, RMS values of output voltage and output current of the solar series connection model. Figure 5.3 shows the odd current harmonics at different harmonic frequencies of the solar series connection model. The horizontal and vertical axes represent the frequency and the current respectively.

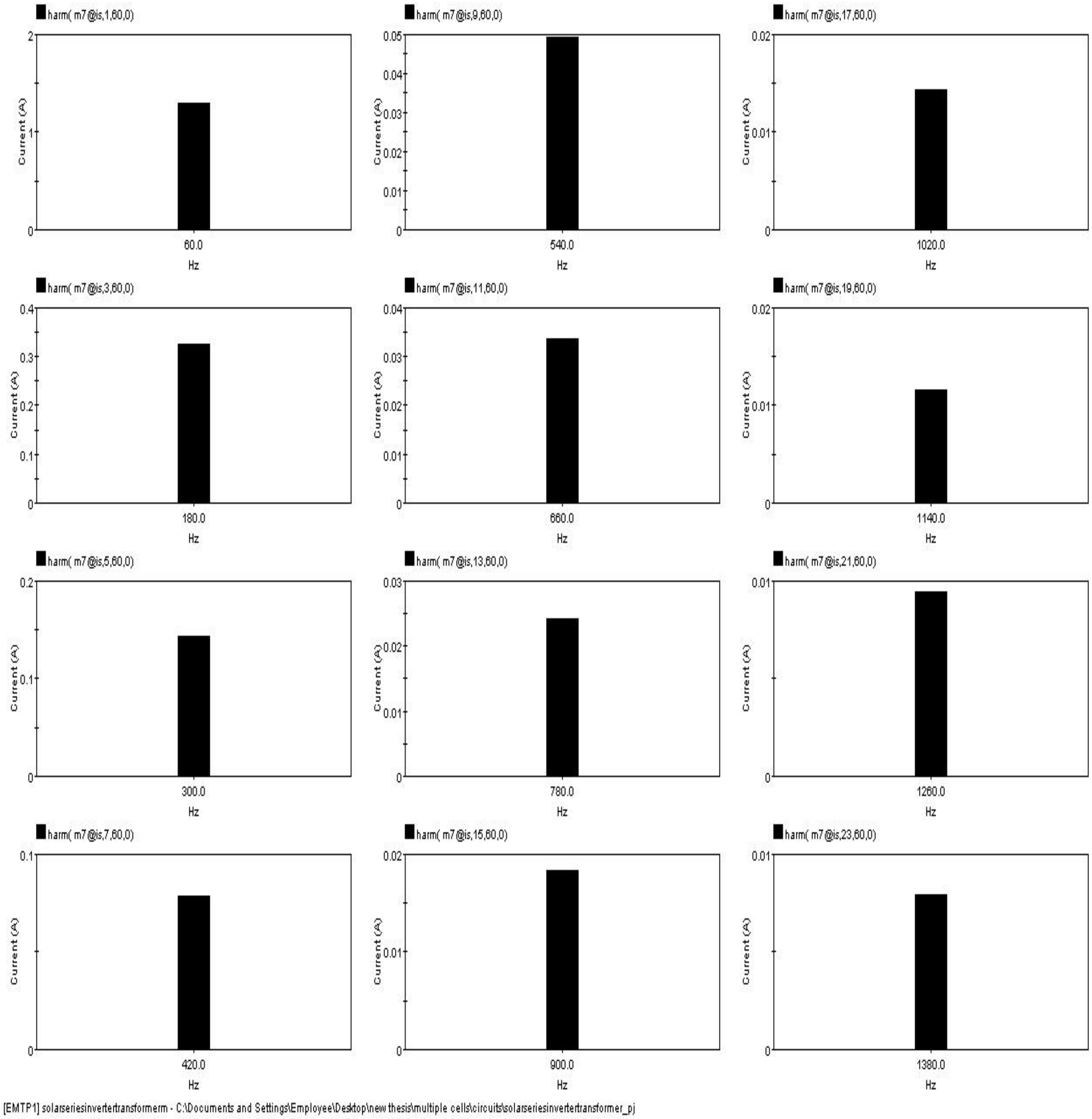

Figure 5.3: Current harmonics for the solar series connection model

For the graphs presented in Figure 5.3, the corresponding numerical values for respective current harmonics are provided in Figure 5.4.

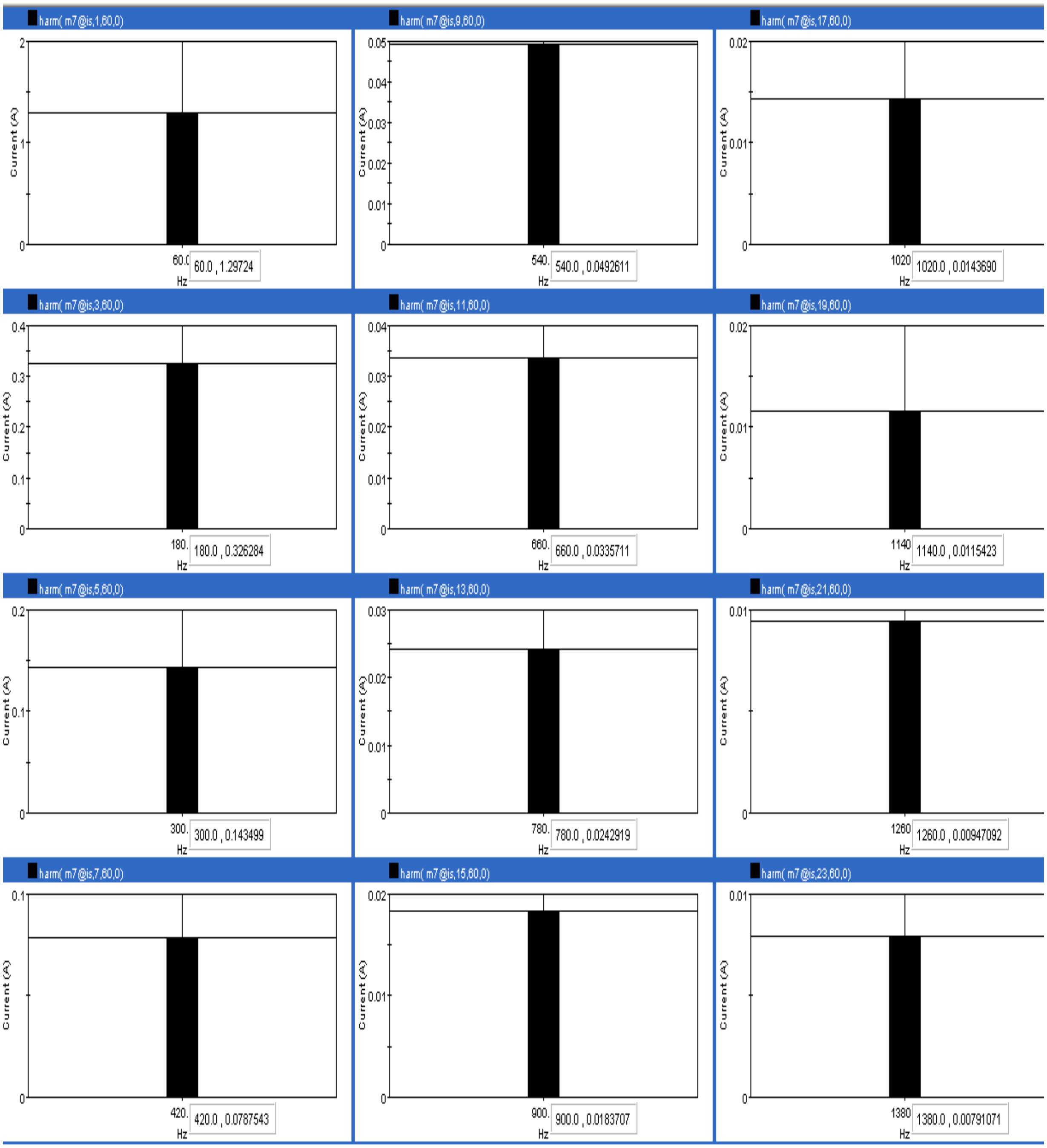

Figure 5.4: Current harmonic values for solar series connection model

5.3 Solar parallel connection model

With the completion of the harmonic analysis for solar cell series connection model, we now continue our study with the harmonic analysis to the solar cell parallel connection model. Similar to section 5.2, harmonic analysis is achieved using EMTP software. The basic circuit layout of the solar cell parallel connection model is shown in Figure 5.5.

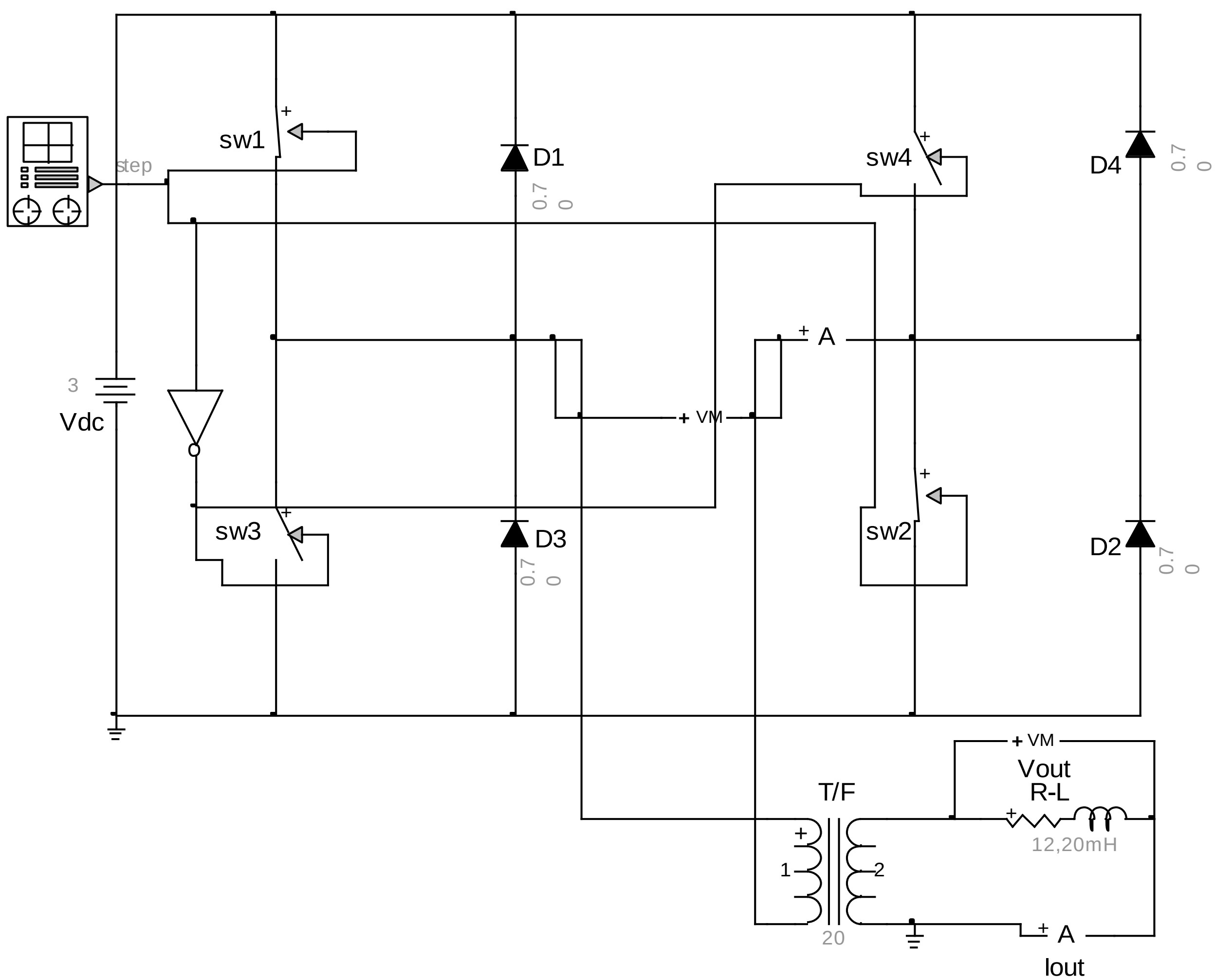

Figure 5.5: Solar parallel connection model

5.3.1 Harmonic Analysis of solar parallel model

Applying Harmonic analysis to the simulated model in Figure 5.5 using EMTP software, voltage at the fundamental frequency, RMS values of the output current and voltage of solar parallel connection model have been obtained. Further, calculations for the current and voltage harmonics at different harmonic frequencies have been performed.

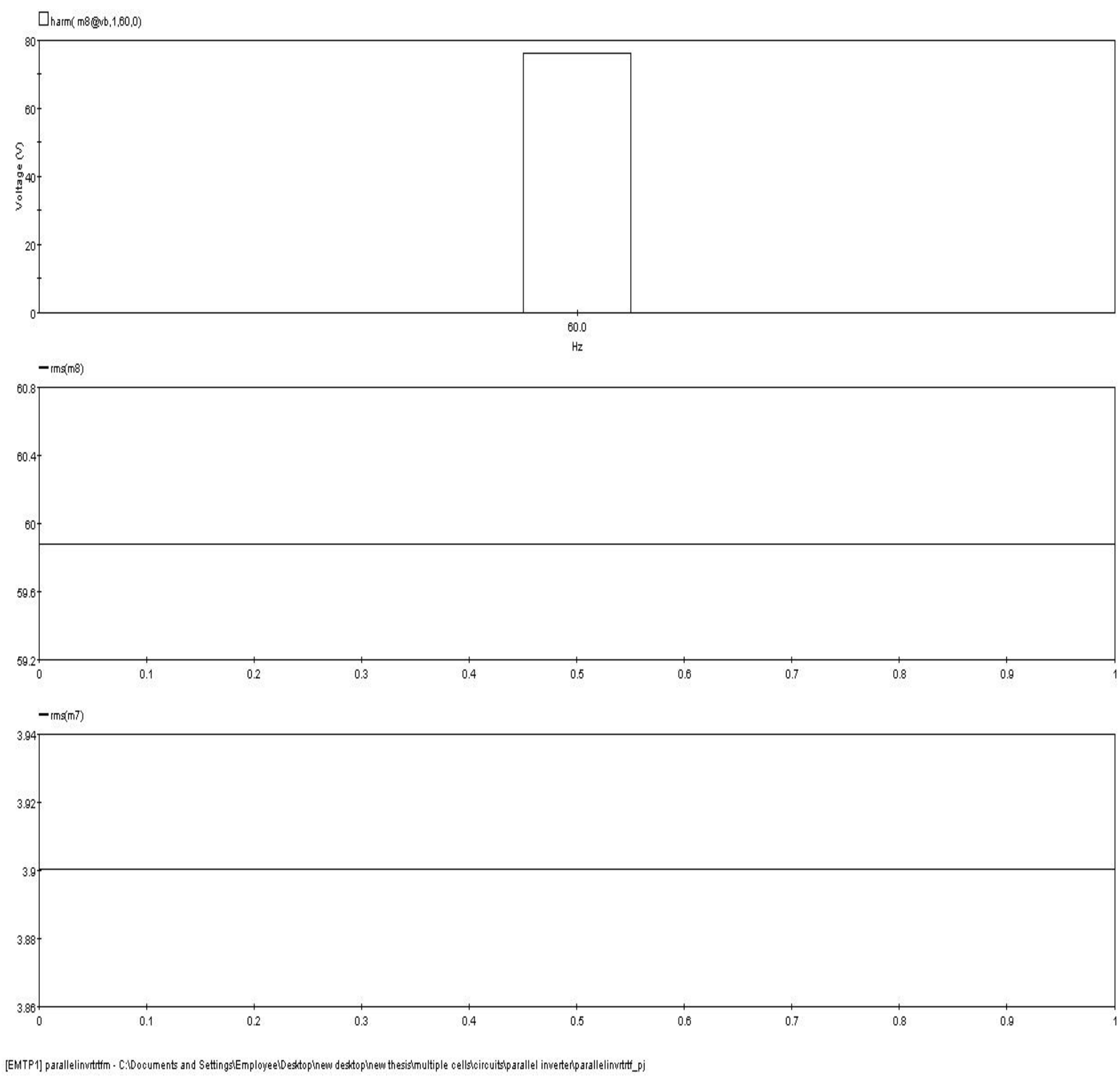

Figure 5.6: Harmonic analysis of the solar parallel connection model

Harmonic analysis of the solar parallel connection model, as graphed in Figure 5.6 shows the output voltage at the fundamental frequency, RMS values of output voltage and output current of the solar series connection model. The obtained odd current harmonics from the harmonic analysis of the solar parallel connection model are shown in detail using Figure 5.7. The horizontal and vertical axes represent the frequency and the current respectively.

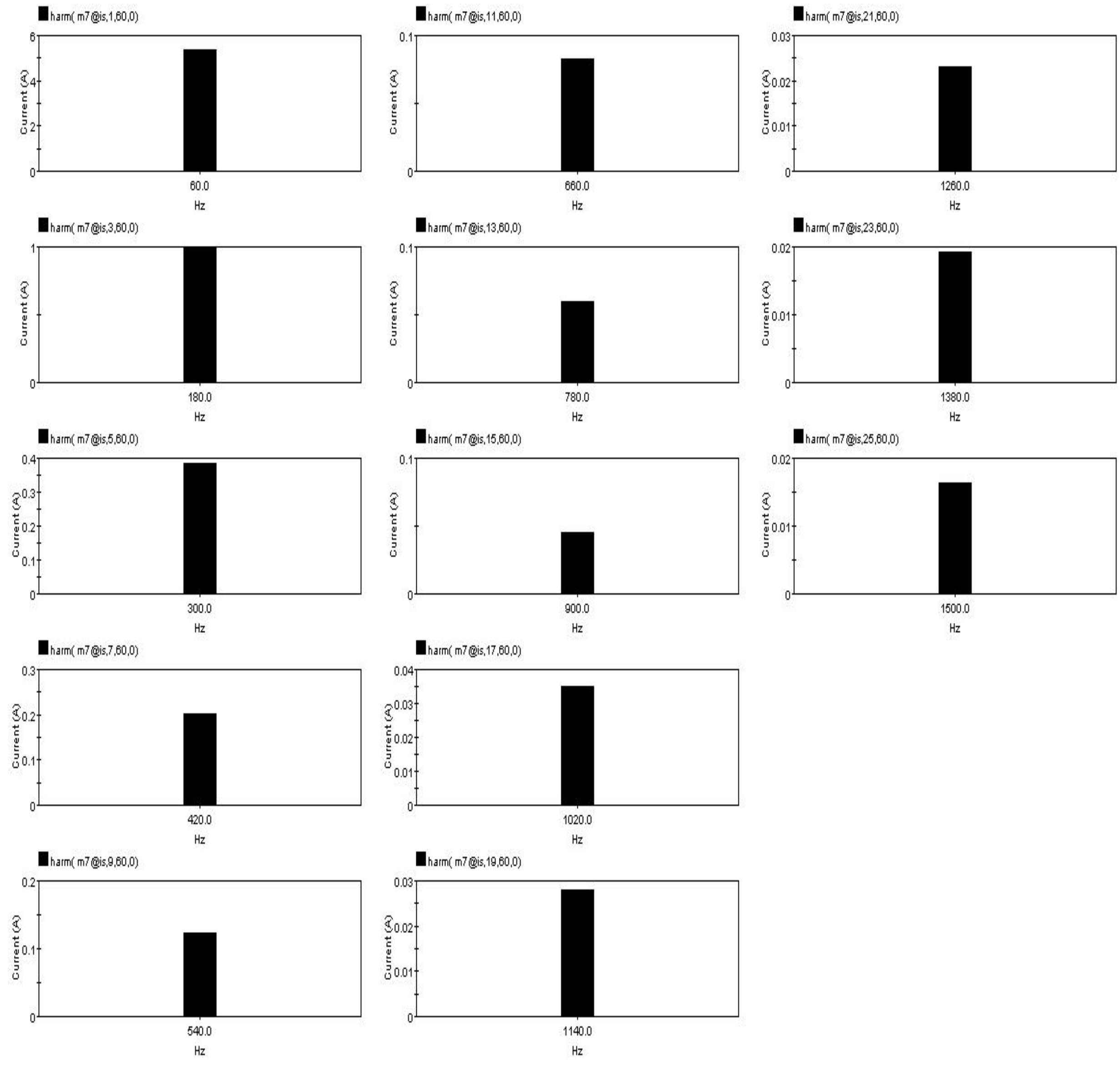

Figure 5.7: Current harmonics of the solar parallel connection model

For the graphs presented in Figure 5.7, the corresponding numerical values for respective current harmonics are provided in Figure 5.8.

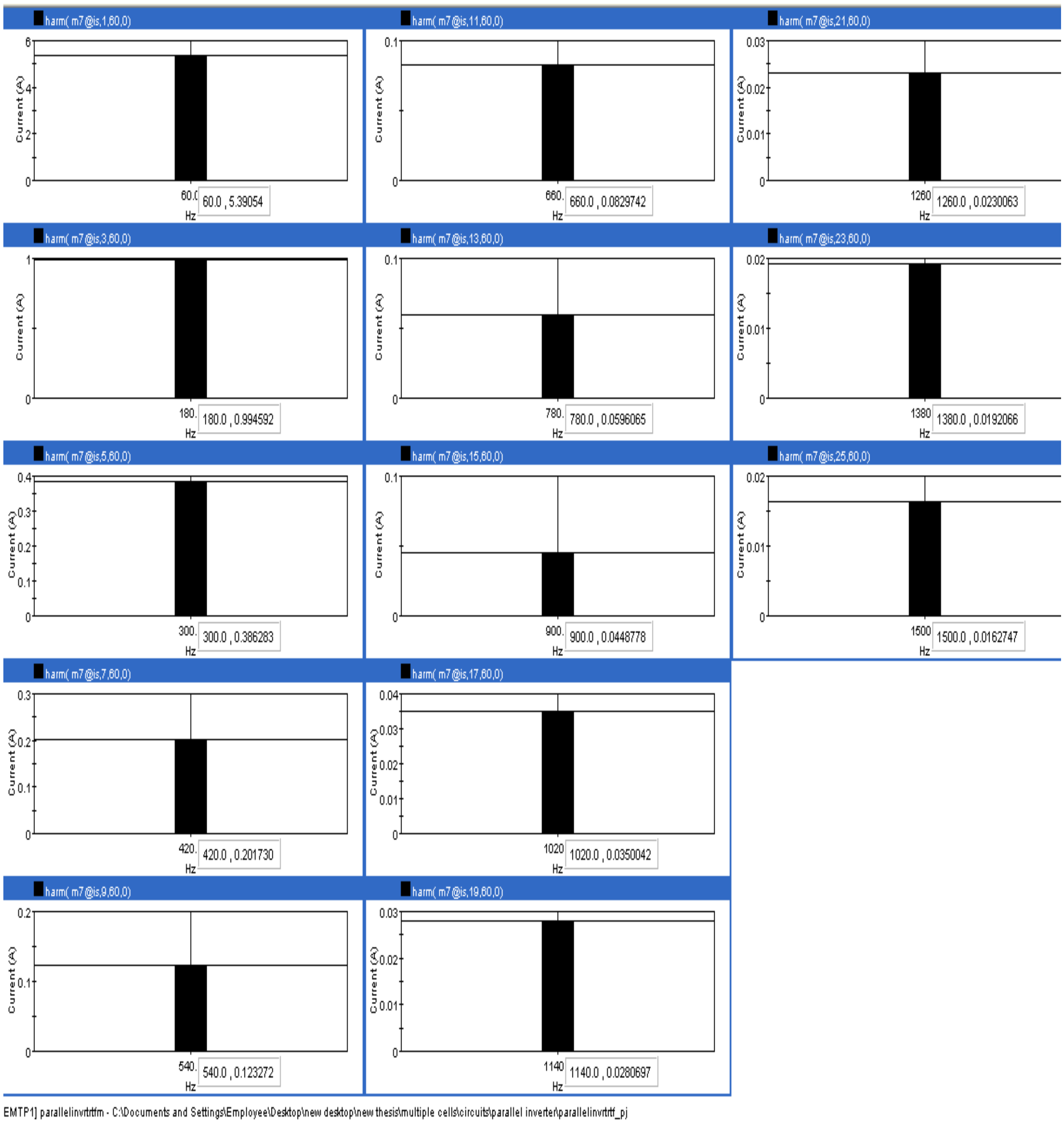

Figure 5.8: Current harmonic values of the solar parallel connection mode

5.4 Harmonics Results

The results of harmonic analysis of the solar series and solar parallel connection models have been used to populate a table specifying the current harmonics for both series and parallel solar models when the transformer ratio changes in the model from 20 to 40.

	Solar Series connection model Transformer ratios					Solar Parallel connection model Transformer ratios				
Harmo-nics	**20**	**25**	**30**	**35**	**40**	**20**	**25**	**30**	**35**	**40**
1	1.29	2.01	2.80	3.21	4.10	5.39	7.23	9.54	12.2	14.68
3	0.32	0.54	0.76	1.01	1.31	0.99	1.84	3.21	4.43	5.21
5	0.143	0.34	0.62	0.93	1.03	0.386	0.96	1.67	2.21	3.14
7	0.078	0.18	0.53	0.81	0.91	0.201	0.75	0.98	1.23	3.64
9	0.049	0.10	0.38	0.72	0.84	0.123	0.59	0.83	0.92	1.98
11	0.033	0.097	0.21	0.61	0.73	0.082	0.35	0.79	0.86	1.01
13	0.024	0..085	0.15	0.53	0.62	0.059	0.21	0.64	0.78	0.91
15	0.018	0.076	0.10	0.41	0.54	0.044	0.17	0.51	0.63	0.84
17	0.014	0.054	0.085	0.33	0.41	0.035	0.10	0.39	0.57	0.73
19	0.011	0.031	0.074	0.27	0.36	0.028	0.092	0.28	0.46	0.62
21	0.009	0.024	0.063	0.18	0.22	0.023	0.078	0.18	0.35	0.51
23	0.007	0.021	0.051	0.11	0.18	0.019	0.062	0.10	0.27	0.39
25	0.005	0.016	0.039	0.093	0.10	0.016	0.051	0.08	0.19	0.26
27	0.002	0.010	0.026	0.073	0.093	0.009	0.038	0.071	0.11	0.13
29	0.001	0.008	0.019	0.061	0.085	0.007	0.026	0.053	0.09	0.10
31	0.001	0.005	0.011	0.041	0.072	0.004	0.018	0.041	0.079	0.099
33	0.001	0.003	0.009	0.029	0.063	0.001	0.011	0.033	0.061	0.081
35	-	0.001	0.005	0.018	0.054	-	0.009	0.019	0.049	0.071
37	-	-	-	0.01	0.031	-	0.008	0.010	0.027	0.051
39	-	-	-	-	0.022	-	-	0.006	0.014	0.38
41	-	-	-	-	0.016	-	-	0.003	0.010	0.02

Table: 5.1: Current harmonics for different transformer ratios for parallel and series models

From the Figures 5.4 and 5.8, we calculated the corresponding values of current harmonics for solar series model and solar parallel model for a transformer ratio of 20%. Similarly, the recorded current harmonics values with respective transformer ratios of 25, 30, 35, and 40 have been calculated and shown in Table 5.1.

5.4.1 Calculation of THD

The following formulas have been employed to calculate both voltage total harmonic distortion and current total harmonic distortion [19]. Total Harmonic Distortion for voltage given as

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty}(V_{n,rms})^2}}{(V_{1,rms})} = \frac{\sqrt{V_{rms}^2 - V_{1,rms}^2}}{V_{1,rms}} \tag{5.1}$$

In the above equation (5.1) we have

$$\mathrm{V_{rms}} = \mathrm{V_{dc}}$$

$$\mathrm{V_{1,rms}} = \frac{4\mathrm{V_{dc}}}{\sqrt{2}\Pi}$$

By using equation (5.1) and substituting the voltage values, Total Harmonic Distortion (THD) voltage of the solar model can be evaluated.

Similarly, Total Harmonic Distortion for current is calculated as[19] -

$$I_{THD} = \frac{\sqrt{(I_3^2 + I_5^2 + I_7^2 + I_7^2 + I_9^2 + I_{11}^2 + ...)}}{I_1} \tag{5.2}$$

$\mathrm{I_3, I_5, I_7, I_9, I_{11}, I_{13}, I_{15}, I_{17}}$............ are the 3rd ,5th ,7th ,9th ,11th ….. current harmonics and $\mathrm{I_1}$ is the fundamental current harmonic.

Hence, by using equations 5.1and 5.2, THD values for voltage and current for both series and parallel solar models have been calculated. The results have been analyzed to see which model is better than the other in terms of harmonic distortion content. From Equation 5.1, Table 5.2 has been derived.

Total Harmonic Distortion voltage for the solar models is:

Voltage	Solar series model	Solar parallel model	Difference in the THD
THD	47.67%	47.70%	0.03%

Table: 5.2: Total Harmonic Distortion voltages for solar models

The values from the above table determine that there is not much difference between the solar series and parallel models in terms of THD of voltage because the difference between the two models is 0.03%, which is negligible.

With the THD values for voltage being almost equal, the total harmonic distortion current for series and parallel solar models have been calculated to see if there is any larger difference between the two values, Table 5.3 includes a summary of the results. Total harmonic Distortion current for two models is :

Current	Solar series model	Solar parallel model	Difference in the THD
THD	28.57%	20.55%	8.02%

Table: 5.3: Total harmonic Distortion currents for solar models

From Table 5.3 calculated values of for THD of current, has a difference of 8.02% between solar series and solar parallel models. Solar parallel model has lower THD current than the solar series model.

To compare these models and see the differences, we changed the transformer ratios in each solar parallel and series model and calculated the difference as provided in Table 5.4.

Total Harmonic Distortion current for two models for different TF ratios is:

Transformer ratio	Solar series model THD	Solar parallel model THD	Measure 1(Difference between models)	Measure 2(Solar series model efficiency)	Measure 3(Solar Parallel model efficiency)
20	28.57%	20.55%	8.02%	28.07%	39.02%
25	28.63%	20.38%	8.25%	28.81%	40.48%
30	28.71%	20.37%	8.34%	29.04%	40.94%
35	28.78%	20.41%	8.37%	29.08%	41%
40	28.70%	20.39%	8.31%	28.95%	40.75%

Table: 5.4: Total harmonic Distortion currents for different transformer ratios.

Table 5.4 includes summary of three measures - Measure 1, Measure 2 and Measure 3. Measure1 is the difference between the solar series model THD current and solar parallel model THD current. Measure 2 is the solar series model efficiency, which is essentially Measure 1 divided by solar series model THD current. Measure 3 is the solar parallel model efficiency, which can be given as Measure 1 divided by solar parallel model THD current. The calculations for Measures 1, 2 and 3 are formulated as in equations 5.3,5.4 and 5.5 respectively.

$$\text{Measure 1} = |\, THD_{cs} - THD_{cp} \,| \quad (5.3)$$

$$\text{Measure 2} = \frac{|\, THD_{cs} - THD_{cp} \,|}{THD_{cs}} \quad (5.4)$$

$$\text{Measure 3} = \frac{|THD_{cs} - THD_{cp}|}{THD_{cp}} \tag{5.5}$$

Where,

THD_{cs} is the Total Harmonics distortion current of solar series model

THD_{cp} is the Total Harmonic Distortion current of solar parallel model

By comparing Measure 2 and Measure 3 from Table 5.4, we can say that solar parallel model has high efficiency than solar series model in terms of lowering Total Harmonic Distortion.

Chapter 6

6.1 Conclusion & Future work

We discussed the basic solar model used for residential purposes and have drawn comparisons between the models used for residential and grid integration purposes. We also focused on analyzing various types of solar electric power systems and solar technologies and arrived at a general conclusion from the usage statistics of different types of customers, namely, residential, industrial and commercial. With the required background knowledge, our contribution to the broad field of Solar Power with this thesis is to build a solar model, with lower harmonics, which could be useful for the industrial customers when it is integrated to the electric grid. To develop the solar cell model we used EMTP software.

EMTP (Electro Magnetic Transient Program) is the real time simulation software which is used in this research to simulate solar models and do harmonic analysis for those models. As part of the study, we designed three solar models – Single solar cell model, Series connected solar cell model, and Parallel connected solar cell model. The single cell solar cell model consists of a single solar cell. The series solar model consists of multiple solar cells in series and the parallel solar model consists of multiple solar cells connected in parallel. To design these models, we developed the single solar cell, series connection of solar cells, parallel connection of solar cells models, an inverter model in EMTP and took the transformer model from EMTP software itself.

By using EMTP software developed the solar cell, solar series and solar parallel models. The main aim of this thesis is to look which solar model has lower harmonics, for that we applied harmonic analysis for both the series and parallel models. After simulating the solar series model and solar parallel model, we calculated the Total harmonic distortion of voltage and Total Harmonic Distortion of current for both the models.

Voltage total harmonic distortion (THD) for solar series model and solar parallel model has been found to be the same. But in the current total harmonic distortion, parallel solar model has low current THD than the series solar model. To confirm the results, we did the simulations for different transformer ratios and found that there is an average of 8.2% difference between the solar parallel model current THD and the solar series model current THD.

Hence we conclude that selection of solar cells in parallel connection (or) solar parallel connection model minimize the harmonics when integrating with the electric grid.

6.2 Future Work

In this thesis we took five solar cells, designed the models and have performed simulations for five solar cells in series and solar cells in parallel. The models designed in the thesis are compatible to up to hundred cells in series and parallel. However, the results may vary when we connect more cells. We hence need to analyze to check for the optimum solution to reduce the harmonics. We also have to determine how many solar cells have to be connected in series and parallel to reduce the THD. By using the EMTP model which we discussed in the thesis, we shall determine the results for sufficient number of solar cells connection for production of Intermediate and large real power Production.

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Vita

The author was born in 1988, in the city of Nalgonda, India. Mr. Gokarapu completed his bachelor's In Electrical and Electronics Engineering from Jawaharlal Nehru Technological University, Hyderabad, India in 2008 with distinction. He finished his Masters in Electrical Engineering from the University Of New Orleans in FALL'2010. The author worked with Dr. Parviz Rastgoufard as a Research Assistant in his Masters.