A DSP-CONTROLLED PHOTOVOLTAIC SYSTEM WITH MAXIMUM POWER POINT TRACKING

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Abstract

In this paper a DSP-controlled single-phase single-stage grid-connected photovoltaic energy conversion system capable of extracting maximum power from solar photovoltaic arrays is presented. The system is based on a voltage source inverter providing P+Resonant current regulation for maximum power point tracking of the PV array in addition to other necessary functions such as synchronisation with the grid. The use of the P+Resonant current regulator leads to an improved regulation of the inverter output current with minimum steady-state error in the fundamental current. The control of the inverter is provided by a 16-bit fixed-point TI TMS320F240 DSP processor. Preliminary experimental results are included.

1. INTRODUCTION

A photovoltaic (PV) array has an optimum operating point known as the maximum power point (MPP), which varies depending on cell temperature and the solar insolation level. To extract maximum power from a PV array, a maximum power point tracking (MPPT) controller is used. Many MPPT methods have been reported in literature [1]. These techniques of MPPT can be classified into three main categories that include; lookup table methods, hill-climbing methods and computational methods. The techniques vary according to the degree of sophistication, processing time and memory requirements.

In this paper, a form of the hill-climbing method of MPPT is implemented, which works by increasing or decreasing the array operating voltage and observing its impact on the array output power. However, it has been shown that when the insolation changes rapidly the hill-climbing method is slow to track the MPP [1]. To overcome this problem, a DSP-based controller is used to provide automatic adjustment of the array reference voltage with a high sampling frequency and an experimentally determined ideal step size. This allows a quick response to sudden changes in conditions, resulting in an improved overall effectiveness of the method.

A two-stage PV energy conversion system consisting of a dc/dc converter followed by a dc/ac inverter is usually employed to connect a PV array to the grid. The dc/dc converter tracks the MPP of the PV array and transfers power to the dc/ac inverter that is controlled to maintain a sinusoidal output current in phase with the grid voltage (i.e. a unity power factor). Since the control aims are independent, the controllers are relatively easy to design but the efficiency of the entire system is compromised due to the large number of devices. Based on this, two-stage systems are generally larger in size, heavier in weight and higher in cost than single-stage systems with no dc/dc converter included. So, by implementing a single-stage PV energy conversion system, the result is a reduction in physical volume and weight and improved system efficiency [2].

The inverter system described in this paper is a single-phase grid-connected voltage source inverter (VSI). The input of the VSI is a fixed dc voltage and the output is pulse-width-modulated (PWM). The modulation process used is asymmetrically sampled unipolar PWM [3].

The VSI is controlled to produce relevant changes in the array voltage based on the MPPT algorithm. The stationary-frame P+Resonant current regulator used in the current regulation stage is directly applicable to single-phase systems and effective in providing nearly zero steady-state error in the target fundamental current [4,5]. The P+Resonant regulator is implemented in the DSP using delta-operator based Infinite Impulse Response (IIR) digital filters compared to traditional shift-based IIR filters that can lead to problems with fixed-point numerical operations [6].

A TI TMS320F240 DSP is used in the VSI control board of the PV energy conversion system to control the output of the PWM generator based on the MPPT algorithm.

2. PV ARRAY CHARACTERISTICS

The PV array characteristics have a profound effect on the VSI and control of the system. An equivalent circuit model of the PV is shown in Figure 1.

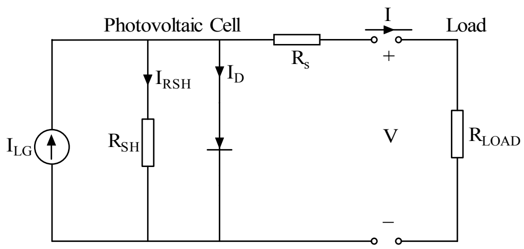

Figure 1: the equivalent PV model

The PV array equivalent circuit current I can be expressed as a function of the PV array voltage V [7]:

$$I = I_{sc}\{1 - K_1[\exp((K_2 V^m) - 1)]\} \qquad (1)$$

where the coefficients K_1, K_2 and m are defined as:

$$K_1 = 0.01175$$
$$K_2 = \frac{K_4}{V_{oc}^m}$$
$$K_3 = \ln\left[\frac{I_{sc}(1+K_1) - I_{mpp}}{K_1 I_{sc}}\right]$$
$$K_4 = \ln\left(\frac{1+K_1}{K_1}\right)$$
$$m = \frac{\ln\left(\frac{K_3}{K_4}\right)}{\ln\left(\frac{V_{mpp}}{V_{oc}}\right)} \qquad (2)$$

where:

I_{mpp} – current at MPP
V_{mpp} – voltage at MPP
I_{sc} – short circuit current
V_{oc} – open circuit voltage

Manufacturers of PV arrays usually provide I_{sc}, I_{mpp}, V_{oc} and V_{mpp} at Standard Test Conditions (STC) of 1.5 AM, 1000 W/m^2 insolation and 25ºC. Table 1 shows data at STC (obtained from the PV array datasheet) for an 80W BPSOLAR BP280 PV panel which was used for the simulations.

Table 1: Specifications of the 80W BPSOLAR BP280

Parameter	Value
Maximum Power Rating, P_{mpp}	80 W
Minimum Power Rating, P_{min}	75 W
Current at MPP, I_{mpp}	4.6 A
Voltage at MPP, V_{mpp}	17.3 V
Short circuit current, I_{sc}	5 A
Open circuit voltage, V_{oc}	21.9 V
Coefficient of voltage, α_{scT}	1.57 mA/ºC
Coefficient of current, β_{ocT}	-78.2 mV/ºC

A point to note is that Equation (1) is only applicable at one particular insolation level, G, and cell temperature, T_c. When insolation and temperature vary, the parameters in Table 1 change according to the following:

$$\Delta T_c = T_c - T_{STC}$$
$$\Delta I = \alpha_{scT}\left(\frac{G}{G_{STC}}\right)\Delta T_c + \left(\frac{G}{G_{STC}} - 1\right) I_{SC,STC}$$
$$\Delta V = -\beta_{ocT}\Delta T_c - R_s \Delta I$$
$$V_{new} = V_{STC} + \Delta V$$
$$I_{new} = I_{STC} + \Delta I \qquad (3)$$

R_s can be calculated from the manipulation of the I-V characteristics of the PV array at constant temperature (provided by manufacturers). The Equations (1)-(3) were used in the Matlab/Simulink simulation of the array. Figure 2 illustrates the simulated characteristics of the array at different levels of insolation and fixed temperature. Note that the output current and power varies according to the percentage of the standard insolation (which is 1000 W/m^2 at 25ºC). The array characteristics with a varying temperature and constant insolation are similar, so they aren't displayed.

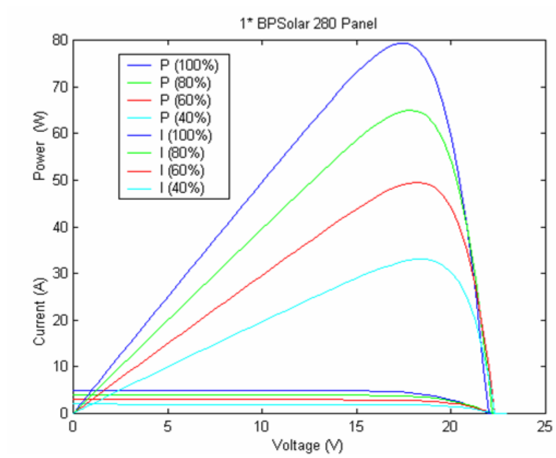

Figure 2: Power-voltage curves of PV array

From the output current and power characteristics shown, the non-linear nature of the PV array is apparent. Thus, in order to compensate for this feature exhibited by PV arrays, a MPPT algorithm must be incorporated to force the system to always operate at the MPP resulting in high efficiency gains.

3. MPPT ALGORITHM

A hill-climbing method is used to control the output current and voltage of the PV array. The flow diagram of this method that requires only 2 sensors is shown in Figure 3.

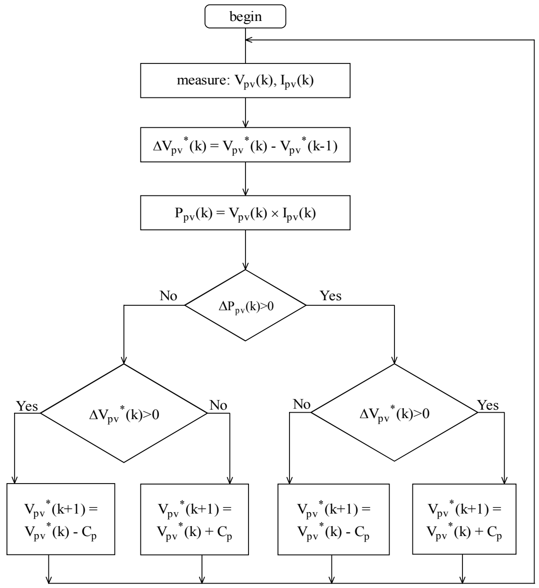

Figure 3: Flow diagram of the MPPT algorithm

This algorithm requires the values of the array voltage V_{pv} and array current I_{pv} as the input values and gives V_{pv}* which is the desired (reference) array voltage as its output value. As can be seen from Figure 3, V_{pv} and I_{pv} are measured to calculate the current array output power $P_{pv}(k)$. This value for $P_{pv}(k)$ is compared to the value obtained from the last measurement $P_{pv}(k-1)$. If the output power has increased since the last measurement, the adjustment of the output voltage continues in the same direction as the last cycle. If the output power has decreased since the last measurement, the change in the output voltage is reversed to the opposite direction of the last cycle.

With this algorithm, the operating voltage V_{pv} is adjusted with every MPPT cycle. As soon as the MPP is reached, V_{pv} will oscillate around the ideal operating voltage V_{mpp}. This causes a power loss which depends on the step width C_p of a single adjustment. If the step width is large, the MPPT algorithm will respond quickly to sudden changes in operating conditions with the tradeoff of increased losses under stable or slowly changing conditions. If the step width is very small the losses under stable or slowly changing conditions will be reduced, but the system will only be able to respond very slowly to rapid changes in temperature or insolation. The value for the step width is system dependent and needs to be determined experimentally.

4. SYSTEM DESCRIPTION

The power stage of the grid-connected PV energy conversion system is shown in the top half of Figure 4. On the dc side, a dc capacitor C_{DC} is required to stabilise the dc-bus voltage. A tuned $L_F C_F$ filter is also used to filter the 100 Hz component. To prevent any negative current flow, a blocking diode is necessary.

On the ac side, an LC filter is used to remove high frequency ripple. Furthermore, a transformer is used to attain higher voltages on the output side noting that the transformer ratio must be chosen carefully. The inductance of the LC filter is located on the low voltage side of the transformer while the capacitor C_{AC} is located on the high voltage side of the transformer.

The VSI used in the system is required to convert the dc power from the PV array to an ac power for the grid by providing an output current that is in phase with the grid voltage (i.e. a unity power factor).

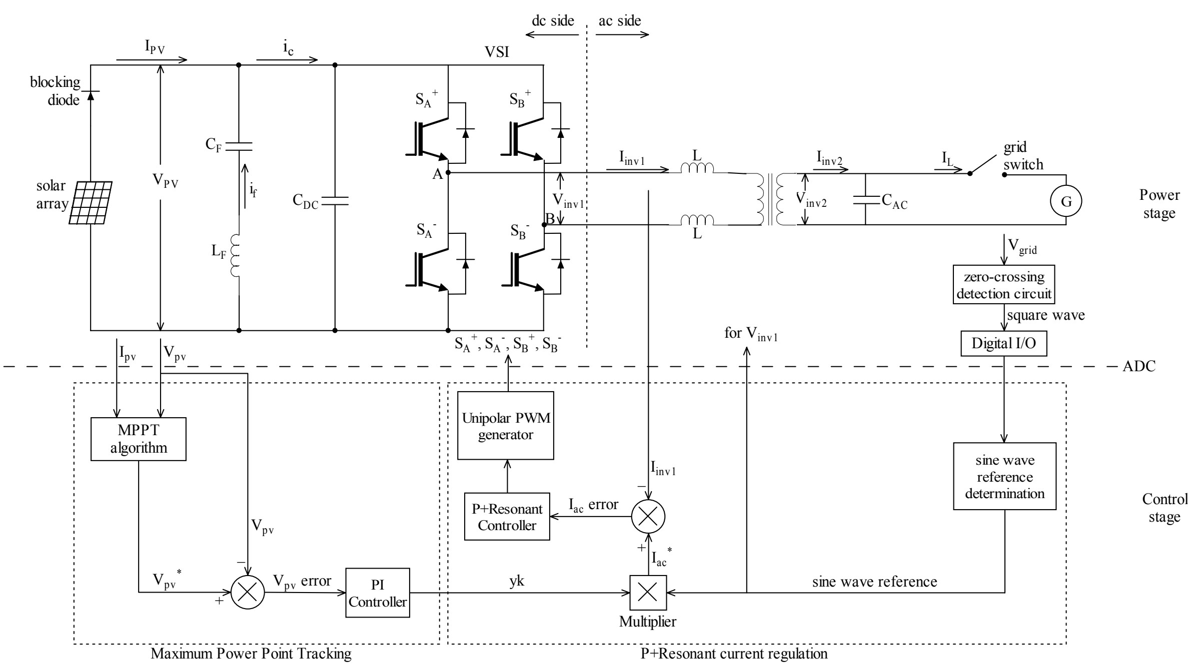

Figure 4: Configuration of proposed single-phase PV energy conversion system showing the power and control stages

5. CONTROL SCHEME

For the control stage of the VSI which can be seen in the bottom half of Figure 4, 5 control variables are included (PV voltage V_{pv}, PV current I_{pv}, VSI output current I_{inv1}, VSI output voltage V_{inv1} and grid voltage V_{grid}). These control variables connect to the DSP ADC channels.

For the system to function as efficiently as possible, it is required to ensure maximum energy transfer from the PV array to the grid. This is achieved through the technique of MPPT. Being DSP based, it means the algorithms implemented into the MPPT controller can be regularly updated by simply making the relevant changes in the control software. Moreover, the sensor inputs for the system are chosen to facilitate future experimentation with other MPPT techniques and algorithms. Another important issue which needs to be addressed is the regulation of the VSI. For the regulation of the VSI output ac current, a P+Resonant current regulator is implemented that is known to have an excellent performance while also being applicable to single-phase systems.

The control of the VSI is designed such that there are 2 main stages which include the Maximum Power Point Tracking stage and the AC-Current Regulation (Figure 4). Synchronisation is also important to enable grid connection of the system.

5.1 Grid synchronisation

To be able to connect the PV energy conversion system to the grid, the sine lookup table that controls the voltage output of the VSI (V_{inv1}) must be brought into phase with the grid voltage (V_{grid}). To do this, the grid period and phase must be detected.

The VSI board provides an analog zero-crossing detection circuit on one of its input ports where the grid voltage is to be connected. The zero-crossing circuit then produces an in-phase square wave output which is fed into the digital I/O port on the VSI board. A register on the DSP is configured such that the rising edges of the square wave (positive zero-crossings) are detected, and on this event the counter value of the timer register is captured. Another DSP register is configured such that on this same rising edge, an interrupt is triggered which keeps a count of the number of zero-crossings detected as well as the time at which they occurred. Based on the number of zero-crossings detected within a certain period of time as measured by the counter register of the DSP timer, the period duration of the grid voltage can be determined. However, there is a special case that must be noted which occurs when the grid voltage has a ripple associated with it. To overcome this issue, a software technique which accounts for double zero-crossings in a short time frame (i.e. much less than the grid period) is used to detect and fix this problem.

The period of the sine lookup table is determined next, and a phase error between the grid signal and sine lookup table is formed. This error must be minimised in an effort to optimise the period of the sine lookup table. When this process is complete, a unit peak amplitude sine wave reference having a near identical period and phase as the grid voltage will be created in the software. This reference sine wave is used to control the VSI output voltage V_{inv1} and hence sychronisation is achieved as shown in Figure 5. The same reference sine wave is also used in the regulation of the VSI ac output current discussed later.

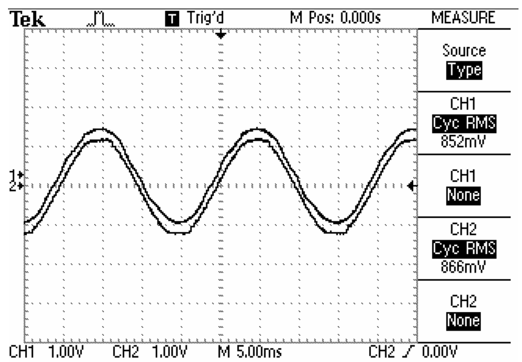

Figure 5: Synchronisation of V_{grid} and V_{inv1}
Ch 1: V_{grid}, Ch 2: V_{inv1}

5.2 Maximum Power Point Tracking

The approach used to track the MPP of the array was a step-based hill-climbing algorithm that is well suited to DSP implementation. The MPP is found by varying the operating point of the solar array and changing the desired array voltage V_{pv}* based on the direction of the change in the PV power. The regular changes to the desired array voltage of the system results in corresponding changes to V_{pv} error to be input into a manually tuned PI controller defined by:

$$H_{PI}(s) = K_p + \frac{K_I}{s} \tag{4}$$

Where K_p and K_I are the proportional and integral filter gains respectively. The output of the PI controller is a variable yk which is the index for the current regulation discussed next.

5.3 AC-Current Regulation

Linear current regulation of three-phase ac systems is commonly performed using the rotating frame *d-q* PI controller. Using the rotating frame allows the PI controller to act on a dc signal, and therefore provide zero steady-state error at the fundamental frequency.

However, for single-phase systems (such as the one described here) the *d-q* transformations are not directly applicable, and many single-phase systems are forced to use either conventional PI, or other methods. The stationary frame P+Resonant current regulator was proposed by Zmood et al. [4], to solve these problems. It is applicable to both three-phase and single-phase systems, and is defined by:

$$H_{P+R}(s) = K_p + \frac{2.K_I.\omega_c.s}{s^2 + 2.\omega_c.s + \omega_o^2} \qquad (5)$$

Where ω_c is the high pass filter cut-off frequency and ω_o is the fundamental frequency.

The P+Resonant current regulator has been shown by Mattavelli [5] to simply be the addition of both positive and negative sequence *d-q* PI controllers, referred back to the stationary frame. Due to the full cancellation of the cross-coupling terms of the two controller sequences, the result is a controller that acts on each phase separately. Therefore, the P+Resonant current regulator is directly applicable for single-phase systems, and is used in this paper to provide near zero steady-state error in the target fundamental current. The P+Resonant current regulator is implemented using delta-operator based Infinite Impulse Response (IIR) digital filters, to overcome the fixed-point numerical problems encountered when implementing the regulator using traditional shift-based IIR digital filters [6].

For the regulation of the VSI output current I_{inv1} (Figure 4), the P+Resonant current regulator described is used. The input to the current regulation is a correction signal yk, from the PI controller. The size of the correction signal depends on V_{pv} error which is the difference between the array voltage V_{pv} and the desired array voltage value, V_{pv}* output by the MPPT algorithm. The value yk, and the unit amplitude sine wave reference signal (created in grid synchronisation section as a sine lookup table) are multiplied (with the relevant scaling considerations) and a resulting ac reference current I_{ac}* is created. This ac reference current is then compared to the actual VSI current I_{inv1} giving I_{ac} error. I_{ac} error is then passed to the P+Resonant current regulator that sends the appropriate correction signals to the PWM generator. The PWM generator then alters the modulation index of the PWM signal in such a way that the desired output VSI ac current is achieved. Another point to be noted is that since the VSI is unable to feed power back into the array, it is also necessary to limit the current to prevent any negative current demanded. Hence, any negative current demand is set to zero. Another important restriction is that in some cases such as low temperatures (where the array voltage becomes too high), a voltage limitation is imposed. This prevents excessive voltages being generated.

6. PRELIMINARY RESULTS

To show the initial performance of the proposed PV energy conversion system, the parameters shown in Table 2 were selected for the preliminary experimental results.

Table 2: Specifications of the Experimental System

Parameter	Value
Nominal grid voltage, V_{Supply}	34.6 V
Switching frequency, f_{sw}	5.0 kHz
Sample frequency, f_s	10.0 kHz
Max. VSI dc-bus voltage, V_{DC}	43.8 V
Capacitance of dc-bus, C_{DC}	2200 μF
Filter inductance, L_f	1.66 mH
Filter capacitance, C_f	1000 μF

6.1 AC-Current Regulation

In the case of the ac current regulation, setting the magnitude of the ac current controls the level of power flow. If a phase offset is chosen a reactive component of power is produced. However, this should not occur since the aim of the PV energy conversion system is to inject power into the grid with a unity power factor and as a result, no ac current magnitude below zero is allowed.

Figure 7 shows the VSI current I_{inv1} for a VSI voltage of V_{inv2}. The waveform of the grid voltage V_{grid} and the VSI voltage V_{inv2} are the same since the system is in synchronisation mode. A current of 5 A_{rms} is demanded by manually setting yk. As can be seen from Figure 7, the resulting waveforms are in phase with a unity power factor, which means there is a positive power flow injection into the grid. The slight oscillation at two points in the VSI current I_{inv2} is caused by small ripple in the grid voltage V_{grid} (noting that $V_{grid} = V_{inv1}$ due to synchronisation). The current waveform shown can be increased or decreased in magnitude and this will be the mechanism used to alter the power flow in the PV system to be able to achieve MPPT.

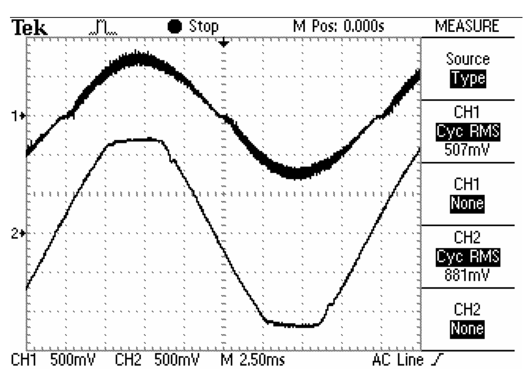

Figure 7: Positive Power Flow,
Ch 1: I_{inv1}, Ch 2: V_{inv2}

6.2 Maximum Power Point Tracking

The time characteristics of the MPPT look similar to that of the AC-Current Regulation. Here the level of power flow depends on the desired array voltage value V_{pv}* determined by the MPPT algorithm.

There are two possible situations that need to be addressed. Firstly, if an increase in the array voltage is required, and secondly, if a decrease is required. Since the ac voltage output of the VSI is fixed (grid connected), the power flow is varied by altering the VSI ac output current. If the MPPT algorithm requires a decrease in the array voltage, the output ac current is increased in phase with the grid voltage to a stable magnitude determined by modulation index designated by the PWM generator. This causes an increase in the positive power flow towards the grid on the ac-side. The extra power comes from the dc side which causes the array voltage to fall to the desired value. Once this desired voltage has been reached, the ac output current then goes down to such a level that the power on the dc side and ac side are equal once again.

If an increase in the array voltage is required, the opposite happens. Initially, the output VSI ac current decreases to a stable magnitude determined by the modulation index designated by the PWM generator. This corresponds to a power drop on the ac side. There is an excess power on the dc side which causes an increase in the array voltage. Once the increase in the array voltage has stopped, the ac output current goes up to such a level that the power on the dc side and ac side are equal once again.

7. CONCLUSION

The paper presents a DSP-controlled single-phase single-stage photovoltaic energy conversion system incorporating a Maximum Power Point Tracking algorithm. The P+Resonant current regulator is known to have an excellent performance with zero steady-state error and less complexity than other forms of current regulation. Also, the use of the delta-operator IIR filter in the P+Resonant current controller means that the problems encountered with traditional shift-operator based IIR filters aren't experienced.

Through the implementation of MPPT the system also achieves very high efficiency gains which are beneficial in grid-connected PV energy systems and related applications.

8. ACKNOWLEGEMENT

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9. REFERENCES

[1] K. H. Hussein, I. Muta, T. Hoshino, and M. Osakada, "Maximum photovoltaic power tracking: An algorithm for rapidly changing atmospheric conditions," Proc. IEE—Generation, Transmission, Distribution, vol. 142, no. 1, pp. 59–64, Jan. 1995.

[2] T.J. Liang, Y.C. Kuo and J.F. Chen, "Single-stage photovoltaic energy conversion system," IEE Proc.-Electr. Power Appl., Vol. 148, No. 4, July 2002.

[3] N. Mohan, T.M. Undeland, W.P. Bobins, "Power Electronics – Converters, Applications and Design," Second ed: John Wiley & Sons, 1995.

[4] D.N. Zmood, D.G. Holmes, "Stationary Frame Current Regulation of PWM VSIs with Zero Steady Stage Error," IEEE Trans. Ind. Electron., vol. 50, pp. 116–122, Feb. 2002.

[5] P. Mattavelli, "Closed-loop selective harmonic compensation for active filters," IEEE Trans. on Ind. Applicat., vol. 37, no. 1, pp. 81-89, 2001.

[6] M.J Newman and D.G Holmes, "Delta Operator Digital Filters for High Performace Inverter Applications," IEEE Trans. on Pow. Elect., vol. 18, no. 1, Jan., pp. 447-454, 2003.

[7] S. Rauschenbach, "Solar Cell Array Design Handbook," Van Nostrand Reinhold company, 1980.