TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol. 14, No. 1, April 2015, pp. 80 ~ 89
DOI: 10.11591/telkomnika.v14i1.7454

Single Phase Z-Source Inverter with Differential Evolution (DE) based Maximum Power Point Tracker

M.F.N. Tajuddin*[1], S. M. Ayob[2], Z. Salam[2], B. Ismail[1], A. Azmi[1]
[1]Power Electronics, Control and Optimization Research Group (PECO),
School of Electrical System Engineering, Universiti Malaysia Perlis (UniMAP),
Pauh Putra Campus, 02600 Arau, Perlis, MALAYSIA
[2]Centre forElectricalEnergySystems, Faculty of Electrical Engineering,
Universiti Teknologi Malaysia (UTM), 81310 Skudai, Johor, MALAYSIA
*Corresponding author, e-mail: faridun@unimap.edu.my

Abstract

This paper presents an efficient power conditioning system for PV power system generation. The proposed Photovoltaic Power Conditioning System (PVPCS) used a single-stage single-phase Z-Source Inverter (ZSI) integrate with a relatively new evolutionary optimization algorithm known as the Differential Evolution (DE) as the Maximum Power Point (MPP) Tracker. Utilization of single-stage power conditioner overcomes several drawback of the two-stage configuration namely a higher part count, lower efficiency, lower reliability, higher cost and larger size. Furthermore, with a highly effective Differential Evolution (DE) based MPPT technique, the maximum power extraction from PV power generator is always at the optimum value. The proposed technique can track the true global MPP in most environmental circumstances particularly during the occurrence of partial shading condition. The proposed PVPCS is developed using MATLAB/Simulink. Simulation results show that the proposed PVPCS is able to realize inversion and boost function in single processing stage as well as dealing with partial shading condition.

Keywords: *z-source inverter, MPPT, differential evolution (DE)*

1. Introduction

In the past, the price of the PV modules was a major contribution to the overall cost of the systems. However, for the past 20 years, solar electric energy has grown tremendously due to the decreasing costs and prices. This decline has been driven by an increasing efficiency of solar cells, manufacturing technology improvements and economies of scale. Therefore, the cost of the power conditioning unit is now becoming more dominant in the overall system cost. Thus, the key issues for PV application system is to lower the cost per inverter watt and at the same time achieve the best performance of the power electronics converter or power conditioner.

Recently, grid connected PV systems have become very popular because they do not need battery back-ups to ensure MPPT. Stand alone systems can also achieve MPPT, but they would need suitable battery back-ups for this purpose. Multi-stage converter systems have been reported for certain application, but PV system applications normally employ dual stages [1]. The first stage is used to track the MPP and perhaps amplify the PV array voltage while the second stage inverts this dc power into high quality ac power. Normally, the first stage comprises of a boost or buck-boost type dc-dc converter topology. Two-stage configurations are proven to be performing well, but have some drawbacks such as higher part count, lower efficiency, lower reliability, higher cost and larger size [2]. The issue is whether it is possible to reduce the number of power processing stages in such systems. Two simple and straightforward solutions to this requirement could be (1) using conventional H-bridge inverter followed with step up transformer (line frequency transformer) [3] or (2) using a large PV array with sufficiently high PV voltage connected to H-bridge inverter [4, 5].

Although these solutions are in fact is practical, they suffer from the following shortcomings. The line-frequency transformer is regarded as a poor component due to increased size, weight, and price [6]. In addition, the inverter has to be oversized to cope with the wide PV array voltage change. On the other hand, a PV array with large dc voltage suffers

Received December 12, 2014; Revised February 3, 2015; Accepted March 1, 2015

from drawbacks such as hot-spots during partial shading of the array, reduced safety and increased probability of leakage current through the parasitic capacitance between the panel and the system ground [7]. Furthermore, in both the options, the inverter must take care of the MPPT.

Therefore, based on the current trends and literatures, it is sensible to conclude that the best option for PV systems is to have a single processing stage between PV array and the grid/load that able to perform the MPPT task, voltage boosting as well as inversion. This is in line with modern day needs which require a system to be compact, highly reliable, excellent performance, less components count and reduced weight at lower cost.

Z-source inverter (ZSI) was first proposed by Fang Zheng (2003) is a new topology in power conversion. One of the main advantages of ZSI is its ability to realize inversion and boost function in single processing stage [8]. In contrast with the traditional voltage source (VSI) or current source inverters (CSI), the Z-Source inverter (ZSI) employs a unique impedance network with split inductor L_1, L_2 and capacitor C_1, C_2 connected in X shape between the input voltage and the inverter bridge. With the unique impedance network, ZSI can intentionally use a switching state that is not permitted in the VSI which is called the “shoot-through” state. By utilizing this switching state, the inverter can output voltage higher or lower than the DC link voltage.

Therefore, the inverter is a buck-boost type converter and can output whatever voltage desired, and overcome the voltage limitation of the voltage source inverter and current source inverter. Furthermore, the reliability of the Z-source inverter is greatly enhanced with the ability to handle the shoot-through state. Hence, by exploiting the advantages of ZSI, number of active switching devices, volume and cost can also be minimized. Finally, the overall efficiency of the system is greatly improved by realizing single stage inversion, boost and maximum power point tracking (MPPT).

So far several researchers have implement ZSI for PV based power conditioning system (PVPCS) and the results are highly encouraging [9-12]. Huang *et. al.* [xx] have proposed a single stage configuration for a split phase system for PV application which uses ZSI. This configuration requires six switches, operating at high frequency is recommended for high power switches. P&O algorithm has been implemented as the MPPT method. Optimal operation performance of a brushless dc motor (BLDC), using ZSI fed by PV system to drive a water pumping system has been proposed in [13]. The proposed system employs a ZSI to extract the maximum power of PV array and supply the BLDC motor. In order to achieve an accurate MPP, a variable step size incremental conductance method was utilized. Since ZSI is regarded as a new type of inverters, a lot of research on this topic is still focusing on the control algorithm [12], switching scheme [14] and new topology derived from it such as quasi z-source [15], multilevel ZSI [16], etc. Most of the works done in this area only used conventional MPPT algorithms such as Perturb and Observe (P&O), Incremental Conductance (IncCond), Hill Climbing (HC) and etc. to track the MPP.

The conventional algorithms perform very well under the uniform insolation conditions, but it deviates from and oscillates around the maximum power point, since the system must be continuously perturbed in order to detect the maximum power point [17]. However, when the weather rapidly changes, the P&O method fails to track the maximum power point effectively [18]. Furthermore, in partial shading conditions, they cannot distinguish between the global peak (GP) and local peak (LP) since local MPP shows the same typical characteristics as global MPP, such as it has $dP/dV=0$ and the slope at its right and left sides have different signs. Thus, an amount of power generation cannot be utilized by using conventional algorithms when partially shaded condition occurs or some parts of PV array are damaged [19].

Obviously, conventional MPPT algorithm will fail to converge to the real value of global MPP point. In effort to overcome the aforementioned problems, several researchers have utilized the artificial intelligent (AI) techniques such as fuzzy logic control (FLC) [20] and neural network (NN) [21]. Both techniques are proven to be very effective in dealing with nonlinear characteristics of solar cell *I-V* curve, but the drawback is that they need an extensive computational and still unable to locate the global peak of MPP. Evolutionary algorithms (EAs) have come out to be a better solution and appear very promising to overcome this problem. EAs are very popular in many engineering applications but to date, number of researchers who apply this method for MPPT application is still very small. Ability of EAs to handle nonlinear functions without requiring derivatives information makes it as an attractive choice. These methods search from a population of points instead of a single point as in conventional search and optimization techniques. Hence, it is foreseen to be very efficient in dealing with MPPT problem [22]. Various EA methods are found in the literature but the most popular ones are genetic algorithm (GA), particle swarm optimization (PSO) and differential evolution (DE). Among them, PSO and DE are highly potential due to its simple structure, easy implementation and fast computation capability.

This paper aims to overcome the shortcoming of the dual-stages VSI or CSI as well as improving the current MPPT strategies by employing ZSI and applying a relatively new evolutionary optimization algorithm known as the Differential Evolution (DE) as the MPP tracker. The main impetus of using DE is based on studies in other fields that demonstrated that DE converges fast, accurate, robust, simple and requires only a few control parameters [23-25]. The method appears to be highly capable and up till now, no researcher has applied this method for MPP tracking of PV system with the use of z-source inverter.

2. ZSI Based PV Power Conditioning System (PV-PCS)

A ZSI can be used to realize both DC voltage boost and DC-AC inversion in single stage with additional features that cannot be accomplished with the traditional PV-PCS. The power circuit of a PV based single-phase ZSI with the traditional direct shoot-through control structure is shown in Figure 1. An impedance network containing two equal (split) inductors in series and diagonally connected to two equal (split) capacitors, outputs DC voltage (DC link voltage) to a single-phase inverter bridge which is comprised of four power IGBT's with anti-parallel diodes. The Z-network facilitates the shoot-through states so that they are utilized more advantageously without any harmful effects to the inverter operation.

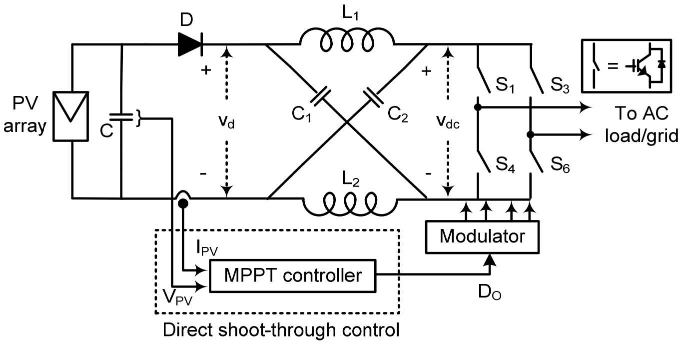


Figure 1. PCS based Z-Source Inverter

The MPPT control algorithm provides a shoot-through interval which should be inserted in the switching waveforms of the inverter to output maximum amount of power to the Z-network. At this instant, the voltage across the Z-source capacitor, V_C is equal to the output voltage of the PV array (V_{PV}). A ZSI has three operating modes, namely an active (non shoot-through) mode, a shoot-through mode and a traditional zero mode.

From the symmetry of the Z-source network the following is obtained:

$$V_{C1} = V_{C2} = V_C \qquad v_{L1} = v_{L2} = v_L \qquad (1)$$

Where V_C is voltage across the Z-source capacitor, and v_L is voltage across the inductor.

Consider that the inverter bridge is in one of the four non-shoot-through switching states, for an interval of T_1. Now the inverter bridge acts as a traditional VSI, thus acting as a current source as shown in Figure 2. Because of the symmetrical configuration of the circuit, both of the equal inductors have identical current values. The diode *D*, shown in the power circuit is forward biased in this case. The voltage across the Z-network in this case can be written as follows:

$$\begin{aligned} v_L &= V_{PV} - V_C \qquad v_{dc} = V_{PV} \\ \hat{v}_{dc} &= V_C - v_L = 2V_C - V_{PV} \end{aligned} \tag{2}$$

Where V_{PV} is the output voltage of the PV array, v_{dc} is the DC link voltage and $\hat{v}_{dc}$ is the peak DC link voltage of the inverter.

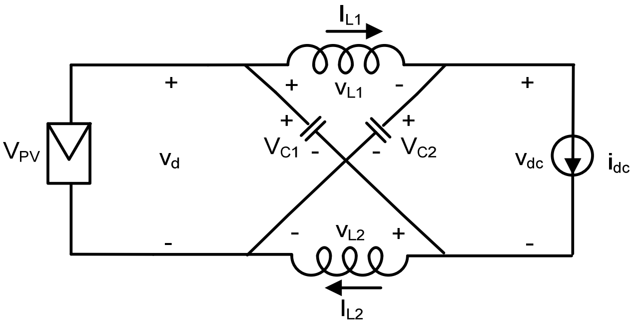


Figure 2. Equivalent circuit of the Z-source inverter viewed from the dc link during non-shoot-through state

During the non-shoot-through switching state of operation, the inverter bridge can be represented by a current source with zero value (i.e., an open circuit). Therefore, Figure 5.3 can represent the equivalent circuit of ZSI from the dc-link point of view when the inverter bridge is in one of the four non-shoot-through switching states.

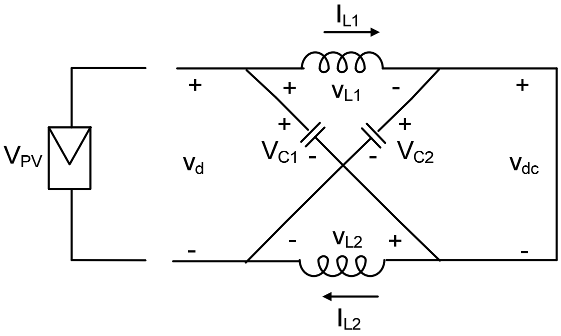


Figure 3. Equivalent circuit of the Z-source inverter viewed from the dc link when the inverter bridge is in the shoot-through zero state

The inverter bridge is under the shoot-through state for an interval of T_0, during a switching cycle, T. During this mode, the inverter bridge is seen as a short circuit from the DC link point of view. From the equivalent circuit shown in Figure 3, the voltage across the impedance elements can be related as:

$$V_L = V_C \,;\; V_{PV} = 2V_C \,;\; v_{dc} = 0 \tag{3}$$

In steady state condition, the average inductor voltage over one switching period, T should be zero. Thus from Equation (2) and (3), one has

$$V_L = \overline{v}_L = \frac{T_0 \cdot V_C + T_1 \cdot (V_{PV} - V_C)}{T} = 0 \tag{4}$$

Or,

$$\frac{V_C}{V_{PV}} = \frac{T_1}{T_1 - T_0} \tag{5}$$

Where T_1 is a the non-shoot-through period and T_0 is the shoot-through period. Similarly, the average dc-link voltage of the inverter can be written as:

$$V_{DC} = \bar{v}_{dc} = \frac{T_0 \cdot 0 + T_1 \cdot (2V_C - V_{PV})}{T} = \frac{T_1}{T_1 - T_0} V_{PV} = V_C \tag{6}$$

The peak dc-link voltage across the inverter bridge, expressed in Equation (2), can be rewritten as:

$$\hat{v}_{dc} = V_C - v_L = 2V_C - V_{PV} = \frac{T}{T_1 - T_0} V_{PV} = B \cdot V_{PV} \tag{7}$$

Where,

$$B = \frac{T}{T_1 - T_0} = \frac{1}{1 - 2(T_0/T)} = \frac{1}{1 - 2D_0} \geq 1 \tag{8}$$

Is the boost factor and D_0 can be referred to as the shoot-through duty ratio and is equal to (T_0/T) On the AC side, the output peak phase voltage from the inverter can be expressed as:

$$\hat{v}_{ac} = M \frac{\hat{v}_{dc}}{2} = M \cdot B \cdot \frac{V_{PV}}{2} \tag{9}$$

Where M is the modulation index ($M \leq 1$). By choosing the appropriate buck-boost factor, B_B , the output voltage can be stepped up and down.

$$B_B = M \cdot B = (0 \approx \infty) \tag{10}$$

From Equation (1), (5) and (8), the capacitor voltage can be written as:

$$V_{C1} = V_{C2} = V_C = \frac{1 - (T_0/T)}{1 - 2(T_0/T)} V_{PV} = \frac{1 - D_0}{1 - 2D_0} V_{PV} \tag{11}$$

2.1. MPPT Control of ZSI

To ensure the optimal utilization of large PV array, maximum power point tracker (MPPT) is employed in conjunction with the power converter (dc-dc converter and/or inverter). However, due to the varying environmental condition such as temperature and solar insolation, the *P–V* characteristics curve exhibit inconsistent maximum power point (MPP), posing a challenge to the tracking problem. A variety of MPPT algorithms have been reported to extract maximum power from a PV array [19]. The MPPT control scheme for a ZSI based PV-PCS is shown in Figure 4. For a ZSI based PVPCS, the MPPT algorithm generates a shoot-through period (T_0) to boost the Z-source capacitor voltage to the PV array voltage at the MPP. As discussed in the previous section, the shoot-through duty period (T_0) required to boost the capacitor voltage is directly calculated and the shoot-through reference straight lines are generated to produce shoot-through pulses with a simple boost control, as shown in Figure 4.

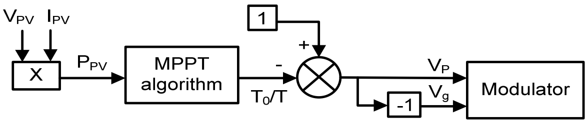


Figure 4. ZSI PV-PCS control block diagram

3. Differential Evolution (DE) Algorithm

Differential Evolution (DE) is one of meta-heuristic method and powerful tools to find global optimal solution. DE was invented by K. Price and R. Storn [26] after they find out the procedure of differential mutation combined with discrete recombination and pair wise selection without annealing factor. A conventional direct search method uses a strategy that generates variations of the design parameter vectors. Once a variation is generated, the new parameter vector is accepted or not. The new parameter vector is accepted in the case it reduces the objective function value. This method is usually named the greedy search. The greedy search converges fast but can be trapped by local minima. This disadvantage can be eliminated by running several vectors simultaneously. This is the main idea of differential evolution (DE) algorithm [27]. The main difference between the genetic algorithm and DE is GA use binary coding for representing problem parameters while DE use real coding of floating point numbers. The crucial idea behind DE is a scheme for generating trial parameter vectors. Basically, DE adds the weighted difference between two population vectors to a third vector.

The key parameters of control are: *NP* - the population size, *CR* - the crossover constant, *F* - the weight applied to random differential (scaling factor). It is worth noting that DE's control variables, *NP*, *F* and *CR*, are not difficult to choose in order to obtain promising results. Storn [28] have come out with several rules in selecting the control parameters. The rules are listed below:

1) The initialized population should be spread as much as possible over the objective function surface.
2) Frequently the crossover probability $CR \in [0,1]$ must be considerably lower than one (e.g. 0.3). If no convergence can be achieved, $CR \in [0.8, 1]$ often helps.
3) For many applications $NP = 10 \times D$, where *D* is the number of problem dimension. *F* is usually chosen at [0.5, 1].
4) The higher the population size, *NP*, the lower the weighting factor *F* should choose.

These rules of thumb for DE's control variables which is easy to work with is one of DE's major contribution [29]. The detailed Differential Evolution algorithm used in the present study is given below:

1) Require:
    a) *D* – problem dimension
    b) *NP*, *CR*, *F* – control parameters
    c) *G* – Number of generation/stopping condition
    d) *L*,*H* – boundary constraints
2) Initialize all the vector population randomly in the given upper & lower bound.

    $$Pop_{ij} = L + (H - L).\mathrm{rand}_{ij}(0,1) \qquad i = 1,...., D,\ j = 1,...., NP$$

3) Evaluate the fitness of each vector.

    $$Fit = f(Pop_j)$$

4) Perform mutation & crossover.
    a) For each vector $x_{j,G}$ (target vector), a mutant vector is generated by:

    $$v_{j,G+1} = x_{r1,G} + F.(x_{r2,G} - x_{r3,G})$$

    Where the three distinct vectors x_{r1}, x_{r2} and x_{r3} randomly chosen from the current population other than vector $x_{j,G}$.

b) Perform crossover for each target vector with its mutant vector to create a trial vector $u_{j,G+1}$

$$u_{j,G+1} = (u_{1j,G+1}, u_{2j,G+1}, \ldots, u_{Dj,G+1})$$

$$U_{ij,G+1} = \begin{cases} v_{ij,G+1} & \text{if } (\text{rand}_i \le CR) \vee (\text{Rnd} = i) \\ x_{ij,G} & \text{otherwise} \end{cases}$$

$i = 1,\ldots, D$

5) Verifying the boundary constraint. If the bound (i.e. lower & upper limit of a variable) is violated then it can be brought in the bound range (i.e. between lower & upper limit) either by forcing it to lower/upper limit (forced bound) or by randomly assigning a value in the bound range (without forcing).

$$\text{if } (x_i \notin [L, H], \qquad x_i = L + (H - L).\text{rand}_i(0,1)$$

6) Selection is performed for each target vector, $x_{j,G}$ by comparing its fitness value with that of the trial vector. Vector with lower fitness value is selected for next generation.
7) Process is repeated until a termination criterion is met.

The flowchart shown in Figure 5 summarizes the DE algorithm.

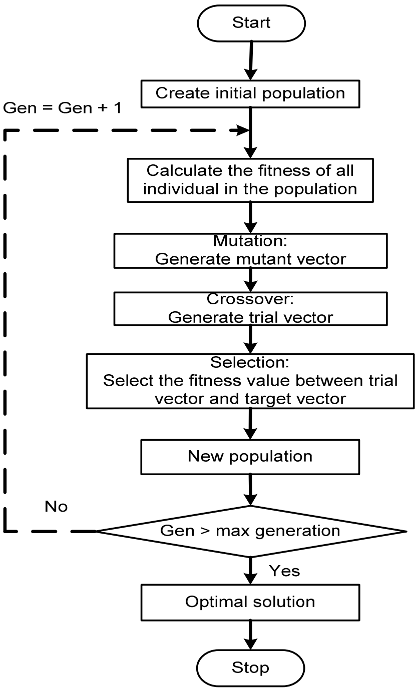


Figure 5. Flowchart of DE method

4. Simulation Results

Figure 6 shows the MATLAB/Simulink simulation model for the converter with the MPPT implemented in this work. To verify the feasibility of the proposed algorithm, first it is implemented by using ZSI. The following specifications for the buck–boost converter are used: $L_1 = L_2 = 1$ mH, $C_1 = C_2 = 1000$ μF. The switching frequency is set to 10 kHz. Furthermore, to ensure the system attains steady state before another MPPT cycle is initiated, the sampling interval is chosen as 0.01 s.

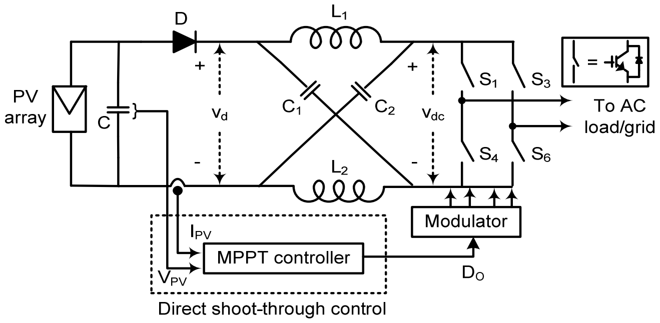
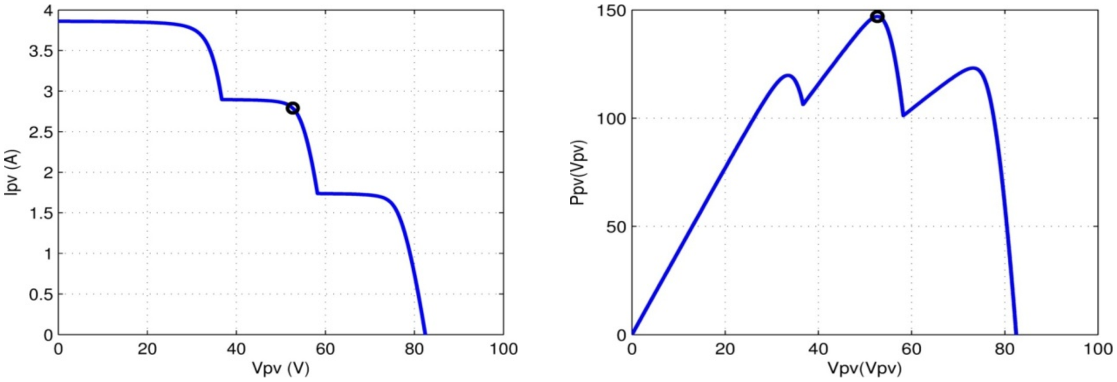


Figure 6. PV system with ZSI



(a) (b)

Figure 7. *I-V* and *P-V* curves during partial shading

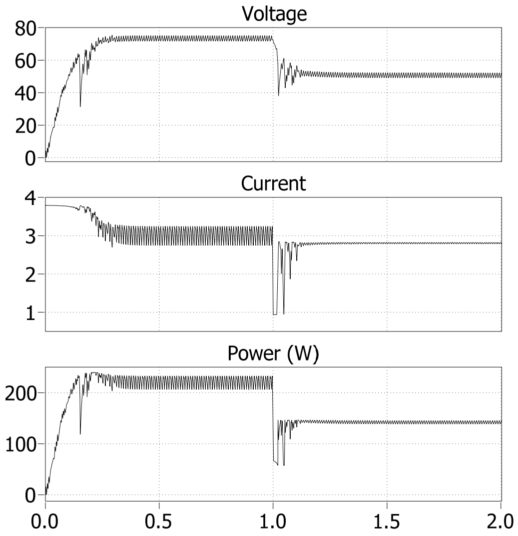


Figure 10. Tracking voltage, current, power of DE MPPT

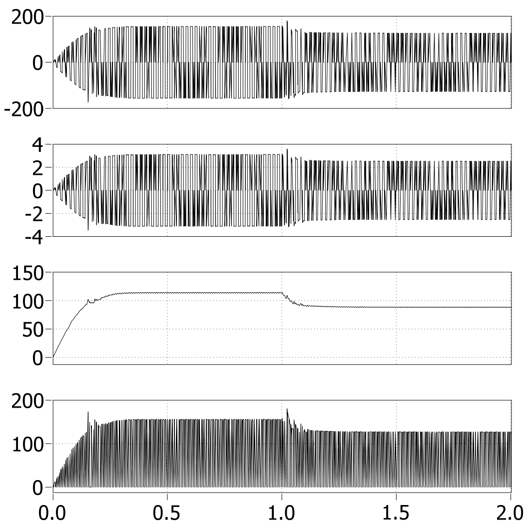


Figure 11. Load voltage V_L, load current I_L, capacitor voltage V_C and inverter voltage V_i of ZSI

As can be seen in Figure 7, until *t* = 1.0 s, at which point shading occurs, the DE based MPPT controller calculates the correct V_{MP} voltage ($17.1\times 4 = 239.4\ \mathrm{V}$) and I_{MP} current (3.5 A), respectively, corresponding to the maximum power point. Due to shading of the PV array (at *t* =

1.0 s), the output power of PV suddenly decreases from its optimal value owing to sudden change in operating current. This will tend to reinitialize the MPPT algorithm and the new MPP (i.e. global MPP) will be search via DE algorithm. It can be seen in Figure 7, the MPPT controller accurately computes the new global I_{MP} current (2.74 A), corresponding to the maximum power point (146.56 W) (see Figure 6). Figure 8 shows the corresponding output of ZSI. It can be seen that the inverter output voltage is boosted without the need of an intermediate stage such as boost dc-dc converter.

4. Conclusion

In this paper, DE based MPP tracker works in conjunction with a single-stage single-phase ZSI is presented. Inability of the conventional MPPT techniques in dealing with multimodality of *P-V* characteristic curve during partial shading can be overcome by the proposed MPPT technique. In addition the overall efficiency of the proposed PVPCS is further enhanced by employing a single-stage power converter. Implementation of the switching scheme and its MPPT control structure are provided as design guidelines. MATLAB/Simulink simulation is used to validate the feasibility of the proposed PVPCS particularly how it handle the partial shading condition.

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