Solar PV Module Based Impedance-Source Inverter for Grid Connected System

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Abstract: *The unpredictability of solar energy can be overcome by using Maximum Power Point Tracking algorithm (MPPT). Perturb and Observation (P&O) MPPT algorithm accomplish fast the maximum power point for rapid change of environmental conditions such as irradiance intensity and temperature. The MPPT algorithm applied to solar system keep the boost converter output constant. Output from boost converter is taken to three phase impedance-source inverter with RL load and grid system. Impedance-source inverter performs the transformation of variable DC output of the solar system in to near sinusoidal AC output. This near sinusoidal AC output consecutively is served to the RL load first and then to grid system. The simulation is carried out in matlab/simulink platform both for RL load and grid system and the simulation results are experimentally validated for RL load arrangement only.*

Keywords: *Impedance-source inverter, Maximum Power Point Tracking (MPPT), Solar Energy System.*

1. Introduction

Amongst biomass, geothermal, hydro and solar energy, solar energy is considered as the most hopeful energy substitute and are potential sources for bulk power generation. Unfortunately, solar characteristics rely on ecological conditions like irradiance intensity and temperature[1]. The fickleness of solar energy transpires us to find an active method to leverage it when they are accessible. The fickleness of solar energy can be overcome using Maximum Power Point Tracking algorithm (MPPT).Perturb and Observation (P&O) MPPT algorithm can execute maximum power point for rapid change in environmental conditions such as irradiance, intensity and temperature. Therefore maximum power point tracking based inverter [2] is requisite in between the solar energy system source and the load arrangement. Many methods and algorithms for tracking the maximum power from the solar energy system are available. P&O[3] and incremental conductance algorithms are commonly used for the reasons of their appropriateness and ease to realize for solar photovoltaic panel. To resolve the problem of undulations nearby the maximum power point under steady state conditions and poor tracking competency during changeable irradiance traditional P&O algorithms, the variable step size P&O has been brought in [4-5]. The various families of power converters have been intended to interface the renewable solar resource for different applications[6]. Owing to development of Power Electronics and Embedded System techniques, control and implementation of renewable energy systems are made promising.

The output from solar system is fed as input to boost converter. The MPPT algorithm is applied to solar system in order to keep the boost converter output constant [7]. The output from boost converter is taken to three phase impedance-source inverter with load arrangement first and then to grid system. The three phase impedance-source inverter is operated in closed loop control for voltage and frequency synchronization. Eventually three phase impedance-source inverter output with LC filters will produce sinusoidal output which is fed to the load first and then to grid system. Thus, a control algorithm with boost converter [8] and three phase impedance-source inverter is proposed to utilize the renewable energy resource to their maximum level. The proposed three phase impedance-source inverter can either buck or boost AC output, a scenario that could not be achieved in conventional Current Source and Voltage Source Inverters (CSI and VSI) [9]. Moreover, the impedance - network of three phase impedance-source inverter comprising a pair of capacitors and inductors forms the second order filter that filters unwanted voltage sags thereby reducing the current total harmonic distortion and

improving the quality of power. Consequently enhanced power quality without sag and lesser total harmonic distortion is given to load [10-15].

Amongst the different controllers, PID controller is proposed for grid connected solar based impedance-source inverter system [11-12]. PD and PI controller improves transient and state responses respectively. Henceforth, combination of both PD and PI controllers improves overall time response of the system. However it affects both transient as well as steady state performance of the system. For effective result it must be tuned properly. There is no offset error in this controller. It makes the system response fast and reduces the settling time.

2. Impedance-Source Inverter

Impedance-source inverter shown in figure 1 has impedance-network on its DC side. The exclusive impedance network consists of passive components (Inductors and Capacitors) that give single-stage conversion.
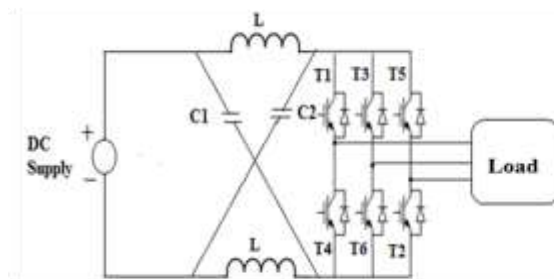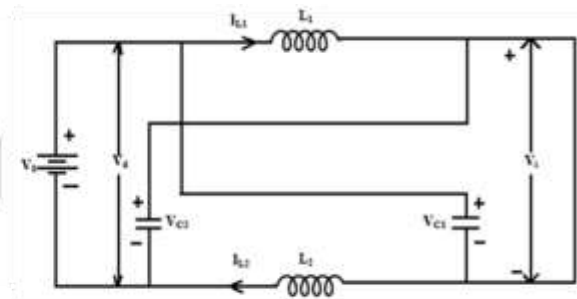
Fig.1. Schematic of Impedance-Source Inverter

Fig.2. Impedance Network

A second-order filter which handles the unwanted voltage sags in a DC voltage source is formed by the impedance network. It reduces the harmonics in the current due to dual inductors in impedance-source network as well as in rush current [13-14]. Existence of two inductors and capacitors in impedance-source network permits both the switches in the same leg in ON state, concurrently named as "shoot through state". This state provides boosting ability to the inverter without destructing the switching devices. In this state, energy is transmitted from capacitor to inductor and hence impedance-source network gains the voltage boosting ability. A diode is mandatory to avoid the discharge of charged capacitor through the source.

The major advantages of impedance-source inverter are:

* Can step down (buck) or step up (boost) voltage outputs which are not possible with voltage source and current source inverters.
* Produce any anticipated voltage outputs, more than the line voltage, irrespective of the voltage input, thus lessen the ratings of motor.
* It provides ride-through at the instance of voltage sags minus any additional circuits
* Less affected by Electro Magnetic Inference (EMI) noise and
* Improve power factor and reduces harmonic current.

2.1. Analysis of Impedance Network

The three states in which the impedance-source inverter functions are shoot-through state, active state and zero state. One among the two switches of each limb will conduct in active state producing fixed output across the load; on the other hand, either switches in upper arm or switches in lower arm will conduct in zero state producing no output across the load. But the load terminals get short-circuited by upper as well as lower switches of either one or both limbs at the shoot-through state thus not producing any output across the load[16].

As the impedance network shown in figure 2 is assumed symmetric, capacitors (C_1 and C_2) and inductors (L_1 and L_2) have the same values of capacitance and inductance respectively [17]. Hence capacitor and inductor voltages are

$$V_{C1} = V_{C2} = V_C, V_{L1} = V_{L2} = V_L \tag{1}$$

In shoot-through state, the DC link voltage (V_i) across the inverter bridge is zero.

$$V_i = 0 \tag{2}$$

Inductor voltage V_L in shoot-through state is V_C

$$V_L = V_C \tag{3}$$

Inductor voltage V_L in non-shoot through state is $V_0 - V_C$

$$V_L = V_0 - V_C \tag{4}$$

where V_O is DC input voltage.

In steady state, average voltage of inductors over one switching period (T) is zero.

$$V_L = \frac{T_0\,(V_C) + T_1\,(V_0 - V_C)}{T} \tag{5}$$

where T- Total Switching Period

   T_O- Shoot through Period

   T_1- Non-Shoot through Period

Simplifying the Eq. (5), we get

$$\frac{V_C}{V_0} = \frac{T_1}{T_1 - T_0} \tag{6a}$$

Likewise, average DC link voltage across inverter bridge can be acquired as below:

$$V_i = \frac{[T_0\,(0) + T_1\,(2V_C - V_0)]}{T} \tag{7}$$

Substituting Eq. (2) in Eq. (7) and simplifying the Eq. (7), we get

$$V_0 = 2V_C \tag{8}$$

Eq. (6a) can be rewritten as

$$V_C = \frac{T_1 V_0}{(T_1 - T_0)} \tag{6b}$$

Peak DC-link voltage across inverter bridge can be established as under:

$$V_i = V_C - V_L = V_C - (V_0 - V_C) = 2V_C - V_0 \tag{9}$$

Substituting Eq. (6b) in Eq. (9) and simplifying the Eq. (9), we get

$$V_i = V_0 \left[\frac{T_1 + T_0}{T_1 - T_0} \right] = V_0 \left[\frac{T}{T_1 - T_0} \right]$$
$$\text{as } T = T_1 + T_0 \tag{10}$$

Defining $B = \frac{T}{(T_1 - T_0)} \geq 1$ as boost factor of inverter, we get

$$V_i = B.V_0 \tag{11}$$

If M is the modulation index, then output peak phase voltage of the inverter is

$$V_{ac} = \frac{M.V_i}{2} \tag{12}$$

Substituting Eq. (11) in Eq. (12), we get

$$V_{ac} = \frac{M.B.V_0}{2} \tag{13}$$

Thus it is obvious from Eq. (13) that, output voltage can be varied by varying M.B=B_B=Buck-Boost factor that varies from 0 to ∞.

Capacitor voltage of impedance network can be derived by substituting $T_1 = T - T_0$ in Eq. (6b)

$$V_C = \left[\frac{(T - T_0)}{(T - T_0) - T_0} \right] V_0 = \left[\frac{1 - \left(\frac{T_0}{T}\right)}{1 - 2\left(\frac{T_0}{T}\right)} \right] V_0 \tag{14}$$

If duty cycle $D = \frac{T_0}{T}$, then Eq. (15) becomes

$$V_C = \left[\frac{1 - D}{1 - 2D} \right] V_0 \tag{15}$$

Boost factor B_B, which is controlled by duty cycle of shoot through zero state is identified by the modulation index 'm' as well as the boost factor 'B'.
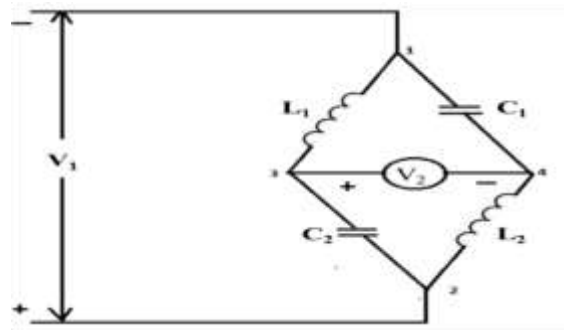
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Fig.3. Modified Impedance Network

The impedance network is modified in the form of bridge network consisting of four points say 1to 4 as shown in figure 3. Assuming current I_1 entering the network at point 1, current I_2 at point 2 as 0 and using Kirchoff's voltage law, the values of series arm inductors ($L_1$and L_2) and values of parallel arm capacitors ($C_1$and C_2) can be designed as below.

Using Kirchoff's voltage law

$$I_1 \frac{L}{2} + V_2 = \frac{I_1}{2C} \tag{16}$$

$$V_2 = \frac{I_1}{2C} - \frac{I_1 L}{2} \tag{17}$$

Knowing the values of V_2 and I_1 and assuming suitable value of C, value of L can be obtained. Simulation has been carried out and a prototype hardware model has been built.

3. Simulation Results

The Simulink models[18] of the following cases are carried out by means of MATLAB software.

   (1) Solar system with closed loop PID controller for RL load
   (2) Solar system with closed loop PID controller for grid system.

The simulation parameters of constructing boost converter, Impedance-source inverter and controllers are tabulated below in table 1 and 2. Also the transient and steady state response parameter for PID controller is tabulated in 3 and simulink model consists of the following blocks:

- MPPT controller based solar panel
- Boost converter
- Impedance-Source Inverter
- RL Load and grid

TABLE I: Simulation Parameters of Converter and Inverter

Boost converter	Impedance-filter	Impedance-source inverter
$V_{in=}40V$	$C_1, C_{2=}$ 3000μF	$L_1, L_2, L_{3=}$ 800mH
$C_{1=}1000$ μF		
$L_{1=}15$ μH		$C_1, C_2, C_{3=}$ 10 μF
$C_{s=}0.6mf$	$L_1, L_{2=}$ 100mH	
$C_{out=}3000μF$		$R=10Ω$
$V_{o=}80V$		$L=800mH$

TABLE II Simulation Parameters of Controller

Type of Controller	K_p	K_i	K_d	T_s
PID	0.009	0.8	0.007	50μs

TABLE II Specifications of Controllers

Type of Controller	Transient Specifications			Steady state error
	Rise time (Sec)	Peak time (Sec)	Settling time (Sec)	
PID	1.2	2.8	2.2	5

3.1. Solar System with Closed Loop PID Controller for RL load without Grid System

The closed loop simulink model shown in figure 4 comprises of solar model, boost converter, impedance-source inverter (impedance-filter and three-phase inverter), PID controller, RL load etc. is aimed for a switching frequency of 5 kHz and the outcomes of the same are presented below.

The output voltage of 40V from solar panel is given to boost converter where it is boosted to nearly 80 V as shown in figures 5 and 6. The firing pulses for three MOSFET switches viz. M_1, M_3 and M_5 of three-phase inverter, a part of impedance-source inverter is shown in figure 7. The three output voltages displaced by certain degree of three-phase inverter is shown in figure 8. The output voltage across connected RL load and output current through connected RL load without grid system are shown in figures 9 and 10.

Fig.4. Simulink Model - Solar System with Closed Loop PID Controller for RL Load without Grid System

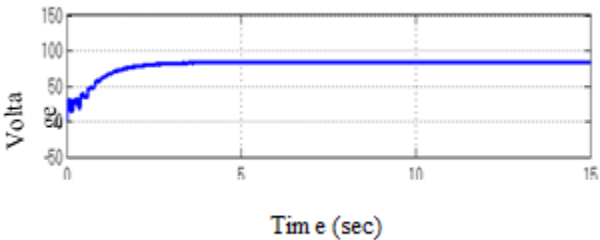Fig.5. Input Voltage of Boost Converter

Fig.6. Output Voltage of Boost Converter

The FFT analysis is obtained as in figure 11 for solar system with closed loop PID controller for RL Load without grid system. The current total harmonic distortion for PID controller is 4.6%.which is well below the standard.

3.2. Solar System with Closed Loop PID Controller for Grid System

The closed loop simulink model shown in figure 12 comprises of solar model, boost converter, impedance-source inverter (impedance-filter and three-phase inverter), PID controller, RL Load, grid system etc. is aimed for a switching frequency of 5 kHz and the outcomes of the same are presented below.
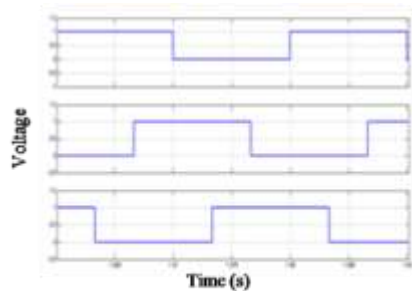

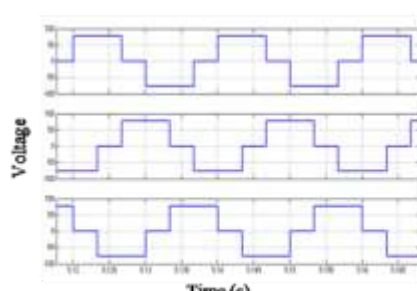Fig.7. Firing Pulses for three phase Inverter (M₁, M₃ and M₅)
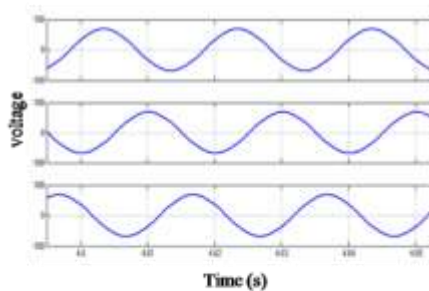

Fig.8. Output Voltage of three phase Inverter

Fig.9. Output Voltage across RL Load without Grid System

Fig.10. Output Current through RL Load without Grid System
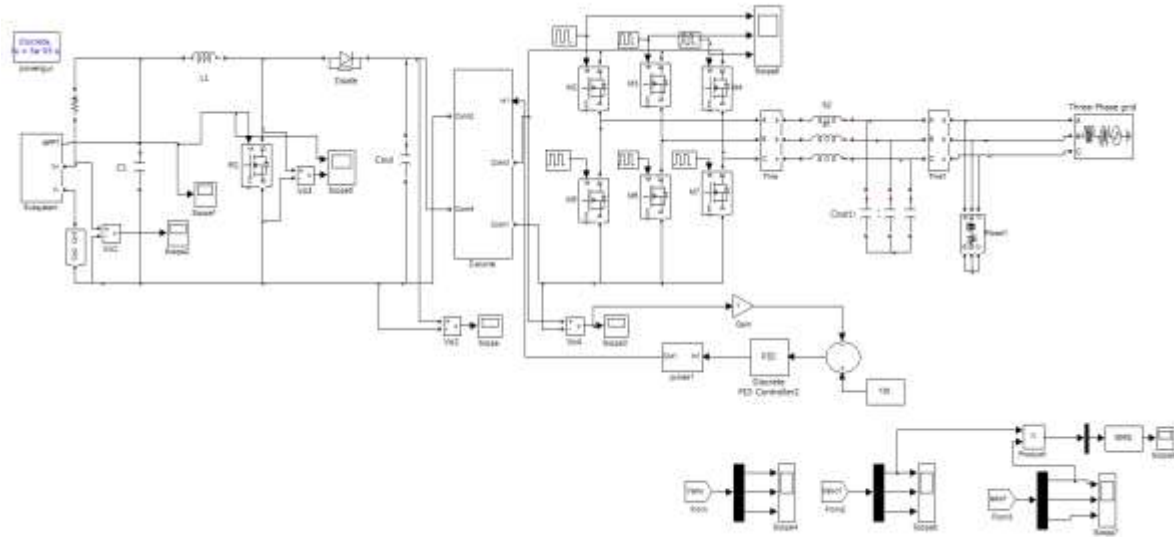

Fig.11. Analysis of Current THD

Fig.12. Simulink Model –Solar System with Closed Loop PID Controller for Grid System

The output voltage of 40V from solar panel is given to boost converter where it is boosted to nearly 80 V as shown in figures 13 and 14.
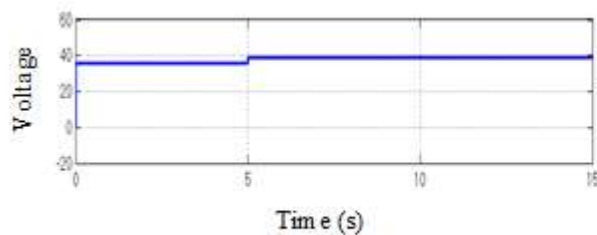

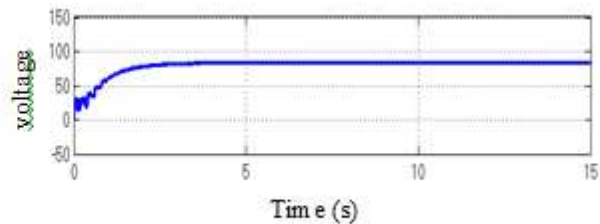Fig.13. Input Voltage of Boost Converter

Fig.14. outut Voltage of Boost Converter

The firing pulses for three MOSFET switches viz. M_1, M_3 and M_5 of three-phase inverter, a part of impedance-source inverter is shown in figure 15. The three output voltages displaced by certain degree of three-phase inverter is shown in figure 16. The output voltage across connected grid and output current through connected grid are shown in figures 17 and 18.
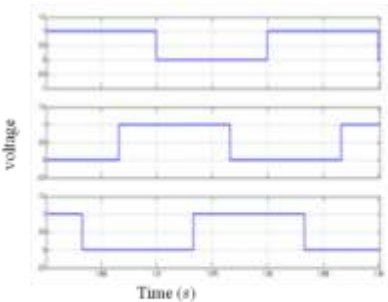
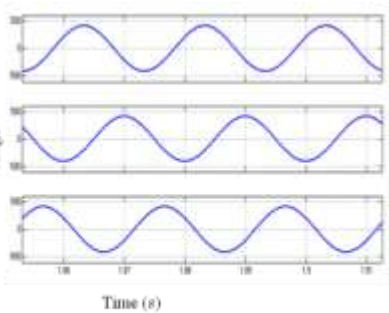Fig. 15. Firing Pulses for three phase Inverter (M₁, M₃ and M₅)

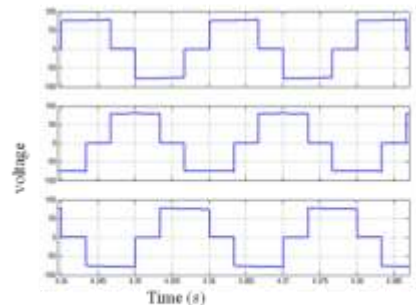Fig. 17. Output Voltage across Grid System

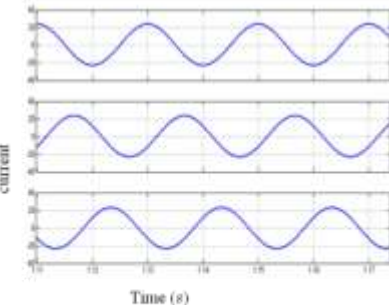

Fig. 16. Output Voltage of three phase Inverter

Fig. 18. Output Current through Grid System

The FFT analysis is obtained as in figure 19 for solar system with closed loop PID controller for grid system. The current total harmonic distortion with PID controller is 3.05% which is comparatively less.
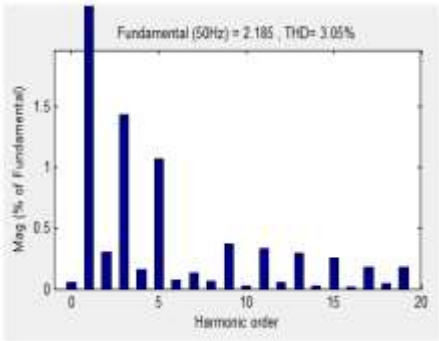

Fig.19. Analysis of Current THD

Different THD levels with RL Load and grid system of solar system are tabulated in table 4.

TABLE IV THD with RL load and grid

Type of Controller	THD for RL-Load without Grid System	THD with Grid System
PID	4.60%	3.05%

4. Experiment Results

The PIC controller PIC16F84A is preferred for this solar energy system for the creation of all control signals to the boost converter and impedance-source inverter. These signals are amplified by driver ICs IR 2110 and IRF 840. The input voltage required both by driver and microcontroller circuits are provided by LM 7812 voltage regulator. The figure 20 is prototype hardware model of impedance-source inverter for solar energy system.

Figure 21 shows the output voltage of solar panel. Switching pulses and output voltage of boost converter are in figures 22. The output voltage across RL load is shown in figure 23.

Fig.20. Prototype Hardware Model –Impedance-source Inverter for Solar Energy System

Fig.22. Output Voltage of Boost Converter

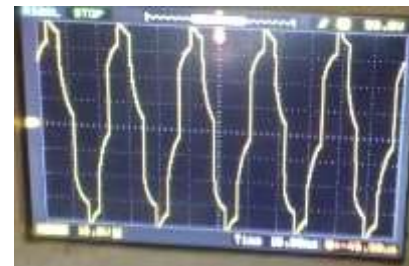Fig.21. Output Voltage of Solar panel

Fig.23. Output Voltage across RL load

5. Conclusions

A solar based impedance-source inverter with PID controllers for both RL load without grid and with grid system are analysed and compared. The accomplishment demonstrates that the performance of the system with grid was better with regard to that of RL load without grid system. Digital simulation and prototype hardware modelling of solar based impedance-source inverter with PID controllers is established and the output obtained under transient and steady state conditions. The future enhancement of this work is to simulate for wind energy system and to realize a hardware model of the system proposed.

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