# Novel Control Scheme for Z-Source Inverter based Wind Energy Conversion Systems

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## Abstract

*Z-source inverter (ZSI) based wind energy conversion systemprovides both the DC link voltage boost and DC-AC inversion in single stage with added features. Traditional maximum power point tracking (MPPT) control algorithm generates the required shoot-through interval to output maximum power to the Z-network. At this instant, the voltage across Z-source capacitor is equal to the MPP voltage of DC link voltage. The capacitor voltage cannot be further increased if it is demanded by the load. This paper presents an improved MPPT control algorithm along with modified MPPT algorithm to achieve both the MPPT as well as capacitor voltage control at the same time. Development and implementation of the proposed algorithm has been carried out by MATLAB/Simulink software and the results are provided.*

## Keywords:

Z-source inverter (ZSI);Wind Energy conversion system (WECS); pulse width modulation (PWM); maximum power point tracking (MPPT); capacitor voltage control (CVC)

## I.Introduction

With India's electricity demand increasing exponentially every year, demand for the renewable energy sources are also increases drastically. Wind, a free and clean energy sources is increasingly competitive with other energy sources in India in the coastal and southern states of India.In one of the southern states of India, Tamilnadu, the installed capacity of windmill is 8,344 MW, which is 35% of the total installed capacity in that state. Whereas the total installed capacity of windmill in India is 28,214 MW, which is around 8.5% of totalinstalled capacity. but the available potential is double the time of installed capacity now and, due to the lack of proper technology all the potentials are not properly tapped. The wind energy conversion system (1) is in general costly and is a vital way of electricity generation only if it can produce the maximum possible output for all weather conditions.

Two level converters were used to boost the DC link voltage to the desired level and convert DC into AC for controlling the AC loads. The number of switching components, total volume of the system and overall cost of the system are increased while adapting the two-stage converter based WECS. Z-source inverter (ZSI) has been proposed to overcome the disadvantages of the traditional inverters with unique impedance network [1]. A ZSIbased shown in Figure 1 created a center of attention for researchers since it offers DC boost and DC-AC inversion in one single stage. Due to its unique features and advantages, it is much suitable for various applications which are much sensitive for supply voltage sags/fluctuations [2-5].

Operating principle of ZSI based and their advantages over the traditional two stage converters have been discussed in [9]. Simple power feedback method is used to achieve MPPT in [9]. The same study has been extended for grid connected WE system in [10]. A simple control method for two-stage utility grid-connected is proposed in [10]. This approach enables maximum power point tracking (MPPT) control with post-stage inverter current information, which significantly simplifies the controller and the sensor. A power conversion circuit for a grid connected WE system using a Quasi-ZSI was suggested and analyzed in [11]. A modified P&O method is used for MPPT control.

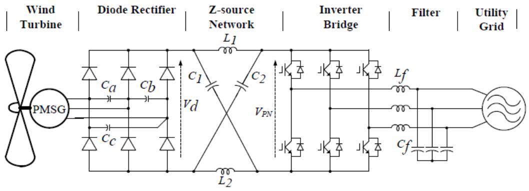



Figure 1. Main circuit configuration of existng Z-source inverter

The Z-source's main circuit is shown in Figure 1. The system composes of a diode rectifier with small input capacitors ($C_a$, $C_b$, and $C_c$), Z-source network ($C_1$, $C_2$, $L_1$, and $L_2$) and an inverter bridge. Having this Z-source network and small input capacitors makes the existing system different from wind energy conversion systems with other types of converters. Formed by the combination of a diode bride rectifier and small capacitors, a dc source feeds dc current to the Z- source network. The input capacitors are used to suppress voltage surge that may occur due to the line and generator inductance during diode commutation and shoot-through mode of inverter, thus requiring small value of capacitance. At any instant of time, there are only two phases that have the largest potential difference may conduct and carry current from the ac line to the dc side.

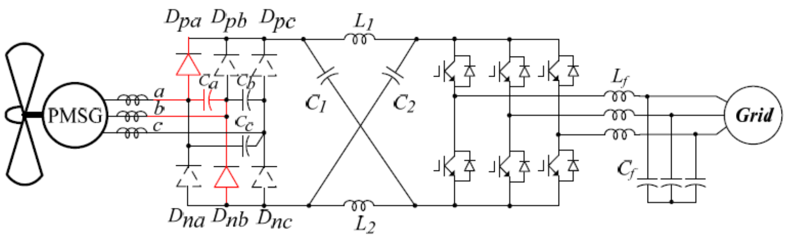



Figure 2. The Example of Equivalent circuit during the interval when the potential difference between phases "a" and "b" is largest.

The order of the suffixes corresponds with their six combinations. For example, in figure 2, $D_{pa}$and $D_{nb}$are conducting as a pair with capacitor $C_a$; $D_{pb}$and $D_{nc}$are conducting as a pair with capacitor$C_b$and so on. When it is viewed from the Z-source, two diodes conduct in a pair and in seriesacting like one. Ultimately, the existing Z-source is reduced to the basic Z-sourceinverter presented in [1] .

An example of operating principle and operating mode is as following. Shown in Figure 2, when the potential difference between phase *a* and *b* is the largest, diodes $D_{pa}$and $D_{nb}$conduct as a pair in series with capacitor $C_a$as the equivalent circuit shown in and Figure 3. The other diodes are reversely biased and cut off. Therefore, phase *c* has no line current (or small resonant/or residual current may exist between the line impedance and capacitors $C_b$and $C_c$). Ignoring this small current in phase *c*, Figure 1 and Figure 2 can be reduced to Figure 3.

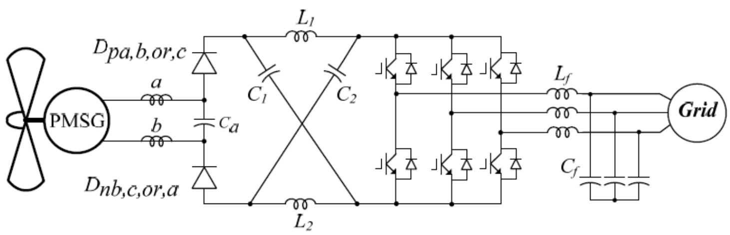


Figure 3. Reduced circuit during the interval when the potential difference between phases “a”and “b” is largest.

From this reduced circuit, there are three operation modes which are depending on the interval bridge’s switching state and, the simulation results are explained below.

**II.Simulation and experimental verifications**

The system includes a 10 kW Z-source inverter transferring power from the wind turbine side to the grid side. The input voltage supplied by the wind turbine generator to the Z-source inverter varies between 150Vrms to 300Vrms. The output voltage of the inverter is held constant at 208Vrms and 50 Hz. The parameters of the system are.

| Quantity | Values |
|---|---|
| Z-source inductors (*L1*= *L2* ) | 550 $\mu$H |
| Z-source Capacitors (*C1* = *C2* ) | 400 $\mu$F |
| Input Capacitors (*Ca*,*Cb*, and *Cc*) | 12 $\mu$F |
| Switching frequency, *fs* | 10 kHz |

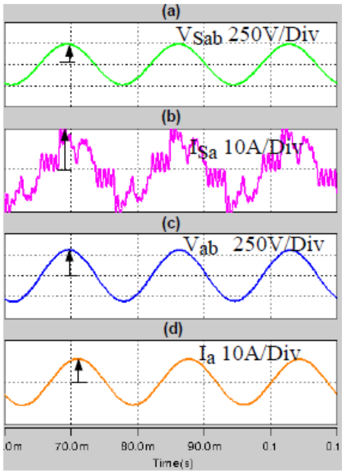



Figure 4. Simulation waveforms under the generator voltage of *160Vrms* at *1.5kW* with boost function.
(a) Generator Voltage, $v_{Sab}$,, 160Vrms(b) Generator Current, $i_{sa}$
(c) Inverter Voltage after filter, *vab*, 208Vrms(d) Inverter Current, $i_{La}$

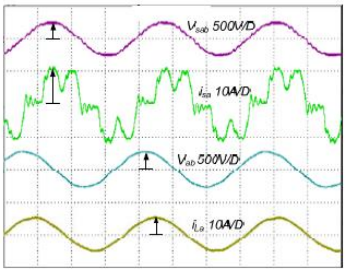


Figure5. Experimental results under the generator voltage of 160Vrms at

1.5kW with the use of the boost control mode;

Where $V_{Sab}$ is the generator voltage, $i_{sa}$is the generator current, $V_{ab}$ is the inverter output voltage and $i_{La}$ is the inverter output current. To get enough of the required output voltage, the maximum modulation index must be 0.98, the boost factor is 1.61.

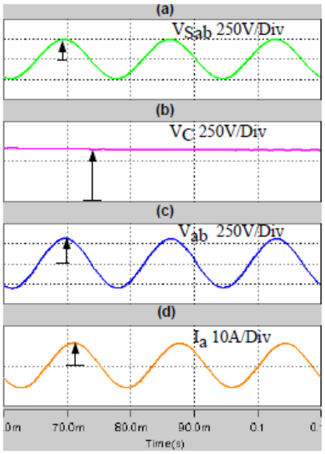



Figure 6. Simulation waveforms under the generator voltage of 160Vrms at 1.5kW with the use of the boost control mode.

(a) Generator Voltage, $v_{Sab}$,, 160Vrms
(b) Z-source Capacitor Voltage, $V_{C1}$and $V_{C2}$
(c) Inverter Voltage after filter, $v_{ab}$, 208Vrms
(d) Inverter Current, $i_{La}$

## III. Types of control schemes:

### 1. Capacitor Voltage Control

In the traditional control schemes of the ZSI based, the shoot-through time period is calculated by the MPPT algorithm and accordingly two reference straight lines are generated to produce shoot-through pulses by simple boost control. The Z-source capacitor voltage can be boosted according to the shoot-through time periods calculated by the MPPT algorithm. If the reference voltage of the capacitor is relatively higher than the generated voltage at MPP, capacitor voltage cannot be increased further since the shoot-through states are generated solely to track the voltage at MPP. To control the capacitor voltage beyond $V_{WC}$* with retaining all the features of the traditional MPPT algorithm, this section presents a unified control algorithm which provides simultaneous control of MPPT and capacitor voltage.

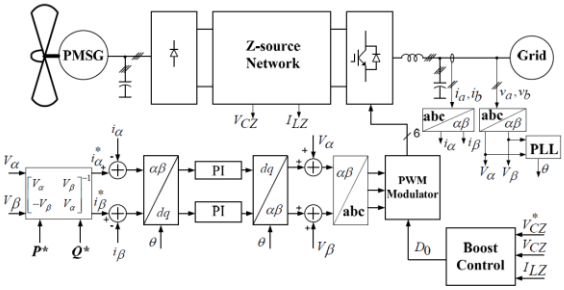



Figure 7. Proposed system with control configuration based power control method

## 2. MPPT Algorithm

According to the wind speed and tip-speed ratio, the output voltage and current varies. A variety of MPPT algorithms are used to extract maximum power from the WECS, since it has nonlinear characteristics. In this paper, perturbation and observation (P&O) algorithm is used to directly calculate the required shoot-through time periods. The input voltage of the Z-network is the output voltage of the WECS. The output voltage of the system can be controlled by controlling the Z-source capacitor or DC link voltage.

This could be achieved by imposing the simultaneous conduction of each or any phase leg switches of the inverter bridge. By adjusting the shoot-through time interval, one can get required amount of voltage across the DC link irrespective of the voltage supplied by the DC source. In P&O method, power is always measured and used as feedback to adjust shoot-through duty cycle to reach MPP. This is done by increasing/decreasing the shoot-through time period ($T_0$) with shoot-through perturbation ($\Delta T_0$). Then two reference straight lines $V_P$ and $V_N$ to generate shoot-through states are generated as follows.

$$\begin{aligned} V_P &= (1-T_0) \\ V_N &= -(1-T_0) = -V_P \end{aligned} \quad (1)$$

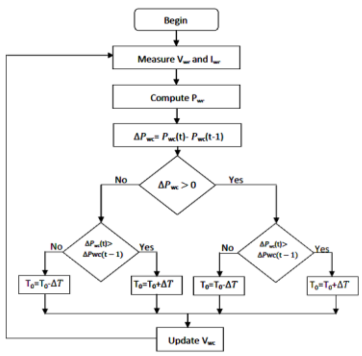



Figure 8. Flowchart of the traditional MPPT algorithm

These two straight lines ($V_P$ and $V_N$) are compared with the high frequency triangular signal in order to generate the shoot-through pulses. The control block diagram of this traditional method is shown in Figure 1. In simple boost control, the shoot-through frequency is twice the switching frequency since two shoot-through pulses are generated in one switching cycle. The capacitor voltage/DC link voltage could be improved to the MPP voltage of a ($V_{Wc}$*) and hence maximum power from could be extracted. Expression for DC link voltage can be.

$$v_{dc} = V_C = \frac{1-D_0}{1-2D_0} V_{PV} = V_{PV}^{\ *} \qquad (2)$$

The AC load voltage can be controlled by the modulation index (M) and can be written as

$$\hat{v}_{ac} = M \frac{V_{PV}^{\ *}}{2} \quad (3)$$

M can be varied from zero to $V_P$. As in the equation (10), MPPT algorithm controls the capacitor voltage until it reaches $V_{wc}$*, since the objective is to generate required shoot-through time ($T_0$) to maintain $V_C$ to be equal to $V_{wc}$*.

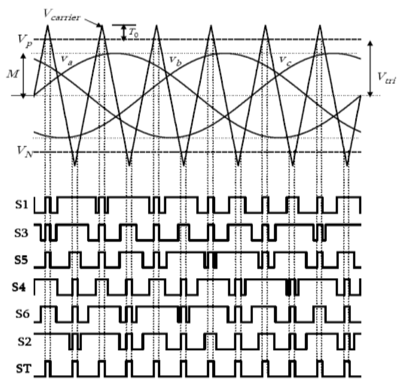
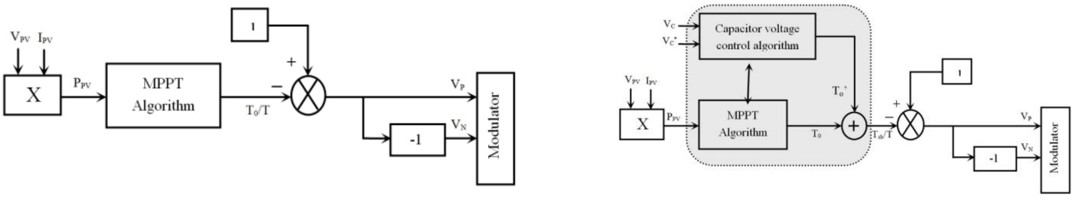



Figure 9. Modulation using P&O algorithm

MPPT algorithm generates shoot-through period ($T_0$) to boost the Z-source capacitor voltage to the voltage at MPP. Further to boost the Z-source capacitor voltage beyond $V_{wc}$*, a capacitor voltage control (CVC) algorithm is presented in this section. The traditional capacitor voltage control scheme is shown in Figure [1-3]. 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 by the equation (1). No capacitor voltage control beyond the output voltage at MPP is facilitated here. Figure 7 shows the proposed control scheme which felicitates the MPPT as well as capacitor voltage control simultaneously. Figure 8 shows the flowchart of the proposed MPPT algorithm which tracks the MPP voltage and also the reference capacitor voltage.

To track the reference capacitor voltage ($V_C$*), proposed algorithm generates an additional shoot-through factor ($T_0$'). The capacitor voltage is first set to the MPP voltage of the PV array for a particular solar irradiation and temperature level by the MPPT algorithm. Then the capacitor voltage is compared with the reference voltage which has to be maintained across the DC link of the inverter bridge. There is no additional shoot-through ($T_0$') generated when the actual voltage of the capacitor is equal to the reference voltage. If the capacitor voltage is needed to be increased substantially, additional shoot-through period ($T_0$') is generated and regulated according to the proposed algorithm shown in Figure 9. This additional shoot-through period could be added with the shoot-through time period ($T_0$) generated by the MPPT to update $V_{PV}$.

The new shoot-through time period ($T_{sh}$) to have simultaneous control of MPPT and capacitor voltage could be defined as follows




(a) (b)

Figure 10.Traditional and proposed control schemes

$$T_{sh} = T_0 + T_0' \quad (4)$$

$T_0$ is used to track $V_{PV}$ *, while $T_0$' is used to control the capacitor voltage beyond $V_{PV}$*.

Range of the new shoot-through time period $T_{sh}$, can be

$$T_{sh} \le (1 - M) \quad (5)$$

From equation (4) and (5), one could get

$$T_0' \le 1 - (M + T_0) \quad (6)$$

Maximum value of the shoot-through factor could be

$$(T_0')_{max} \le 1 - (M + T_0) \quad (7)$$

Hence the modulation index and MPPT shoot-through periods limit the range of capacitor voltage control. Since the value of $T_0$ would be very small to track MPP voltage, the capacitor voltage boost factor ($B_C$) could be controlled as the traditional ZSI.

The reference straight lines to generate new shoot-through periods can be

$$\begin{aligned} V_P^* &= (1 - T_{sh}) \\ V_N^* &= -(1 - T_{sh}) = -V_P^* \end{aligned} \quad (8)$$

Figure 10 shows the generation of new shoot-through states ($T_{sh}$) by simple boost control method. In the first stage, the capacitor voltage is boosted to the MPP voltage of the WECS ($V_{wc}$*). This is done by regulating the shoot-through state ($T_0$) by using MPPT algorithm. When the DC link voltage of the inverter is needed to be increased beyond $V_{PV}$*, the new shoot-through time period ($T_{sh}$) could be generated by inserting an additional shoot-through time period ($T_0$').

It could be noted that, the two straight lines ($V_P$* and $V_N$*) are continuously regulated to maintain the Z-source capacitor to be equal to the reference capacitor voltage ($V_C$*). The shoot-through period is adjusted according to the changes in $V_{wc}$ voltage at MPP. The minimum shoot-through period required to maintain the capacitor voltage as the $V_{wc}$ voltage at MPP is generated by the MPPT algorithm and the supplementary shoot-through duty ratio is generated by the unified algorithm to provide additional boost in the capacitor voltage to track the reference value. By substituting (4) in to (2) one could get the average value of Z-source capacitor and DC link voltages as follows:

$$V_C = \frac{T-\left(\frac{T_0+T_0'}{T}\right)}{T-2\left(\frac{T_0+T_0'}{T}\right)} V_{PV}{}^* = \frac{T-\frac{T_{sh}}{T}}{T-2\frac{T_{sh}}{T}} V_{PV}{}^* = \frac{1-D_{sh}}{1-2D_{sh}} V_{PV}{}^* = v_i \quad (9)$$

Peak value of the AC output voltage of the ZSI can be defined as

$$\hat{v}_{ac} = M\left(\frac{1-D_{sh}}{1-2D_{sh}}\right)\frac{V_{PV}{}^*}{2} = M\,\frac{v_i}{2} \quad (10)$$

Shoot-through states are applied to all the legs simultaneously. This can significantly reduce the current stress on the each switch during shoot-through state. Figure 11 shows the PWM pulse generation for ZSI using simple boost control technique. It also shows the relation between the reference sinusoidal and reference shoot-through ($V_P$ and $V_N$) signals and it holds true for $V_P$* and $V_N$* too. The shoot-through periods should be diminished from the traditional zero periods without altering the active time periods to produce less distorted AC output.

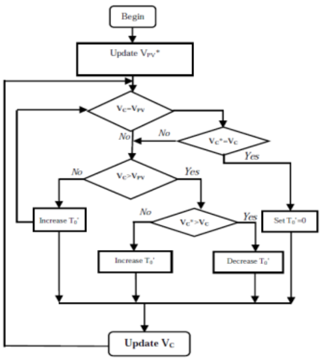



Figure 11.Flowchart of CVC algorithm

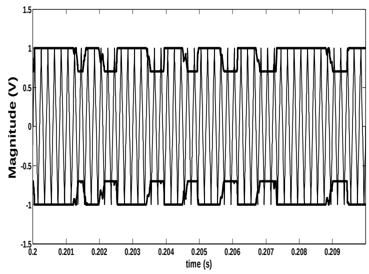



Figure 12.Simulation results of $V_P$ and $V_N$ to generate shoot-through period

## 3.Results and Discussion

Proposed CVC method is carried out for ZSI based PV system through Matlab/Simulink software. A simple boost control is used to generate the required shoot-through periods by the proposed algorithm. The Z-network is comprised of 1mH inductors and 1000µF. The PV array is modeled using the basic mathematical equations by considering the temperature and irradiation changes. LCL filter is inserted between the inverter bridge and three phase RL load (5kW with 0.9 power factor lagging).

Figure 12 shows the simulated results of signal comparison to generate shoot-through periods by the proposed algorithm. It could be noted that, the two straight lines ($V_P$ and $V_N$) are continuously regulated to maintain the Z-source capacitor to be equal to the reference capacitor voltage ($V_C$*). The shoot-through period is adjusted according to the changes in PV voltage at MPP.

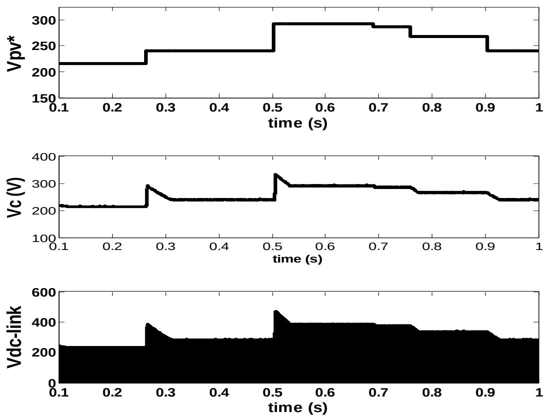



Figure 13. simulation results of traditional MPPT control

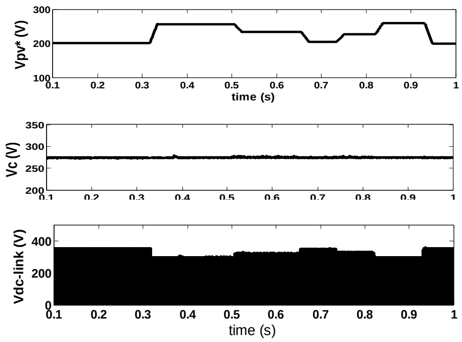
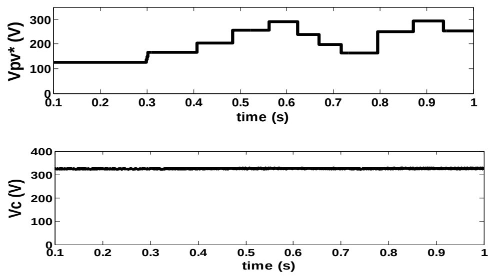



Figure 14.Simulation results of traditional MPPT with CVC algorithm to maintain $V_c$=275V



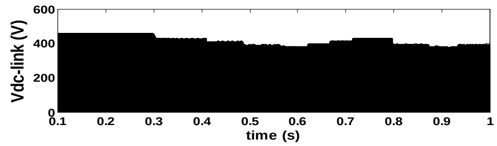
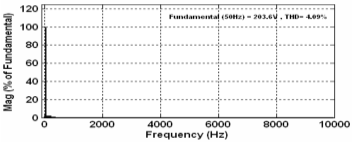
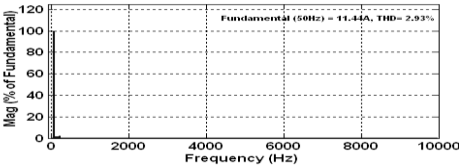




Figure 15.Simulation results of the proposed system to maintain Vc=315




(a)




(b)

Figure 16. THD of output parameters using proposed method (a) output voltage (b) output current

The minimum shoot-through period required to maintain the capacitor voltage as the PV voltage at MPP is generated by the MPPT algorithm and the supplementary shoot-through duty ratio is generated by the proposed CVC algorithm to provide additional boost the capacitor voltage to track the reference value. Figure 13 shows the simulation results of the traditional MPPT algorithm, which maintains the Z-source capacitor voltage equal to the PV voltage at MPP. From this figure one can understand that, the capacitor voltage tracks the MPP voltage of the PV. The DC link voltage waveform for the above case is also shown in Figure 14. From this, it is evident that, there is no additional boost in the capacitor voltage is allowed since the traditional MPPT generates shoot-through periods to directly track the MPP voltage of the PV cell. The simulation results of the proposed CVC algorithm are shown in Figures 12-14.

Figure 12 shows the results of the system, when the capacitor voltage reference is increased to 275V (greater than $V_{PV}$*). Even though there are plenty of variations in the MPP voltage of the PV array, the voltage across Z-source capacitor is constantly maintained as 275V. This is because of the additional shoot-through period ($T_0$') generation by the proposed CVC algorithm. The same response is obtained when the reference voltage of the capacitor is increased to 315V and it is shown in Figure 15. The harmonic profile of the output voltage/current waveforms of the proposed system is shown in Figure 16 (a),(b) and it confirms the improvement of THD.

## 4. Conclusion

This paper has presented CVC algorithm for Z-source inverter-based PV PCS along with MPPT control. It is shown that, by adapting CVC one can control the Z-source capacitor voltage beyond the voltage at MPP of the PV array. The whole system is simulated using Matlab/Simulink software and the results of the traditional and proposed algorithms are presented. The advantage of the proposed algorithm is discussed for different operating conditions of the PV array.

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