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An Extended Control Algorithm in PV-ZSI Capacitor-Assisted with Allowable Boundary

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Abstract- This paper proposed an extended controller on capacitor voltage control (CVC) for Z-source inverter (ZSI) network when it is applied on the PV generation. The improved controller has been combined with the existing MPPT algorithm. Currently, the existing CVC has some drawback as it produces an unnecessary shoot-through signal period which caused the capacitor voltage at ZSI not to be constantly maintained. Therefore, the modified algorithm has been included by a deviation of the shoot-through duty cycle. It is to enhance the existing CVC performance and increase the effectiveness of the whole PV generation whenever the input PV irradiation is changed. At the same time, it is also able to maintain a constant dc-link voltage at ZSI. This proposed control algorithm has been verified throughout simulation tests using linear and non-linear loads by observing the constant dc-link capacitor voltage. This proposed controller has also been compared to the conventional CVC with the same load conditions. At the end, the improved controller has shown the ability to maintain the dc-link inverter at PV generation and to limit the shoot-through allowable boundary of the capacitor voltage to not over flow from the rated value. In terms of quality at the output, the proposed controller is able to reduce the total harmonic distortion at the load connections.

Keywords: Capacitor voltage control (CVC), Z-source inverter (ZSI), photovoltaic (PV), maximum power point tracking (MPPT).

1. Introduction

Solar photovoltaic (PV) is one of the inexhaustible energy emitted conversion from the sun and this renewable energy source has been found to be extremely useful in power generation. PV technology produces a significant amount of electrical energy consumption particularly in the area where grid-connected electricity is not available [1], [2]. Due to the power variation in the PV system caused by unpredicted sunlight changes, a so-called system known as maximum power point tracking power (MPPT) circuit is needed to smoothen the power produced and achieve a maximum possible power generation [3], [4] as well as at the output. After that, the power electronic circuit is applied to convert the DC power generated by PV input into AC power. Adoption of a single-stage power conversion is the best choice, especially in terms of efficiency and reliability [5]. An impedance-source power converter abbreviated as Z-source inverter (ZSI) with buck-boost capability is used for this DC/AC power conversion system. This is in contrast to traditional voltage and current-source inverters that cannot provide such feature as explained in [6]–[8]. The control of ZSI-based PV inverter is more complicated than the control of the conventional inverter. The conventional inverter has only one control immunity that can be used to control the output AC voltage while ZSI has two independent control immunities, modulation index and shoot-through duty ratio. This can probably cause an increased difficulty of the ZSI control. However, those immunities have the ability to produce any desired AC output voltage to be obtained. Furthermore, with the extended modified controller presented in this paper, the voltage from the PV input through the Z-source impedance circuitry can be maintained and increased to track the given reference voltage.

There are four methods for controlling the ZSI dc-link voltage; which are: direct dc-link control, indirect dc-link voltage control, capacitor voltage control, and unified control [9]–[12]. Current research states,- that all MPPT controllers need to be modified or combined with one of this four methods in order to have a constant Z-source capacitor voltage and simultaneously maintain the dc-link inverter circuit [13]–[15]. Presently, the conventional MPPT is unable to create a shoot-through to extract MPPT from PV input source. To overcome this disadvantage, many researchers have proposed an additional shoot-through period to the conventional MPPT controller [16]. This approach is able to boost the Z-source capacitor voltage further than the desired level and give a constant capacitor voltage range at ZSI. In addition, this proposed technique is also reliable towards Z-source implementation and also produces a highly efficient output power generation in terms of inverter efficiency, MPPT efficiency and the components in PV system [17], [18]. The efficiency of an inverter depends on the conversion and fast-tracking of the MPPT. Due to this advantage, this paper used Perturb and Observe (P&O) as the MPPT algorithm for tracking the MPP of PV system [19]. It also included an extended capacitor voltage control (CVC) algorithm to limit the allowable boundary of the capacitor voltage at Z-network in order to protect the rated capacitor for a constant dc-link at the inverter.

From the aforementioned information, special attention is needed for the PV conversion system as shown in Fig.1 by dealing with an extended controller to produce a constant voltage at input dc-link inverter [20]. As mentioned in papers [21], [22], the minimum shoot-through period, T_0 in conventional MPPT algorithm is able to extract maximum power point voltage from the PV module. Meanwhile, the extra shoot-through period, T_0' generated by the CVC algorithm is required to increase the Z-network capacitor voltage from the PV panel input. However, this extra shoot-through period, T_0' added to the MPPT shoot-through interval, T_0 for obtaining the total shoot-through states, T_{sh} has increase above the limit in tracking reference capacitor voltage (V_C*). Noticed that, the existing CVC algorithm will boost the capacitor voltage (V_C) further than the desired level and cause the capacitor voltage of Z-network cannot be constantly maintained. Therefore, the authors have proposed an extended and improved CVC control algorithm to reduce this drawback of the existing controller performance. By adding ∓∑% of changes ($\Delta T_0'$) in shoot-through duty ratio, D_0 and the additional shoot-through duty ratio, D_0', the voltage at dc-link will be maintained even after changes to the PV irradiance input. Under this circumstance, D_0 can be denoted as T_0/T while D_0' is equal to T_0'/T. Moreover, the extended control algorithm has ability to limit the shoot-through allowable boundary of the capacitor voltage to not over flow from the reference value.

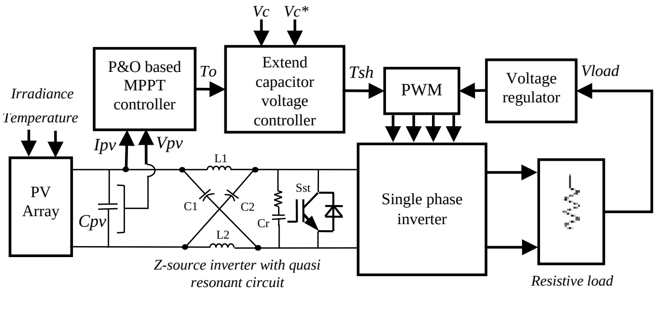
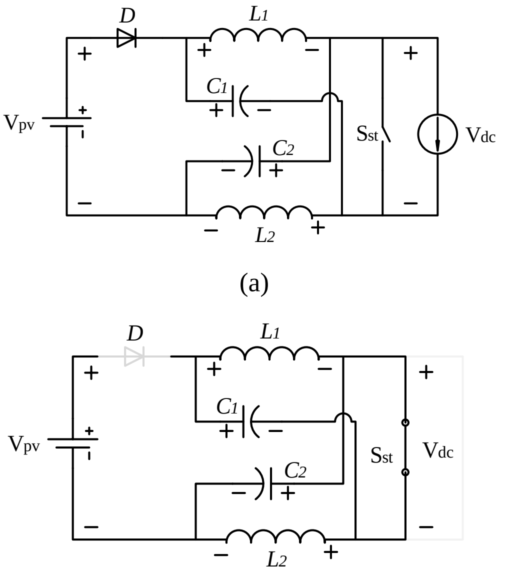


Fig. 1. The proposed control scheme for Z-source inverter based PV power conversion system.

This paper comprises five sections, in which the first section is the introduction. Section 2 gives an overview of the Z-source inverter topology for the proposed system. An extended and improved CVC strategy to control the Z-source capacitor is presented in details in Section 3. Section 4 discusses the simulation results by comparing the conventional CVC controller to proposed extended CVC controller. The proposed concept has been tested to ensure its validity. This has been done by using linear and non-linear loads for both controllers, where the dc-link inverter, capacitor voltage, the total harmonics distortion for the inverter voltage are analysed. All these discussions are finally followed by a conclusion in Section 5.

2. Z-Source Inverter Topology for the Proposed System

Z-source inverter (ZSI) consists of the equal number and arrangement with two capacitors and two inductors, coupling with the main inverter circuit to the dc input source from PV module [6], [23]. ZSI operates in three different modes: active (non-shoot-through) mode, a shoot-through mode, and traditional zero-state mode. The shoot-through mode is generated by an imaginary switch, S_{st} as shown in Fig.2. During active and zero-state modes as shown in Fig.2(a), the ZSI operates under the traditional pulse width modulation (PWM) pattern. In the shoot-through mode, the inverter bridge is seen as a short circuit from the dc-link point of view [21], [24] as represented in Fig.2(b).



(a)

(b)

Fig. 2. Operating modes of ZSI. (a) During non-shoot-through (b) During shoot-through

3. Voltage Control Technique of the Z-Source Inverter

This section explains the conventional capacitor voltage control and the implementation of the extended and modified control set for the allowable boundary condition. The discussions is categorized into several sub-chapters.

3.1. Review of existing MPPT with CVC for ZSI

The conventional MPPT algorithm produces only a shoot-through period (T_0) to boost the capacitor voltage at Z-network to the PV module voltage at MPP. There is no capacitor voltage control beyond this point. Thus, [25] proposed a conventional capacitor voltage control (CVC) algorithm in ZSI shoot-through technique. Fig. 3 shows the existing shoot-through generation with the CVC-based MPPT controller. During this process, an additional shoot-through period (T_0') is assisted by the control algorithm in order to have a constant capacitor voltage at impedance circuitry.

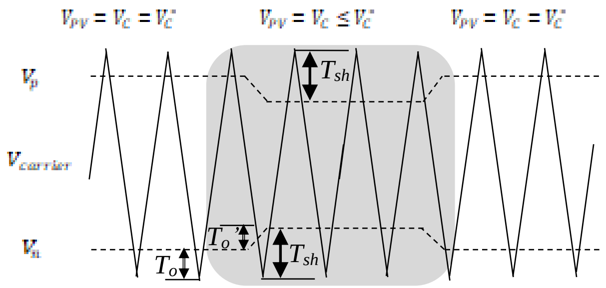


Fig. 3. Shoot-through generation by existing CVC controller [25].

From the Fig.3, the shoot-through time period can be calculated as follows:

$$T_{sh} = T_0 \pm T_0', \tag{1}$$

$$D_{sh} = \frac{T_{sh}}{T} = \frac{T_0}{T} \pm \frac{T_0'}{T}. \tag{2}$$

where T_0 is used to track voltage at MPP while T_0' is used to control the capacitor voltage correspond to the reference capacitor voltage V_C*. D_{sh} represents the total shoot-through duty ratio for one switching interval. The two straight lines (Vp and Vn) keep regulating to maintain the Z-network capacitor voltage in order to achieve a constant dc-link voltage as well. The reference straight lines are equal to:

$$V_P = \left(1 - \frac{T_{sh}}{T}\right) = \left(1 - D_{sh}\right) \tag{3}$$

$$V_N = -\left(1 - \frac{T_{sh}}{T}\right) = -V_P. \tag{4}$$

In which (Vp and Vn) are the controlled values that collaborated with modulation index, M. M can be varied from zero to Vp while the dc-link voltage or the average value of Z-source capacitor voltage can be obtained as:

$$v_{dc} = V_C = \frac{1 - D_{sh}}{1 - 2D_{sh}} V_{PV} = V_{PV}^*. \tag{5}$$

Nevertheless, this additional shoot-through period (T_0') have some drawbacks as it boosts the capacitor voltage to a greater extent. Unexpectedly, this will contribute to the unstable of capacitor voltage of Z-source inverter and affected to the dc-link voltage as well. Hence, an improvement to the controller seems to give advantage to overcome this issue.

3.2. The proposed extend algorithm on capacitor voltage control (CVC) strategy

For the reliability of the ZSI in PV generation system, the capacitor voltage at Z-source needs to be considered. Therefore, this paper proposes an extended modification of the CVC algorithm in order to increase the efficiency of control strategy by limiting the capacitor voltage from exceeding the allowable rated value. At the same time, it will increase the tracking efficiency of the MPPT and maintain the dc-link inverter. The concept and operating principle of extending modified CVC-based MPPT technique is described in this section.

The P&O as MPPT technique has been applied mainly due to their simplicity and robustness to generate shoot-through time interval (T_0) in order to extract the maximum power from the PV module [15], [16], [26]. As stated in Section 3.1, the CVC is used to control the Z-network capacitor voltage beyond the maximum power point voltage. It is calculated that using the shoot-through period (T_0), will boost the capacitor voltage to the MPP voltage point by combining with the additional shoot-through period (T_0') to control the capacitor voltage beyond the MPP voltage. However, this additional shoot-through period (T_0') has some drawbacks as it boosts the capacitor voltage to more than allowable limit which is not necessary and may cause the ZSI capacitor to be over rated. Fig. 4 shows the generation of the proposed controller with simple boost control method. The operation of ZSI has three modes as mentioned earlier. The shoot-through mode is given more consideration in this paper since the other two modes operate in the same manner as the traditional inverter operation. To enhance this mode of operation, a modification towards the controller is applied to the algorithm.

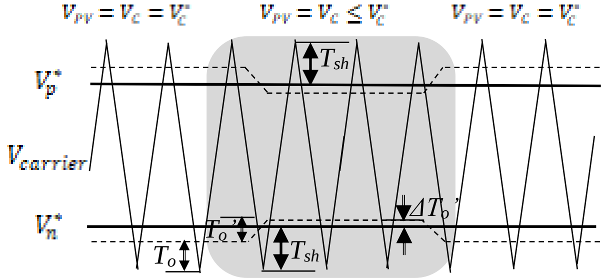


Fig. 4. Shoot-through generation by modified CVC control strategy.

P&O technique is used as a perturbation method where the terminal voltage and current of PV module are detected and processed to vary the shoot-through state (T_0) to reach MPP [27], and it will provide a further boost to the Z-source capacitor voltage when required. By increasing or decreasing the perturbation step size (ΔT_0), the amount of voltage across the dc-link will be obtained and maintained respectively. An extended algorithm has been added to the existing capacitor voltage control algorithm as shown in Fig.5. The CVC algorithm produces the additional shoot-through period (T_0') to track any reference capacitor voltage (V_C*) in which up to the maximum value of the capacitor would stand [28].

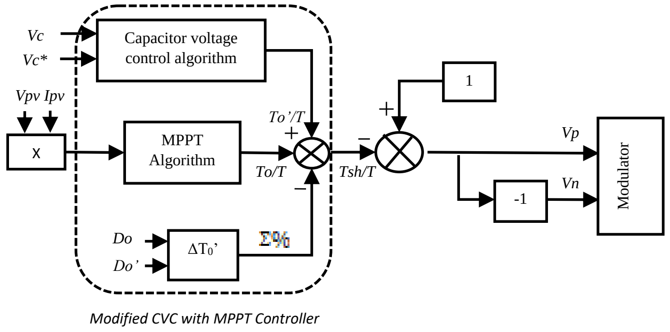


Fig. 5. Proposed CVC controller for ZSI-based PV conversion system.

In case of the allowable limit boundary for the capacitor voltage at ZSI, modification has been done by the additional shoot-through period. Specifically, the conventional capacitor voltage does not deal with the changes between shoot-through duty ratio, D_0 and the additional shoot-through duty ratio, D_0' (also known as $\Delta T_0'$). Here, by introducing the limit about $\mp\sum\%$ of $\Delta T_0'$ to the CVC algorithm, this improved algorithm gives a better performance in the tracking of V_C* and consequently able to give a constant dc-link voltage at the inverter input.

To verify the application of $\mp\sum\%$ $\Delta T_0'$, let the reference capacitor voltage, V_C* is equal to the voltage of PV at MPP, Vpv* and the shoot-through duty remains unchanged which is $D_0=D_0$ initially. Then, take the reference capacitor voltage, V_C* more than to the voltage of PV at MPP, Vpv*. Thus, the additional duty cycle requires to boost is $D_0'=X$ and the total shoot-through duty ratio (D_{sh}) will regulate a constant DC input value by $D_{sh}=D_0+X$. However, during the changes between those transition, D_{sh} there is an extra increment which is more than the desired level. Since then, an additional $\mp\sum\%$ will be applied to reduce the increment in delta changes of shoot-through over the additional shoot-through duty, $\Delta T_0'$, where $\Delta T_0'$ given as,

$$\Delta T_0' = \frac{D_0}{D_0'} . \tag{6}$$

The given flowchart in Fig. 6 shows the improved algorithm will be functioning whenever the actual capacitor voltage (V_C) is not equal to the given reference capacitor voltage (V_C*). There is no additional shoot-through (T_0') period generated when the actual voltage across the Z-source capacitor is equal to the reference voltage. Before comparing the V_C and V_C*, the Vc is set to be equal to the voltage at MPP. This is followed by the CVC algorithm. There are two possible conditions, if the Z-source capacitor voltage has to be increased significantly (V_C*>V_C), an additional shoot-through period (T_0') is generated by eliminating ∑% of $\Delta T_0'$ and is added to the T_0. If the reference voltage is less than the MPP voltage of the PV module (V_C*<V_C), the total shoot-through period is calculated by subtracting an additional shoot-through period (T_0') from the shoot-through time period (T_0) generated along with additional ∑% of $\Delta T_0'$ to provide a net shoot-through period (T_{sh}) to update the Z-source capacitor voltage (V_C). Hence, equation 1 and 2 can be redefined as follow:

$$T_{sh} = T_0 \pm T_0' \mp \sum\%\Delta T_0' , \tag{7}$$

$$D_{sh} = \frac{T_{sh}}{T} = \frac{T_0}{T} \pm \frac{T_0'}{T} \mp \sum\%\Delta T_0' . \tag{8}$$

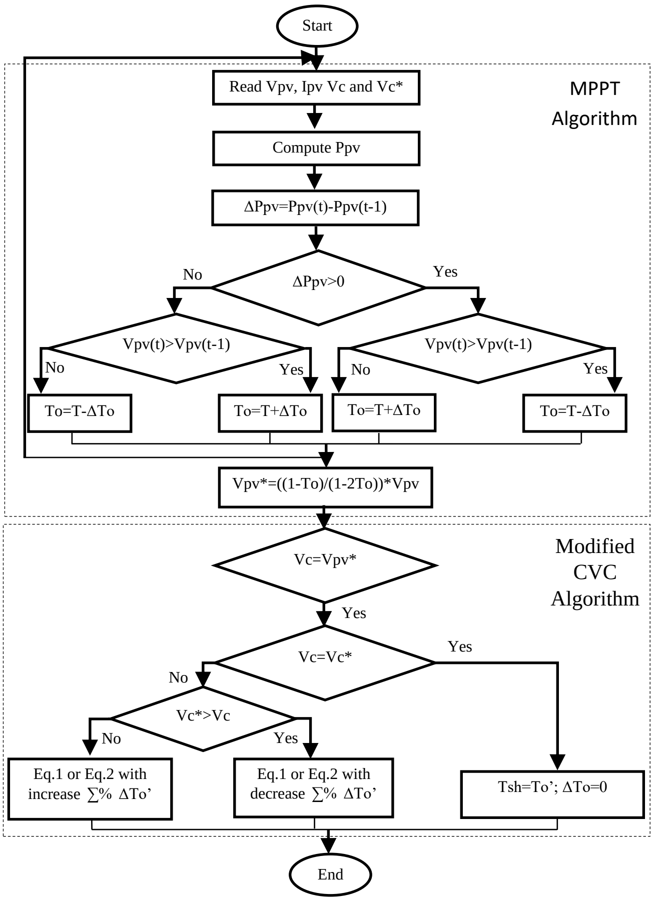


Fig. 6. Modified P&O based MPPT algorithm with improved CVC algorithm.

3.3. *Modulation scheme of pulse width modulation generation with extend CVC algorithm*

Fig. 7. shows a simple boost control (SBC) based on modulation technique for controlling the single-phase ZSI. In SBC, shoot-through is achieved by comparing the dc reference line with the triangular carrier wave. One sinusoidal reference signal is required to compare between the sinusoidal reference with a triangular carrier to generate gating signal for switches at the inverter.

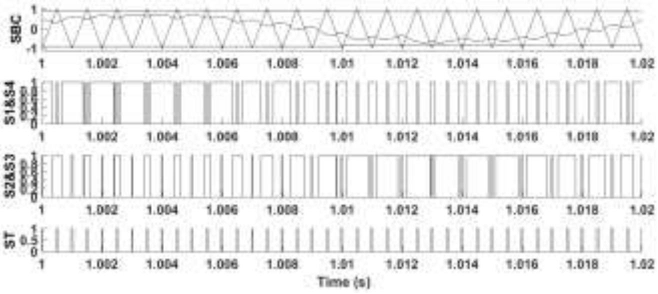


Fig. 7. The modified PWM and switching state of ZSI.

In addition, to have an extra switching based on the shoot-through topology, a quasi-resonant soft-switching Z-source inverter is necessary by adding a quasi-resonant network with only one auxiliary switch, S_{st} to achieve the soft-switching. All switches in the inverter are turned on and off under a zero voltage switching condition. During this condition, an inrush current of the inductor can damage the IGBTs due to the high rate of current changes [29]. Thus, this auxiliary switch is added to protect one leg of the inverter. This topology for ZSI has increased almost 10% of overall efficiency compared to the hard switching as suggested by [30]. Therefore, the auxiliary switch is added in parallel between Z-network and the inverter in this paper. This high-performance design structure can eliminate the possibility of the dc-link voltage drop with an additional advantage of being stable for all ranges of the modulation index during shoot-through state that had been proven in the simulation results section.

4. Simulation Results

The performance of Z-source inverter with the extended and improved capacitor voltage control technique is simulated using MATLAB/Simulink. Simulation results are separated into two cases; firstly, for linear resistive load, R=10Ω and secondly, with a diode rectifier as a non-linear load. The Z-source inverter parameters are $L_1=L_2=870\mu H$ and $C_1=C_2=2000\mu F$. The additional $\mp\sum\%$ of $\Delta T_0'$ to the algorithm is set to 12%.

4.1. Performance of PV system based Z-source inverter

For the simulation process, a variable condition of solar irradiance is utilized in order to see the effectiveness of PV-ZSI with its shoot-through effects. Fig.8 shows the performance of PV output voltage at MPP for both, conventional and modified controller. It can be seen that the proposed CVC has the ability to track voltage at MPP, VMPP*=17.1V about 0.08s faster compared to the existing algorithm can performed.

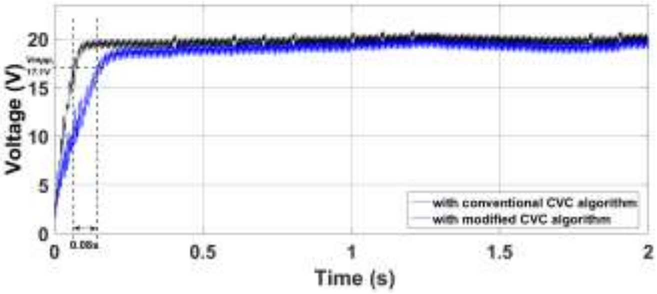


Fig. 8. PV output voltage at MPP

4.2. Z-source inverter with a linear load

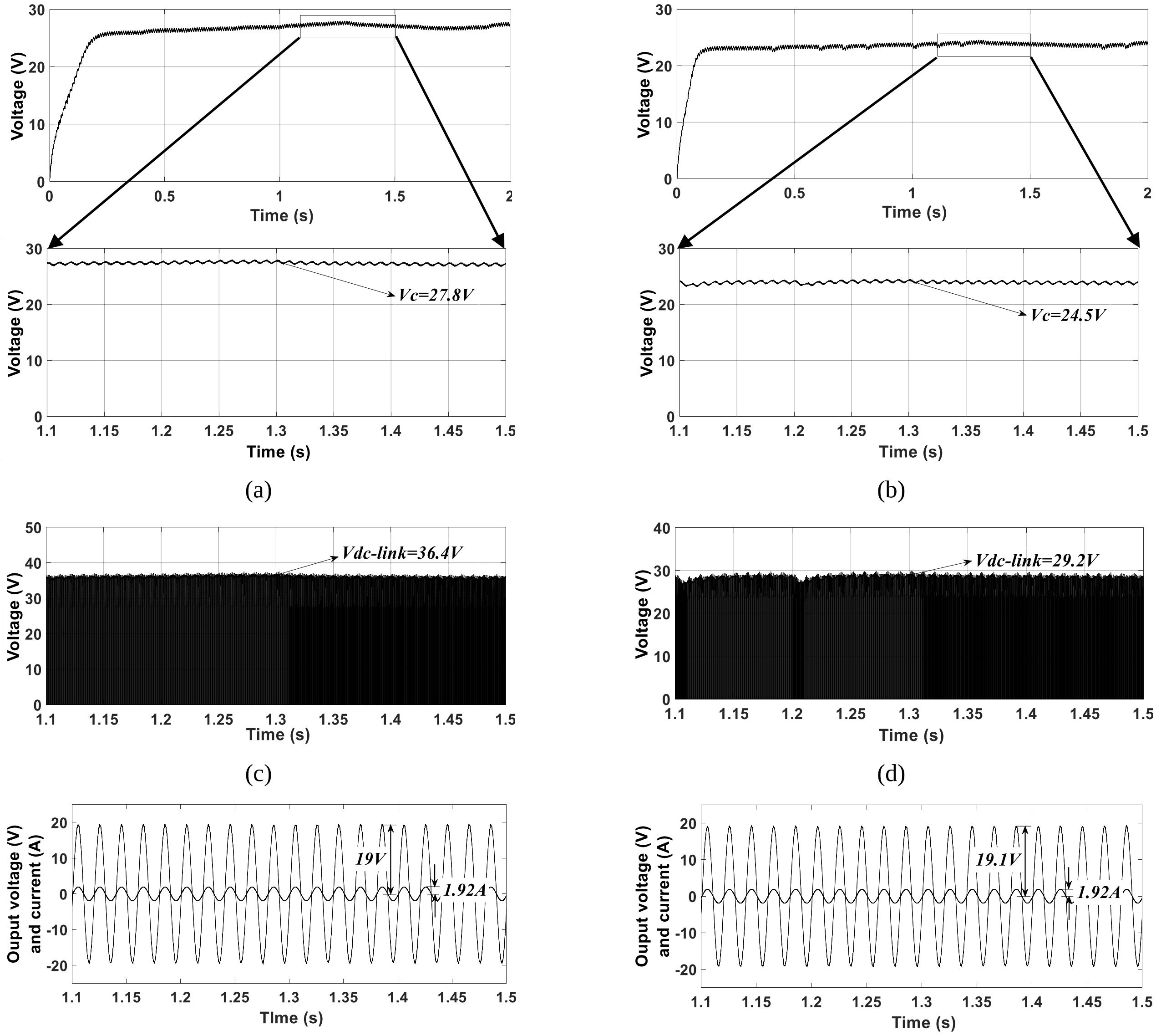
Fig. 9 shows the simulation results of the conventional and proposed controller with changes in input PV irradiation at constant 25˚C temperature for the first case. Here, Fig. 9(a) and (b) show the capacitor voltage at Z-network for both controllers (conventional and extend version). For the conventional CVC, the voltage is away from the reference voltage which is set to V_C^*=22V. This is caused by the over limit range of voltage by the additional shoot-through period (T_0') that will cause a problem to the Z-source capacitor. Meanwhile, Fig. 9(b) shows the proposed new control which does not effect to the changes of irradiation and it also able to maintain a constant capacitor voltage through simulation. Moreover, the proposed CVC algorithm can track the given reference voltage closer and faster as compared to the conventional CVC.

By comparing Fig. 9(c) with Fig. 9(d), the peak dc-link voltage for proposed CVC control is more stable than using the existing control algorithm. It is noticed that, whenever there is a change in irradiation, the enhanced shoot-through duty period is able to regulate the capacitor voltage beyond the MPP voltage smoothly. Fig. 9(e) and (f) show the AC output voltage and current at the linear resistive load, respectively.

The proposed CVC control algorithm is focused on shoot-through effect while remaining the non-shoot-through state is fixed. Clearly, the CVC controller is more effective at a lower shoot-through duty ratio, D_{sh} instead of having a higher D_{sh}. Furthermore, the analysis of total harmonic distortion (THD) by the output voltage of the proposed system shows an improvement. Fig. 10 shows THD_v is found to be 1.76% by using the existing CVC while the modified CVC has been reduced to 1.65%.

4.3. Z-source inverter with a non-linear load

As in the second test, Fig. 11 shows the simulation results for the single-phase Z-source inverter when connected to a non-linear load (uncontrolled rectifier). During the changing of irradiation, the existing CVC controller suffered more fluctuation and voltage ripple compared to the new control algorithm as shown in Figs. 11(a)-(d). Even the tracking speed for both control algorithm is almost at the same speed, the proposed control is able to maintain a constant capacitor voltage as well as the constant dc-link voltage. In addition, by comparing Figs. 11(e) and (f), the improved CVC gives better steady-state performances at the output of ZSI compared with the existing CVC. Fig. 11(g) shows the current at the rectifier which is a non-linear load condition. The output current of ZSI for both CVC controls is nearly the same. There is no current control in this study, therefore the performance of the output current is not discussed here. Nevertheless, the whole system of the proposed voltage control reduced THD_v from 20.60% to 16.67% for this case as shown in Fig.12.

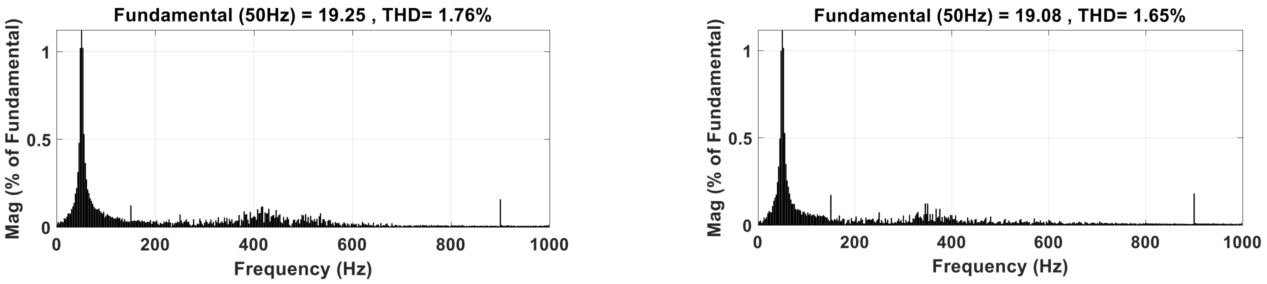


(a) (b)

(c) (d)

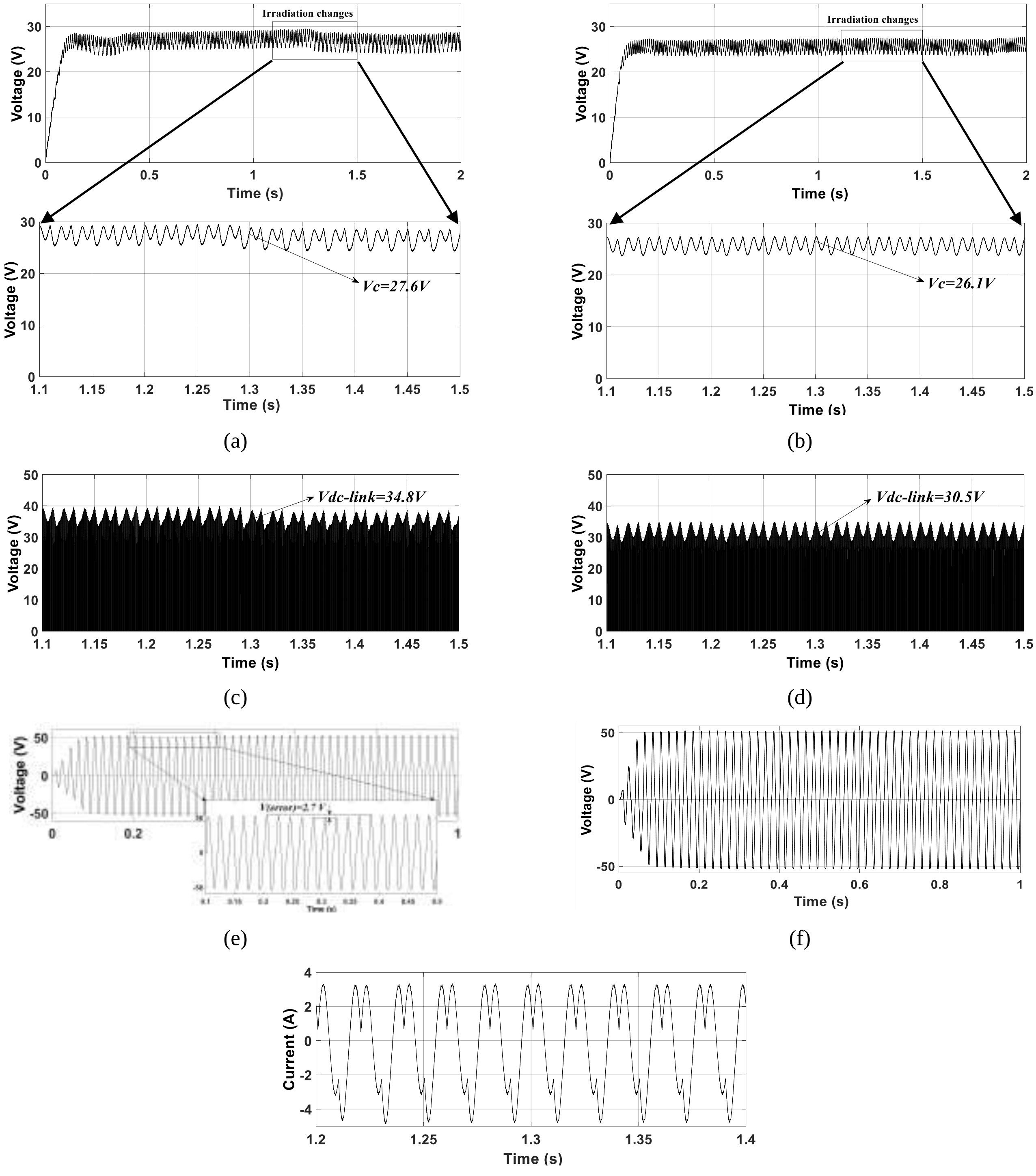
(e) (f)

Fig. 9. Comparison between the conventional and proposed capacitor voltage controller for a linear load. (a) and (b) capacitor voltage for conventional and proposed controller respectively, (c) and (d) output dc-link voltage of Z-source inverter, (e) and (f) AC output voltage and current at the load for both cases.



(a) (b)

Fig. 10. THD of output voltage for a linear load connected using (a) conventional CVC algorithm, and (b) proposed CVC algorithm.



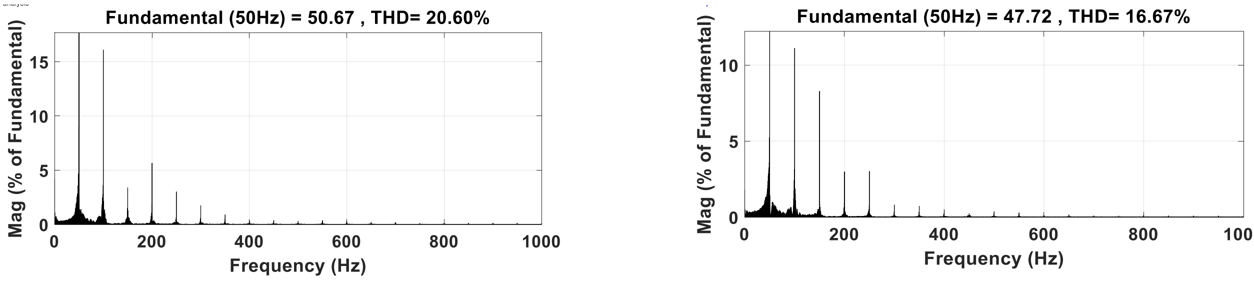
(a) (b)

(c) (d)

(e) (f)

(g)

Fig. 11. Comparison between the conventional and proposed capacitor voltage controller for a non-linear load. (a) and (b) capacitor voltage for conventional and proposed controller respectively, (c) and (d) output dc-link voltage of Z-source inverter, (e) and (f) output voltage of inverter for non-linear load, and (g) current on rectifier type of non-linear load connected to the output.



(a) (b)

Fig. 12. THD of output voltage for a non-linear load connected using (a) conventional CVC algorithm, and (b) proposed CVC algorithm.

4.4. *Comparative analysis of capacitor voltage control at Z-source inverter*

Fig. 13 shows the line graph of the performance analysis on capacitor voltage at Z-source inverter for the existing CVC controller compared to the improved CVC controller. The plotted lines indicate a clear observation to both cases, connected with linear and non-linear load. Extended capacitor voltage control algorithm is seemed closer to the given reference capacitor voltage as can be seen at line II. In addition, the proposed CVC shows an ability to maintain capacitor voltage at impedance network as well as constant dc-link voltage for non-linear load performed by line IV. In contrast, the conventional CVC for both cases is far from the reference capacitor voltage of ZSI especially during changes in irradiation.

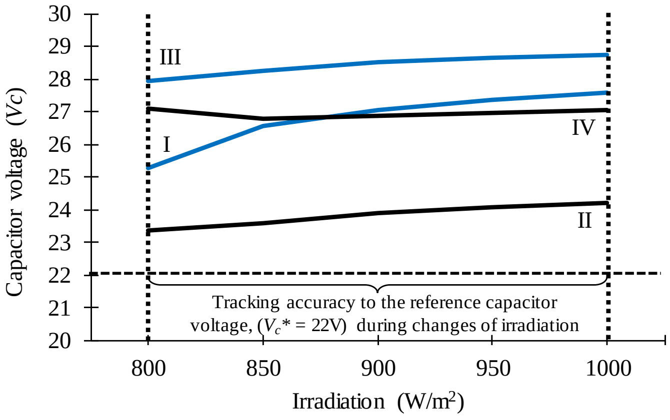


Fig. 13: Performance of capacitor voltage of ZSI in tracking reference capacitor voltage by using existing and modified CVC controller.

5. Conclusion

This paper presents an extended controller on CVC for the shoot-through effect in order to maintain the capacitor in Z-source whenever the PV input is changing. Moreover, it gives fast-tracking for voltage signal with the given reference capacitor voltage and at the same time it constantly maintains the dc-link capacitor between the allowable limit voltage compared to the existing CVC controller. As verified in simulation results, the dc-link inverter voltage can be raised by approximately 1.2 times from the initial PV input voltage in the low shoot-through duty ratio of 0.158. It is clearly stated here by a small amount of duty cycle in shoot-through, the output can be increased to about 120% for the initial input. This proved that introducing $\mp\sum\%$ of $\Delta T_0^{'}$ to the control algorithm helps in achieving a better steady-state performance, more stable output voltage and reduces the total harmonic distortion as compared to the traditional CVC in the MPPT algorithm. This paper has also shown that the extended version control has a much better output compared to the normal CVC in MPPT algorithm in terms of stabilizing the output of PV whenever the irradiation of the PV is changed.

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