INDIRECT CONTROL OF PEAK DC-LINK BOOST AND AC OUTPUT VOLTAGE OF THE MODIFIED Z-SOURCE INVERTER FOR POWER CONDITIONING SYSTEM

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Abstract – The emerging impedance source inverter topologies provide an efficient power conversion suitable for almost all renewable energy sources to be used by loads or fed to the grid. This paper presents a simple indirect control strategy for modified Z-source inverter (ZSI) integrated power conditioning system to ascertain constant DC link boost voltage under wide input voltage variations and constant AC output voltage under load variations. An enhanced Space Vector Pulse Width Modulation scheme with feedback control is presented to achieve both DC boost and AC output voltage at desired level without any steady state errors. With this proposed control technique the system has good reference tracking, excellent disturbance rejection, and fast transient response. Voltage ride through capability during input voltage sags and swells is achieved which is essential for Power Conditioning Systems (PCS). The feasibility of the proposed control technique is validated with results obtained using Matlab / Simulink.

Keywords: *Modified Z-source inverter, Enhanced SVPWM, Indirect control strategy, Ride through capability, Power Conditioning System*

1. INTRODUCTION

The recently developed modified Z-source inverter is attracting attention in renewable energy based Power Conditioning Systems. Generally an inverter interfaced system is known as Power Conditioning System (PCS). The traditional PCS requires an additional DC - DC boost converter which increases system complexity and thus reduces efficiency and reliability. The Z-source inverter (ZSI) is a single stage power converter that can perform DC-DC, DC-AC, AC-AC and AC-DC conversion efficiently without any front end boost converter [1]. Hence reduces the cost of the system and increases reliability. The modified Z-source inverter has two inductors and two capacitors connected in X-shape with connection directions illustrated in Fig.1. Compared with traditional Z-source inverter topology, voltage stress across capacitors in modified ZSI is greatly reduced, inrush current at startup is eliminated and soft start strategy is achieved with same boost capability [2].

The unique features of modified Z-source inverter can be effectively utilized for renewable energy systems. Renewable energy includes Solar, Wind, Battery, Fuel cells etc. The output voltage of renewable energy sources depend on many uncontrolled factors in nature such as temperature, humidity, irradiation, wind etc. Hence the output of renewable energy sources are always fluctuating and varying. To overcome the above limitations and to meet the technical challenges, the recently emerging Z-source inverter concept can be introduced to PCS for renewable energy sources.

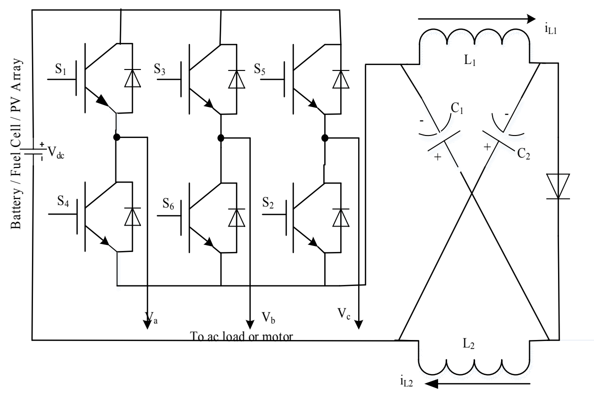

Figure. 1. Modified Z-source Inverter

This paper presents modified Z-source inverter for renewable energy systems. Many grid connected systems require constant output voltages during input voltage variations and load fluctuations. As explained in [3] the DC side of modified Z-source inverter has non-minimum phase characteristics. Because of energy resettling at impedance network, the input DC voltage fluctuations are transferred to DC link boost voltage thereby significant overshoot and undershoot happens at DC Link and this could be further transferred into output inversion stage, resulting distorted output waveforms. Hence it is essential to design a suitable controller with good disturbance rejection and fast transient response to overcome the aforementioned limitations of renewable energy sources. Many linear and non linear control strategies for both DC and AC sides were discussed and validated in [4] - [17]. The two popular methods are Capacitor voltage control and DC Link boost control. Using capacitor voltage control method, capacitor voltage is maintained constant but the change in input voltage affects DC link boost and it is transferred to AC side. In DC link boost control, direct sensing of DC link high frequency pulsed voltage is difficult. Hence it is essential to design a suitable controller with indirect control of DC link voltage [18]-[19].

This paper proposes an indirect control of DC link boost by sensing input DC voltage to perform rough regulation and to maintain constant DC link boost voltage under wide input voltage variations. Feedback control strategy with delicate regulation is proposed to maintain constant output voltage under load variations. Enhanced Space Vector Pulse Width Modulation (SVPWM) scheme is used to generate switching signals in order to minimize inductor current ripples. Thus reduces the size of required passive components. This indirect control strategy has two degree of freedom, such as shoot through duty ratio with saturation level control and selection of Modulation Index to obtain quality output waveforms. By properly designing the controller, transferring of the input DC side disturbance into AC inversion side can be avoided.

2. DC LINK VOLTAGE CONTROL IN MODIFIED ZSI

The modified Z-source inverter is shown in Fig.1 as derived and explained in [2]. The capacitor voltage $\mathbf{V_C}$ and Peak DC Link voltage $\mathbf{V_{dc\,link}}$ is

$$\mathbf{V_C} = \frac{D_{sh}}{1-2D_{sh}}\left(V_{dc}\right) \quad (1)$$

$$\mathbf{V_{dc\,link}} = \frac{1}{1-2D_{sh}}\left(V_{dc}\right) \quad (2)$$

Where D_{sh} is the shoot through duty ratio and the boost factor **B** can be represented as

$$\mathbf{B} = \frac{1}{1-2D_{sh}} \qquad (3)$$

During shoot through state the DC link voltage is zero and during non shoot through state the DC link voltage reaches its maximum thereby obtaining high frequency pulse waveform. Direct sensing and deriving peak value of pulse waveform is difficult. From equation (2)

$$\mathbf{D_{sh}} = \frac{1}{2} - \left(\frac{V_{dc}}{2V_{dclink}}\right) \qquad (4)$$

Let the required peak DC link voltage be $\mathbf{V_{ref}}$ then equation (3) can be rewritten as

$$\mathbf{D_{sh}} = \frac{1}{2} - \left(\frac{V_{dc}}{2V_{ref}}\right) \qquad (5)$$

From equation (5), shoot through duty ratio can be calculated by sensing input DC voltage. The indirect controller adjusts the shoot through duty ratio $\mathbf{D_{sh}}$ during variations of input DC voltage $\mathbf{V_{dc}}$ thereby simply maintains constant DC link voltage. Good regulation can be achieved in the input side.

Complex algorithms and sensing circuits are not required to maintain constant DC link voltage. The input voltage variations in renewable energy sources could be avoided by varying shoot through duty ratio $\mathbf{D_{sh}}$. In boost mode $\mathbf{V_{dc}}$ is less than reference DC link voltage $\mathbf{V_{ref}}$; shoot through duty ratio increases when $\mathbf{V_{dc}}$ decreases; while in non boost mode $\mathbf{V_{dc}}$ is greater than reference DC link voltage $\mathbf{V_{ref}}$; $\mathbf{D_{sh}}$ will be zero and modified Z-source inverter behaves like conventional voltage source inverter.

3. AC OUTPUT VOLTAGE CONTROL

The DC link boost voltage control at input DC side provides good regulation during wide input voltage variations. During load fluctuations output AC voltage should be maintained constant to improve the performance of entire system. Fig. 2 illustrates the DC and AC side control of Modified Z-source inverter for power conditioning system. The input may be Battery, Fuel Cell, Solar PV, Wind etc.

The three phase output voltage of inverter is measured to calculate the peak value of output phase voltage as per equation (6).

$$V_P = \sqrt{\frac{2}{3}\left(V_a^2 + V_b^2 + V_c^2\right)} \qquad (6)$$

During steady state, the phase voltages are

$$V_a = V_m Sin(wt) \qquad (7)$$

$$V_b = V_m Sin(wt - 120^\circ) \qquad (8)$$

$$V_c = V_m Sin(wt + 120^\circ) \qquad (9)$$

From equations (6) – (9) the peak phase voltage is,

$$V_P = V_m \qquad (10)$$

V_P is a constant DC value. Hence there is no steady state error in the reference peak phase voltage and output phase voltage under load variations. The output voltage is maintained constant by appropriate design of PI controller in feedback loop as illustrated in Fig.2. The error signal and shoot through duty ratio with selected saturation level are given to Enhanced SVPWM module for signal synthesis to obtain gate signals of IGBT switches. Both DC Link boost and AC output voltages are regulated with good reference tracking and fast transient response by the proposed simple indirect control strategy.

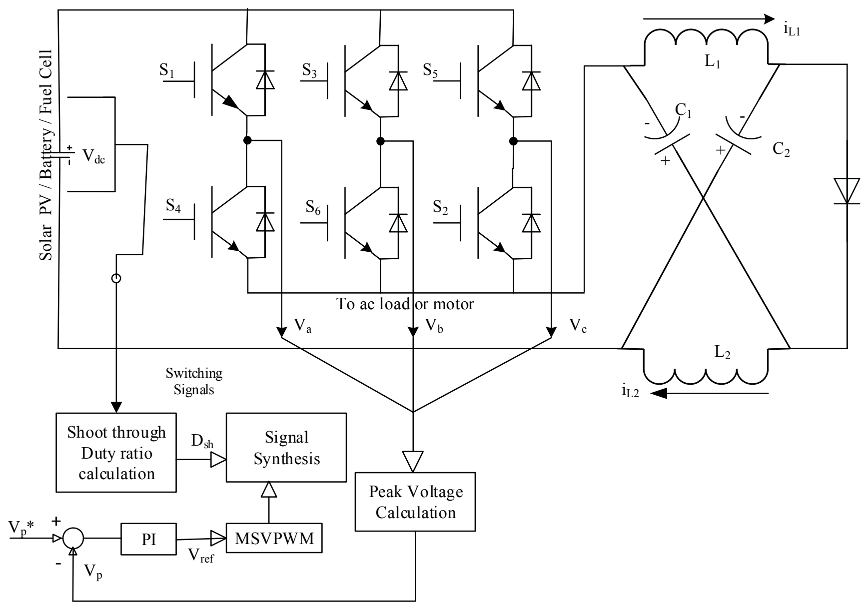

Figure. 2. Block Diagram for both DC Link boost and AC Output Voltage Control of Modified ZSI

4. ENHANCED SVPWM STRATEGY

Space Vector Pulse Width Modulation Techniques are most popular and widely used at industrial applications of PWM inverters and Power Conditioning Systems because of their lower current harmonics and higher modulation index compared to conventional pulse width modulation techniques[20]. SVPWM technique is best suited for controlling shoot through states of modified Z-source inverter. There are seven shoot through states that short circuits any one phase leg, any two phase legs or all three phase legs. Shoot through states of any one phase legs are used to control the DC link capacitor voltage and can partially diminishing the null states within a fixed switching cycle by short circuiting the three phase inverter phase legs and producing zero voltage across the AC load [21]-[22].

As an illustration, Fig. 3 shows the Enhanced Space Vector Pulse Width Modulation by inserting the shoot through states in existing SVPWM state patterns of a traditional VSI for controlling a three phase leg modified ZSI topologies. In conventional SVPWM technique, six state transitions in one carrier period $\mathbf{T_s}$ are possible. Preferably, six equal interval shoot through states are inserted at every transits and null states are partially diminished and again equal interval null states are maintained at the start and end of the switching period $\mathbf{T_s}$ to realize the same harmonic performance. By keeping the active state time period constant, shoot through states are inserted immediately adjacent to the left of first state transit and to the right of second state transit and so on. This way of inserting shoot through states ensures single device switching at all transitions and allows the application of only one phase leg to undergo shoot through condition. The other shoot through states cannot be used since they require the switching of two or three phase legs at every transition. In this manner, correct insertion of shoot through states during falling and rising carrier edge leads to better harmonic profile and minimum current ripple across the inductors connected in impedance network. Hence size of the inductors can be reduced.

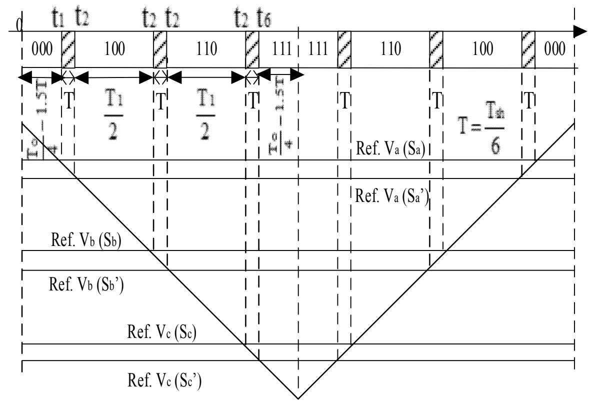

Figure. 3. Sketch Map of Enhanced SVPWM

T_s = Time period for one Switching cycle
T_{sh} = Shoot-through time period
T_1, T_2 = Time interval for active states
T_0 = Time interval for Null states

Thereby Enhanced SVPWM provides greater flexibility to optimize switching waveforms.

5. DESIGN OF IMPEDANCE NETWORKS

Designing impedance network is not the main scope of this paper. But based on the analysis and verification done by [23]-[24], the impedance network L_1, L_2 and C_1, C_2 were designed. The inductors and capacitors at input side can act as filtering and storing elements which improves the power quality at ac side. Generally we require inductors either in the input side or in the output side to improve the power factor. These inductors at input side can limit the current ripple through the devices during shoot through state which act as boost mode. Capacitors at input side can absorb the current ripple and maintain almost constant voltage to keep the output voltage sinusoidal. To avoid undesirable operating modes called as pseudo active states, the impedance network elements should satisfy the following conditions as derived, explained and verified in [23]-[24].

$$C \geq \frac{D_{sh} I_l}{2 f_s \Delta V_c} \quad \text{and} \quad L \geq \frac{D_{sh} I_c}{2 f_s \Delta I_l}$$

Where

D_{sh} - Shoot through duty ratio
I_l - Average inductor current
V_c - Capacitor voltage ripple at peak power (5% is chosen)
I_l - Inductor current ripple at peak power (5% is chosen)
f_s - Switching frequency

6. SIMULATION RESULTS, DISCUSSION AND ANALYSIS

Modified Z-source inverter with Enhanced Space Vector Pulse Width Modulation control strategy is simulated using Matlab / Simulink environment. The input voltage is varied from 200V to 400V; Switching frequency is 10 Khz; $L_1 = L_2 = 500\mu H$; $C_1 = C_2 = 1000\mu F$; Cut off frequency of output LC filter is 1 Khz; Output voltage is chosen for 110V applications; Three phase R load of 3KW is connected Three phase AC load is varied from 750W to 3000W to observe the response of system during load changes;

For all the figures, **Fig. 4** to **Fig. 7** from the top, shows Input DC voltage, Capacitor Voltage, DC Link boost voltage, Inverter output L – L voltage, Load Voltage and Load Current.

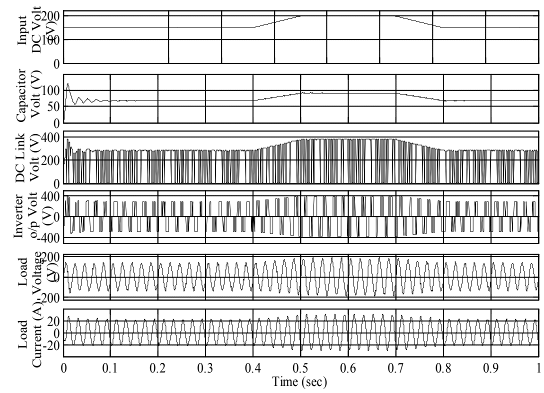

Figure. 4. Simulation results without any Controllers

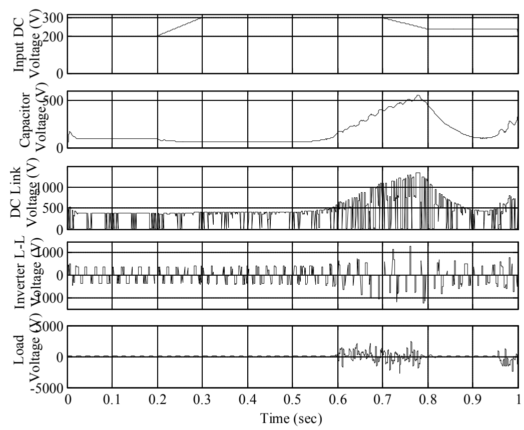

Figure. 5. Simulation results with input DC Link boost voltage Controller but without output AC voltage controller

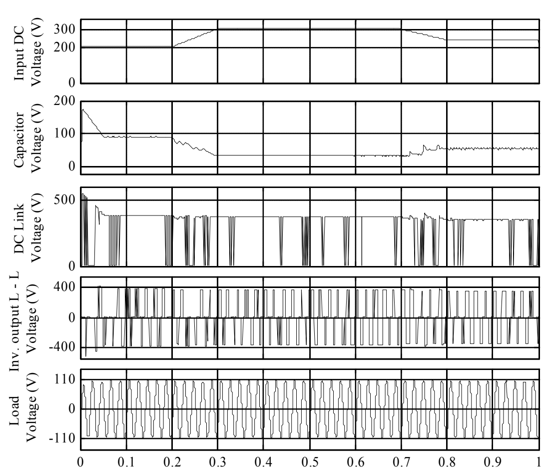

Figure. 6. Simulation results with input DC Link boost voltage Controller and output AC voltage controller

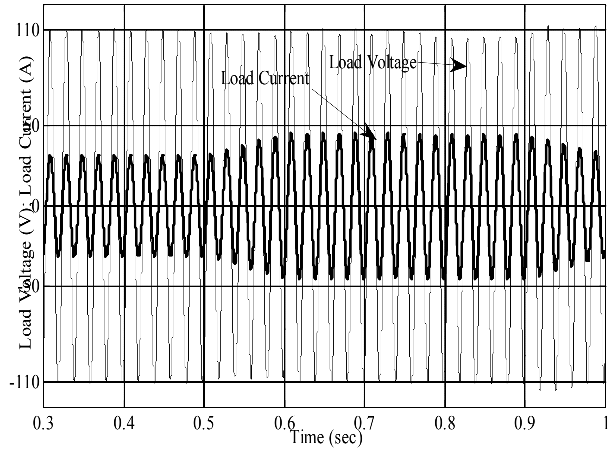

Figure. 7. Simulation results of load voltage and load current when three phase R load varies from 750W to 3KW

Fig. 4 shows the simulated results of modified Z-source inverter without any controllers. The step change in input voltage is being transferred to AC side is clearly visible. Fig. 5 shows the simulation waveforms of modified Z-source inverter with DC side controller but without any controller at output load side. Hence load fluctuations at 0.6sec affect the system stability and voltage regulation in the AC side as well as DC side.

Fig. 6 shows the simulation results of the proposed Modified Z-source Inverter with DC link Boost controller and AC output voltage controller.

In order to improve the dynamic response, to eliminate over shoot, under shoot and steady state errors, to keep the DC link boost voltage constant and to have good ride through capability, shoot through interval is adjusted by the DC side controller with proper saturation level. Hence transferring of DC side voltage sag and swell can be avoided with greater ride through capability.

In Fig. 6 the input DC voltage varies from 200V to 300V at 0.6sec and decreases from 300V to 240V at 0.7sec. The DC side controller senses the input DC voltage and adjusts the shoot through interval indirectly. This indirect controller keeps the DC link Boost voltage constant but varies the capacitor voltage, thereby minimizing voltage stress across the switches used in the inverter. Transferring these effects into AC side is avoided by the proposed controller. Moreover AC side controller adjusts the modulation index with respect to shoot through duty interval and keeps the AC output voltage constant.

Fig. 7 shows the application load change at 0.5sec and 0.9sec respectively. This load change may demand more energy from DC side causes an undershoot in DC link voltage. But these effects could be avoided by the proposed control technique with PI controller in the AC side.

Compared with traditional Z-source inverter, the connection directions of capacitors used in Modified Z-source inverter are reversed. Hence there is a possibility of negative voltage across capacitors during transient period. This effect is avoided by the application of proposed controller. But the speciality of this topology is reduction in capacitor voltage stress across capacitors, hence reduction in the size of capacitors.

Enhanced Space Vector Pulse Width Modulation Strategy minimizes the current ripple across the inductors in impedance network; hence there is a reduction in inductor size. Thus reduction in cost of passive elements ed.

Despite the presence of input and output disturbance the proposed system has better ride through capability, good reference tracking and reasonable disturbance rejection.

7. CONCLUSION

In this paper, an indirect controller was developed for controlling DC link boost voltage and AC output voltage in Modified Z-source inverter fed Power Conditioning System. Enhanced Space Vector Pulse Width Modulation Strategy was employed to minimize the ripple in inductor current. By simulating in open loop mode the DC side effects were transferred to AC side. In closed loop mode with proposed controllers considered separately at DC side and AC side the aforementioned effects was eliminated. The system showed good robustness. It was clear that the system showed good disturbance rejection, fast transient response and better ride through capability during input voltage variations and during load fluctuations. In all renewable energy sources, the voltage was subjected to change due to external properties. But the proposed Modified Z-source inverter fed power conditioning system with indirect controllers could withstand and overcome the aforementioned drawbacks. The designed controllers with appropriate impedance network proved the rigid performance of Power Conditioning System.

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