PERFORMANCE ANALYSIS OF AN IMPROVED Z-SOURCE INVERTER INTEGRATED STANDALONE POWER SYSTEM WITH RIDE THROUGH CAPABILITY UNDER DIFFERENT LOAD CONDITIONS

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Abstract- Standalone or off-grid power systems are demand-driven and can be installed in isolated places. Solar PV, tidal, wind, etc are mostly used as input energy source in standalone power systems. In order to facilitate and assure the sustainability, quality and reliability, this paper presents an Improved Z-Source Inverter (IZSI) integrated standalone power system with ride through capability during input voltage changes and load variations. The traditional dual stage inverter can be replaced with the recently developed single stage Improved Z-source inverter. The DC input voltage obtained from alternate energy sources are subjected to fluctuations due to several uncontrolled factors that can be further transferred into AC side of standalone power systems. To improve the quality of output waveforms and to reduce the effect of source voltage sags and load side fluctuations in an off-grid system, closed loop controllers are essentially required. The feedback controllers with feed forward loop has been modeled and designed under stationary reference frame. Thereby transferring of DC side fluctuations into AC side has been avoided. The feasibility of the proposed system is validated by extensive simulation using MATLAB/Simulink. Furthermore, fast transient response and better reference tracking have been obtained for IZSI integrated standalone power system.

Keywords- *Standalone power system; Improved Z-source inverter; Sustainable energy; Induction motor; Ride through capability.*

I. INTRODUCTION

The progressive rising of energy demand leads to the development of standalone power systems. They are small and self-contingent and can be employed in remote areas such as islands. The prerequisites for off-grid systems are economically producing energy and utilizing energy efficiently. Sustainable standalone systems can provide an economic solution for local generation and distribution of power. The traditional standalone power system is illustrated in Figure 1. The major components of standalone systems are input power source, batteries for backup and an inverter. The alternate energy sources like solar PV, wind, fuel cell, tidal, biomass, hydro, etc are generally used as input power source. The standalone systems solely depend on the onsite power generation, and hence back up batteries are essential. Nowadays, the traditional voltage source inverter (VSI) or current source inverter (CSI) is used as an interface in standalone systems. They can be operated in either buck mode or boost mode. They have many restrictions and limitations such as less reliability; reduced energy efficiency; electromagnetic interference problem; need of dead time to avoid shoot through of power switches and reduced operating range. Hence an intermediate DC-DC boost converter is required to boost the available DC- link voltage. Hence traditional inverter setup requires two stages of conversion, which is complex and expensive.

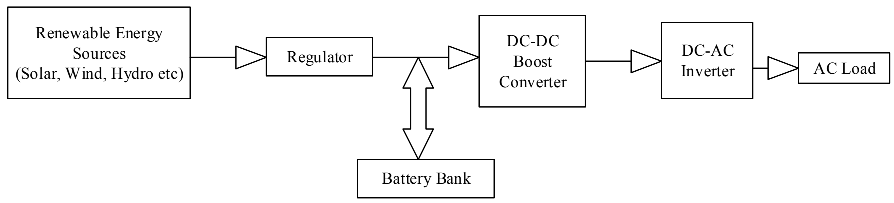

Figure 1. General block diagram of traditional Standalone power system

For better power conditioning, the two stage inverter setup can be replaced by the recently emerged improved Z-source inverter in standalone power system. As illustrated in Figure 2, the improved topology of Z-source inverter has two equal value inductors and two equal value capacitors connected in X-shape with a diode. Improved ZSI is buck-boost in nature, produces any value of current or voltage up to its rating and eliminates the need of DC-DC boost converter [1-2]. Hence reliable and economic implementation is possible for standalone power system. The standalone power system applications require quality output voltage and current waveforms, better harmonic profile and capability to withstand load fluctuations and wide input voltage variations. The aforementioned requirements can easily be achieved by proper designing of closed loop control system. The feedback controllers with current and voltage control is modeled and designed in this paper. This cumbersome task can be implemented easily for IZSI based standalone system by sensing and controlling the impedance network capacitor voltage and three phase AC output voltage of the inverter. The Improved ZSI and designed controllers are combined together as a unique single unit to deliver the desired power and frequency with better regulation [3]. Nowadays the cost of renewable energy generation is going on decreasing, and so the proposed standalone system with good self-regulation can be implemented economically at affordable cost.

Most of the research papers published in the aforementioned field is discussing the design of an open loop control system [4]. Till today, many linear controllers [5-9] and non-linear controllers like sliding mode control [10], model predictive control [11] etc. have been designed and implemented for various applications. They are very complex in nature.

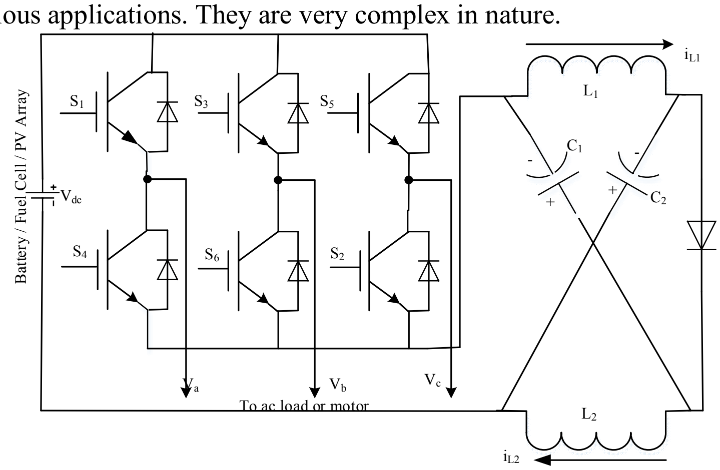

Figure 2. Improved Z-source inverter topology

Space vector pulse width modulation technique has been used in adjustable speed AC drives for better harmonic profile. Closed loop controllers with an ability to control both AC output and DC boost voltage are designed and implemented for traditional Z-source inverter based utility applications. Comprehensive design and modeling of controllers for traditional Z-source inverter DG systems have been implemented [12-13].

But, there is a void in using Improved Z-source inverter (IZSI) for standalone applications with proper controllers for controlling and maintaining desired DC link boost voltage and AC output voltage. This opens up a new dome to get on design and implementation of closed loop controllers for

IZSI based standalone power system with ride through capability; good reference tracking; fast transient response and zero steady state error.

II. REVIEW OF IMPROVED Z-SOURCE INVERTER AND ITS CONTROL TECHNIQUES

As discussed and implemented in [14], an improved ZSI has very less capacitor voltage stress than that of classical ZSI. This can be achieved by reversing connection directions of capacitors, inductors and diode as illustrated in Fig.2. Hence reduction in the size of capacitors required thus minimizes the cost. ZSI topologies can withstand and advantageously utilize the shoot through or cross conduction of switches in the same phase leg due to the presence of impedance network. Hence mis-gating of switches or short circuit problem can be overcome. By gradually varying the shoot through duty ratio, a soft-start strategy can be achieved. Hence inrush current problem of classical ZSI can be overcome. The boost capability of both classical and improved topology remains the same.

Control techniques of classical ZSI can also be applied to improved ZSI with the same boost capability. Each control technique has its own advantages and disadvantages. They can be classified into two groups such as constant shoot through duty ratio control and variable shoot through duty ratio control. In the constant shoot through control technique,

Modulation Index (MI) = 1 D_{sh} (1)

Where D_{sh} is the shoot through duty ratio; the dependability of MI with shoot through duty ratio leads to one degree of freedom to control. Moreover, the maximum value of shoot through duty ratio is 0.5; reduction in MI increases the voltage stress across the switches;

By employing a control technique with one degree of freedom, either the DC side or three phase AC side can be regulated. Simultaneous regulation of both DC and AC sides cannot be achieved [15]. Hence it is required to employ a control technique with two degrees of freedom for the regulation of both DC link boost and three phase AC output voltage. The enhanced space vector pulse width modulation technique has two degrees of freedom to control and regulate the DC side as well as AC output of three phase inverter. D_{sh} can be controlled independently [16-18]. The objective of this work is to control and regulate the IZSI based standalone power system in a distinctive manner.

2.1 Enhanced space vector pulse width modulation (SVPWM) technique

The most popular and extensively used control technique is Space Vector Pulse Width Modulation (SVPWM) control. The existing VSI based standalone systems are using traditional SVPWM technique because of their lower current harmonics and higher modulation index. The traditional SVPWM technique is enhanced to design a closed loop controller and to control shoot through duty ratio for an IZSI based standalone power system. An optimization of switching waveforms can easily be achieved with greater flexibility. As an illustration, Figure 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 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[19]. This way of inserting shoot through states ensures single device switching at all transitions and allows only one phase leg to undergo shoot through at a time. The other shoot through states cannot be used since they require the switching of two or three phase legs at every transition. Hence reduces the common mode voltage and leakage currents in AC drives [20].

$$t_1 = \frac{T0}{4} - \frac{3}{2}T_{sh} \quad (2)$$

$$t_2 = \frac{T0}{4} - \frac{1}{2}T_{sh} \quad (3)$$

$$t_3 = t_2 + \frac{1}{2}T_1 \quad (4)$$

$$t_4 = t_3 + T_{sh} \quad (5)$$

$$t_5 = t_4 + \frac{1}{2}T_2 \quad (6)$$

$$t_6 = t_5 + T_{sh} \quad (7)$$

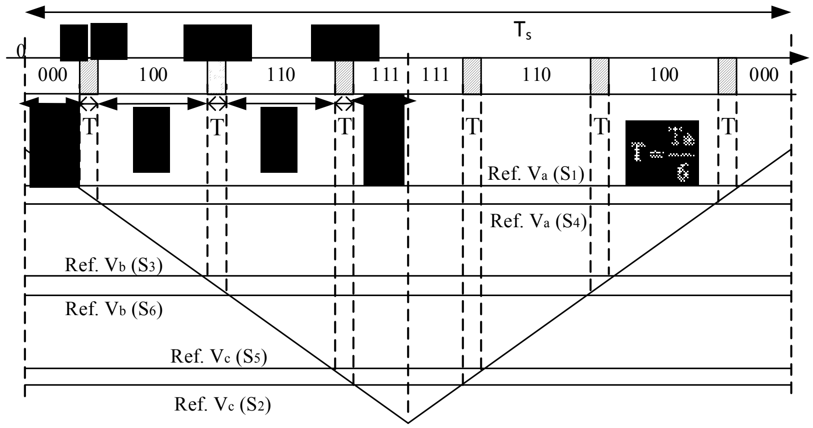

Figure 3. Sketch map of Enhanced SVPWM

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

In this manner, correct insertion of shoot through states during falling and rising carrier edge leads to minimum switching losses and better harmonic profile. During the shoot through or cross conduction period the DC link voltage is zero and otherwise reaches its maximum as illustrated in Figure 4.

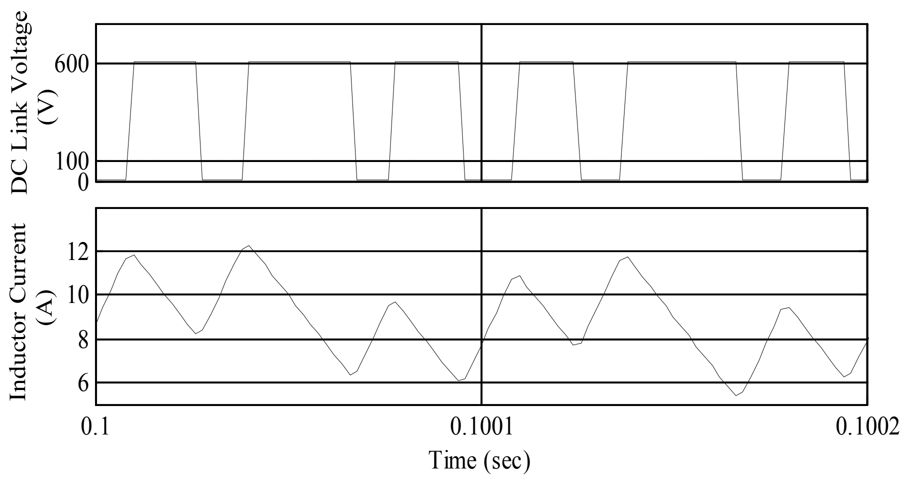

Figure 4. Inductor current ripple and DC link voltage

III. CONTROL METHODOLOGY

This paper proposes a simple control technique as illustrated in Figure 5 to achieve whole system stability and to guarantee global inverter operation in power conditioning based standalone power system. The impedance network capacitor voltage at input side and output AC voltage need to be sensed for better and easy control of input voltage sags and output load fluctuations. The DC side capacitor voltage can be effectively controlled by adjusting shoot through duty ratio, whereas the output AC voltage can be controlled by modulation index. Hence two degrees of freedom control is available to regulate the entire standalone power system. Adopting enhanced SVPWM technique makes the implementation easier [21].

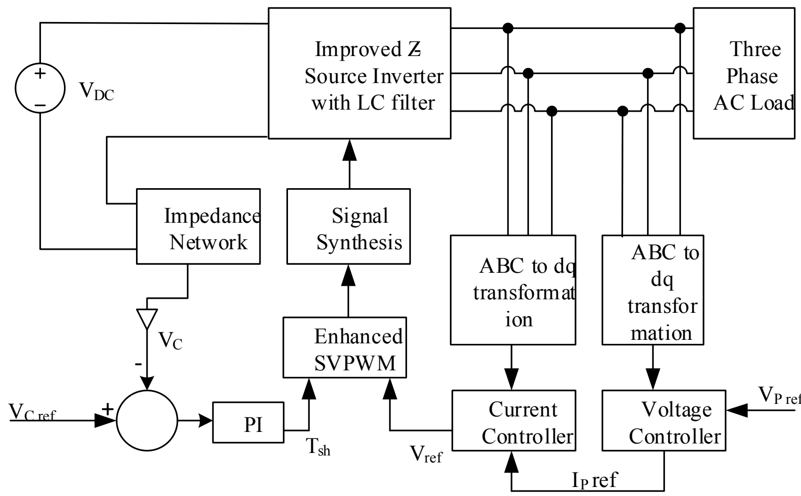

Fig. 5 Block diagram for indirect control of improved ZSI integrated standalone system

The objective of designing controllers is to achieve fast transient response, good reference tracking and better disturbance rejection with zero steady state error. The designed control variables need to be changed continuously with the fluctuations due to uncontrolled factors at input source side and with load variations at output AC side. The selected control parameters are dependent on each other; hence change in one parameter inflicts a limitation on the other parameter's freedom. This is due to the insertion of shoot through periods by diminishing zero state in traditional pulse width modulation as illustrated and explained in [22].

3.1 Modeling of DC side controller

The DC side controllers are designed to have slower dynamics than AC side controllers. Hence it is required to increase the operating bandwidth of inner current loop and outer voltage loop controllers. A small change in input DC voltage results in large change in DC link voltage. Furthermore, the non minimum phase characteristics of impedance network lead to the propagation of DC side fluctuations into AC side [23]. Hence an indirect controller is required in the feed forward path to control shoot through time (T_{sh}), capacitor voltage (V_c) and DC link boost voltage ($V_{dc\ link}$). The relationship between Capacitor voltage, DC link voltage and Boost factor is given in the equations (8) to (10).

$$\mathbf{V_C} = \frac{D_{sh}}{1-2D_{sh}}\left(V_{dc}\right) \tag{8}$$

$$\mathbf{V_{dc\ link}} = \frac{1}{1-2D_{sh}}\left(V_{dc}\right) \tag{9}$$

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

$$\mathbf{B} = \frac{1}{1-2D_{sh}} \tag{10}$$

In the DC side capacitor voltage is sensed and controlled with PI controller and shoot through time (T_{sh}) is calculated and fed to the Enhanced SVPWM controller.

3.2 Modeling of AC side controller

The inner current controller and outer voltage controller known as feedback controllers can regulate the load variations and voltage fluctuations at AC side. The AC side controllers are transformed and designed in synchronous reference frame. Synchronous frame PI regulators are used along with inner current control and outer voltage control loops. The inner loop with current controller has fast response and stabilizes the output for current variations. Good reference tracking and fast transient response can be achieved with outer voltage control loop. As explained in [23] the comprehensive small signal modeling and the resultant control to capacitor voltage transfer function clearly shows the location of zeros on the right hand side. Hence, the non minimum phase characteristics of impedance network at DC side affect the stability. Moreover, the overall system is divided into two subsystems for reducing the complexity and to analyze the system dynamics in a better manner.

Comprehensive design of DC and AC side of IZSI with second order filter is illustrated in Figure 5. Both active states and null states are combined together to differentiate the shoot through and non shoot through states. During shoot through states the diode does not conduct and the inverter leg is shorted through impedance network. Moreover inductors of impedance network get charged during shoot through period. During non shoot through states the impedance network output is connected to the AC side and at the same time capacitors get charged.

To get stable and controlled output, the reference current needs to be changed with the input voltage; hence there is a need of reference generator; the easiest way to achieve this is to have an outer voltage control loop; The error signal of the outer voltage control loop is used as the reference for the inner current control loop. Stabilizing the capacitor voltage does not guarantee stable output voltage [24]. The output voltage depends on variable factors such as shoot through duty ratio D_{sh} and capacitor voltage V_c. The sensed AC output voltage is pulsating in nature and requires ABC to d-q transformation. To obtain required bandwidth and to achieve stability, a cascaded PI controller is required. The chosen parameters prevent clashes between the dynamics of the DC and AC sides, as the cross over frequency of the DC side control loop is made much smaller than that of the outer voltage loop in the AC side. Though it is difficult to design a robust controller for a system with non minimum phase characteristics, the proposed control methodology for an improved ZSI integrated standalone system exhibits fast transient response, good reference tracking and zero steady state error [25-26].

IV. SIMULATION RESULTS, ANALYSIS AND DISCUSSION

The proposed indirect control technique for Improved Z-source inverter integrated standalone system has been simulated using MATLAB/Simulink. Extensive simulations are carried out with proposed state-space averaged comprehensive model for R, RL and three phase induction motor loads. An enhanced Space Vector Pulse Width Modulation control technique is used to generate gate pulses. Battery is used as DC input source. IGBTs are used as power switch in inverter. The input DC supply is varied from 200V to 250V; the impedance network inductors $L_1 = L_2 = 1mH$ and capacitors $C_1 = C_2 = 2mF$; the Switching Frequency is 10 KHz; the inverter decides the output frequency; the circuit is designed and simulated for 400V, 50 Hz three phase AC applications in standalone power systems.

Due to the presence of energy resettling behavior, overshoot and undershoot nature of impedance network elements, severe transients could be transferred and sensed at the AC side. However this will make the AC side non minimum as well and could be realized for a few cycles. Hence appropriate corrective action is required to improve the dynamic performance. The shoot through time is varied gradually from zero, thereby minimizing severe transients significantly. Proper selection of operating points and control parameters reduces the aforementioned effects. The shoot through control within its boundary at the DC side causes instability. The indirect closed loop controller at DC side senses the capacitor voltage and calculates shoot through time appropriately. The input DC voltage from sustainable energy source is always subjected to fluctuations due to some uncontrolled parameters. The designed PI controller adjusts the shoot through interval within the specified limits and achieves desired capacitor voltage and DC link voltage.

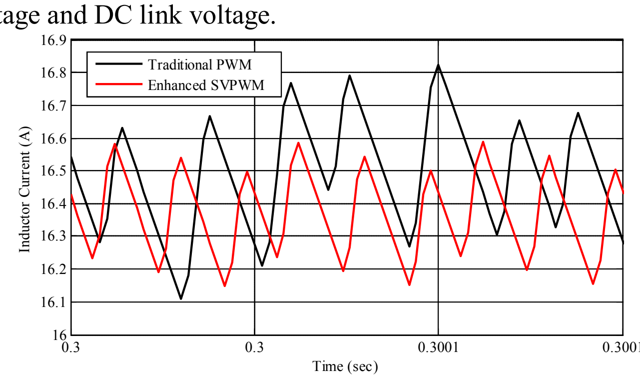

Fig. 6 Inductor Current ripple comparison (steady state)

During the shoot through period, inductors are charging and during non-shoot through period inductors are discharging. The enhanced SVPWM technique reduces the high current ripples through the Z-network inductors than traditional PWM technique as illustrated in Fig. 6. In traditional PWM method the current ripple is approximately 0.55A. Whereas in enhanced SVPWM current ripple is approximately 0.35A. Hence inductor current ripple is greatly reduced in the proposed enhanced SVPWM technique. Thereby reducing the size of inductors required. The resettling time can be reduced with lower LC values selected for impedance network. Thereby minimizing the size of inductors required and reduces the cost of passive elements required.

Fig. 7 illustrates the simulated results of enhanced SVPWM controlled IZSI for standalone power system without any closed loop controllers. Moreover, the negative going of capacitor voltage in IZSI as illustrated in Figure 7 is overcome by employing the proposed capacitor voltage control technique.

The AC side controllers are quick and gives fast response. Modulation index is the key factor in controlling AC side parameters. The null states are partially diminished and only one phase leg is allowed to shootthrough at a time as explained in section 2.1. Thereby attenuates the non minimum phase effect seen by the AC side. Hence, the selection of setpoint, shoot through time with saturation control and maximum limit of modulation index is crucial to realize fast transient response and good reference tracking. The inner current control and outer voltage control loops are faster and maintains steady output voltage during load fluctuations. Hence the system has good ride through capability.

Fig. 10 shows the simulated results of IZSI with three phase induction motor of 400V, 50Hz, 1500rpm. The illustrated results clearly demonstrates the fast dynamic response, good reference tracking, zero steady state error and ability to control the entire system with different types of load in standalone system.

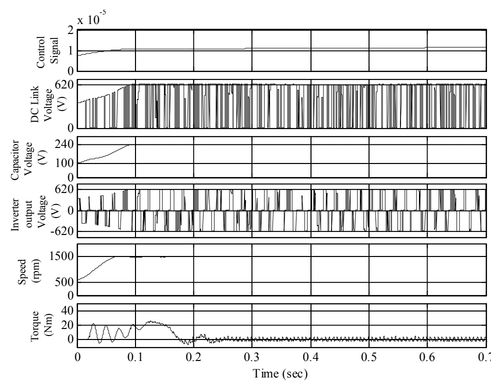

Fig. 7 Simulated results of IZSI with indirect closed loop controllers with three phase induction motor

(From the top, control signal from the controller, DC link voltage, capacitor voltage, Inverter output line-line voltage, Speed of the motor and Electromagnetic torque)

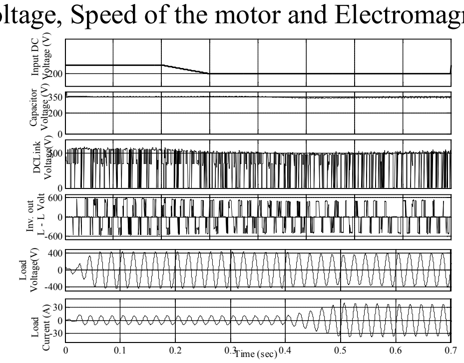

Fig. 8 Simulated results of IZSI with closed loop controllers with changes in input DC voltage from 250 to 200v

(From the top, input DC voltage, capacitor voltage, DC link voltage, Inverter output line-line voltage, load voltage and load current)

The input transients due to DC voltage fluctuations can be overcome effectively by the proper selection of closed loop controllers. The transient period depends on LC time constants of impedance network as well as bandwidths of inner current control and outer voltage control loops in the DC side. Fig. 11 illustrates the effect of input DC voltage variations and load fluctuations. The input DC voltage is varied from 250V to 200V at 0.2sec and by varying the load from 3KW to 750W the load current can be varied at 0.5sec. Eventhough the input DC supply varies, the capacitor voltage is maintained constant. Thereby DC link voltage is also maintained constant and no change in the output AC side. This clearly demonstrates the proper reference tracking and good dynamic response of closed loop control system proposed for standalone applications. The disturbance injected at the input side is rejected by proper application of controllers at DC side and AC side. In the load side at 0.5sec, the load is varied for a step change in load current. This load change may demand more energy from the input DC side. Transferring more energy from DC side may cause undershoot in the DC link voltage. But load voltage is maintained constant and shows good disturbance rejection as per the aforementioned control strategy.

Table 1: Simulated results with input DC voltage = 200V

Improved ZSI	Three phase load type	Capacitor Voltage (V_C) in volts	DC Link Voltage ($V_{dc\ link}$) in volts	Peak inverter output voltage (V_{LL}) in volts	Total Harmonic Distortion of Load Current
without feedback controllers	R = 6Ω	100	450	450	1.66%
with feedback controllers	R = 6Ω	240	622	622	1.38%
	R = 50Ω L=20mH	240	620	620	1.38%
	Induction Motor	239	622	622	3.22%

The DC side and AC side voltage values are presented in Table 1. The Total Harmonic Distortion analysis of load current is also presented.

With the proper design and employment of indirect closed loop controllers, the improved Z-source inverter (IZSI) exhibits good disturbance rejection, fast transient response and better ride through capability. Hence the proposed system is suitable for standalone power system applications.

V. Conclusions

This paper describes the modeling and design of closed loop controllers for an IZSI integrated standalone system. In the proposed system, improved Z-source inverter acts as a power conditioner. The voltage ride through capability during input voltage sags and load fluctuations has been obtained with quality output waveforms. Using MATLAB / SIMULINK environment the proposed closed loop controllers for IZSI integrated standalone system is modeled and simulated for three phase 400V, 50Hz induction motor applications. Performance analysis is carried out on the basis of simulated results. Based on the analysis Improved Z-source inverter with less passive components are suitable for standalone applications without the need of transformers. Fast transient response, good reference tracking and zero steady state error has been obtained. Total Harmonic Distortion analysis for load current is also done. Hence the power quality of the proposed standalone power system is improved.

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