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Wind Energy Conservation System Performance is Improved using a Novel Z-Source Buck–Boost Matrix Converter

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Abstract

The growth of wind energy conversion system for domestic applications has various technologies to improve the performances. This paper proposed a single stage conversion of AC-AC, novel Z-source buck–boost matrix converter structure and a switching technique for unity voltage transfer ratio. The conventional matrix converter is well known for its advantages over a DC-linked back-to-back. The converter can buck and boost with step-changed frequency, and both the frequency and the voltage can be stepped up or stepped down. In addition, the converter employs a safe-commutation strategy to conduct along a continuous current path, which results in the elimination of voltage spikes on switches without the need for a snubber circuit. With the use of matrix converter the need for rectifier circuit and DC-Converters are reduced. The operating principles of the proposed single-phase Z-source buck–boost matrix converter are described. A simulation of the overall system is carried out and theoretical calculations and feasibility of the proposed topology are verified and that the converter can produce an output voltage with four different frequencies 100, 50, 25 and 12.5 Hz, and that the amplitude of the output voltage has been bucked and boosted from fundamental frequency and voltage.

Index Terms: Maximum power point tracking (MPPT) control, Buck–boost voltage, single-phase matrix converter, Z-source converter, permanent-magnet synchronous generator (PMSG)

Introduction

Wind Turbine usage as sources of energy has increased significantly in the world. With growing application of wind energy conversion systems (WECS), various technologies are developed for them. With numerous advantages, permanent-magnet synchronous generator (PMSG) generation system represents an important trend in development of wind power applications [1]-[5] to realize these objectives; the AC–AC converter is one of the best topology for Wind Energy Conversion system.Figure.1 shows a conventional configuration of AC-DC-AC topology for PMSG. This configuration includes diode rectifier, boost DC–DC converter and inverter. In this topology, boost converter is controlled for maximum power point tracking (MPPT) and converter is controlled to deliver high-quality power.

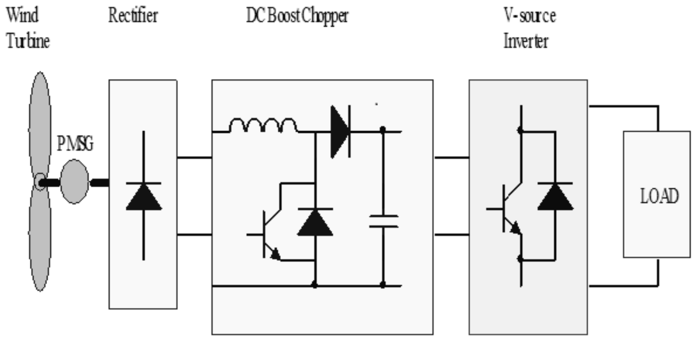

Figure 1: Conventional PMSG-based WECS with Z-Source Inverter

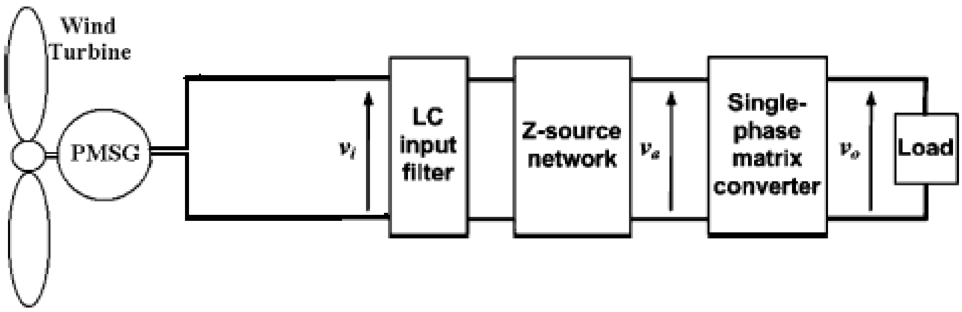

Figure 2: General Block diagram of the proposed Topology.

The *Z*-source matrix converters have been reported recently as a competitive alternative to existing inverter topologies with many inherent advantages such as voltage boost [13]. This inverter facilitates voltage boost capability with the turning ON of both switches in the same inverter phase leg (shoot-through state). In this paper, a new PMSG-based WECS with *Z*-source matrix converter is proposed. The proposed *Z*- source matrix converter topology is shown in Figure.2.With this topology, reliability of the system is greatly improved and converter output power distortion is reduced. Section II of this paper introduces Z-source matrix converter and describes operation of the Z-source matrix converter. Then, power delivery and MPPT control of system are explained. Finally, simulation results are presented to verify the voltage and current performance of the proposed system for 12.5 Hz, 50 Hz and 100 Hz.

Z-Source Inverter

A MATRIX converter is an ac-ac converter that can directly convert an ac power supply voltage into an ac voltage of variable amplitude and frequency without a large energy storage element. In 1980, Venturini and Alesina presented the first algorithm capable of synthesizing output Sinusoidal reference voltages from a balanced three-phase voltage source connected to the converter input terminals. Recent research on matrix converters has focused mainly on modulation schemes and on ac drive applications.

The first study of a single-phase matrix converter was performed by Zuckerberger on a frequency step-up and fundamental voltage step-down converter. The research in [6] - [8] focused on step-up/step down frequency operation with a safe-commutation strategy. Applications of single-phase matrix converters have been described for induction motor drives, radio-frequency induction heating, audio power amplification, and compensation voltage sags and swells [9] - [11]. It has been reported that the use of safe-commutation switches with pulse width modulation (PWM) control can significantly improve the performance of ac-ac converters [12]. However, in the conventional single-phase matrix converter topology, the ac output voltage cannot exceed the ac input voltage. Furthermore, it is not possible to turn both bidirectional switches of a single-phase leg on at the same time; otherwise, the current spikes generated by this action will destroy the switches. These limitations can be overcome by using Z-source topology [13]. Research on Z-source converters has focused mainly on dc-ac inverters and ac-ac converters. Recently, the work on Z-source DCAC inverters has focused on modeling and control, the PWM strategy, applications, and other Z-network topologies. The Z-source ac-ac converters focus on single-phase topologies and three-phase topologies [6] and [13]. In applications where only voltage regulation is needed, the family of single-phase Z-source ac-ac converters proposed has a number of merits, such as providing a larger range of output voltages with the buck–boost mode, reducing inrush, and harmonic current. However, no one has designed a converter based on a Z-source structure and a matrix converter topology that can provide ac-ac power conversion with both a variable output voltage and a step-changed frequency. In this paper, we apply the Z-source concept to a single-phase matrix converter to create a new type of converter called a single-phase Z-source buck–boost matrix converter [14] - [16]. In contrast to the existing single-phase PWM AC-AC converters, this proposed single-phase Z-source buck–boost matrix converter can provide a wide range of output ac voltages in buck–boost mode with step-up/step-down frequencies.

The result has been shown by operating principles, analyzes, simulation, and experimental results that the proposed single-phase Z-source buck–boost matrix converter can buck and boost voltages in step-up/step-down frequency operation [8] and [17]. We use a safe-commutation technique that is very simple to implement as a free-wheeling path to provide the required free-wheeling operation similar to what is available in other converter topologies [6]. The safe-commutation scheme establishes a continuous current path in dead time to eliminate voltage spikes on switches without a snubber circuit.

We also performed a MATLAB simulation. Both the simulation and experimental results shows that the output voltage can be obtained at four different frequencies 100, 50, 25 and 12.5 Hz and in the buck–boost amplitude mode. Thus, the proposed single-phase Z-source buck–boost matrix converter can be used for voltage applications that require step-changed frequency or amplitude.

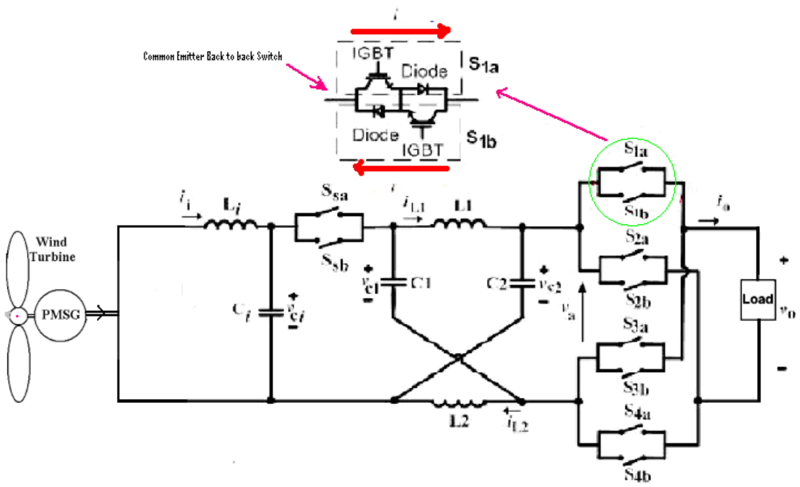

Figure 3: Proposed single-phase Z-source matrix Converter topology

Single-Phase Matrix Converter (SPMC)

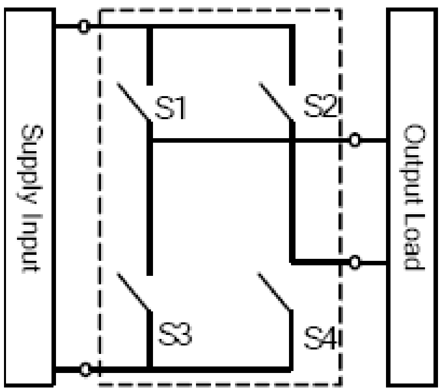

Figure 4: SPMC circuit configuration

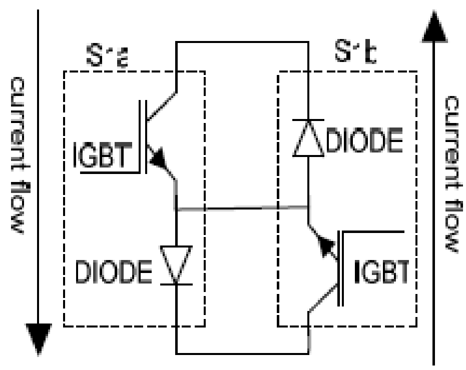

Figure 5: Bi-directional switch module (common emitter configuration)

The SPMC topology with its 4 bi-directional switches and its individual power switches are as shown in Figure.4 and Figure.5 respectively; each capable of conducting current in both directions, blocking forward and reverse voltages [14]-[15]. Theoretically the switching sequence in the SPMC must be instantaneous and simultaneous; unfortunately impossible for practical realization due to the turn-off IGBT characteristic, where the tailing-off of the collector current will create a short circuit with the next switch turn-on. This problem occurs when inductive loads are used. A change in current due to switch commutation and PWM switching will result in two damaging phenomena. First current spikes will be generated in the short-circuit path and secondly voltage spikes will be induced as a result of change in current direction across the inductance. Both will subject the switches with undue stress leading to destruction. A systematic switching sequence is hence required that lengthens the dead time between conduction of each IGBT's in SPMC so as to allow for a complete turn-off prior to the next switching sequence.

This is to minimize development of spikes as described. In conventional converter this is normally implemented in the form of free-wheeling diodes as shown in Figure.5. In SPMC a switching algorithm strategy need to be developed that will be described subsequently.

Proposed Topology

Figure 2 shows a block diagram of the proposed topology. The ac voltage across the single-phase matrix converter *Va* is boosted by the ac-ac Z-source converter with ac input voltage *vi.* Then, the single-phase matrix converter modulates the frequency of *Va* The output voltage *Vo* is obtained with a step changed frequency and a variable amplitude.Figure.3 shows the proposed single-phase Z-source buck–boost matrix converter. It employs an *LC* input filter; a Z-source network, bidirectional switches, and an *RL* load. The *LC* input filter is required to reduce switching ripple included in input current. All the inductors and capacitors are small and are used to filter switching ripples. The symmetrical Z-source network, a combination of two inductors and two capacitors, is the energy storage/filtering element for the single-phase Z-source buck–boost matrix converter. Since the switching frequency is much higher than the ac source (or line) frequency, the requirements for the inductors and capacitors should be low. As shown in Figure.3, the proposed single-phase Z-source buck–boost matrix converter requires four bidirectional switches S1*j*, S2*j* ,S3*j* , and S4*j* (*j* = a, b) to serve as a single-phase matrix converter and one source bidirectional switch S*sj* (*j* = a, b), where a and b refer to drivers 1 and 2, respectively. All bidirectional switches are common emitter back-to-back switch cells. The five switches S*sj*, S1*j*, S2*j*, S3*j*, S4*j* (*j*=a, b) used in the single-phase Z-source buck–boost matrix converter are bidirectional switches, as shown in Figure. 4 and Figure.5. The bidirectional switches are able to block voltage and conduct current in both directions. Because these bidirectional switches are not available at present, they can be substituted for by combinations of two diodes and two insulated gate bipolar transistors (IGBTs) connected in anti parallel(common emitter back to back), as shown in Figure.5.The diodes are included to provide the reverse blocking capability.

Because of the high switching Capabilities and their high current-carrying capacities IGBT's are used for switches, which are desirable for high-power applications. As indicated in the Figure.4, D refers to the equivalent duty ratio and T is the switching period. Implementing the single-phase Z-source buck–boost matrix converter requires different bidirectional switching arrangements depending on the desired amplitude and frequency of the output voltage. The amplitude of the output voltage is controlled by the duty ratio D, while the frequency of the output voltage depends on the switching strategy.

In this paper, the frequency of input voltage fs is assumed to be 50 Hz, and the desired output frequency fo is synthesized to be 100 Hz (step-up frequency), 50 Hz (same frequency), or 25 Hz, 12.5 Hz (step-down frequency). For example, Figure.3 illustrates the converter's switching strategy over one cycle of input voltage for a 100-Hz output frequency in boost mode to double output frequency of the input voltage, the operation of the converter is divided into four stages, as shown in the Figure. 6.

Figure. 6 illustrates stage 1 in the boost mode when both input voltage and output voltage are positive. The switches Ssa, S1a, S2b, and S4a are fully turned on (S2b is turned on for commutation purposes, while Ssa and S4a are turned on for continuous current flow); S1b, S3b, and S4b are modulated complementary to the dead time. In state 1, as shown in Figure.6(a), S4b turns on and conducts current flow during the increasing positive cycle of input voltage; Ssb and S1b turn on and conduct negative current flow from the load to the source, if possible; S2b turns on for commutation purposes. Then, Ssb and S4b turn off, and S3b has not yet turned on, and there are two commutation states that occur. If $iL1 + iL2 + io > 0$, the current flows along a path from Ssa , as shown in Figure. 6(b); if $-iL1 - iL2 + io > 0$, the current flows along a path from S4a and S2b, as shown in Figure. 4(c). As shown in Figure. 6(c), the path of the current flowing through S2b is $-iL1 - iL2 + io$. Because switch S2b must be conducting, the current condition for this state is $-iL1 - iL2 + io > 0$. In state 2, as shown in Figure.6 (d), S3b turns on and conducts current flow in the Z-source network as a hoot-through path; the positive load current may be freewheeled through S2b and S1a; the negative load current may be freewheeled through S3b and S4a. In these switching patterns, the current path is always continuous whatever the current direction. Thus, the voltage spikes are eliminated during switching and commutation processes. The analysis for stages 2, 3, and 4 is similar to that for stage 1. The dotted line in Figure.6 indicates the safe-commutation switch during each particular stage. The operations at the other output frequencies of 50 and 12.5 Hz are performed by changing the switching strategies. The operation for an output frequency of 50 Hz is implemented by omitting stage 2 and stage 3 and doubling the time intervals for stage 1 and stage 4. Similarly, the operation for an output frequency of 12.5 Hz is implemented by interchanging stage 2 and stage 3 and doubling the time intervals of all stages. In the operations for output frequencies of 50, 25 and 12.5 Hz, the time interval of each stage is 8.33 ms.

Circuit Equations

Ignoring the effects of dead time, the single-phase Z-source buck–boost matrix converter has two operating states in one switching period: state 1 and state 2, as shown in Figure. 6. as shown in Figure. 6(a), the time interval in state 1 is $(1-D)\,T$, where D is the equivalent duty ratio and T is the switching period. Thus the voltage across the capacitor of the Z-network is

$$Va\,(t) \approx vC1\,(t) = vC2\,(t) = \frac{1-D}{1-2D}\,vi(t). \quad (1)$$

The amplitude of the voltage across the single-phase matrix converter can be calculated as

$$V_{am} = \sqrt{2}Va = \frac{1-D}{1-2D}\,\sqrt{2}Vi \quad (2)$$

Where *Va* and *Vi* are, respectively, the rms value of the voltage across the single-phase matrix converter and the input voltage.

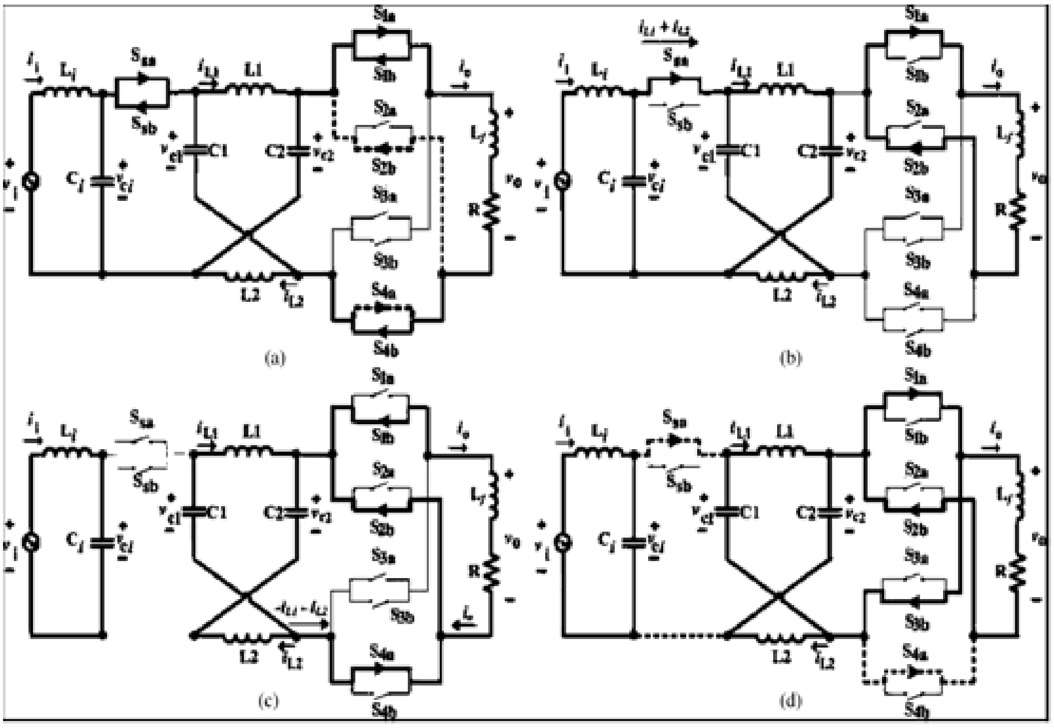

Figure 6: Stage 1 for the boost mode for a frequency of 100 Hz. (a) State 1. (b) Commutation state when $iL1 + iL2 + io > 0$ (c) Commutation state when $-iL1 - iL2 + io > 0$ (d) State 2.

The rms value of the fundamental voltage across the load is calculated according to the amplitude of the voltage across the Single-phase matrix converter.

$$\text{i.e } Vo = \frac{Vam}{\sqrt{2}} \quad (3)$$

The voltage gain K can be defined as

$$K = (Vo/Vi) = (1\text{-}D/1\text{-}2D) \quad (4)$$

Where Vi and Vo are, respectively, the rms value of input voltage and output voltage. The proposed single-phase Z-source buck–boost matrix converter has two operation regions. When $D<0.5$, the single-phase Z-source buck–boost matrix converter operates in boost mode, and when $D > 0.66$, the single-phase Z-source buck–boost matrix converter operates in buck mode.

Simulation Results

The MATLAB simulation results have been provided in order to verify the properties described before for the proposed single-phase Z-source buck–boost matrix converter. The simulation parameters have been selected such as LC input filter, Z-source network, and load to be Li = 0.1 mH, Ci = 6.8 μF, $L1$ = $L2$ = 1 mH,$C1$ = $C2$ = 1 μF, R = 100 Ω, and Lf = 3 mH. The switching frequency was set to 20 kHz, and the dead time for commutation at 0.5 μs. The input voltage was 40 Vrms/50 Hz, and the output voltage was 65 Vrms with D = 0.3 in boost mode. Figures. 7–10 show the simulation results for the proposed single-phase Z-source buck–boost matrix converter in boost mode with D = 0.3 at output frequencies of 100, 50, and 12.5 Hz, respectively. As shown in Figure.6, when D = 0.3, the output voltage is boosted to about Vo = 250 Vrms from an input voltage of 180 Vrms. In addition, the output frequency is modulated to either 100 Hz (step-up frequency), 50 Hz (the same frequency), or 25Hz, 12.5 Hz (step-down frequency) from the input frequency of 50 Hz

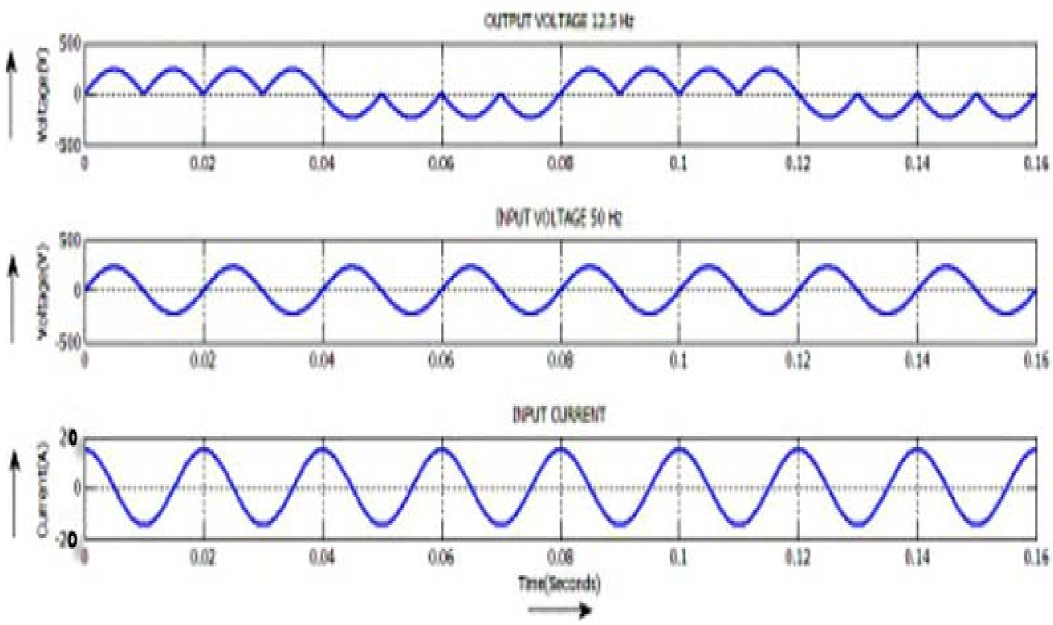

Figure 7: Input current and input voltage for 50 Hz and output voltage for 12.5 Hz.

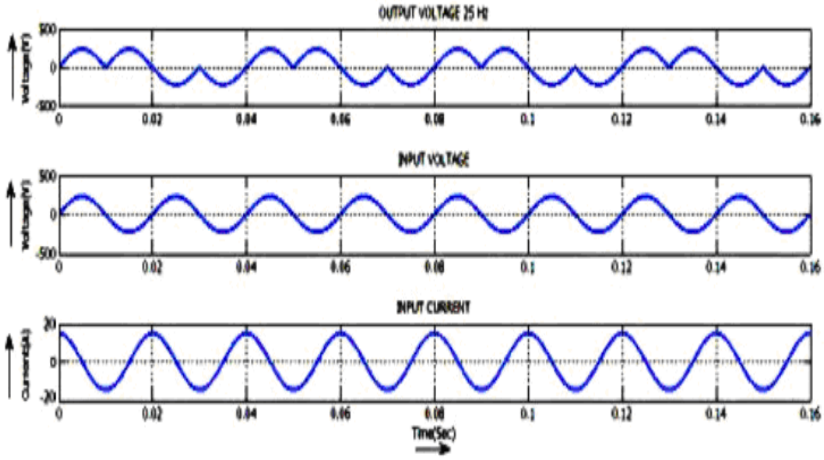

Figure 8: Input current and input voltage for 50 Hz and output voltage for 25 Hz

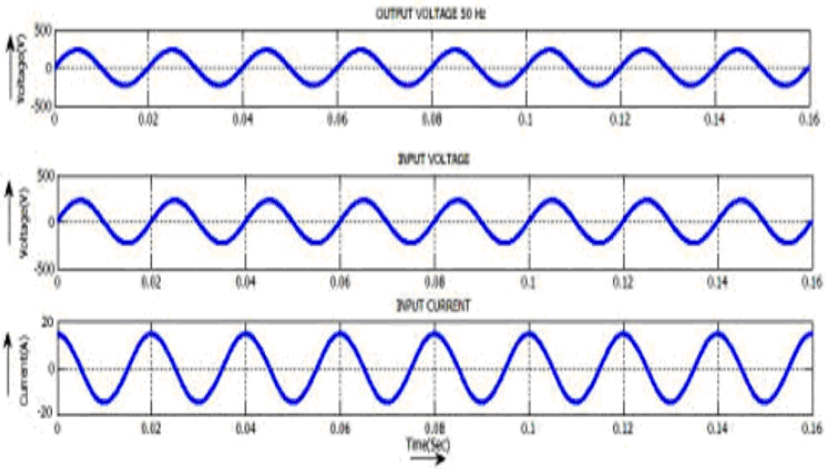

Figure 9: Input current and input voltage for 50 Hz and output voltage for 50 Hz

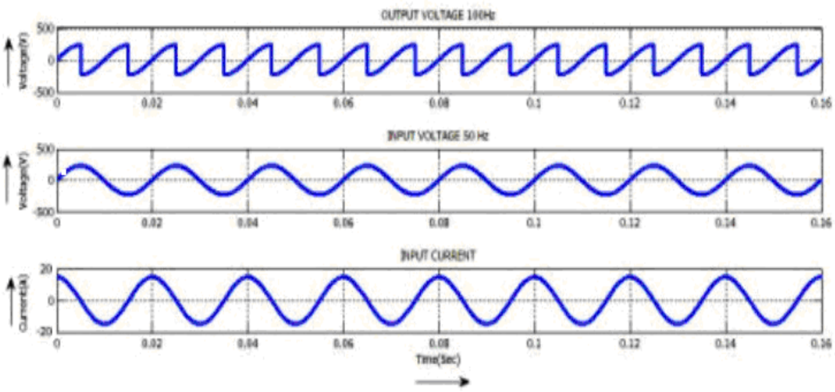

Figure 10: Input current and input voltage for 50 Hz and output voltage for 100 Hz

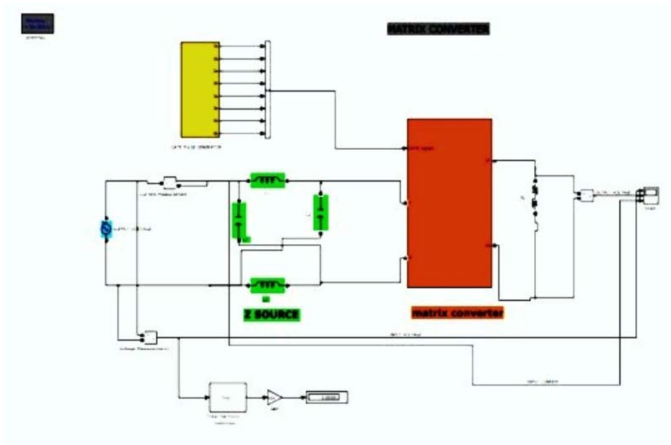

Figure 11: Simulation scheme for the single phase matrix converter

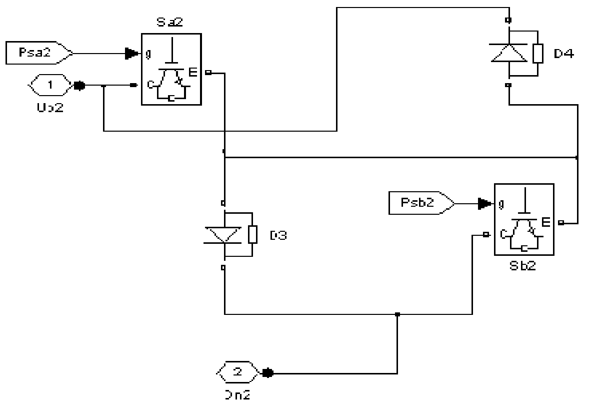

Figure 12: Simulation scheme for switch control

Table 1: Sequence of switching control

Input Frequency	Target Output Frequency	Time Interval	State	Switch modulated
50Hz	25Hz	1	1	S1a , S4a
		2	4	S2b , S3b
		3	3	S2a , S3a
		4	2	S1b , S4b
	12.5Hz	1	1	S1a , S4a
		2	4	S2b , S3b
		3	1	S1a , S4a
		4	4	S2b , S3b
		5	3	S2a , S3a
		6	2	S1b , S4b
		7	3	S2a , S3a
		8	2	S1b , S4b

Conclusion

In this paper, a new Single stage conversion, Z-source buck–boost matrix converter has been developed for the domestic windmill applications. It can buck and boost to the desired output voltage with step-changed frequency. The output of this single-phase Z-source buck–boost matrix converter produces the voltage in buck–boost mode with a step-changed frequency, in which the output frequency is either an integer multiple or an integer fraction of the input frequency. It also provides a continuous current path by using a commutation strategy. The use of this safe-commutation strategy is a significant improvement as it makes it possible to avoid voltage spikes on the switches without the use of a snubbed circuit. A steady-state circuit analysis has been presented and described the operational stages.MATLAB simulation has been used to verify the performance of the proposed converter from the fundamental frequency 50 Hz. The simulation and the experimental results with a passive *RL* load showed that the output voltage can be produced at four different frequencies for 100, 50, 25 and 12.5 Hz, and in the buck–boost amplitude mode. The developed converter is particularly suitable for controlling the windmill voltage without the use of DC-Converter, rectifier and inverter.

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