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Certain investigations on power generation using repulsive magnets and new stepped DC coupled quasi Z-inverter

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Abstract: This paper presents a novel approach for power generation from rotating machines in textile mills using externally coupled repulsive magnets and a new stepped DC coupled Quasi Z-inverter. Power is obtained as a byproduct of the effective harnessing of rotational energy with the use of repulsive magnets. This derived power is stored in a battery arrangement and is retrieved, buck/boosted, and converted to multilevel AC voltage with the new stepped DC coupled quasi Z-inverter. The proposed inverter is powered by isolated voltage sources, uses fewer switches, and produces less distortion in the resulting multilevel voltage compared to its counterpart, and thus reduces the filter requirements. The derived AC power from the system can be used for light-load applications in textile mills, thus compensating for the energy demands. Simulation of the entire proposed setup is performed in MATLAB/Simulink and the results are presented. The repulsive force produced by the magnets is assessed with K & J Magnet software. To validate the simulation, experimentation is done using rotating machines available in the laboratory. The prototype model of the stepped DC coupled quasi Z-inverter is used to study the performance of the system and the results are evaluated. The optimum modulation index is identified for different numbers of sources at the input.

Key words: Magnets, rotational energy, inverter, textile mills, adjustable speed drives

1. Introduction

The textile mills in Tirupur, Tamil Nadu, India, underwent a huge energy crisis in the year 2013. This led to the stoppage of many mills in that region. Research is being carried out on the various systems involved in yarn processing to reduce energy costs and to meet the energy emergency. The processing of raw fiber into fabric is performed by ginning, spinning, and weaving processes, which employ different types of motors at various stages [1,2]. The energy cost consumed by these rotating machines for various operations is about 4% of the total input cost [3]. Optimizing the design of the rotating machine is one strategy by which the operating cost of the system is lessened and energy demands are met [4]. An alternate method of power generation with the available resources in the textile mills can help reduce overall energy consumption and serves as one option for meeting the energy crisis.

This paper attempts to present one such method that effectively utilizes the rotational energy available from the rotating machines in the textile mills. Along with meeting the loading needs, the rotational energy available from the machine can be used for power generation to meet the needs of light-load applications.

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This power generation is established with a repulsive magnetic system and a new stepped DC coupled Quasi Z-inverter.

The interaction of the magnetic flux lines creates physical movement of the magnetic substances. With like poles or poles of different polarity, a force of repulsion or attraction is encountered between the magnets [5]. This fundamental phenomenon is used in all machines to generate rotational power. The same concept is extended for power generation with the aid of repulsive magnets [6]. The power generation system uses a repulsive magnetic disc coupled to the drive motor and the DC generator. This does not establish any physical connection with the rotating machine and hence does not turn as a passive load. This generated power can be used as a standby power supply, to power light loads, etc. The power produced by this method from individual machines is stored in a separate battery arrangement, which forms an input to the inverter circuit.

The conversion of DC to AC is aided by conventional voltage source inverters (VSIs) or multilevel inverters. Multilevel inverters take an upper hand over VSIs but suffer from the drawbacks of only having buck operation, the simultaneous switching ON of switches of the same leg not being allowed, and requiring an additional power conditioning stage to enhance the voltage level. A Z-source inverter overcomes these drawbacks and serves as a better option, but the component cost and high distortion in the output voltage are constraints that should be considered [7]. Topological renovation is required in the field of the Z-source inverter to improve its performance from its predecessor. Quasi Z-source inverters, extended boost quasi Z-source inverters, and improved Z-source inverters are a few examples of this type [8–10]. References [11–14] enumerate applications for the Z-source inverter in the field of renewable energy sources and adjustable-speed drives. Multilevel Z-source inverters are discussed in references [15,16], which have all the advantages of the Z-source inverter and produce multilevel output. However, the component requirement for higher levels and the stress on the device require a modification in the Z-source inverter. Hence, the new stepped DC coupled quasi Z-inverter is proposed for the power conversion process in this system. This new type of Z-source inverter consists of a 2-stage conversion process and utilizes an isolated energy source as the input. The first stage operates at fundamental frequency and produces stepped DC voltage, which is boosted and inverted by the second stage operating at a high switching frequency. The whole system is aimed to produce multilevel AC voltage with a simple configuration, and the buck-boost operation is obtained by a quasi impedance source network. Along with all the advantages of the quasi Z-network, the inverter eliminates the fly-back diodes and capacitors present in the conventional Z-source multilevel inverter and uses fewer switches for increasing levels in the output voltage.

The repulsive power of the magnet is determined in simulation by the K & J Magnet Calculator. The new stepped DC coupled Z-multilevel inverter is simulated in a MATLAB/Simulink environment and its performance is analyzed. The total power conversion system is modeled in MATLAB and is coupled to the inverter. The voltage and current waveforms across each stage are analyzed and the results are presented. The experimental validation of the proposed work is performed in the laboratory with available permanent magnet synchronous motor and brushless DC motor. The repulsive magnets are fabricated and are placed in the shafts of the 2 motors. The power generated by this technique is analyzed and is fed to the proposed inverter. The output of the inverter is investigated and the results are presented. The experiment validates the proposed theory of power generation and the efficacy of the proposed inverter.

2. Repulsive magnet system

A repulsive magnet system is proposed to utilize the rotational energy from the adjustable speed drives of the textile mills. Two discs consisting of permanent magnets of similar polarity are placed at calculated distances to produce the desired repulsive force. The model diagram of the repulsive magnet system is given in Figure 1.

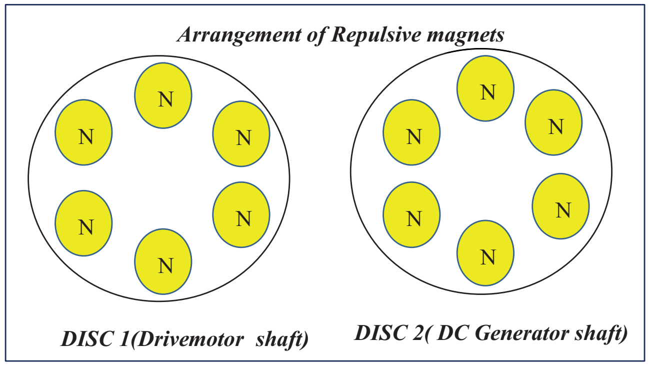

Figure 1. Model diagram of repulsive magnet system.

The implementation block diagram of the proposed system is shown in Figure 2. The system consists of the rotating machine, the DC generator, and the new stepped DC coupled Quasi Z-inverter (SDQZMLI) to effectively utilize the rotational energy. Disc 1 is placed on the shaft of the rotating machine, and Disc 2 is placed on the DC generator. When the drive is operating, Disc 1 rotates. Due to the repulsive force, Disc 2 rotates, which serves as mechanical energy for the DC generator and results in generating DC power. The DC power produced by the generator is stored in the battery arrangement. This power is converted to AC with the help of the SDQZMLI inverter, which produces multilevel buck/boosted AC voltage in a single-stage conversion process. The SDQZMLI can accommodate 'n' number of DC voltages to produce 'n' level in the output voltage.

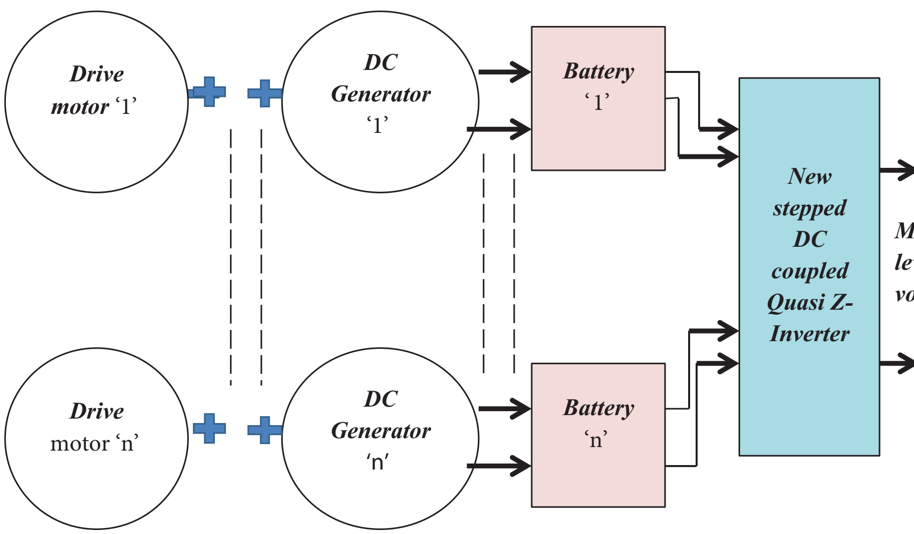

Figure 2. Block diagram of proposed system for textile mills.

3. New stepped DC coupled quasi Z-Inverter

The Z-source inverter is an emerging area in the field of power electronics. Topological modifications are being carried out in this area to improve its performance and to reduce losses. The proposed inverter is a topological exploration of its type, which produces boosted multilevel AC voltage that could be utilized by renewable energy sources. The structure of the new inverter is shown in Figure 3.

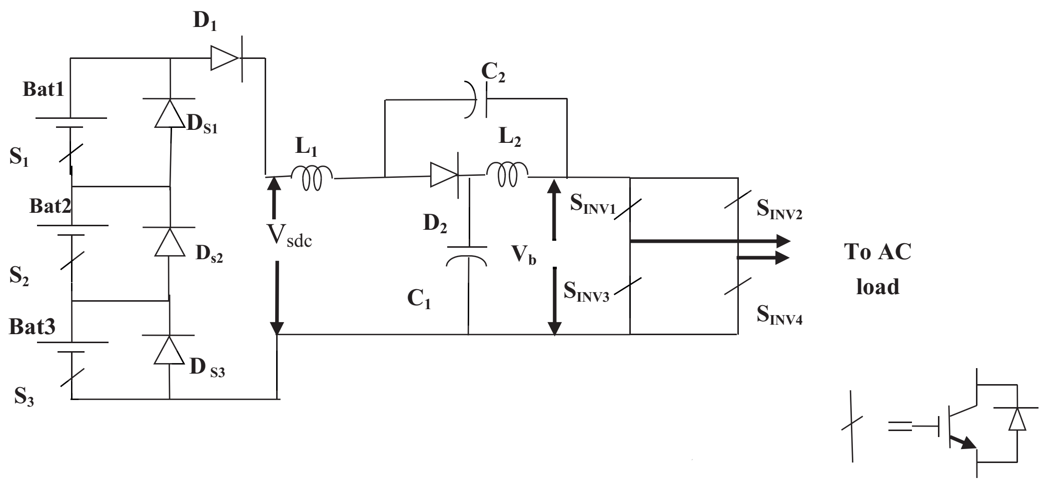

Figure 3. Structure of stepped DC coupled quasi Z-inverter.

Multilevel DC link voltage can be produced with different circuit arrangements, and this is one type of arrangement [17,18]. Each battery output from the rotating machine serves as input to the inverter. This configuration comprises a simple structure that utilizes isolated DC voltage sources connected through switches (S_1, S_2, and S_3) and bypass diodes (D_{S1}, D_{S2}, and D_{S3}) to the quasi Z-inverter. The switching ON and OFF of switches S_1, S_2, and S_3 produces stepped DC link voltage (Vsdc). The number of levels of the DC link voltage is decided by the number of DC sources and switches used. This topology claims the advantage of using a minimum number of switches for a higher level of output voltage. The switching algorithm for the stepped DC circuit is given in Table 1.

Table 1. Switching algorithm to produce stepped DC link voltage (V_{SDC}).

Voltage level	Switches to be turned ON	Diode in conduction
0 volts	Nil	DS_1,DS_2, DS_3
V_1 volts	S_3	DS_1,DS_2
2 V_1 volts	S_2, S_3	DS_1
3 V_1volts	S_1, S_2, S_3	nil

The stepped DC link voltage appearing at the input is buck/boosted and inverted by the quasi Z-inverter. The quasi network is a unique combination of LC elements (L_1, L_2, C_1, and C_2) and diodes D_1, which is a reverse current protection diode, and D_2, which helps to build energy in Z-components during the shoot-through state. This setup aids the buck/boost operation; its advantages include high boost factor and less stress on the components. Both buck and boost operations are obtained by controlling the shoot-through period of the inverter. The firing pulses for the DC circuit are obtained by comparing triangular waves at fundamental frequency and a constant DC line at various levels; for the inverter, the pulses are generated by maximum constant boost control with the third harmonic injection scheme, which is the same as that used for traditional Z-source inverters [19,20]. This scheme is preferred as it maintains constant shoot-through and produces high boost factor. Figures 4a and 4b depict the operation of the inverter during the shoot-through state and the non-shoot-through state.

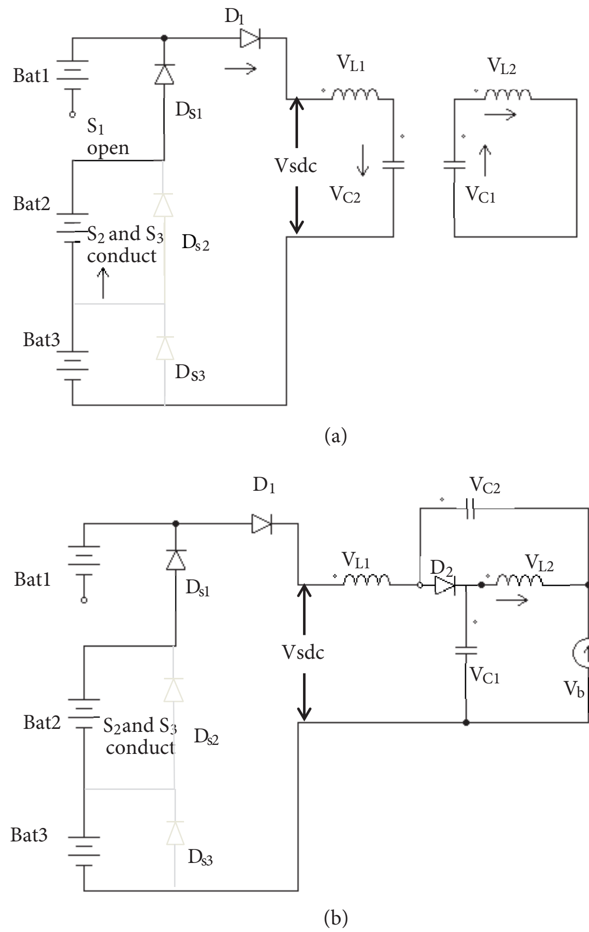

Figure 4. Circuit operation of the proposed SDQZMLI inverter during (a) shoot-through state and (b) non-shoot-through state.

The shoot-through state arises when switches of the same leg or of both legs are shorted and produce a short circuit. During the non-shoot-through state, the inverter acts as a current source when viewed from DC supply.

4. System analysis

The mathematical equations governing the system are presented in this section.

4.1. Force between 2 magnetic poles

Coulomb's law of magnetism gives the force between 2 magnetic poles of strength qm1 and qm2 separated by a distance 'r' [5]. Eq. (1) gives the expression of force:

$$F = \frac{\mu q_{m1} q_{m2}}{4\pi r^2}; \tag{1}$$

μ defines the permeability of the medium.

The magnetic material produces its own magnetic flux density (B); the torque produced by the magnet is given by Eq. (2):

$$T = mxB \text{ N}; \tag{2}$$

m gives the magnetic moment of the magnet.

The torque produced by the machine in the system under study is dependent on the load to which the machine is connected. This rotational power is responsible for the production of DC voltage in the generator.

Eq. (3) gives the generalized expression of the generated DC voltage in a DC generator [21].

$$V_{dc} = \frac{\emptyset ZNP}{60A} \text{ volts} \tag{3}$$

This DC power is stored in individual batteries and fed to the new SDQZMLI inverter.

The voltage equations of the inductor and capacitor and the AC output voltage of the inverter are given by Eqs. (4) to (7). The expressions are derived for the shoot-through state and the non-shoot-through state. The inductor voltage during the shoot-through state is given as:

$$V_{L1} = 2V_{sdc} + V_{C2} \text{ and } V_{L2} = V_{C1}; \tag{4}$$

during the non-shoot-through state:

$$V_{L1} = 2V_{sdc} - V_{C1} \text{ and } V_{L2} = V_{C1} - V_b, \tag{5}$$

where V_{L1} and V_{L2} are the inductor voltages, and V_{C1} and V_{C2} are the capacitor voltages.

$$V_b = V_{C1} + V_{C2} = \frac{1}{1 - \frac{2T_0}{T}} 2V_1 = 2BV_1 \tag{6}$$

B gives the boost factor of the inverter. Eq. (6) gives the Vsdc appearing across the inverter with 2 independent DC sources. Similarly, to obtain 'n' steps, the stepped DC voltage will be boosted to nBV1. The boosted multilevel AC voltage available at the inverter is given by Eq. (7):

$$V_{ac} = M\frac{V_{sdc}}{2} = M\frac{BV_1}{2}, \tag{7}$$

where M is the modulation index of the inverter.

5. Results and discussion

Simulation studies are performed in MATLAB/Simulink to examine the performance of the system. The magnetic force is analyzed using K & J Magnet Calculator software. This software helps determine the repulsive force and magnetic field distribution in various types of magnets. This helps to determine the force exerted by different magnets; a comparative study is done to choose the optimum type of magnet for the system. The new SDQZMLI inverter is built in Simulink with the following circuit parameters: $L_1 = L_2 = 800\ \mu$ H and $C_1 = C_2 = 0.6\ \mu$ F. Maximum boost control with a third harmonic injection technique is used to generate the firing pulse for the inverter. The front end circuit producing V_{sdc} is switched at the fundamental frequency, and the inverter is switched at 10 kHz. It is observed that the obtained simulation results track the theoretical study. To validate the simulation, experimentation of the proposed system is performed with the rotating machines available in the laboratory, and the results are presented in this section. The generated voltage is stored in the battery with the aid of the charge controller. Switching pulses for the inverter are realized with the microcontroller, and the experimental results of the inverter comply with the simulation results.

5.1. Force analysis of magnet

Figure 5 shows the repelling force produced by an N42-grade cylindrical disc magnet with both diameter and thickness of 2.5 cm. The N42 grade is chosen for having a magnetic flux density of 1.25 T, which is comparatively higher than other magnets. They have high resistance to demagnetization and are available in circular dimensions, which suits the purpose; hence, they were chosen for study. The distance of separation between the 2 magnets is 3 mm and it produces a force of 147 N. The inverse relation between the force and the distance is depicted in the graph.

A sequence of analyses is performed using the simulator for different materials with varying dimensions. Figure 6 reveals that 1.25-cm-thick N42-grade material experiences a high repulsive force of 28.56 N between 2 magnets of the same grade. The repulsive force decreases for different materials.

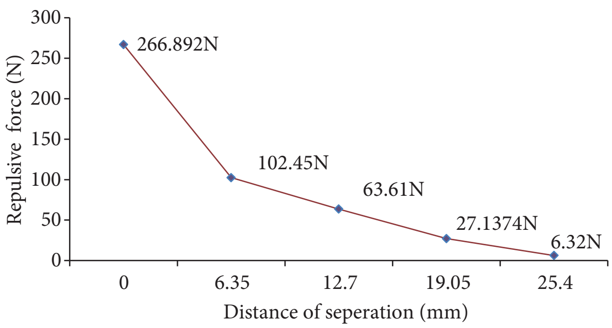

Figure 5. Simulation result of magnetic force for 2.5-cm magnet.

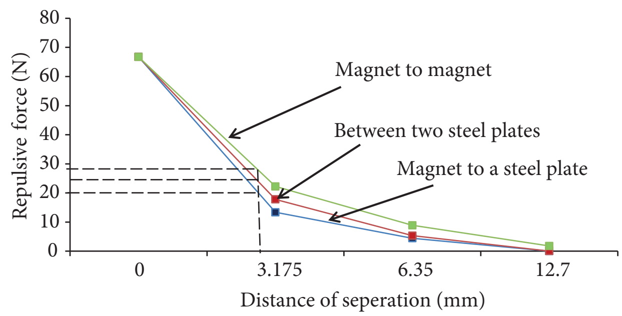

Figure 6. Simulation of magnetic force for 1.25-cm magnet.

Figure 7 shows the hardware implementation of the proposed system using a switched reluctance motor and brushless DC motor. The magnetic disc is fabricated as shown in Figure 8. Four permanent magnets of similar polarity are placed in quadrature in a single disc with a diameter of 10 cm. The same is replicated in the second disc, and this arrangement is fitted to the shaft of a switched reluctance motor (SRM) and brushless DC motor (BLDC). The effect of stray flux is neglected in the prototype model.

Figure 7. Hardware setup in the laboratory.

The switching pulses for the SRM motor are fed from a DSP controller, which enables the motor to rotate. The 2 machines are separated by a distance of 3.5 cm to create the necessary force of repulsion. The speed of the SRM motor is adjusted to 300 rpm by varying the input and the loading conditions. Figure 9 shows the physical arrangement of the 2 rotating machines.

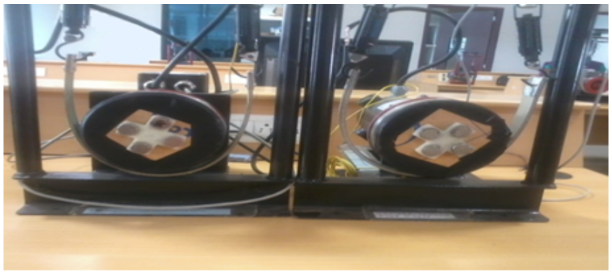

Figure 8. Magnetic disc fitted to the shaft of the rotating machines.

Figure 9. Physical arrangement of the 2 rotating machines.

The machine generates a voltage of 12 V for the speed of 300 rpm, which is shown in Figure 10. The ripple in the voltage is 0.15 V. The current drawn is 5 A to meet the loading requirements.

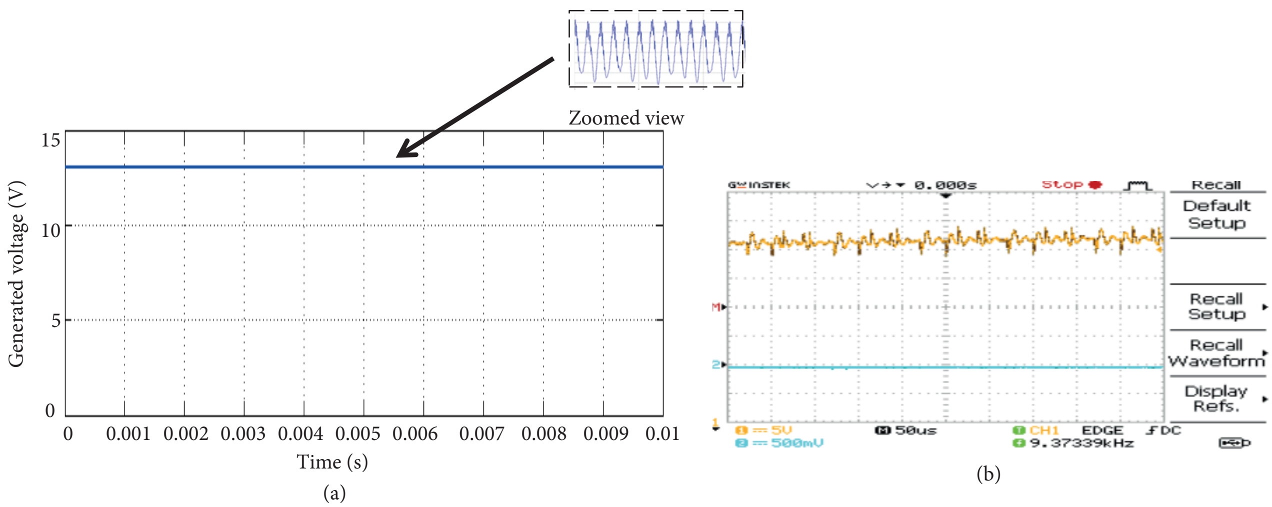

Figure 10. Simulation and hardware results of the DC voltage generated by the SRM motor due to the repulsive rotational power.

With continuous experimentation at different speeds, it is observed that the generated voltage in the generator increases with an increase in speed of the SRM motor. Figure 11 depicts the variation in generated voltage for different speeds.

5.2. Performance analysis of stepped DC coupled Z-inverter

The performance analysis of the proposed inverter is shown for the specified topology in Figure 3. The isolated input voltage is maintained at a constant 20 V for each source, and an RL load of impedance 100 Ω is used for simulation. The simulation results obtained in Figure 12 depict the waveforms of stepped DC at fundamental frequency, boosted stepped DC link voltage, inverter voltage, and current.

It is observed that the output available at the first stage of the inverter is 100 V stepped DC, which is boosted to a value of 376 V peak by the quasi impedance network of the inverter for a modulation index of 0.74 and is flipped to get the multilevel AC voltage of level 11. The load current is 2.8 A and the capacitor voltage is 203 V. The input current on the DC side is 5 A.

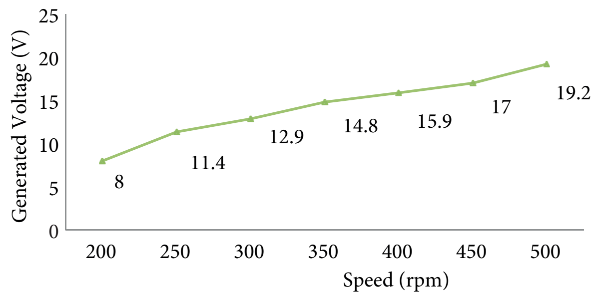

Figure 11. Performance analysis of the SRM motor with and without repulsive power generation.

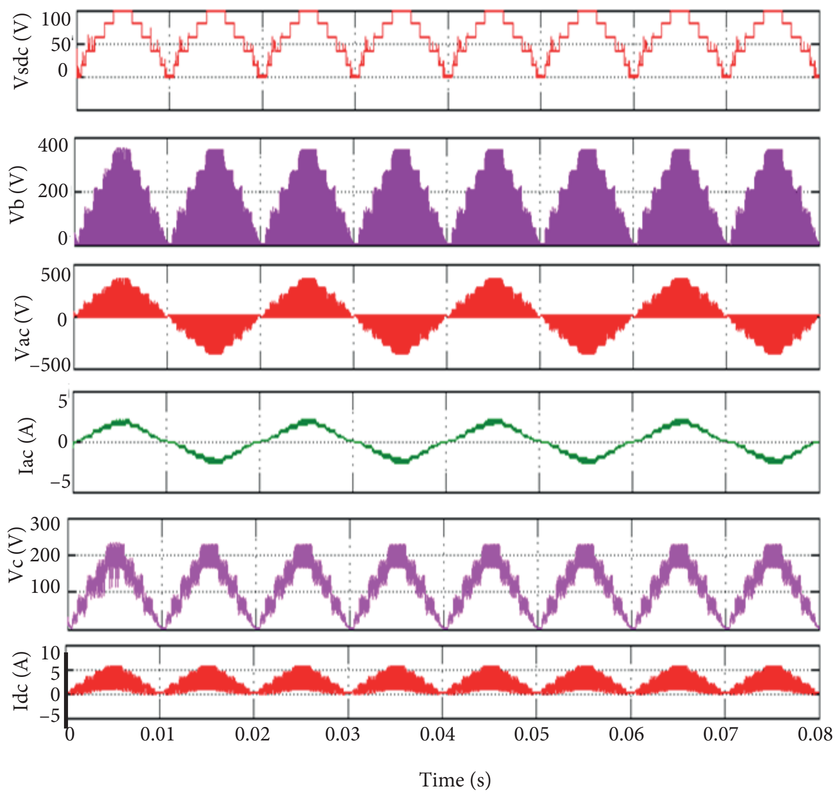

Figure 12. Simulation results at various stages of 11 level inverter.

The load current in the system is 2 A. On decreasing the modulation index, greater boost in the voltage is obtained. This helps us to maintain a constant output voltage from the inverter for varying input conditions, like stoppage of any machine.

To comply with the experimental results, the topology is reduced to 2 input circuits, and each is fed with an input of 12 V. Figures 13a and 13b show the simulated and experimental waveform of Vsdc, which is a stepped DC voltage of peak 24 V.

This stepped DC voltage is buck/boosted by the second stage of the inverter depending on the shoot-through state. Boost operation is obtained by setting a modulation index of 0.7.

In experimentation, the generated voltage stored in the battery is fed to the hardware circuit. The simulation and experimental results of the output voltage are shown in Figures 14a and 14b. The input voltage of 24 V is boosted to a value of 64 V by the quasi Z-network, and a multilevel voltage is obtained.

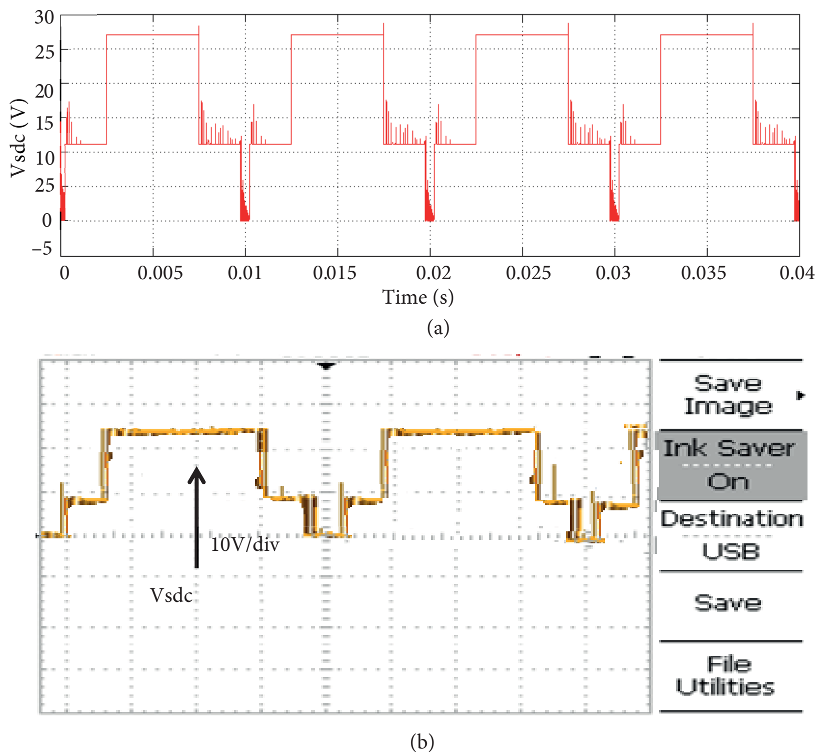

Figure 13. Simulation and hardware result of first stage of SDQZMLI inverter (a, b).

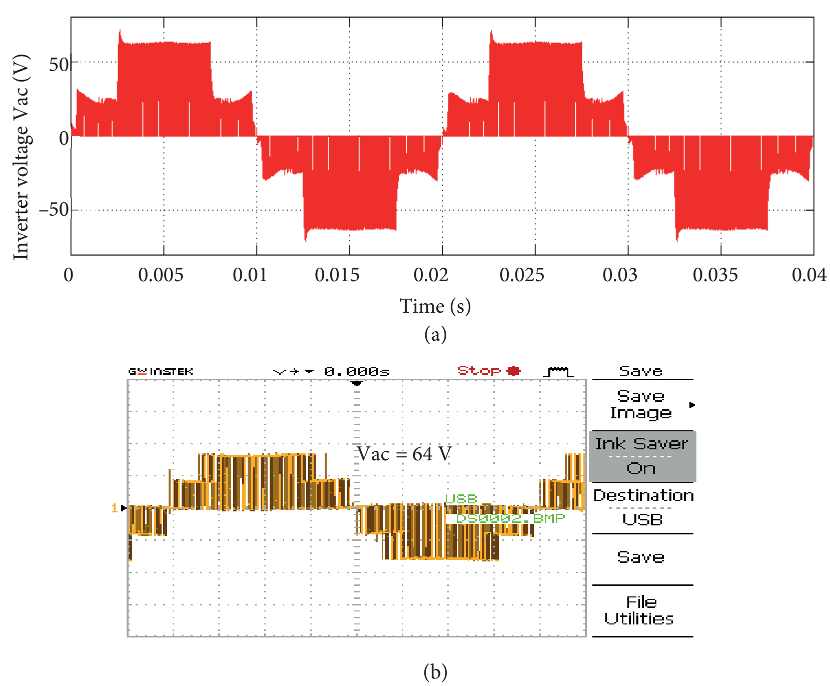

Figure 14. Simulation and experimental output waveforms of SDQZMLI inverter voltage at MI = 0.7 for an input of 12 V from the battery (a, b).

A filter circuit is used to filter the harmonics present in the output voltage; this filtered AC voltage could be fed to light-load applications. The battery output from the 'n' isolated rotational machines can be appended to get n level, thereby reducing the requirements of the filter components.

Table 2 projects the comparison of total harmonic distortion obtained for various levels in the output voltage and that of the conventional Z-source inverter.

Table 2. Comparative study of SDQZMLI with Z-source inverter.

Number of levels in output voltage	Total harmonic distortion in SDQZMLI	Total harmonic distortion in Z-source inverter
3	86.54	87.12, higher levels are not obtainable
5	79.81	
7	72.32	
11	66.51	
13	59.23	
15	46.92	

The THD is considerably reduced, and the high frequency components could be eliminated with the help of a filter.

Even under conditions where few rotating machines are not in operation, the desired voltage can be maintained at the output of the inverter by controlling the modulation index. Figure 15 gives the optimum modulation index to get the desired voltage for a different number of sources. The optimum modulation index falls within the range of 0.78 to 0.72 for the number of sources to be increased from 5 to 7. Furthermore, it is also observed that the inverter voltage increases as the modulation index is decreased.

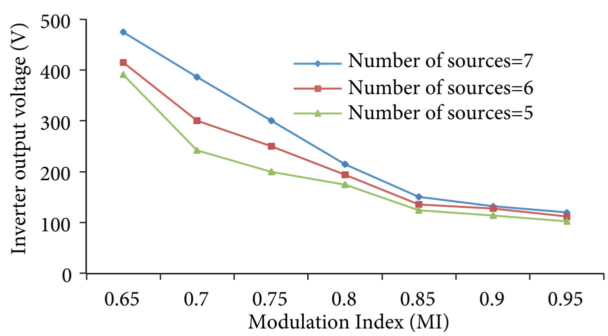

Figure 15. Identification of optimum modulation index for different number of sources.

Hence, this method is revealed to be effective in utilizing the rotational energy available in textile mills for power generation. It is also evident that the use of the SDQZMLI inverter is efficient and minimizes the cost of the system. This power can be used for light-load applications and hence partially solve the energy crisis faced by the various mills.

6. Conclusions

This paper has presented a new method for utilizing rotational energy from rotating machines in textile mills by employing repulsive magnets and the new stepped DC coupled quasi Z-inverter. Theoretical analysis, simulation, and experimental validation with a prototype system were performed to illustrate the concept. The experimentation is in agreement with that of the simulation and confirms the advantages of the system.

By using the SDQZMLI inverter, multilevel AC voltage with self-boost is obtained. An oversized battery is not required, since only isolated energy sources are utilized by the inverter. The stress on the LC component is lowered, and the multilevel operation reduces the filter requirements. Since there is no direct coupling between the 2 systems, the loading effect of the system is not present on the rotating machine. During fluctuating conditions in the input, the inverter voltage could be kept constant by adjusting the modulation index, thus reducing instabilities in the voltage. Light loads in the industry could be powered with this system; this is shown to be a promising method to meet energy demands.

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