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RESEARCH PAPER

A Novel Design and Development of Multilevel Inverters for Parallel Operated PMSG-Based Standalone Wind Energy Conversion Systems

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Abstract

The article presents the new power conversion for parallel-operated wind energy conversion systems. It has been formulated by new multilevel inverter (MLI) topologies with reduced switch counts, lowered conduction losses and a very good output voltage spectrum. The wind energy conversion systems included permanent magnet synchronous generator (PMSG), a diode bridge rectifier, a conventional boost converter and a novel multilevel inverter connected to an isolated load. The power conversion utilizing a novel multilevel DC to AC converter has been proven for its better efficiency, voltage utilization and power quality. The integration of wind energy conversion systems has been explored in MATLAB Simulink, and the hardware setup does the authentication of the MLI structure.

Keywords Multilevel inverter · Wind turbine · PMSG · Parallel connection · Switch count

1 Introduction

Renewable energy sources like wind, solar, biomass, hydro and tidal will be complete sources of future power generation replacing traditional sources from fossil fuels. Consumer in remote areas faces the challenges of getting energy resources and requires high voltage transmission to transmit power from the plant. Wind energy is the best solution for distributed energy generation with reduced energy costs (Krishnakumar et al. 2021; Zhang et al. 2019). The independent wind energy source can easily suit all communities avoiding grid instability. It has been available with small-to-large wind turbines. The Double fed Induction generator (Barendse and Pillay 2006) and permanent magnet synchronous generator (PMSG) (Anbarasan et al. 2021) types of generators are mostly used in conversion systems for better control of frequency and voltage regulation. The role of power electronics makes the conversion and utilization of wind energy more efficient (Liu et al. 2019). In standalone wind energy conversion systems, multilevel inverters have been acknowledged for producing good quality as well as lower distortion of output voltage and a low blocking voltage of semiconductors compared to the classical VSI (Malik and Sharma 2020). Several new MLI topologies have been developed and proven maximum utilization voltage with reduced switch count. In Anbarasan et al. (2020), a new MLI topology has been developed using dc link capacitor and H-Bridge inverter for photovoltaic application which proven for reduced switch count. A topology named series parallel switched

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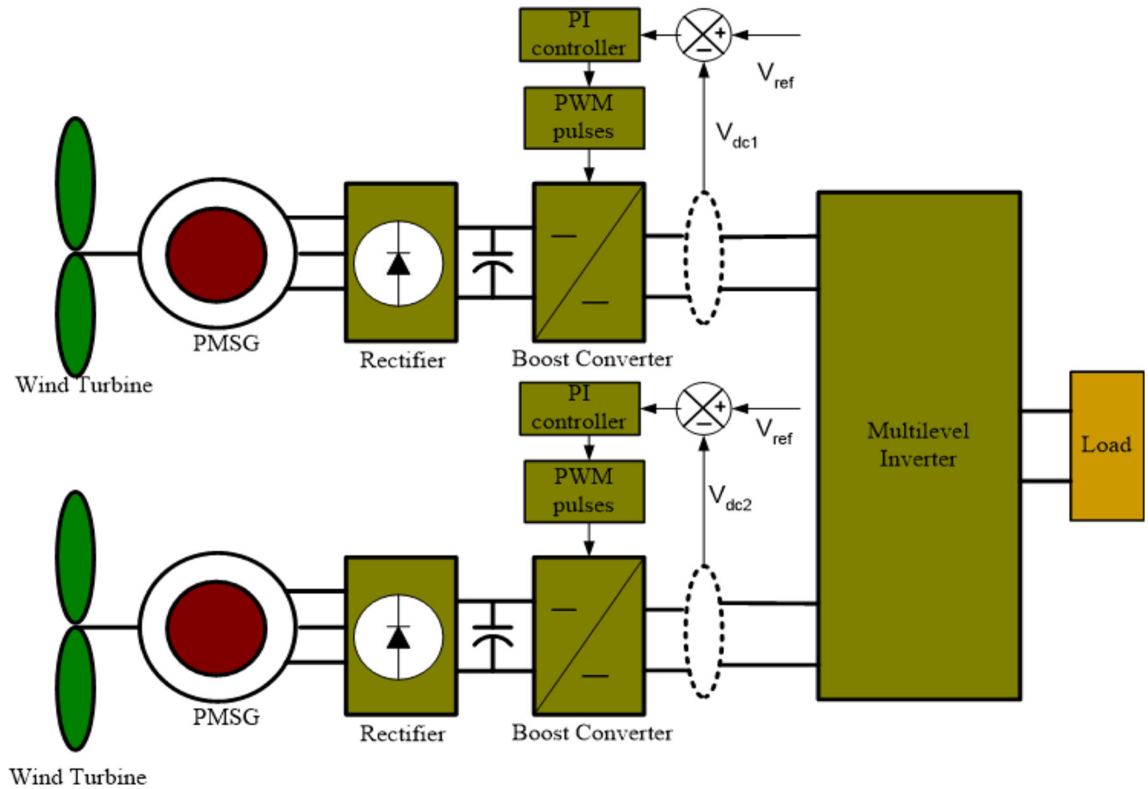


Fig. 1 Schematic diagram of wind energy conversion system

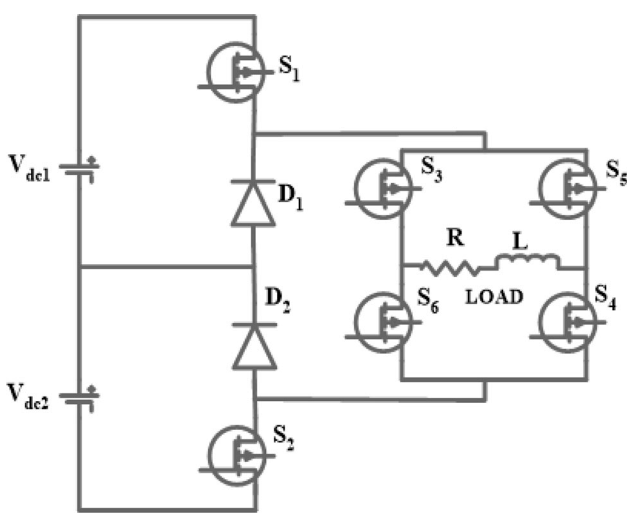


Fig. 2 Five-level multilevel inverter

Table 1 Switching states for five level output

Voltage level	Conducting switches
V_{dc}	D_1, S_3, S_4,S_2
$2V_{dc}$	S_1, S_2, S_3, S_4
0	D_1, D_2, S_3, S_5
$-V_{dc}$	D_1, S_2, S_5, S_6
$-2V_{dc}$	S_1, S_2, S_5, S_6

MLI has been developed to achieve higher voltage with minimum switch count and good quality of output voltage. This topology has been extended to a higher number of levels using the generalized structure (Ramkumar et al. 2012). A dual bridge type of hybrid MLI has been proposed for 15 level with the reduced number of power switches and voltage source are arranged in the 1:3 (Thamizharasan et al. 2012). The auxiliary reverse voltage source-based MLI has been proposed to achieve minimal power devices with maximum utilization (Thamizharasan et al. 2013). A new algorithm has been proposed to determine the voltage magnitude of asymmetrical MLI (Babaei et al. 2007) which improves the power quality of the output waveform. The carrier shifting algorithm has been applied to Neutral Clamped MLI-based induction motor drives which reduces common mode voltage (Anbarasan et al. 2017). In Dekka et al. (2020), series connected capacitor clamped MLI has been used with reduced isolated dc sources. The new optimum structure of MLI is proposed, which generates high voltages with reduced switches and utilizes lower blocking voltage capability (Laali et al. 2010). An asymmetric seventeen-level switched capacitor MLI has been proposed, and a comparison has been made with a symmetric hybrid MLI utilizing a modified H-bridge inverter

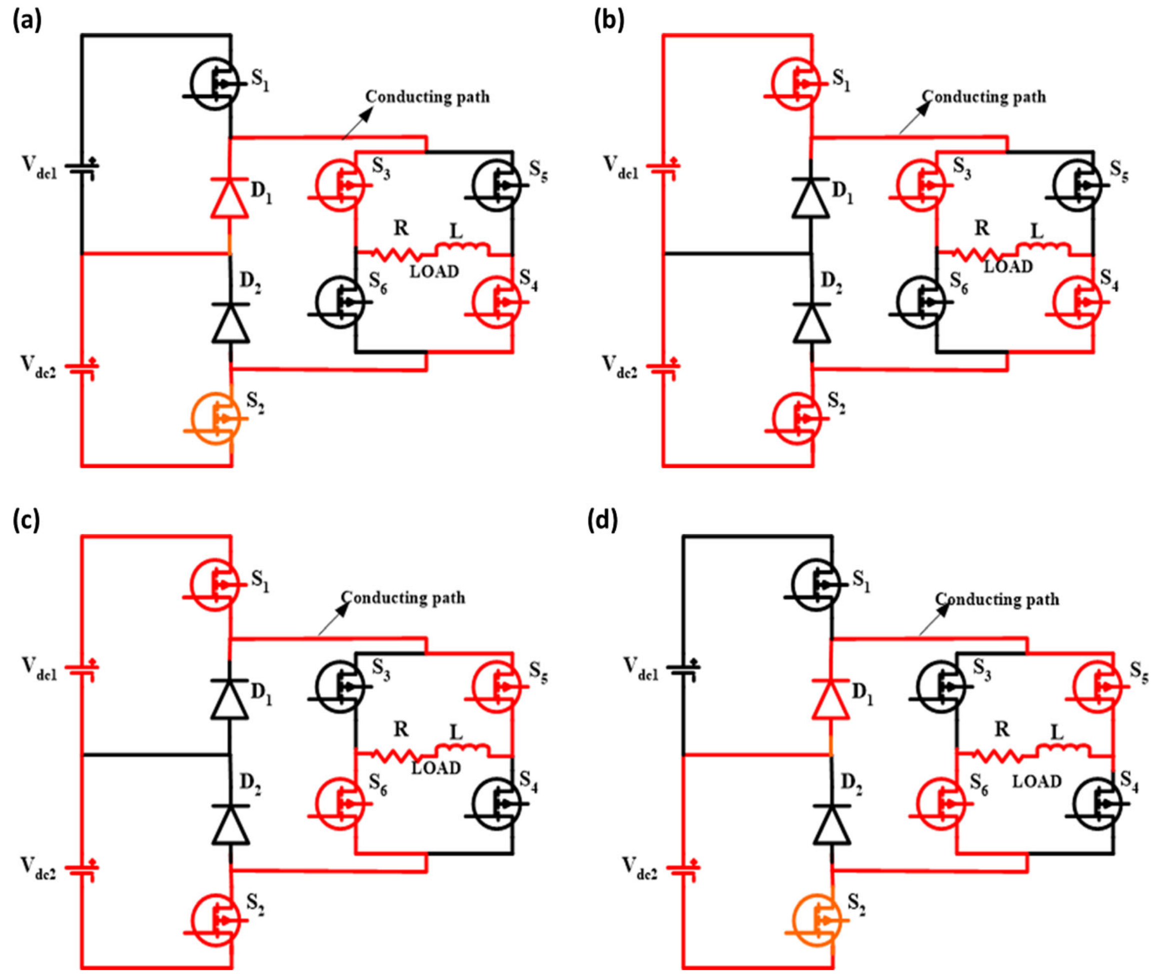


Fig. 3 Operating modes **a** $V_0 = +V_{dc}$ **b** $V_0 = +2V_{dc}$ **c** $V_0 = -V_{dc}$ **d** $V_0 = -2V_{dc}$

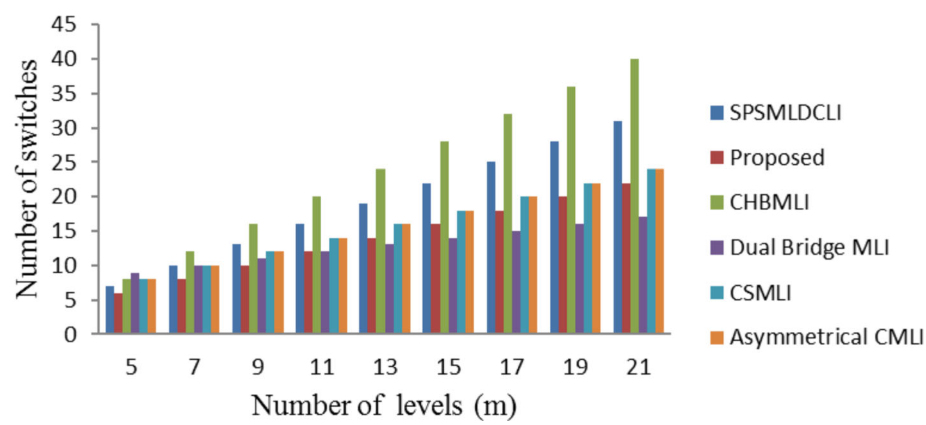
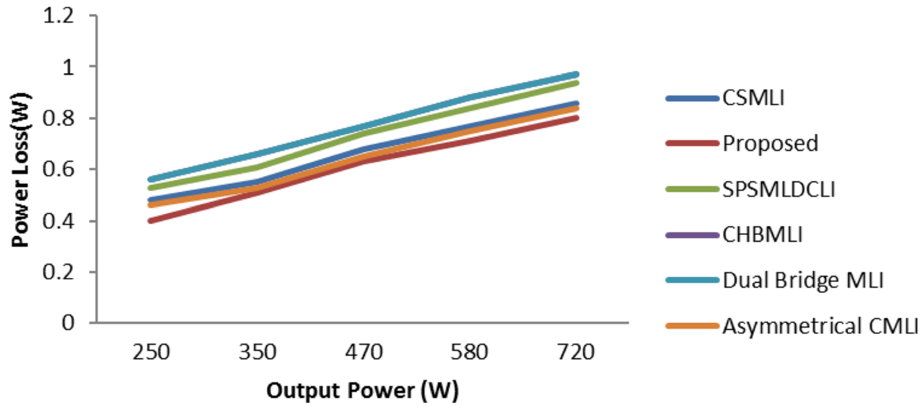


Fig. 4 Topologies switch count versus number of levels

(Dhanamjayulu and Meikandasivam 2018). The switched capacitor type MLI with boosting the capability of the converter has been proposed (Khoun-Jahan et al. 2021). In this MLI, the drawback of inrush current in switched capacitors has been eliminated by using an inductor or quasi-resonant capacitor. Very few topologies can be used for the integration of renewable energy applications.

In Chong et al. (2008), a modular multilevel converter coupled with an H-bridge inverter has been used in the power conversion of the wind system. In this system, a transformerless wind energy conversion system (WECS) provided lightweight and analyzed power-sharing by a suitable switching strategy. In Xia et al. (2011), three-level neutral point clamped inverter along with a boost converter

Fig. 5 Topologies power loss versus output power



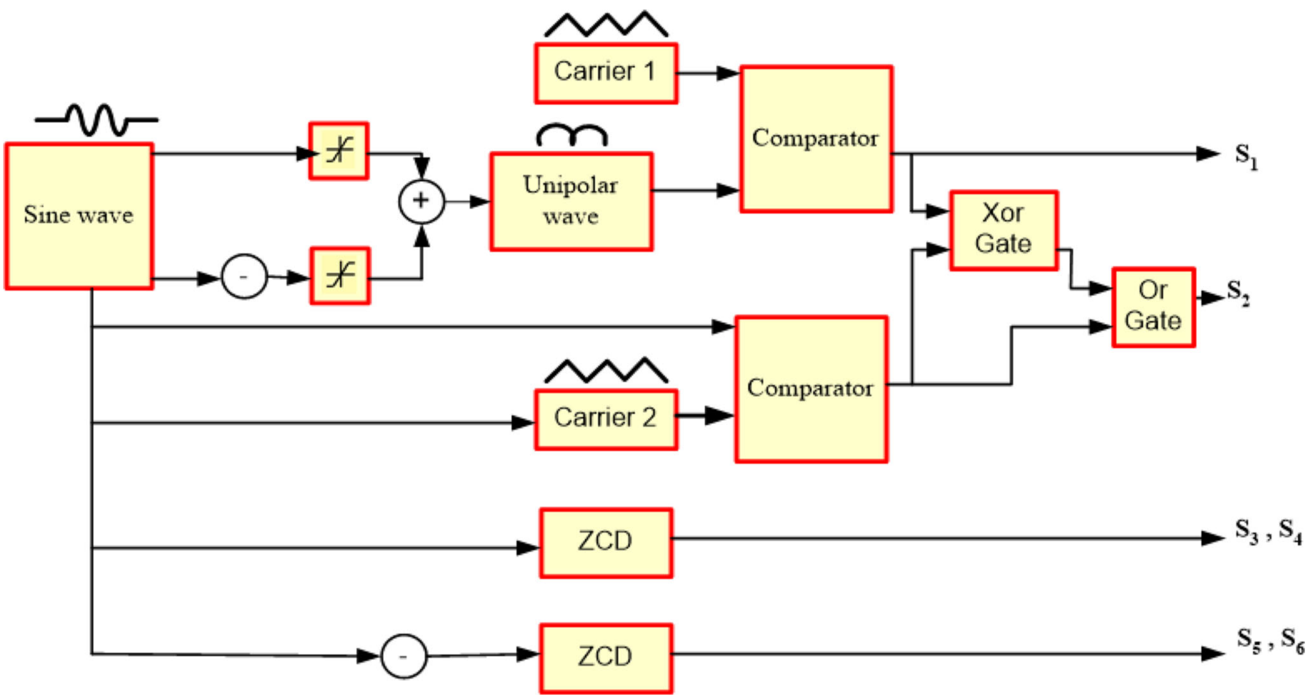


Fig. 6 Switching pulse generation

has been used for power conversion of wind systems with the regulation of PI controller tuning the PWM pulses of boost converter for extract maximum power. In (Samuel et al. 2011), a series of connected H-bridge inverters has produced multilevel output in grid-connected wind energy systems. In this, a closed loop reference current has been generated for the voltage source inverter of the wind system. The boost converter and four-level neutral point clamped inverter has been integrated with the wind turbine with a model predictive control method for regulating dc link voltage, active and reactive power (Yaramasu and Wu 2014). In Yuan et al. (2012), modular converter of cascading H-bridge and two levels inverter has been used for wind systems. A suitable approach has been formulated to integrate modular MLI with wind turbines, and the utilization of dc link capacitors is much reduced. In Polat and Yıldırım (2022), wind turbine emulator has been developed to obtain performance analysis of WECS, and in which output power has been analyzed for different duty cycle of the boost converter. A bridgeless cuk converter has been used for power conversion of PMSG-based WECS (Singh et al. 2023). This conversion system eliminates the diode rectifier, which make it suitable for low-cost small-scale turbine applications. In Nasiri et al. (2022), a new PID-based sliding mode controller has been used to control machine and grid side converter of WECS, which improves the robustness and efficiency of the system. A novel T–S fuzzy observer has been implemented for compensation control of PMSG-based WECS which calculates the non-measurable states of wind system (Kuppusamy and Joo 2023).

Table 2 Wind yurbine and PMSG parameters

Wind turbine	
Rated power in Kw	300
Number of blades	3
Rated speed in rad/sec	22.5
Pitch angle of the turbine blade	4
Rated wind speed in m/s	12
Permanent synchronous generator	
Voltage constant V-peak in Volt	415
Stator phase resistance in Ohm	2.875
d& q axis inductance in mH	8.5
Torque constant	4.1
Inertia in Kg m^2	0.0008
Friction factor in N m s	0.001

In this paper, a parallel-operated wind energy conversion system utilizing a new appropriate MLI topology has been attempted for a standalone load. The MLI has been constructed with fewer switches producing a five-level output voltage (Kannan et al. 2023). The schematic representation of parallel connected WECS is shown in Fig. 1. The MLI has two dc sources, V_{dc1} and V_{dc2}, each comprising PMSG driven by horizontal axis wind turbine and voltage regulation by power electronics converters of the diode bridge rectifier and boost converter, respectively (Suresh et al. 2022).

The horizontal axis wind turbine has been used for study, and its turbine output power depends on wind velocity, air density, the area swept out by blades, tip speed ratio and power coefficient. The power coefficient mainly depends on the radius and angular speed of the wind turbine rotor. PMSG has been used as a generator for WECS, considering the less cost, reduced size, and less maintenance due to its absence of dc excitation (Ramamoorthi et al. 2022). The diode bridge rectifier and conventional boost converter regulated by the PI controller have been used to control the voltage and frequency over the variation of wind velocity.

2 Proposed Multilevel Inverter Structure

The MLI structure shown in Fig. 2 comprises 2 switches S_1, S_2 in dc link part and 4 switches S_3, S_4, S_5, S_6, in the H-bridge part to generate five levels of output voltage. The structure shown in Fig. 2 generates 2 levels in dc-link, 5 levels in phase and 9 levels in line, respectively. The conducting switches states to produce 5 levels of output are tabulated in Table 1, supposed to produce $+2V_{dc}$, the switches S_1, S_2, S_3, S_4 are turn on. The operating modes for the output $V_0 = +V_{dc}$, $V_0 = +2V_{dc}$ $V_0 = -V_{dc}$ and $V_0 = -2V_{dc}$ are shown in Fig. 3 and its conduction path through load has been illustrated in red color line. The MLI has been operated in both symmetric and asymmetrical sources, which helps to be suitable for WECS and it can be extended to any number of levels (Cholamuthu et al. 2022). The MLI switches require low standing voltages and offer fewer switches in the conduction path.

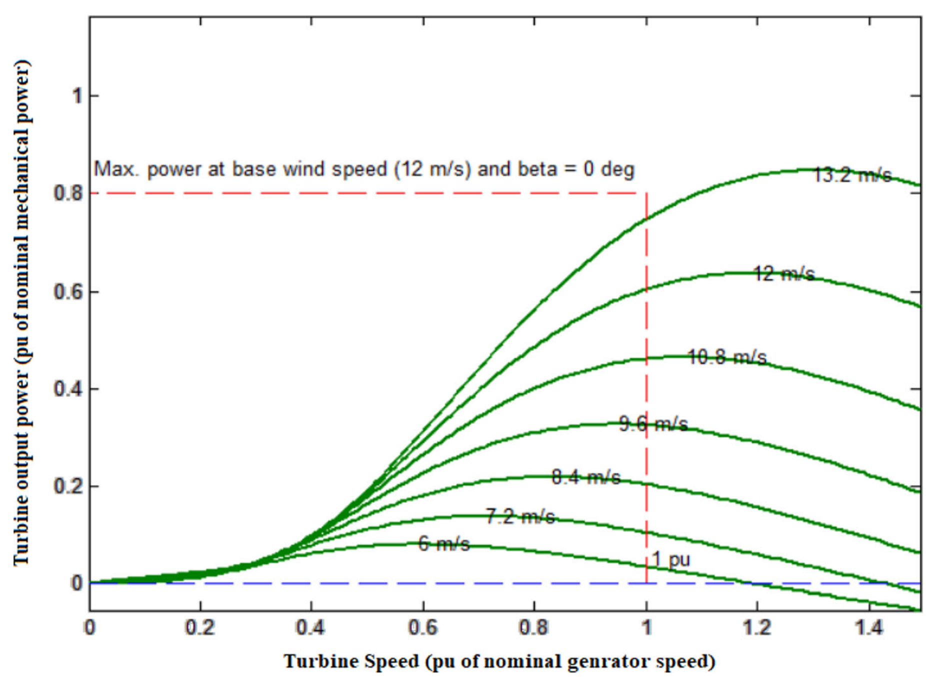


Fig. 7 Turbine output power characteristics

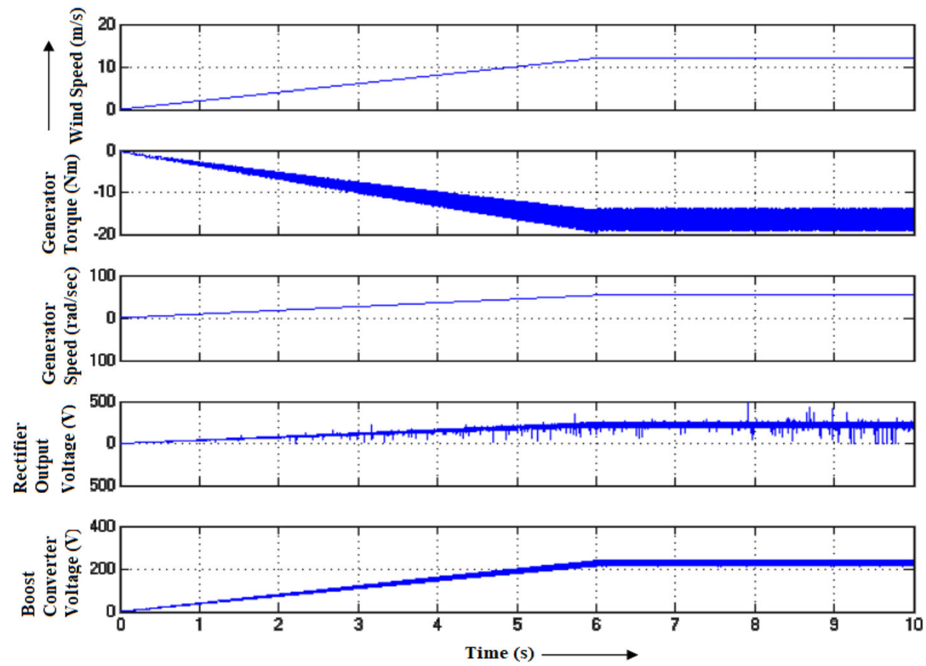


Fig. 8 Wind speed, generator torque, generator speed, rectifier output voltage and boost converter voltage of a single wind turbine

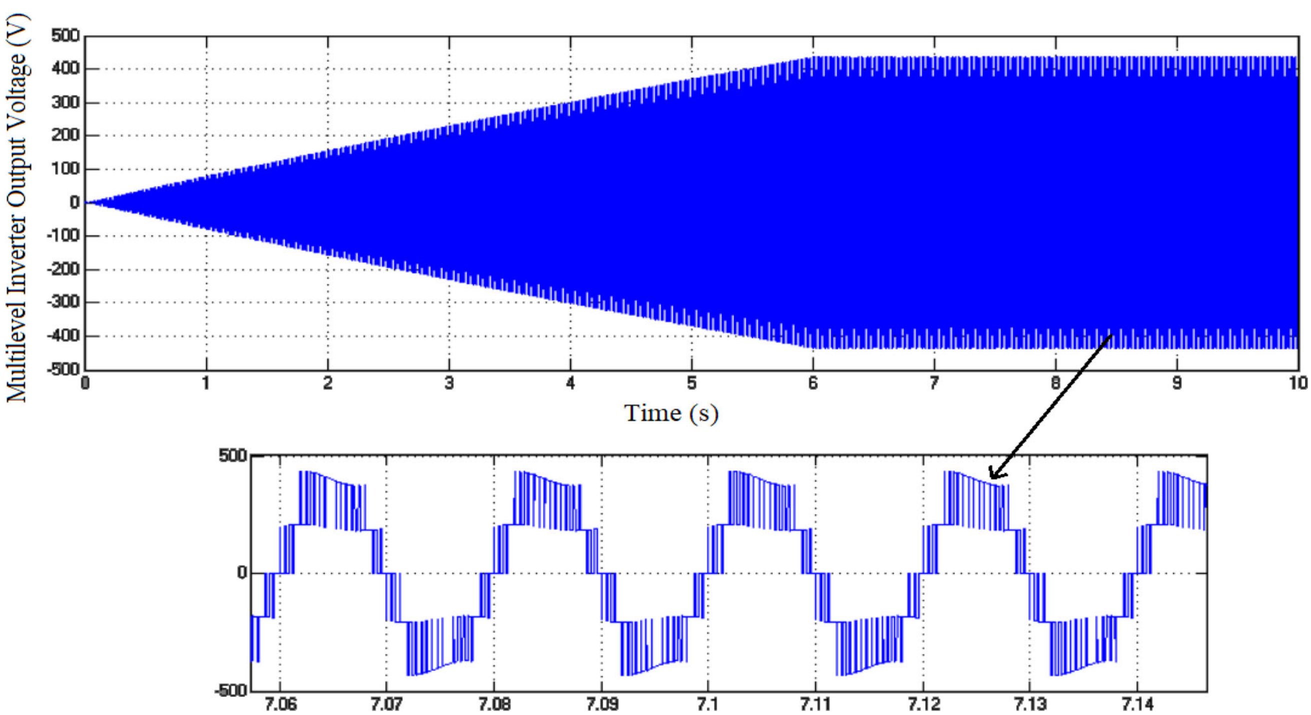


Fig. 9 Multilevel inverter output voltage

The number of levels (m) generated by the MLI is $m = 2n + 1$.

The number of switches (N) required by the MLI structure is $N = 2n + 2$.

where n is the number of sources.

The proposed topology has been compared with other established topologies like Cascaded H-Bridge, Series parallel switched MLI, cross-switched MLI and dual bridge MLI. The comparison chart in Fig. 4 shows that for those particular odd levels from 5 to 21, the proposed topology has fewer switches (Balan et al. 2022). To prove the topology efficacy, the proposed topology's power loss has been calculated and compared with other established topologies, as shown in Fig. 5. The power loss is calculated

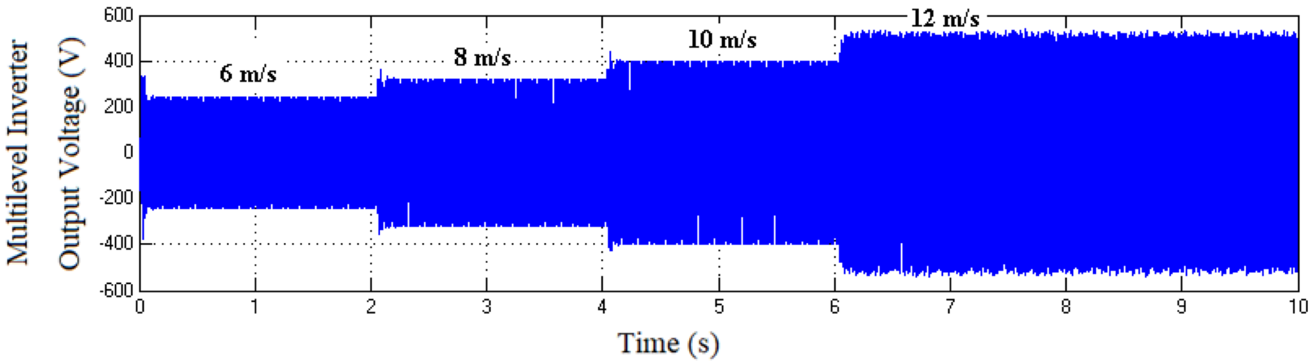


Fig. 10 Multilevel inverter output voltage for different wind velocity

Fig. 11 Load current

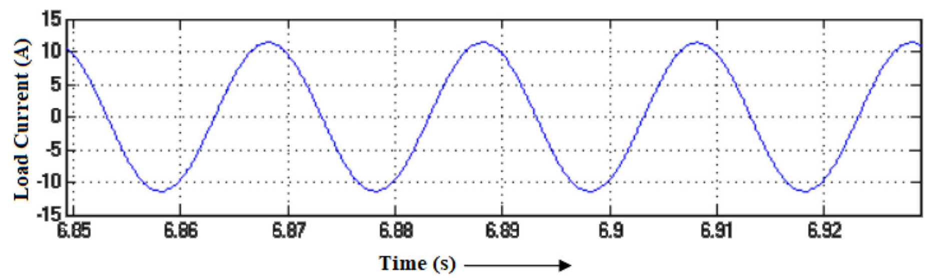


Fig. 12 Active and reactive power

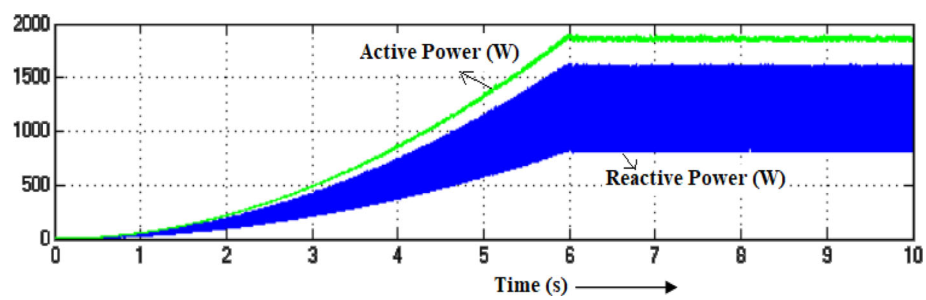


Table 3 Performance analysis of WECS

Wind velocity (m/s)	Regulated DC output voltage (V)	MLI output voltage (V)	Power (Watts)
6	112	208	552
7	138	280	754
8	154	424	1410
9	248	496	2475
10	250	500	2500
11	252	510	2530
12	254	512	2540

considering the energy loss during the switch turn on and off period. The proposed MLI requires multicarrier Sinusoidal Pulse Width Modulation (SPWM) signal for dc link switches S_1 and S_2, fundamental switching for H-Bridges S_3, S_4, S_5, S_6. The carrier switching frequency for SPWM technique is 2 kHz. The proposed MLI requires a multicarrier signal for dc link switches S_1 and S_2, fundamental switching for H-Bridges S_3, S_4, S_5, S_6. The method of pulse generation has been implemented in Fig. 6. This topology requires only 2 carrier signal for generating five level output which makes the circuit simple and less cost.

3 Simulation Results

The simulation is carried out for parallel operated WECS depicted in Fig. 1 with simulation parameter shown in Table 2. Figure 7 depicts the wind turbine output power

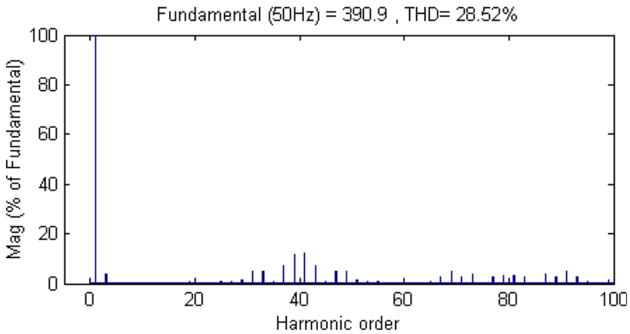


Fig. 13 Voltage harmonic spectrum

characteristics for the variation of wind speed, and it is seen that the maximum turbine power obtained at the base turbine speed of 12 m/s. In simulation wind turbine speed has been varied linearly and reaches the speed of 12 m/s for up to 6 s. The wind speed has been kept constant from 6 to 10 s for 12 m/s. The wind turbine drives the PMSG by electromagnetic torque and the generator reaches maximum speed of 53 rad/sec at 6 s. The variable AC of PMSG has been converted into variable DC voltage by three phase diode rectifiers. The rectifier DC voltage has been controlled by conventional boost converter whose switching PWM pulses are controlled by PI controller. The PI controller has been tuned manually by varying the gain value

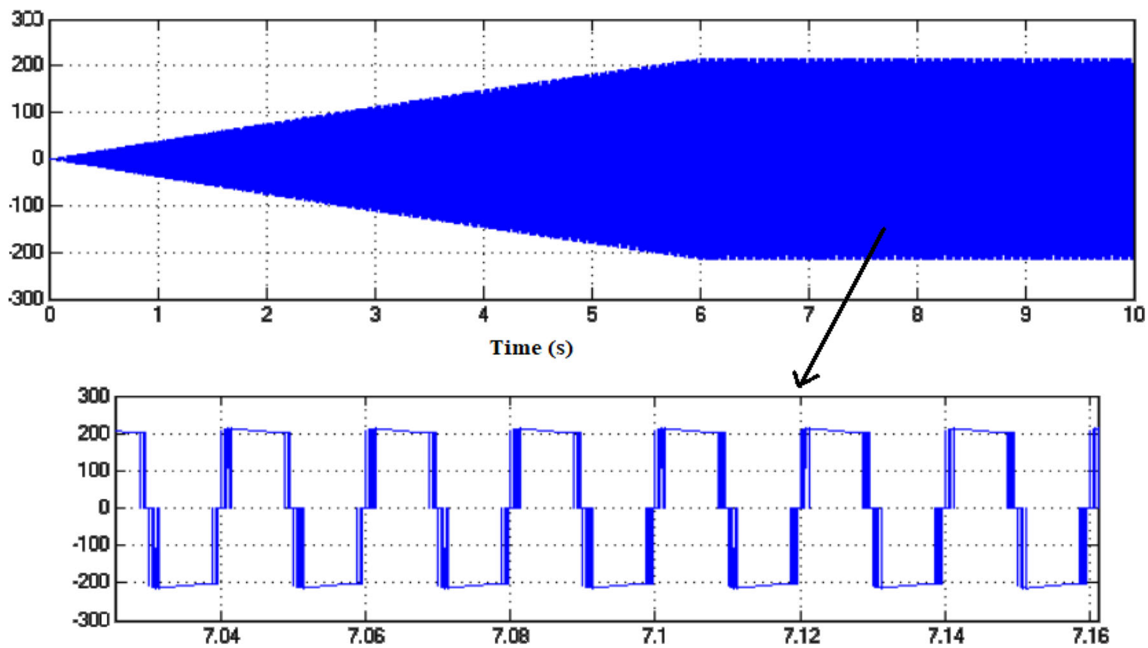
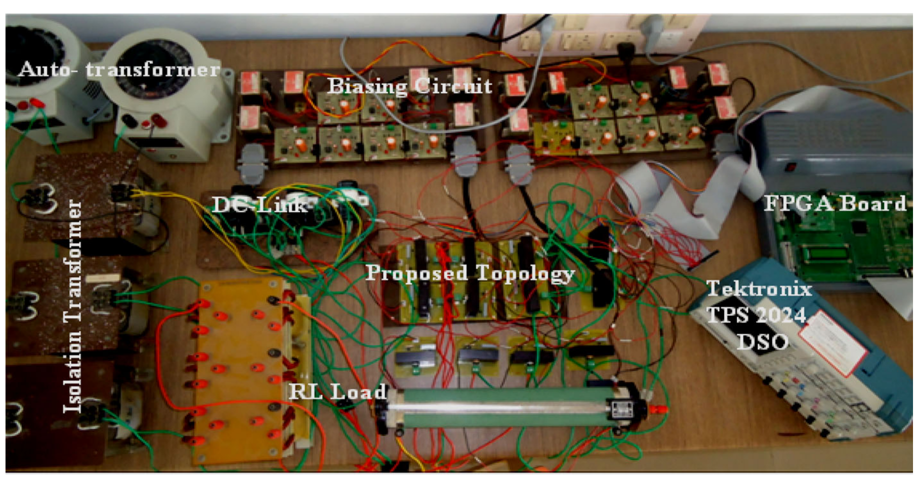


Fig. 14 Output voltage-single wind turbine operating

Fig. 15 Experimental setup



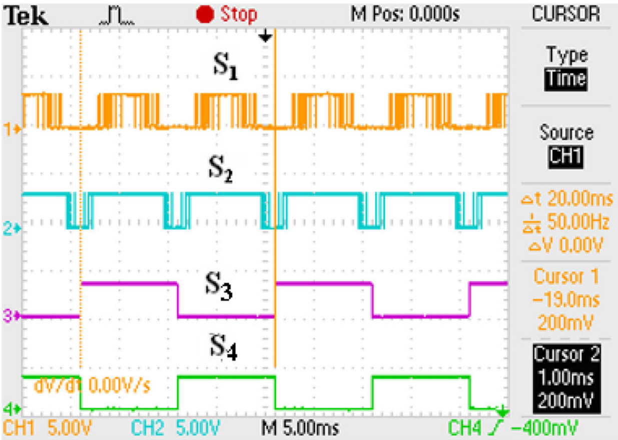


Fig. 16 Gating pulses

of K_p and K_i. The reference voltage has been maintained constant for the tuned value of $K_p = 150$ and $K_i = 60$. The wind turbine speed, generator torque, generator speed, rectifier output voltage and boost converter output voltage obtained from the single wind turbine are displayed in Fig. 8. The regulated dc output voltage has been used as input voltage for five level proposed MLI. The SPWM pulse and fundamental switching pulse has been generated by using pulse generation methodology shown in Fig. 6 for five level MLI. The five level MLI output voltage along with zoomed view from parallel connected WECS shown in Fig. 9. The inverter output has also been captured by varying wind velocities of 6 m/s, 8 m/s, 10 m/s and 12 m/s shown in Fig. 10. The corresponding load current, active and reactive power is depicted in Figs. 11 and 12, respectively, for the RL load of resistance 20 Ω and inductance 100 mH. The output performance of WECS for varying wind velocity is tabulated in Table 3. The regulated dc voltage from first wind turbine, MLI output voltage and output power has been almost maintained constant from wind velocity of 9 to 12 m/s. The harmonic output voltage profile is obtained as 28.49% which is shown in Fig. 13. When one wind turbine is not operated, three level of output voltage is obtained from second wind turbine which is depicted in Fig. 14.

4 Experimental Results

The experimental setup of the MLI structure of Fig. 2 has been implemented for symmetrical sources with its components comprising of input autotransformer, DC link,

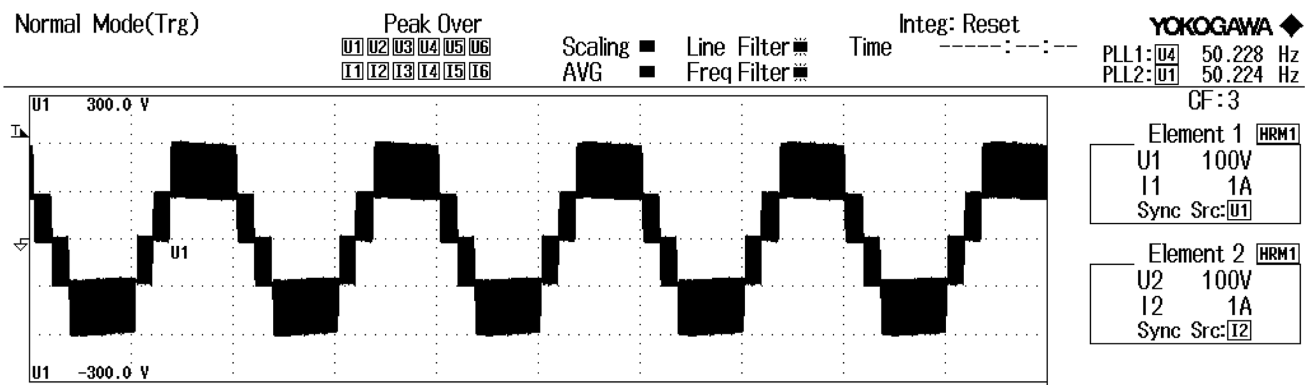


Fig. 17 Five level output voltage waveform

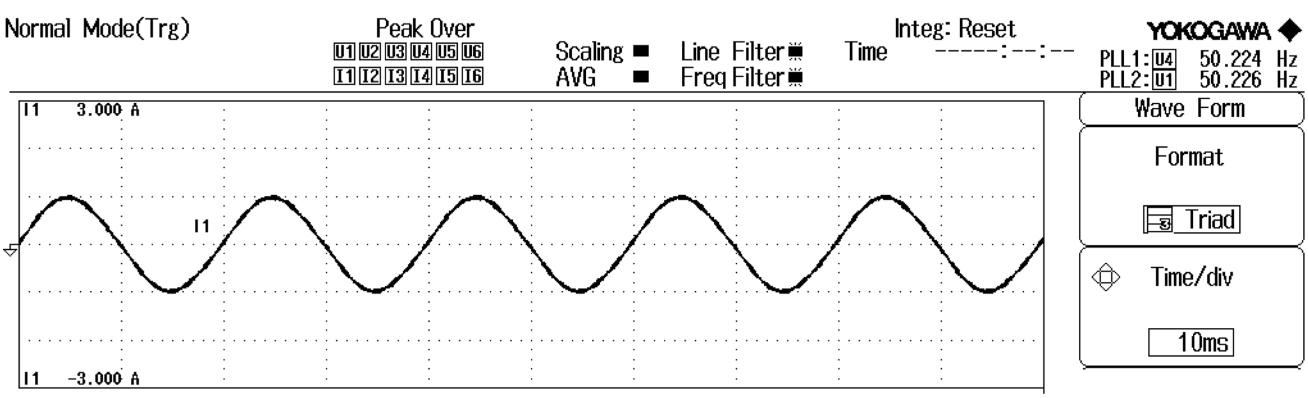


Fig. 18 Load current waveform

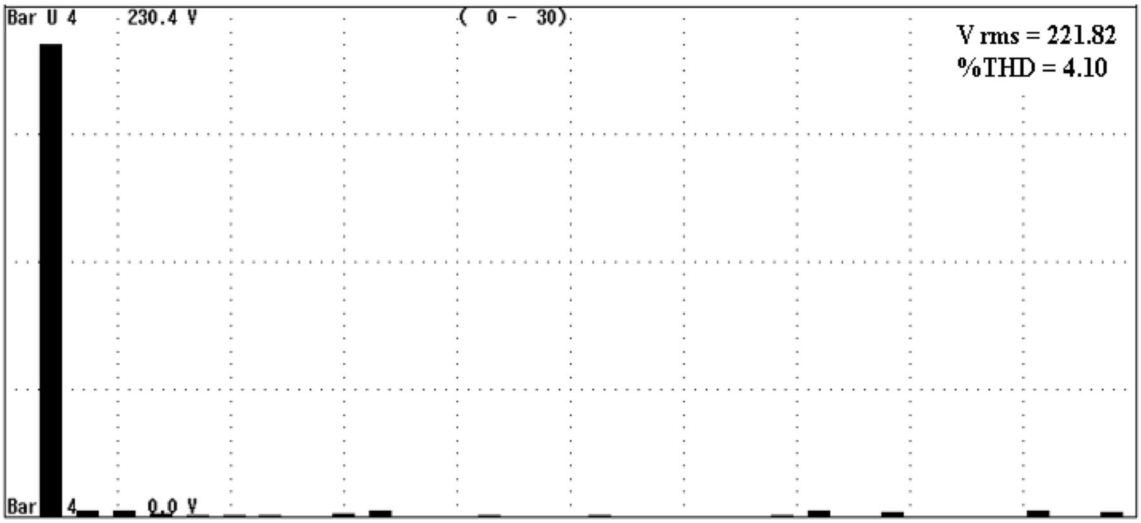


Fig. 19 Harmonic voltage spectrum

MOSFET switches, biasing circuit, isolation transformer, RL load and scope depicted in Fig. 15. The FPGA utilizes specific integrated circuit platform embedding both software and hardware with quick responses and higher frequency range. The look up table has been created for pulse generation by calculating ON time and OFF time of each switch of MLI using the FPGA Xilinx processor. The MLI switches have been gated by multicarrier and fundamental pulses and are shown in Fig. 16. The five-level output voltage and load current have been captured and depicted in Figs. 17 and 18, respectively. The voltage THD is obtained as 4.04% and shown in Fig. 19 which is match with simulation results.

5 Conclusion

A new reduced switch count multilevel inverter has been integrated to parallel connection of WECS of wind turbine connected to isolated load through PMSG and boost converter. The WECS has been simulated in MATLAB simulation compared with hardware setup, observed output voltage almost a sinusoidal waveform with five level of phase voltage. It also concluded from the result that the MLI structure is appropriate inverter for renewable source applications. It has been proved two wind turbines operating for WECS. The power conversion will not stop even one of the wind turbines in faulty condition. The number of wind turbines has been extended with increases in the number of levels in proposed MLI structure.

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Data Availability The data used to support the findings of this study are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare no potential conflicts of interest concerning this article's research, authorship and publication.

Ethical Approval This material is the author's original work, which has not been previously published elsewhere. The paper is not currently being considered for publication elsewhere. The paper reflects the author's research and analysis truthfully and completely.

Human and Animal Rights The authors at this moment assure that this research does not involve any human participants or animals.

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