A Novel 9-Level Multilevel Inverter for Water Pumping System

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***Abstract*—In agricultural and residential applications where the grid power is unavailable, water pumping devices assisted by photovoltaic (PV) array are growing more popularity. The performance of a proposed multilevel inverter (MLI) fed induction motor water pumping system (WPS) is investigated in this research. V/*f* method is adopted for speed control of the induction motor in the single-stage WPS system. The proposed multilevel inverter with phase opposition disposition sinusoidal pulse width modulation (POD-SPWM) technique is employed to produce the reference voltage for the WPS system. Simulations are carried for the proposed system in MATLAB/Simulink platform. The system is tested under different test case conditions and are tabulated. The proposed MLI for water pumping is easy to use, needs less devices compared to traditional ones and produces optimal voltage and current waveforms with lower harmonics, which minimizes the need of filters.**

Keywords—Novel MLI, SPWM Technique, V/f Control, Water Pumping System

I. INTRODUCTION

Solar Photovoltaic is the quickly expanding field in the vicinity of renewable power generation. The application of PV water pumping system is annually growing by 6.9% as per CAGR 2024 - 2031. The solar water pumping comprises of source, power converter unit (PCU) and motor. This paper majorly focuses on power conversion unit. Power control unit is said to be single-stage system if it uses either DC-AC inverter or DC-DC converter. However, the system is regarded as a double-stage system if it uses both the converters i.e., DC-DC converter and DC-AC converter [1]. Single stage system is gaining more popularity as it requires fewer components compared with double-stage system. Also, the complexity of the system reduces, increases efficiency, reduces weight of the system, simple control algorithms, improves reliability and fast response.

At present two-level inverters are used in PCU's. But it also causes the motor currents losses and ripple content to grow [2]. Further, it requires filter circuit which makes circuit bulker and costly. However, to overcome this problem, multilevel inverters are gaining attention for this application. To provide three-phase AC voltage in the system, the Neutral Point Diode Clamped (NPC) inverter with SPWM technique approach is suggested in [3]. However, Cascaded H- Bridge type converters are more suitable for this application. Since, it involves more isolated DC sources [4] and additionally it does away with fluctuations and the requirement for extra clamping diodes and flying capacitors. Also, several MLI topologies [5-9] are introduced by researchers in recent years.

Several motors like BLDC, PMSM, SRM, DC motors are used for WPS application. High starting torque, wide speed range, lower cost, minimum maintenance, ease of use, etc. are the benefits with induction motor. So, in practical majority of the WPS systems are fed with induction motor because of their superiority over other motors. Further several control techniques like V/*f* control, Direct Torque Control (DTC), Indirect Field Oriented Control (IFOC) are implemented on Induction motor. V/*f* control is applied in wide applications because of its simplicity, economical, robustness, reliable, easy to implement and good performance in steady state operation.

This work focuses on proposing a multilevel inverter for induction motor fed WPS system using V/*f* control. This paper proposes a 9-level inverter with twelve switches can provide lesser harmonic voltage with reduced switch requirement. Using Proportional Integral (PI) Controller, the MLI fed IM drive's performance is evaluated [10]. In most of the speed control applications, PI controllers are used because of their superior stability, zero steady state error and peak overshoot. Generally, MLIs achieve lower Total Harmonic Distortion (THD) thereby flowrate and speed increases in the system with smooth operation. The proposed MLI for water pumping is easy to use, needs less devices compared to traditional ones and produces optimal voltage and current waveforms with lower harmonics, which minimizes the need of filters thereby reduces both size and cost of the system.

This article is structured as follows; the schematic of the entire system, novel MLI topology with switching states and their modes of operation, modelling of induction motor and WPS system are discussed in section II, MATLAB simulation results obtained with the proposed WPS system are discussed in detailed and are presented and tabulated under different test conditions in section III, and conclusions are made in the final section of the article.

II. PROPOSED SYSTEM

The Schematic of the proposed 9-level MLI fed water pumping system driven with three-phase IM is shown in Fig.1. The proposed MLI generates 9-level output voltage in each phase. It is fed to three-phase squirrel cage induction motor fed water pumping system with closed loop operation. In this case V/*f* scheme controls the motor speed. Where, the ratio between the voltage & frequency is maintained constant such that the torque also remains constant and this can be achieved by change in modulation index value of the reference wave in the SPWM technique.

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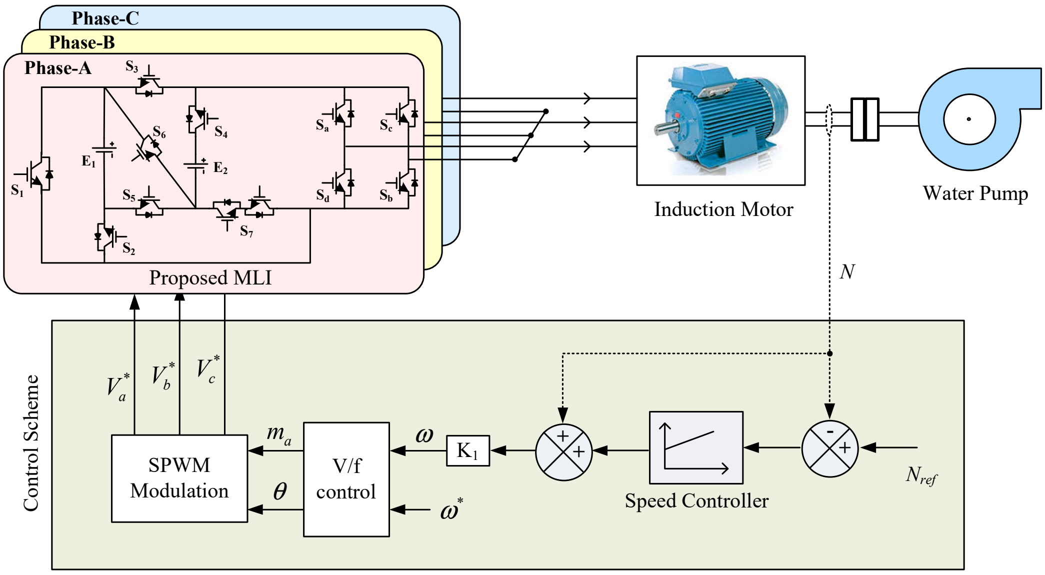


Fig. 1. Schematic of the proposed MLI fed WPS system.

A. Proposed Inverter

Multilevel inverter reduces harmonics into the load and also it can control the output voltage to regulate the speed of the Induction Motor. Here, the proposed single-phase topology is shown in Fig.2.

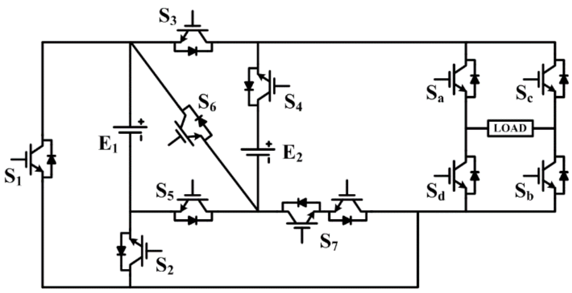
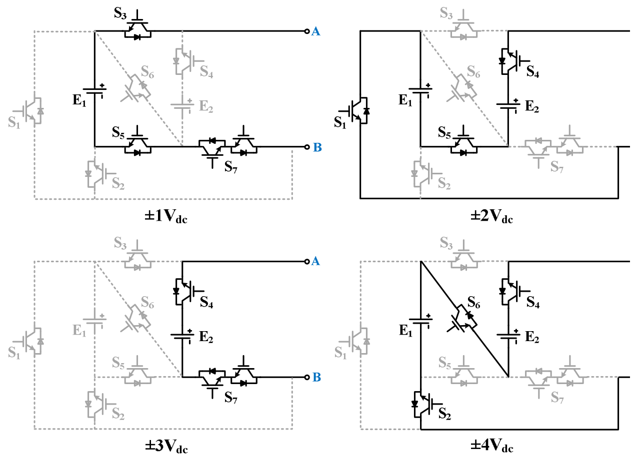


Fig. 2. Proposed Multilevel Inverter

TABLE I. SWITCHING STATES FOR THE INVERTER

Output Voltage (V_0)	@ $E_1 = V_{dc}$ & $E_2 = 3V_{dc}$	Switching States
0	0	$S_1\ S_3\ S_a\ S_b$
E_1	V_{dc}	$S_3\ S_5\ S_7\ S_a\ S_b$
E_2-E_1	$2V_{dc}$	$S_1\ S_4\ S_5\ S_a\ S_b$
E_2	$3V_{dc}$	$S_4\ S_7\ S_a\ S_b$
E_1+E_2	$4V_{dc}$	$S_2\ S_4\ S_6\ S_a\ S_b$
-E_1	-V_{dc}	$S_3\ S_5\ S_7\ S_c\ S_d$
E_1-E_2	-$2V_{dc}$	$S_1\ S_4\ S_5\ S_c\ S_d$
-E_2	-$3V_{dc}$	$S_4\ S_7\ S_c\ S_d$
-E_1-E_2	-$4V_{dc}$	$S_2\ S_4\ S_6\ S_c\ S_d$

It consists of 10 unidirectional switches (S_1, S_2, S_3, S_4, S_5, S_6, S_a, S_b, S_c, & S_d), one bidirectional switch (S_7) and two DC voltage sources (E_1 & E_2). DC voltage sources are selected in 1:3 ratio such a way that it can generate maximum of 9-levels. Also, the proposed topology is suitable to adopt both symmetrical & Asymmetrical (Unary, Binary and Trinary) selection of source voltages to vary the output levels. The switching/ON states for the proposed inverter is shown in Table I. Here the modes of operation for all the output voltage levels across the H-Bridge circuit are shown in Fig.3. Here the positive and negative voltages are generated with the help of H-Bridge circuit.



The proposed topology can stretch out by cascading the basic modules to achieve desired output levels. Also, the selection of source voltages in the proposed inverter should be either symmetrical or asymmetrical selection as mentioned earlier. But the trinary sequence yields more output levels compared with remaining.

Number of levels in output,

$$N_L = 3^{2n} \tag{1}$$

Maximum output voltage,

$$V_{0,max} = \left(\frac{3^{2n}-1}{2}\right)V_{dc} \tag{2}$$

Where 'n' represents number of modules.

TABLE II. COMPARISON OF DIFFERENT MLI TOPOLOGIES

Reference	*MLI Topology*	N_L	N_{sw}	N_{DC}	$V_{0,max}$
[5]	ST Type	$16n+1$	$12n$	$4n$	$8nV_{dc}$
[6]	Asymmetrical MLI	$32n+1$	$16n$	$4n$	$16nV_{dc}$
[7]	Reduced switch count Inverter	$(4n+1)^2$	$8n+4$	$2n$	$4n(2n+1)V_{dc}$
[8]	Trinary-CHB	3^n	$4n$	n	$((3^n-1)/2)V_{dc}$
[9]	Trinary seq. Inv.	3^n	$5n$	n	$((3^n-1)/2)V_{dc}$
Proposed	Cascaded-Modules	3^{2n}	$8n+4$	$2n$	$((3^{2n}-1)/2)V_{dc}$

Comparative analysis is made between level count (N_L), switch count (N_{sw}) and DC sources required in the inverter (N_{DC}) to estimate the performance of the proposed topology with recent MLI topologies shown in Table II. From the above table, it concludes that this MLI generates more number of output levels with less devices count. So, this inverter yields better performance at higher levels rather than at lower levels.

B. Induction Motor fed Water Pumping System

In water pumping applications squirrel cage induction motors are widely used because of its significance like high starting torque, compatible with variable speed drives, robustness at different conditions, reliable and efficient, etc.

For dynamic analysis, the three-phase IM is modelled in dq- axis. The voltage equations in the d-q reference frame for both stator & rotor modelling are given below,

$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} - \omega\lambda_{qs} \tag{3}$$

$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} + \omega\lambda_{ds} \tag{4}$$

$$v_{dr} = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} - (\omega - \omega_r)\lambda_{qr} \tag{5}$$

$$v_{qr} = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} + (\omega - \omega_r)\lambda_{dr} \tag{6}$$

Where, $v_{ds}, v_{qs}, v_{dr}, v_{qr}$ are d-q axis voltages for stator & rotor, $i_{ds}, i_{qs}, i_{dr}, i_{qr}$ are d-q axis currents for stator & rotor, $\lambda_{ds}, \lambda_{qs}, \lambda_{dr}, \lambda_{qr}$ are d-q axis flux linkages for stator & rotor, R_s, R_r are stator and rotor resistances, ω, ω_r are synchronous & rotor speeds.

Typically, centrifugal pumps are widely used in the applications of water pumping system. Now, the mechanical energy induced in the induction motor is converted into fluid flow. The Speed-Torque relation for the centrifugal pump is given by,

$$T_L = K\omega_m^2 \tag{7}$$

K is constant and it is obtained using power equation $P = K\omega_m^3$. Here, P and ω_m are considered as 4KW and 149.75 rad/sec respectively.

III. SIMULATION RESULTS

Simulations for a closed-loop operation of the MLI based WPS system are carried in MATLAB/Simulink. Here, DC-AC conversion takes place through the three-phase MLI and to achieve per phase rms voltage of 230V on the output side of inverter, the DC voltage sources are chosen with $E_1 = 81V$ & $E_2 = 243V$. A High switching frequency modulation technique of POD-SPWM technique with 5KHz switching frequency is adopted to fire the power switches as shown in Table I. The three-phase 9-level MLI output voltage is shown in Fig.4. Also, the current waveforms of proposed MLI are shown in Fig.5. Here, the voltage and current THDs are about 13.72% and 1.2% respectively.

Now, the reference speed is set to approximately half the

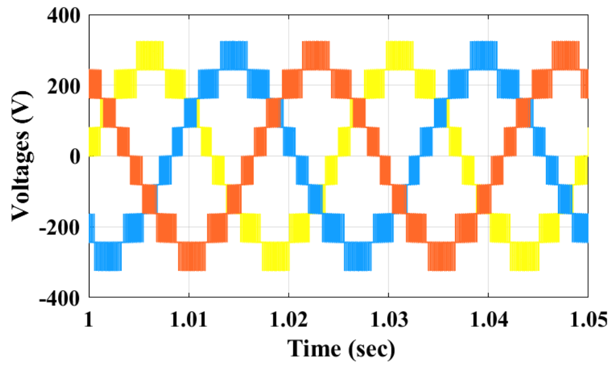


Fig. 4. A 9-Level three-phase voltage waveforms of MLI

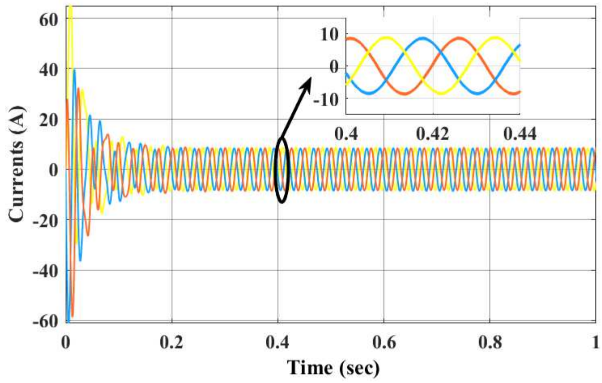


Fig. 5. Three-phase currents of MLI in the system

rated speed i.e., 700 rpm for an induction motor with rated speed of 1430 rpm. In closed-loop operation the speed error is

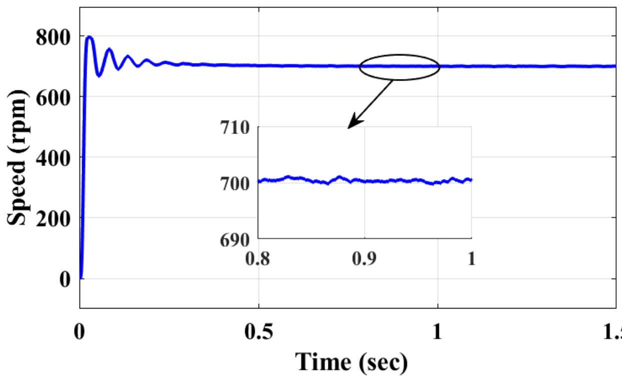


Fig. 6. Motor speed of the IM @ N_{ref}=*700rpm*

nullified with PI controller. The PI controller gains are chosen as $K_p = 2$ and $K_i = 10$ by trial-and-error method. Therefore, the modulation index changes to 0.467 and frequency is set to 23.34Hz such that the V/*f* ratio remains constant. The speed of

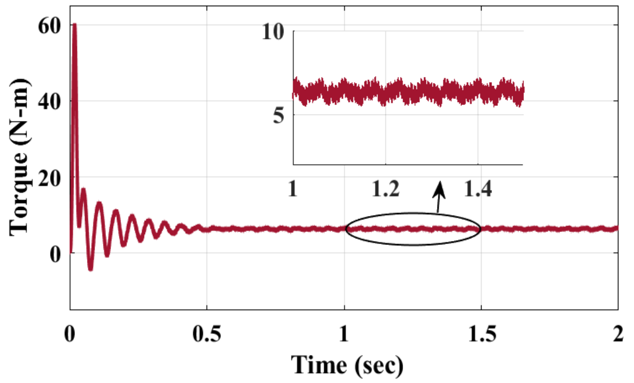


Fig. 7. Electromagnetic torque of IM

the IM and electromagnetic torque are shown in Fig.6 and Fig.7.

From the above figures, the settling time for both the parameters are about less than 0.4 sec. In steady-state operation, the speed oscillations in the motor is approximately 0.5% which is desirable.

TABLE III. MODULATION INDEX AND FREQUENCY AT DIFFERENT MOTOR SPEEDS.

Motor Speed *(rpm)*	**M_a**	**Freq. *(Hz)***
700	0.467	23.34
800	0.533	26.67
900	0.6	30
1000	0.67	33.34
1100	0.73	36.67
1200	0.8	40
1300	0.87	43.34
1400	0.93	46.67
1500	1	50

By varying the reference speed of the motor in closed-loop operation from 700rpm to 1500rpm the modulation indices (M_a) and frequencies are noted and are shown in Table III. Therefore, at all the conditions the ratio between the M_a & frequency are maintained constant.

IV. CONCLUSION

The proposed MLI produces 9-level output voltage for water pumping system. The motor is controlled at desirable speeds and the ratio of V/*f* is maintained constant which offers the motor to run at desired speed. Compared to few MLIs existing in the literature, the suggested topology requires less components. The proposed MLI generates output waveforms with minimum THD, which is desirable for any load applications. The current harmonics are 1.2% which eliminates the necessity of filters. Further, the proposed system has good steady state stability. The proposed topology finds good application in PV water pumping system.

CONFIGURATION PARAMETERS

Induction Motor	
Nominal Power	4KW (5.4HP)
Rated Speed	1430RPM
Line-Line voltage	400V
Frequency	50Hz
Stator & Rotor Resistances	1.405Ω & 1.395Ω
Stator, Rotor & Mutual Inductances	5.839mH, 5.839mH & 172.2mH
Centrifugal Water Pump	
Head Pressure	260Psi
Capacity	145.35m3/hr
Efficiency	65%

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