Multi-Level Inverter Fed Induction Motors Based on Simplified and Efficient Modulation Techniques

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***Abstract*—Speed control of three phase and single phase induction motors represents a very important issue in residential and industrial applications. This paper presents a voltage to frequency speed control of both single phase and three phase induction motors derived by multi-level inverters (MLIs). 15-level and 31-level multi-level inverters are considered. Both MLIs are operated by applying two proposed simplified and efficient modulation techniques in addition to the application of conventional multicarrier sinusoidal pulse width modulation technique MC-SPWM. The proposed modulation techniques overcome several difficulties related to MC-SPWM. The scaler voltage to frequency control method operates very well during starting along with step changes in motor speeds. Simulation results verify the high performance of the proposed modulation techniques when controlling both induction motors based on 15-level and 31-level MLIs.**

***Index Terms*—Multi-level inverters, induction motors, voltage to frequency control, simplified modulation techniques, speed control**

I. INTRODUCTION

In recent years, multilevel inverters MLIs have gained increasing popularity due to their advantages of less voltage and current stresses on semiconductor devices, low switching loss and very low harmonic contents in the output voltage. MLIs have been widely used in medium and high voltage variable speed drives, direct current (DC) distributions, photovoltaic applications, and high-voltage direct current transmission [1–5].

Variable speed drive systems are a very special and attractive application of MLIs. Out of these systems, induction motor IM speed drive systems are the most important and popular motors. The major reasons of induction motors popularity are: 1) motor lower cost when compared to synchronous motors and DC motors, 2) high reliability and low maintenance requirements, 3) induction motors are rugged and robust in construction which enable these motors to be employed in several environmental conditions for a long time, 4) speed control of IMs can be achieved easily by controlling the supply frequency and 5) induction motors can provide very high starting torque which is required for many applications [6–9]. The main drawback of IMs is the very high starting currents which can reach ten times the rated values. These starting inrush currents are very serious to the IMs themselves and the electric grid as well [10, 11]. They can result in motor damage and destabilization of power systems. In addition, the very high starting currents can cause unnecessary trips in protection relays. One of the most efficient methods of reducing these high starting currents are the utilization of motor soft starting trough voltage to frequency method. Speed control of IMs can be achieved by applying the voltage to frequency method [12, 13]. Induction motors voltage/frequency control method is utilized in enormous applications such as pumping systems, elevators and home appliances although it is considered as a scaler conventional control strategy when compared to advanced control methods such as field orientation control and direct torque control [14–16]. The reasons are that the voltage/frequency control method is very effective, simple to implement and has lower cost when compared to advanced control methods.

Minimizing the total harmonic distortion (THD) and consequently getting sinusoidal voltage and current is a crucial issue in induction motors drive systems. This will result in reduction in motor losses, improvement of motor performance and achievement of high motor efficiency [6, 17]. The authors in [18] presented a DTC IM drive system for THD minimization applying MLI. However, the values of THD are significantly high at medium and low speeds. MLIs can realize the minimization of THD and therefore it is very useful in IM drive systems. In addition, MLIs performs very well when applying the so-called voltage to frequency control method in induction motors [7, 19].

In MLIs, high-frequency modulation techniques have several advantages over their low frequency modulation counterparts regarding the dynamic performance and flexible change in the modulation index during real time. Triangular multicarrier sinusoidal pulse width modulation TMC-SPWM is the most popular method of high frequency modulation techniques [20–22].

When applying TMC-SPWM, the control procedure involves many comparisons between a reference sinusoidal fundamental signal and several high frequency carrier signals with specific requirements. Additional

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hardware logic circuits are needed to generate the required gate signals of power switches. When the MLI output voltage has several possible levels, utilizing many triangular carrier signals is inevitable. Unfortunately, these multiple carrier signals have a lot of problems. 1) additional hardware circuits make the system more complex, 2) accurate synchronization of the multicarrier signals in amplitudes, level shifting, and frequency is not easy, and 3) several comparators are required. As the number of possible inverter levels increase, these difficulties increase [23, 24].

This paper presents a voltage to frequency speed control of both single phase and three phase induction motors derived by multi-level inverters (MLIs). In this scaler speed control, the proposed control strategies maintain the ratio of motor supply voltage to its frequency constant, hence maintaining constant maximum available developed torque. 15-level and 31-level multi-level inverters are considered for this purpose. The paper proposed two simplified modulation techniques to generate the required switches' control signals in both MLIs. The proposed modulation techniques overcome the several difficulties of conventional triangular multicarrier sinusoidal pulse width modulation technique TMC-SPWM. Detailed analysis of the proposed techniques is presented. Simulation results of the system are introduced and compared with the case of TMC-SPWM to verify the effectiveness of the proposed techniques during starting the induction motors passing through step changes in motor speeds. The paper is organized as follows: Section II gives the analysis of voltage to frequency control method when applied to both induction motors. Principle of operation of 31-level and 15-level MLIs are presented in Section III. Analysis of the proposed modulation techniques in addition to the description of conventional TMC-SPWM are presented in Section IV. Simulation results, discussion and comparisons are presented in Section V then conclusion is introduced in Section VI.

II. Voltage to Frequency Control Method

The main idea of voltage/frequency control method is to keep the ratio of the stator voltage to stator frequency constant, hence maintaining constant maximum available developed torque. This method is considered as a scaler control method where the command stator reference voltage is calculated directly from the required reference stator frequency, thus the air gap flux is maintained constant in the machine. The method is very efficient for starting and speed control of both three phase and single phase induction motors. Induction motors account for a very high percentage of electric motors in residential and commercial applications as they are usually termed as the "Workhorse of the Industry". Single phase induction motors are utilized in household appliances, and laboratories while three phase induction motors are used in elevators, electric vehicles, and enormous industrial applications.

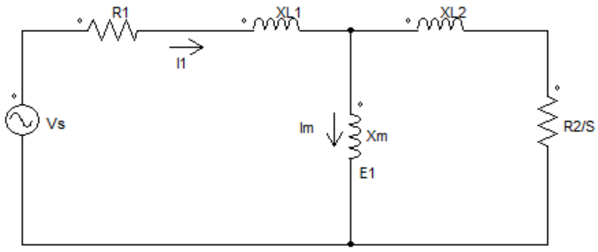


Fig. 1. Three phase induction motor equivalent circuit per phase.

A. Three Phase Induction Motor V/f Control

Referring to the equivalent circuit per phase of three phase induction motor in Fig. 1, the induced voltage in the stator winding E_1 is:

$$E_1 = 4.44Nf\,\varphi_p \tag{1}$$

where N is the motor speed (rpm), f is the stator frequency (Hz) and φ_P is the flux per pole (Weber).

If the voltage drops across the stator resistance R_1 and stator reactance X_1 are neglected, the supply voltage V_1 will equal E_1. Thus, if V_1/f is maintained constant, the flux per pole φ_p will be constant. Regarding the rated values of motor speed and stator voltage, the voltage to frequency control method is oriented in such a manner that the motor will always run at a speed equal to or less motor rated speed. If for instance, the frequency is above the rated value, the stator voltage should be adjusted at a value high than the rated voltage which is not permitted. Then the stator voltage will be kept at the rated value and as a result, poor motor performance will occur due to flux weakening. Therefore, in *V/f* method, the motor speed and stator voltage are not permitted to exceed the rated values.

The rated magnetizing current I_{mr} at the rated values of induced voltage E_r and rated magnetizing reactance X_{mr} can be obtained as:

$$I_{\text{mr}} = \frac{E_r}{X_{\text{mr}}} \tag{2}$$

If the desired stator operating frequency is f_d which is a percentage of the rated stator frequency f_r as:

$$f_d = yf_r \qquad y \le 1 \tag{3}$$

The magnetizing current I_m in this case becomes:

$$I_m = \frac{E_1}{X_m} = \frac{E_1}{yX_{\text{mr}}} \tag{4}$$

Hence, to maintain the magnetizing current I_m equal the rated magnetizing current I_{mr}, the induced voltage E_1 should equal yE_r and consequently the supply voltage should be set to yV_1

Now if the induced voltage is set properly to yE_r at the desired frequency f_d, the developed torque T_d is then:

$$T_d = \frac{P_{\text{AG}}}{\omega_s} \tag{5}$$

$$\omega_s = y\omega_{\text{sr}} \tag{6}$$

where P_{AG} is the air gap power and ω_s is the synchronous speed at the operating frequency f_d and ω_{sr} is the rated synchronous speed.

$$P_{AG} = \frac{3I_2^2 R_2}{S} \tag{7}$$

where I_2 is the rotor phase current referred to primary side.

$$I_2 = yE_r \Big/ \sqrt{\left(\frac{R_2}{s}\right)^2 + (yX_r)^2} \tag{8}$$

Substituting ω_s, P_{AG} and I_2 in (5), gives the relation of the developed torque as:

$$T_d = \frac{3R_2}{\omega_r} \cdot \frac{syE_r^2}{R_2^2 + s^2 y^2 X_r^2} \tag{9}$$

where s is the motor slip. The condition for the motor slip s_m corresponding to maximum torque is:

$$s_m = \frac{R_2}{yX_r} \tag{10}$$

Substituting s_m in (9) then, the maximum torque T_{max} is

$$T_{max} = \frac{3E_r^2}{2X_r \omega_r} \tag{11}$$

B. Single Phase Induction Motor V/f Control

Single phase induction motors are widely utilized in low power domestic and commercial applications. Also in single phase IM, soft starting and speed control can be achieved by controlling the supply frequency keeping the ratio of supply voltage to supply frequency constant to maintain the air gap magnetic flux constant and get the maximum torque at any operating frequency.

Double Revolving Field Theory is always employed to analyze the performance of single phase induction motor in which the rotor parameters (resistance, reactance, induced voltage and air gap power) are separated into two components, forward components and backward components.

Referring to the equivalent circuit of single phase induction motor in Fig. 2, the induced voltage E_f due to the forward rotating flux wave φ_f and the induced voltage E_b due to the backward rotating flux wave φ_b are represented as:

$$E_f = 4.44 N_s f \varphi_f \tag{12}$$

$$E_b = 4.44 N_s f \varphi_b \tag{13}$$

If the motor rotates in the forward direction, then $\varphi_f >> \varphi_b$ and as a result $E_f >> E_b$. Also in this case, the forward resistance $R_f >> R_b$ and as a result, the forward air gap power P_f is much greater than the backward air gap power P_b.

If E_f/f and E_b/f are kept constant, the air gap fluxes φ_f, φ_f and the resultant air gap flus will be maintained constant. The developed torque T_d is expressed as:

$$T_d = \frac{P_f}{\omega_s} - \frac{P_b}{\omega_s} \tag{14}$$

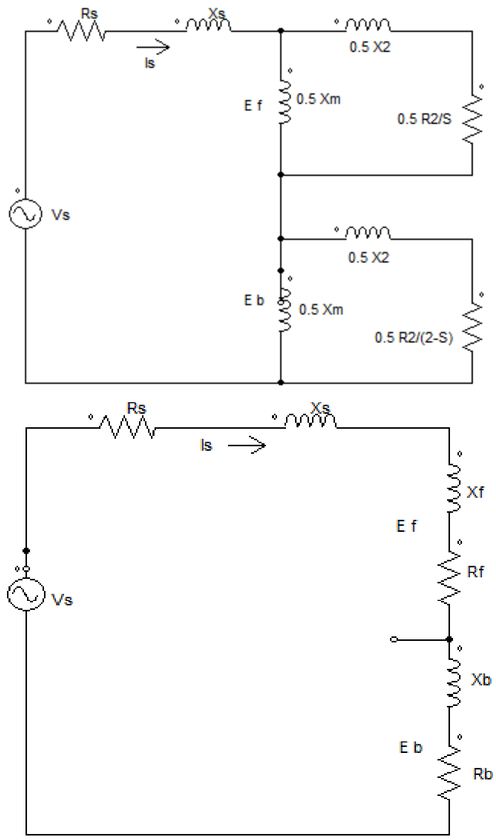


Fig. 2. Single phase induction motor equivalent circuit.

The first term in the torque equation, the dominant term, mimics the developed torque in three phase induction motors at low slip values. Therefore, keeping the voltage to frequency ratio constant will result in the achievement of maximum torque at any desired operating frequency.

III. Multi-level Inverter Operation

Fig. 3 presents the multi-level dc-ac inverter circuits that are employed in the previously described three phase and single phase induction motors. These MLIs can provide an output voltage having up to 31 levels as in Fig. 3(a) and an output voltage having up to 15 levels as in Fig. 3(b). Each pair of switches in one cell are switched “ON” and “OFF” in a complementary mode. Both MLIs have the benefits of low switches to levels ratio LSR.

The states of the odd switches of the 31-level MLI with the corresponding inverter output voltage V_o are given in Table I. In case of 15-level MLI, the switching states and inverter output voltage V_o are presented in Table II. Both tables present the states when a positive output voltage is desired. If the states of all switches are inverted, the sign of the inverter output voltage will be inverted as well. As an example, in 31-MLI the states of switches S_1, S_2, S_3, ···, S_{10} providing $2V_d$ are 0101011001 while the inverted states 1010100110 will provide $-2V_d$.

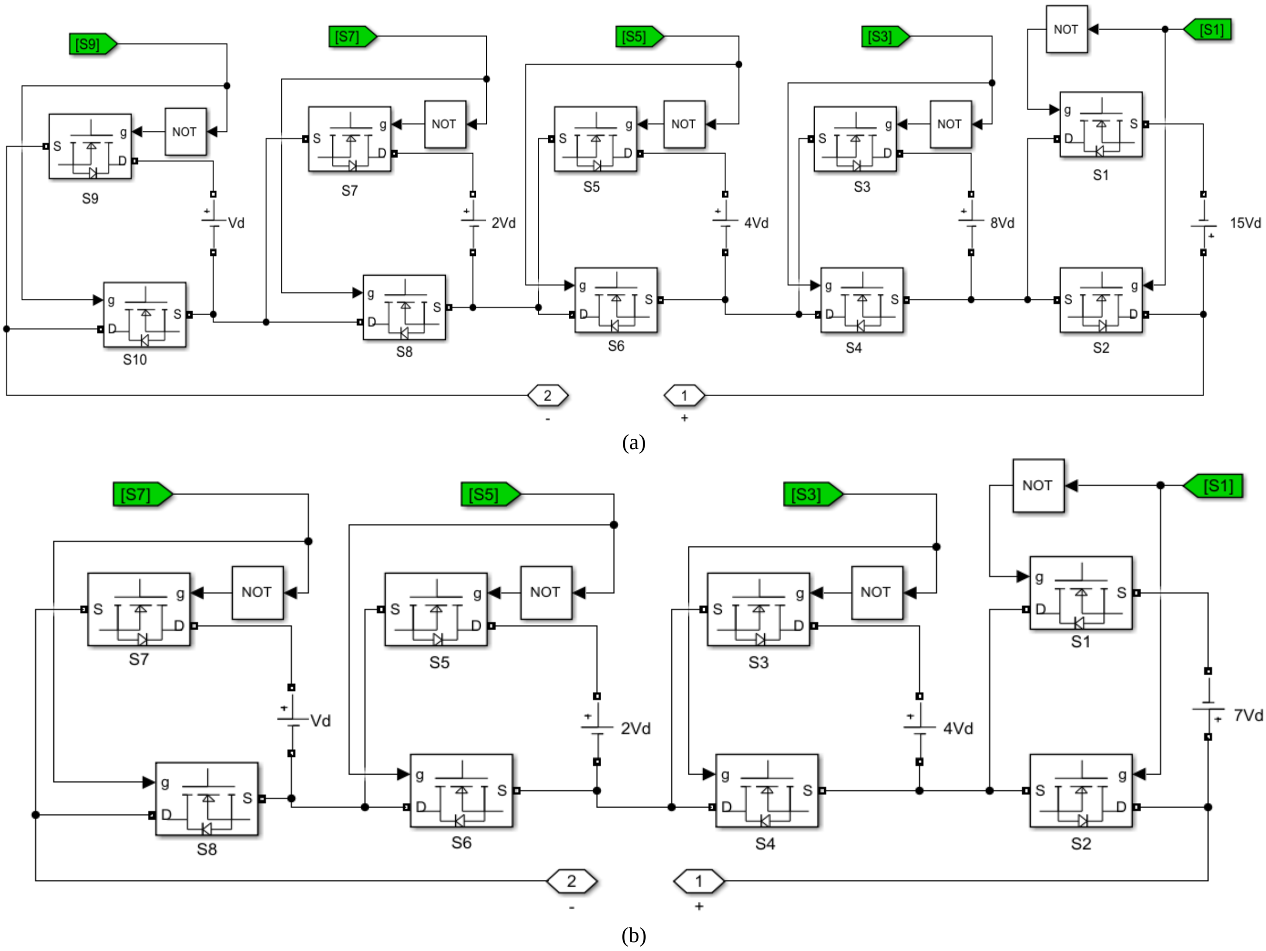


Fig. 3. Multi-level inverter circuits (a) 31-level MLI and (b) 15-level MLI.

TABLE I: STATES OF POWER SWITCHES AND CORRESPONDING INVERTER OUTPUT VOLTAGE (31-LEVEL MLI)

State No.	S_1	S_3	S_5	S_7	S_9	V_o
1	0	1	1	1	1	15 V_d
2	0	1	1	1	0	14 V_d
3	0	1	1	0	1	13 V_d
4	0	1	1	0	0	12 V_d
5	0	1	0	1	1	11 V_d
6	0	1	0	1	0	10 V_d
7	0	1	0	0	1	9 V_d
8	0	1	0	0	0	8 V_d
9	0	0	1	1	1	7 V_d
10	0	0	1	1	0	6 V_d
11	0	0	1	0	1	5 V_d
12	0	0	1	0	0	4 V_d
13	0	0	0	1	1	3 V_d
14	0	0	0	1	0	2 V_d
15	0	0	0	0	1	V_d
16	1	1	1	1	1	0

TABLE II: STATES OF POWER SWITCHES AND CORRESPONDING INVERTER OUTPUT VOLTAGE (15-LEVEL MLI)

State No.	S_1	S_3	S_5	S_7	V_o
1	0	1	1	1	7 V_d
2	0	1	1	0	6 V_d
3	0	1	0	1	5 V_d
4	0	1	0	0	4 V_d
5	0	0	1	1	3 V_d
6	0	0	1	0	2 V_d
7	0	0	0	1	V_d
8	1	1	1	1	0

In the 15-MLI the states of switches S_1, S_2, S_3, ···, S_8 providing $4V_d$ are 01100101 while the inverted states 10011010 will provide $-4V_d$.

IV. PROPOSED SIMPLIFIED MLI MODULATION TECHNIQUE

The conventional sinusoidal pulse width modulation based on multicarrier signals is first described as illustrated in Fig. 4. A reference rectified sinusoidal wave V_r is individually compared with multicarrier signals. each carrier signal has an amplitude of A_c. Adjacent carrier signals are shifted by a voltage level equals A_c. The reference rectified sinusoidal wave has an amplitude of A_r where,

$$A_r = 0.5(N-1)A_c \tag{15}$$

where N is the maximum possible inverter output levels.

In general, $0.5(N-1)$ carrier signals are required to be compared with the reference rectified sinusoidal wave. i.e., 7 carrier signals are required for the 15-level MLI and 15 carrier signals are required for the 31-level MLI. The outputs of comparisons between the reference signal and carrier signals are manipulated mathematically. In addition to these outputs, hardware logic circuits are needed to generate the required power switches control signals.

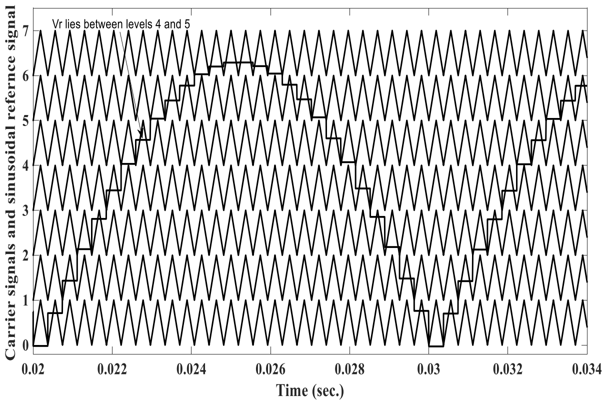


Fig. 4. MLI conventional sinusoidal pulse width modulation based on multicarrier signals.

Several difficulties exist in this conventional TMC-SPWM; 1) additional hardware circuits increase the system complexity 2) accurate synchronization of the multicarrier signals in amplitudes, level shifting, and frequency is practically very difficult and 3) several comparators are required especially if the MLI has high number of output levels. As the number of possible inverter levels increase, these difficulties increase. In addition, very narrow pulses may exist as the modulation index changes. To overcome these difficulties, two simplified modulation techniques will be proposed in the following sections.

A. Proposed Higher Level Modulation (HLM)

In this modulation technique, first the discrete value of the reference sinusoidal wave is determined. This reference sinusoidal wave lies between two successive inverter output levels. In the proposed technique, the control signals of the power switches corresponding to the higher inverter output level are generated during the whole discrete period. For instance, if the reference sinusoidal wave lies between the third and the fourth levels, the proposed algorithm directly generates the control signals corresponding to $4V_d$, i.e., 00100 for switches S_1, S_3, S_5, S_7 and S_9 in the 31-level MLI and 0100 for switches S_1, S_3, S_5 and S_7 in the 15-level MLI. The difficulties of conventional SPWM are significantly reduced and there is no need for comparing multi carrier signals with the reference signal. However, two drawbacks are recognized in the proposed algorithm. The first is the absence of zero level voltage and the second is that the rms of the desired inverter output voltage is less than the actual one. The first drawback has a negligible effect as will be seen in simulation results especially with the 31-level MLI. The second drawback can be completely overcome by readjusting the modulation index to match both the desired and actual inverter output voltage.

B. Proposed 50% Duty Cycle Modulation (FPDCM)

This proposed algorithm overcome the recognized drawbacks in the higher-level modulation algorithm. Two successive control signals are generated each occupy 50% of the discrete period. The first control signals are generated to produce the lower level while the second control signals are generated to produce the higher level. For instance, suppose that in case of 31-level MLI, the sinusoidal reference value lies between the 12th and the 13th levels, then the two successive control signals for switches S_1, S_3, S_5, S_7 and S_9 are 01100 and 01101 to produce $12V_d$ and $13V_d$ respectively. Another example for the 15-level MLI, suppose that the sinusoidal reference value lies between the 2nd and the 3rd levels in the negative half cycle, then the two successive control signals for switches S_1, S_3, S_5 and S_7 are 1100 and 1101 to produce $-3V_d$ and $-2V_d$ respectively. Also in this proposed algorithm, in addition to better performance than the previously proposed algorithm, there is no need for comparing multi carrier signals with the reference signal.

V. APPLICATION OF MLI TO INDUCTION MOTORS

Both 15-level MLI and 31-level MLI are applied to single phase and three phase induction motors. The proposed modulation techniques in addition to conventional multicarrier pulse width modulation technique are applied to the systems. Dynamic behavior of the induction motors is presented regarding speed step changes, developed torque, stator voltages (inverter output voltages) and stator currents (inverter load current).

A. Three Phase Induction Motor Results

Fig. 5 presents the application of three phase MLI to three phase induction. The motor parameters are listed in Table III. The load is considered as a pump where the load torque T_L is related to the motor speed N_m by:

$$T_L = kN_m^2 \tag{16}$$

TABLE III: PARAMETERS OF THREE PHASE INDUCTION MOTOR

Type	Squirrel cage
Rated voltage	400 V
Rated power	5.4 hp
Rated torque	25.6 N m
No. of poles	4
Rated frequency	50 Hz
$R_1 \cong R_2'$	1.405 Ω
$X_1 \cong X_2'$	1.833 Ω
X_m	54 Ω

To match the shaft torque with the load torque, the constant k is set to 0.001026 N·m·s^2/rad^2 The motor reference speed is set to three set-points; 1400 rpm from 0 s to 2 s, 1000 rpm from 2 s to 4 s and 1300 rpm from 4 s to 7 s. PI controller is utilized to determine the proper modulation index so that the reference speed is tracked.

To match the shaft torque with the load torque, the constant k is set to 0.001026 N·m·s^2/rad^2 The motor reference speed is set to three set-points; 1400 rpm from 0 s to 2 s, 1000 rpm from 2 s to 4 s and 1300 rpm from 4 s to 7 s. PI controller is utilized to determine the proper modulation index so that the reference speed is tracked. The reference modulation index is updated by the PI-controller to simultaneously adjust the operating frequency and the output voltages of the three MLIs. Both 15-level and 31-level MLIs are applied with the applications of the proposed approaches and the conventional multicarrier PWM. In case of 15-level MLI, Fig. 6 presents the stator voltages and currents when applying the proposed FPDCM algorithm. The voltages and currents are very close to sinusoidal shapes. Similar results of voltages and currents are obtained in case of TMC-SPWM and the proposed HLM algorithm. To emphasize and justify the comparison between the proposed algorithms and TMC-SPWM, the total harmonic distortion (THD) is calculated along speed steps and the results are summarized in Table IV which illustrates close results with reduced THD values when applying the three algorithms.

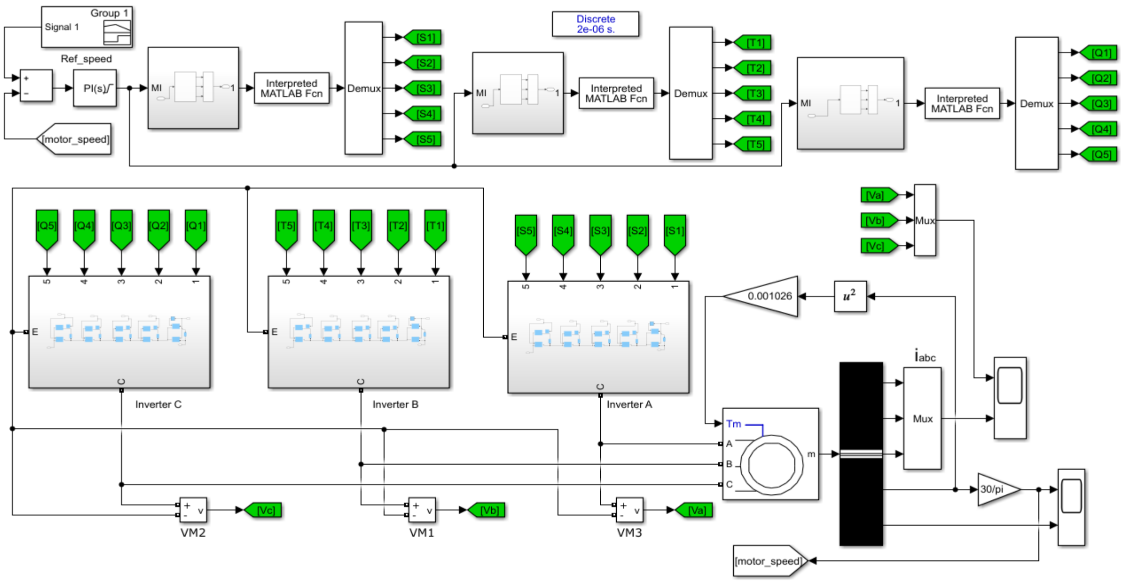


Fig. 5. Application of three phase MLI to three phase induction.

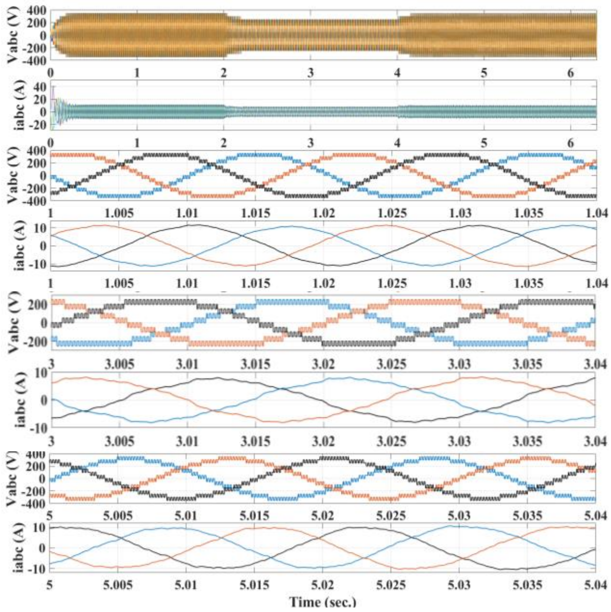


Fig. 6. Stator voltages and currents when applying 15-level MLI and 50% duty cycle modulation.

TABLE IV: THD (%) OF STATOR VOLTAGE AND CURRENT WHEN APPLYING 15-LEVEL MLI AT DIFFERENT SPEEDS (THREE-PHASE IM)

Control Algorithm	Quantity measured	Motor speed (rpm)		
		1400	1300	1000
FPDCM	Voltage THD	12	13	17
	Current THD	3.3	6.2	7.2
HLM	Voltage THD	7.2	7.6	9.8
	Current THD	4.9	6.5	8.1
TMC-SPWM	Voltage THD	3.1	5.3	6.4
	Current THD	1.1	1.2	1.6

Fig. 7 to Fig. 9 give the motor speed and developed torque. The results present very good motor dynamic performance. Regarding the higher level modulation, the results show some distortion in stator currents and their effects on the motor speed and developed torque. In case of 31-level MLI, Fig. 10 presents the stator voltages and currents when applying the proposed FPDCM algorithm. Regarding the shapes of voltages and currents in Fig. 6 and Fig. 10, better performance is achieved here with 31-level MLI. Similar results of voltages and currents are obtained in case of TMC-SPWM and the proposed HLM algorithm. Table V summarizes the comparison between the three algorithms based on THD values. Excellent performance is achieved based on the THD criterion with 31-level MLI.

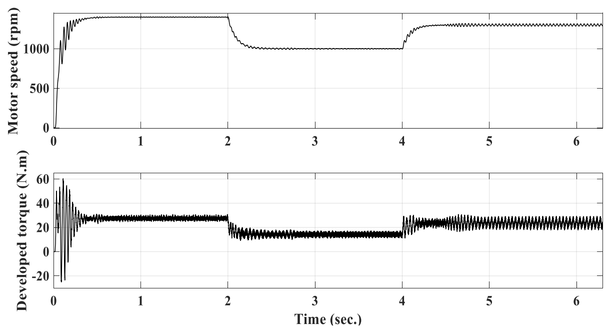


Fig. 7. Motor speed and developed torque when applying 15-level MLI and 50% duty cycle modulation.

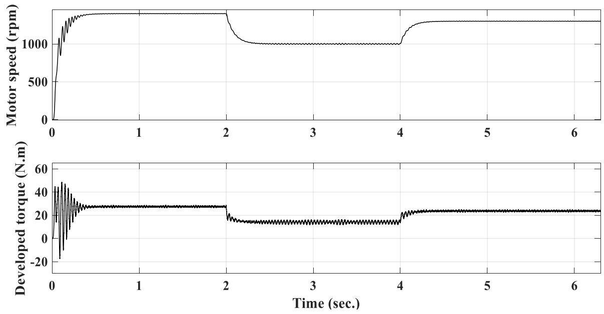


Fig. 8. Motor speed and developed torque when applying 15-level MLI and conventional multicarrier SPWM.

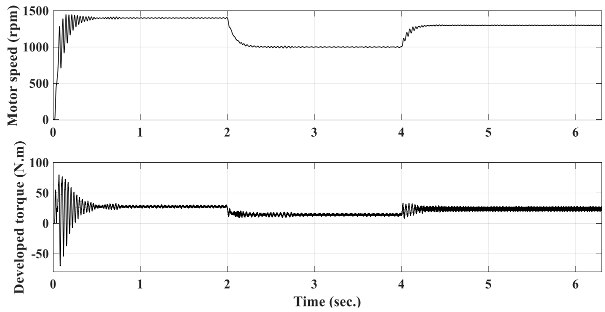


Fig. 9. Motor speed and developed torque when applying 15-level MLI and higher level modulation.

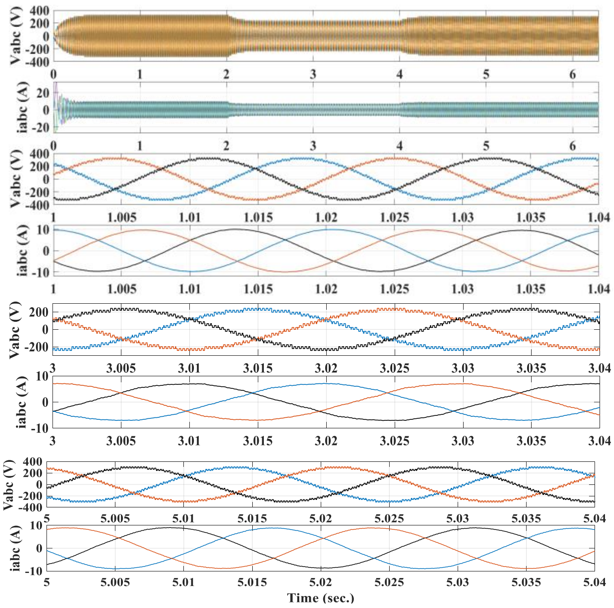


Fig. 10. Stator voltages and currents when applying 31-level MLI and 50% duty cycle modulation.

TABLE V: THD (%) OF STATOR VOLTAGE AND CURRENT WHEN APPLYING 31-LEVEL MLI AT DIFFERENT SPEEDS (THREE-PHASE IM)

Control Algorithm	Quantity measured	Motor speed (rpm)		
		1400	1300	1000
FPDCM	Voltage THD	5.5	6.1	8
	Current THD	1.8	2.3	2.7
HLM	Voltage THD	2.5	2.7	5.1
	Current THD	3.4	3.7	4.9
TMC-SPWM	Voltage THD	4.2	4.4	5.1
	Current THD	1	1.1	1.6

Fig. 11 to Fig. 13 give the motor speed and developed torque. The results present very good performance when applying the 50% duty cycle and higher level modulation which are very close to multicarrier PWM results. The stator currents are very close to sinusoidal shape and the dynamic behavior of motor speed is very well. Also, some torque ripples are recognized in case of higher level modulation.

Illustrating stator voltages and stator currents, it can be noticed that the voltage to frequency ratio is kept constant for each reference speed by generating the proper modulation index from the PI controller. The inrush stator currents are reduced significantly to safe values.

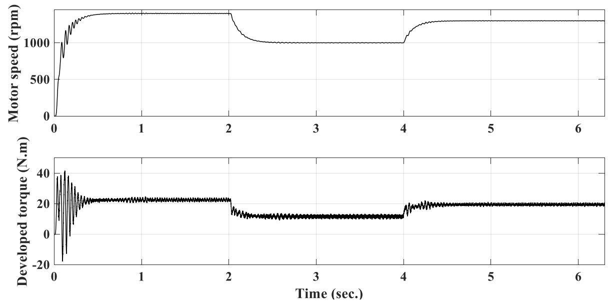


Fig. 11. Motor speed and developed torque when applying 31-level MLI and 50% duty cycle modulation.

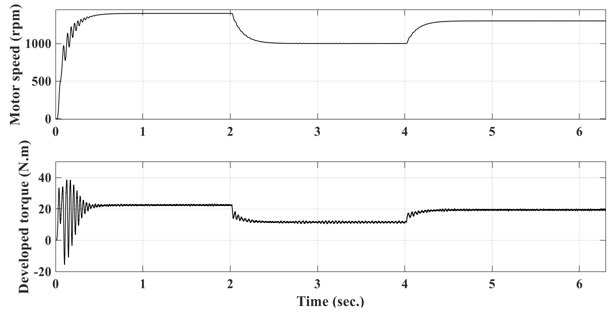


Fig. 12. Motor speed and developed torque when applying 31-level MLI and conventional multicarrier SPWM.

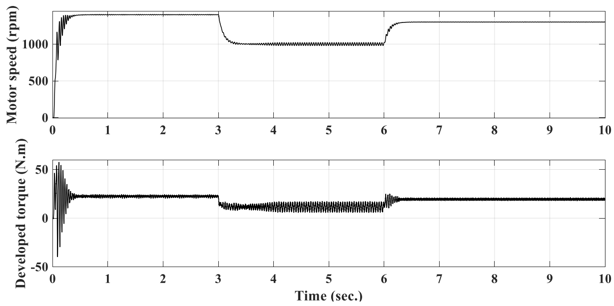


Fig. 13. Motor speed and developed torque when applying 31-level MLI and higher level modulation.

Investigating the results of three phase induction motors in Fig. 6 to Fig. 13, the following points have been achieved successfully when applying the proposed modulation techniques (FPDCM and HLM):

- Multicarrier signals and their associated problems are completely avoided.
- Speed control of the motor is realized at different desired levels.
- Constant voltage to frequency ratio is achieved at any desired speed.
- Stator currents are very close to sinusoidal shape.
- Developed torque is tracked with the desired torque.

In both 15-level and 31-level MLIs, proper modulation index from the PI controller is determined to achieve constant voltage to frequency ratio at each reference speed as can be noticed in voltage magnitudes and frequency in Fig. 6 and Fig. 10.

B. Single Phase Induction Motor Results

Fig. 14 presents the application of single phase MLI to single phase induction. The motor parameters are listed in Table VI. The load is also considered as a pump with the load torque T_L given by the relation as in (16). The constant k is set to 0.00048 N·m·s^2/rad^2. The motor reference speed is set to three set-points; 1400 rpm from 0 s to 3 s, 1000 rpm from 3 s to 6 s and 1300 rpm from 6 s to 10 s. Similar procedures and results are obtained with single phase induction motor.

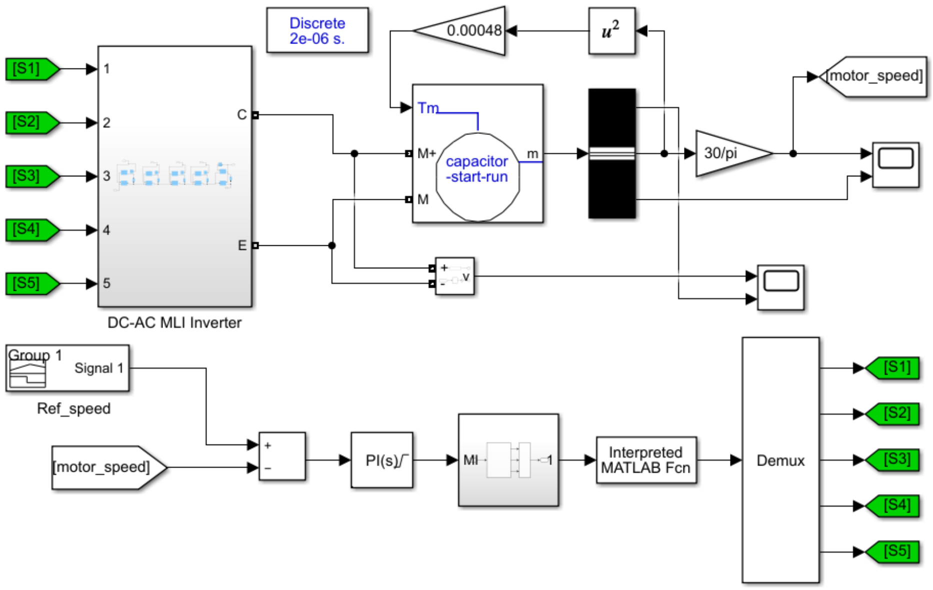
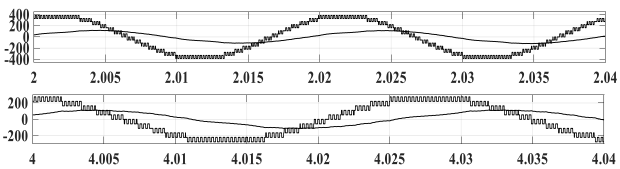


Fig. 14. Application of single phase MLI to single phase induction motor.

TABLE VI: PARAMETERS OF SINGLE PHASE INDUCTION MOTOR

Type	Capacitor start – capacitor run
Rated voltage	220 V
Rated power	2000 VA
No. of poles	4
Rated frequency	50 Hz
R_s	2.02 Ω
X_s	2.324 Ω
X_m	55.6 Ω
R_2	2.02 Ω
X_2	2.324 Ω
Capacitor start	254.7 µF
Capacitor run	21.1 µF
Disconnection speed	At 75% of synchronous speed

In case of 15-level MLI, Fig. 15 shows the stator voltage and current when applying the proposed FPDCM algorithm. The voltage and current are very close to sinusoidal shapes. Similar waveform results are obtained in case of TMC-SPWM and the proposed HLM algorithm. A comparison between the proposed algorithms and TMC-SPWM based on values of THD is summarized in Table VII which illustrates close results among the three algorithms.



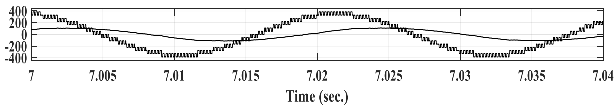


Fig. 15. Stator voltage and stator current *10 when applying 15-level MLI during each period of speed reference with 50% duty cycle modulation.

TABLE VII: THD (%) OF STATOR VOLTAGE AND CURRENT WHEN APPLYING 15-LEVEL MLI DURING EACH PERIOD OF SPEED (SINGLE-PHASE IM)

Control Algorithm	Quantity measured	Motor speed (rpm)		
		1400	1300	1000
FPDCM	Voltage THD	12.2	12.7	16.9
	Current THD	6.1	5.5	6.6
HLM	Voltage THD	7.2	7.5	10
	Current THD	10.9	7.5	12.2
TMC-SPWM	Voltage THD	8	9.2	11.2
	Current THD	7.2	11	11.2

The motor speed is shown in Fig. 16. It can be noticed that the motor speed tracks the reference speed successfully when applying the three modulation techniques. The instantaneous and average motor toque is presented in Fig. 17 where the instantaneous torque involves the double frequency torque component which is expected in single phase induction motors due to the backward components.

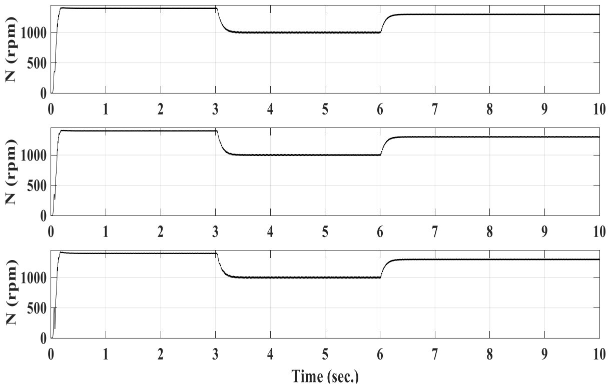


Fig. 16. Motor speed when applying 15-level MLI.

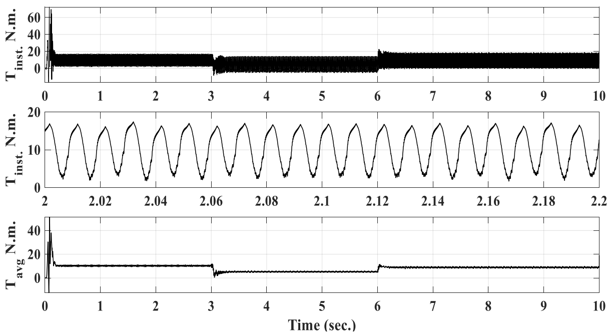


Fig. 17. Instantaneous and average developed torque when applying 15-level MLI.

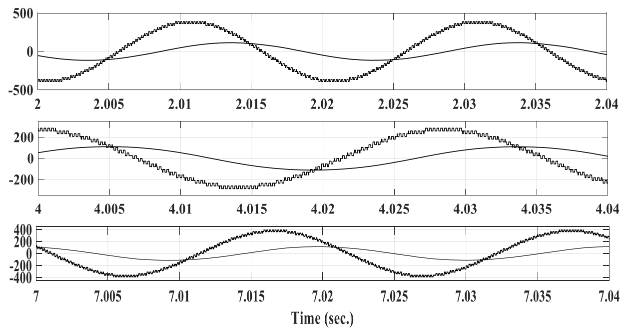


Fig. 18. Stator voltage and stator current *10 when applying 31-level MLI during each period of speed reference with 50% duty cycle modulation.

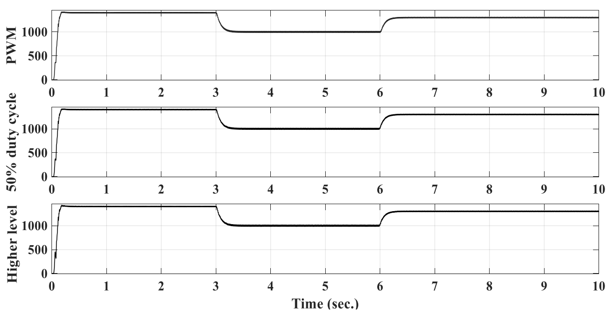


Fig. 19. Motor speed when applying 31-level MLI.

In case of 31-level MLI, Fig. 18 presents the stator voltage and current while the motor speed is shown in Fig. 19. Better performance is obtained with 31-level MLI considering the shapes of stator voltage and currents which become nearly pure sine-waves. In addition, the controller tracks the reference speed very well. Table 8 presents the THD values when applying the three algorithms. THD values are very small with the proposed algorithms with the 31-level MLI. Similar to 15-level MLI, the instantaneous and average motor toque is presented in Fig. 20, where the instantaneous torque also involves the double frequency torque component. Investigating the results of Fig. 15 to Fig. 20, similar points have been achieved successfully when applying the proposed modulation techniques (FPDCM and HLM) to single phase induction motors verifying the high performance of the proposed modulation techniques. As a general investigation of the results in both three phase IM and single phase IM, it can be said that the performance of the scaler voltage to frequency speed control based on 15-level MLI and controlled by the proposed algorithms (HLM and FPDCM) is very good when compared to TMC-SPWM. Furthermore, excellent performance is obtained with 31-level MLI and controlled by the proposed algorithms (HLM and FPDCM). Both proposed algorithms overcome the difficulties associated with TMC-SPWM. It should be noted that MLIs having few output voltage levels may present unsatisfied results and this issue may be involved in a future work.

TABLE VIII: THD (%) OF STATOR VOLTAGE AND CURRENT WHEN APPLYING 31-LEVEL MLI DURING EACH PERIOD OF SPEED (SINGLE-PHASE IM)

Control Algorithm	Quantity measured	Motor speed (rpm)		
		1400	1300	1000
FPDCM	Voltage THD	6.1	6.3	7.5
	Current THD	2.6	2.7	3.5
HLM	Voltage THD	3.9	4.2	4.5
	Current THD	3.6	3.7	4
TMC-SPWM	Voltage THD	4.6	4.7	5.7
	Current THD	2.1	2.5	2.9

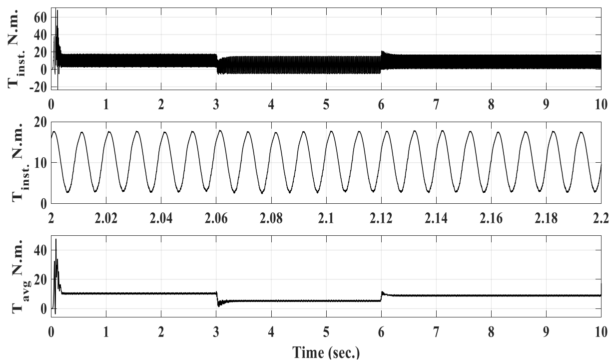


Fig. 20. Instantaneous and average developed torque when applying 31-level MLI.

VI. CONCLUSION

Two simplified and efficient modulation techniques are proposed and successfully tested to operate 15-level MLI and 31-level MLI. Analysis and operation of the considered MLIs are presented. Analysis of three phase and single phase induction motors based on voltage to frequency control are introduced. The proposed techniques namely 50% duty cycle modulation (FPDCM) and higher level modulation (HLM) avoid the great difficulties of triangular multicarrier sinusoidal pulse width modulation TMC-SPWM. Multi carrier signals are no longer required with the proposed techniques. Details analysis of the proposed techniques are presented. The considered MLIs are applied to the induction motors to achieve voltage to frequency control based on the proposed techniques in addition to TMC-SPWM for the aim of performance comparison. Through both 31-level and 15-level MLIs, the proposed techniques perform very close to TMC-SPWM regarding the dynamic behavior of motors' speeds, achievements of constant voltage to frequency operation from motor starting until steady state operation, reduction in the inrush starting current and shapes of the stator steady state currents which are very close to sinusoidal shape with slight deviation from sinusoidal shape in case of 15-level when applying HLM technique. THD has very low values when applying 15-level MLI and extremely low values with 31-level MLI. In three phase induction motor, the results of developed torque are very close when applying the FPDCM and TMC-SPWM while slight torque ripples are recognized with HLM. Regarding single phase induction motor, the results of the developed torque are similar for the three modulation techniques. Based on the obtained results, the proposed techniques can replace TMC-SPWM in many other applications of multi-level inverters.

CONFLICT OF INTEREST

The author declares no conflict of interest.

REFERENCES

[1] C. Oates, "Modular multilevel converter design for VSC HVDC applications," *IEEE J. Emerg. Sel. Topics Power Electron*., vol. 3, no. 2, pp. 505–515, Jun. 2015.

[2] S. K. Sahoo and T. Bhattacharya, "Phase-shifted carrier-based synchronized sinusoidal PWM techniques for a cascaded H-bridge multilevel inverter," *IEEE Trans. Power Electron*., vol. 33, no. 1, pp. 513–524, Jan. 2018.

[3] J. Rodríguez, J. Lai, and F. Z. Peng, "Multilevel inverters: A survey of topologies, controls, and applications," *IEEE Trans. Ind. Electron*., vol. 49, no. 4, pp. 724–738, Nov. 2002.

[4] V. Jammala, S. Yellasiri, and A. K. Panda, "Development of a new hybrid multilevel inverter using modified carrier SPWM switching strategy," *IEEE Trans. Power Electron*., vol. 33, no. 10, pp. 8192–8197, Oct. 2018.

[5] C. I. Odeh, "A cascaded multi-level inverter topology with improved modulation scheme," *Electr. Power Compon. Syst*., vol. 42, no. 7, pp. 768–777, May 2014.

[6] M. P. Kazmierkowski, L. G. Franquelo, J. Rodriquez, M. A. Perez, J. I. Leon, " High Performance Motor drives" *IEEE Industrial Electronics Magazines*, vol. 5, no. 3, pp. 6–26, 2011.

[7] P. V. Kapoor and M. M. Renge, "Improved Performance of Modular Multilevel Converter for Induction Motor Drive," *Energy Procedia*, vol. 117, pp. 361–368, 2017.

[8] M. Errouha, A. Derouich, N. E. Ouanjli, and S. Motahhir, "High-performance standalone photovoltaic water pumping system using induction motor," *International Journal of Photoenergy*, vol. 2020, pp. 1–13, 2020.

[9] A. Leicht and K. Makowski, "Analysis of a single-phase capacitor induction motor operating at two power line frequencies," *Electrical Engineering*, vol. 61, no. 2, pp. 251-266, 2012.

[10] P. C. Sen, *Principles of Electric Machines and Power Electronics*, Wiley, 3rd Edition, 2013

[11] M. Habyarimana and D. G. Dorrell, "Methods to Reduce the Starting Current of an Induction Motor," in *Proc. IEEE International Conference on Power, Control, Signals and Instrumentation Engineering (ICPCSI)*, 2017, pp. 34–38.

[12] S. N. Mahsahirun, N. R.i Nik Idris, Z. M. Yusof, and T. Sutikno, "Fundamental elements of constant volt/hertz induction motor drives based on dSPACE DS1104 controller," *International Journal of Power Electronics and Drive System*, vol. 11, no. 4, pp. 1670–1685, Dec. 2020.

[13] M H. V. Reddy and V. Jegathesan, "Open loop V/f Control of Induction Motor based on hybrid PWM with Reduced Torque Ripple," presented at International Conference on Emerging Trends in Electrical and Computer Technology, March 2011, India.

[14] R. Doncker, D. W. J. Pulle, and A. Veltman, *Advanced Electrical Drives: Analysis, Modeling, Control*, 2nd ed. Berlin, Germany: Springer, 2020.

[15] P. Naganathan and S. Srinivas, "Direct torque control techniques of three-level H-bridge inverter fed induction motor for torque ripple reduction at low speed operations," *IEEE Trans. Ind. Electron*., vol. 67, no. 10, pp. 8262–8270, Oct. 2020.

[16] X. Wu, W. Huang, Y. Zhao, and C. Huang, "An efficient model predictive torque control for induction motors with flexible duty ratio optimization," *IEEE J. Emerg. Sel. Topics Power Electron*., vol. 10, no. 4, pp. 4014–4025, Aug. 2022.

[17] H. A. Mohamed and H. M. D. Habbi, "Power quality of dual two-level inverter fed open end winding induction motor," *Indones. J. Electr. Eng. Comput. Sci*., vol. 18, no.2, pp. 688–697, 2020.

[18] S. K. Chien, S. Y. Sim, W. M. Utomo, S. L. Kek, F. Mustafa, N. A. Zambri, A. J. L. M. Siang, and G. Y. Sim, "Enhanced DTC induction motor drives for THD minimization performance improvement with multilevel inverter," *International Journal of Power Electronics and Drive Systems*, vol. 13, no. 1, pp. 93–101, Mar. 2022.

[19] A. Ramesh, O. C. Sekhar, and M. S. Kumar, "A novel three phase multilevel inverter with single dc link for induction motor drive applications," *Int. J. Electr. Comput. Eng*., vol. 8, no. 2, pp. 763–770, Apr. 2018.

[20] P. W. Hammond, "A new approach to enhance power quality for medium voltage AC drives," *IEEE Trans. Ind Appl*., vol. 33, no.1, pp. 202–208, Jan. 1997.

[21] M. S. A. Dahidah and V. G. Agelidis, "Selective harmonic elimination PWM control for cascaded multilevel voltage source converters: A generalized formula," *IEEE Trans. Power Electron*., vol. 23, no.4, pp. 1620–1630, Jul. 2008.

[22] J. I. Leon, S. Vazquez, and L. G. Franquelo, "Multilevel converters: Control and modulation techniques for their operation and industrial applications," in *Proc. IEEE*, vol. 105, no.11, pp. 2066–2081, Nov. 2017

[23] M. Samy, M. Mokhtar, N. H. Saad, and A. A. El-Sattar, "Modified hybrid PWM technique for cascaded MLI and cascaded MLI application for DTC drive," *International Journal of Power Electronics and Drive Systems*, vol. 13, no. 1, pp. 47–57, Mar. 2022.

[24] J. Ma, X. Wang, F. Blaabjerg, W. Song, S. Wang, and T. Liu, "Realtime calculation method for single-phase cascaded H-bridge inverters based on phase-shifted carrier pulsewidth modulation," *IEEE Trans. Power Electron*., vol. 35, no.1, pp. 977–987, Jan. 2020.

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