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Original Article

DC-Link Voltage Gain Enhancement Using Z-Source Converter in Vector Controlled Interior Permanent Magnet Synchronous Motor Drives

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Abstract

In this paper, the vector control of an interior permanent magnet synchronous motor (IPMSM) with a Z-source inverter (ZSI) is investigated. The vector control strategy is employed to achieve independent control of speed and flux. According to the properties of the Z-source converter such as buck-boost capability and reliability, it is a proper candidate in electric drive systems. The boost capability of this converter results in the requirement of a lower DC-link voltage compared to the conventional voltage source inverter. The proposed drive system is analyzed under different operating scenarios to comprehensively assess its dynamic and steady-state performance. Furthermore, the DC-link voltage variation analysis confirms the capability of the proposed topology to maintain satisfactory motor performance under reduced input voltage conditions. The performance of the inverter in a permanent magnet synchronous motor (PMSM) drive has been evaluated. Simulation results demonstrate that the proposed drive maintains accurate speed tracking, stable torque response, and balanced stator currents under all operating conditions.

Keywords: Permanent magnet synchronous motor, z- source converter, speed control

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NOMENCLATURE

B	Boost factor
D_{st}	Shoot-through duty cycle
i_d, i_q	d- and q-axis stator current components
J	Rotor moment of inertia
L_d	d-axis inductance
L_q	q-axis inductance
M	Modulation index
p	Number of pole-pairs
R_s	Per-phase stator winding resistance
T_{sw}	Switching period
$\hat{V}_{ac}$	Voltage RMS value
V_{in}	Input voltage of Z-ISI
v_o	Output voltage of Z-ISI
v_d, v_q	d- and q-axis stator voltage components
v_d^D, v_q^D	d- and q-axis decoupling circuit
τ_{damp}	Damping torque
τ_{em}	Electromagnetic torque
τ_{mech}	Mechanical torque
ψ_m	Magnetizing flux
ψ_d, ψ_q	d- and q-axis stator flux components
ω_m	Synchronous speed

1. INTRODUCTION

Permanent magnet synchronous motors (PMSMs) have several outstanding features compared to other types of AC and DC motors. They are usually employed in applications in which the performance is of prime importance such as medical, military, aerospace and robotic industries [1].

The impedance source converter was first introduced in 2003 known as the Z-source converter (ZSC) [2]. This structure has provided a new concept of power transmission in power electronics [3]. The features of this converter are as follows:

- Single stage buck-boost capability
- Improved reliability due to shoot-through immunity
- Increased efficiency

In [4], the conventional six-switch voltage source inverter has been used to control the speed of an interior permanent magnet synchronous motor considering the structure of the inverter which is only capable of operating in the buck mode. Due to limitations and problems of the conventional voltage source inverters and current source inverters such as low reliability, limitation in the output gain, and low efficiency, as mentioned in [5], the impedance source converters are used to overcome these limitations and barriers.

The appearance of ZSCs has created a new window in the field of power electronic converters especially for electric drive systems [6]. In addition to the previously mentioned features, the application of this structure in the electric drive control system minimizes the cost because there is no need to have a separate converter for boosting purposes. A comprehensive review of ZSC applications in motor drive systems was presented in [7], covering various topologies and control strategies.

A Z-source inverter (ZSI) has been used to drive a single-phase induction motor [8]. In [9] and [10], z-source and quasi-z-source inverters have been used in PMSM drive systems to improve the voltage boosting capability and overall drive performance. In [11], a ZSI based drive system for interior

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permanent magnet synchronous motors (IPMSMs) has been proposed, enabling DC-Link voltage adjustment in the flux weakening region. Although this study demonstrated the capability of ZSI based IPMSM drives for DC-link voltage adjustment in the flux-weakening region, its main focus was extending the high-speed operating range. In contrast, the present study investigates the DC-link voltage reduction capability of a ZSI based IPMSM drive while maintaining satisfactory dynamic and steady-state performance under various operating conditions. Also, in [12], a bidirectional ZSI based drive system for PMSMs in electric vehicles was proposed, demonstrating controllable DC-link voltage and improved high-speed operation without conventional flux-weakening. In [15] and [16], quasi-Z-source converters have been employed to improve voltage control and enhance PMSM drive performance under varying load and speed. Also, a number of topologies of impedance source converter has been introduced in [17] and [18]. Moreover, in [19] and [20], optimized control methods have been employed to improve the performance of PMSM drive systems, while in this study, vector control has been selected as the primary approach to enhance drive system performance.

TABLE1: Comparison of the ZSI based IPMSM drive with existing related studies

Ref.	Motor Type	Converter Topology	Control Strategy	Main Objective	DC-link Voltage Reduction Analysis	Operating Conditions	Comparison with VSI
[7]	Motor Drives	Z-source inverter	Various methods	Review of Z-source motor drives	Not investigated	Limited conditions	Not reported
[11]	IPMSM	Z-source inverter	Vector control	ZSI application in IPMSM drives	Not investigated	Steady-state operation	Not reported
[13]	PMSM	Z-source inverter	Vector control	Extending constant power speed range	Partially analyzed	High-speed operation	Limited comparison
[14]	PMSM	Bidirectional Quasi-Z-source inverter	voltage loop control	PMSM operation under low DC-link voltage	Partially analyzed	Undervoltage and steady-state operation	Not reported
This work	IPMSM	Z-source inverter	PI-based vector control	DC-link voltage reduction and comprehensive drive performance evaluation	300 V DC-link instead of 622 V VSI equivalent	Steady-state, speed variation, load disturbance, four-quadrant operation	Quantitative comparison

Although several studies have investigated the applications of impedance-source converters in PMSM drive systems, the main objectives and evaluation criteria of these works are different. Some studies have focused on extending the high-speed operating range through flux-weakening techniques, while others have investigated bidirectional power capability, voltage regulation, or improved converter performance. However, the influence of a ZSI based configuration on the overall performance of an IPMSM drive, particularly regarding DC-link voltage reduction while maintaining satisfactory dynamic and steady-state performance, has not been comprehensively investigated. Therefore, Table 1 summarizes the main characteristics of the most relevant previous studies and compares them with the previous studies. Therefore, the main objective of this paper is to investigate the capability of a ZSI based IPMSM drive.

As summarized in Table 1, previous studies have investigated ZSI based PMSM drives from different perspectives, including flux-weakening operation, bidirectional power capability, voltage control improvement, and high-speed performance enhancement. However, these studies have mainly focused on specific operating conditions or converter-level improvements. A comprehensive evaluation of DC-link voltage reduction capability while maintaining satisfactory dynamic and steady-state performance under various operating scenarios has received limited attention in previous studies. Therefore, the main objective of this paper is to investigate the capability of a ZSI based IPMSM drive to reduce the required DC-link voltage and maintain acceptable drive performance.

In this paper, a PMSM is controlled by using a z-source impedance inverter, with relatively low DC-link voltage. This mode of operation will improve the reliability of the system. Moreover, using the vector control method and ZSI, speed and flux control of the IPMSM has been investigated.

Considering the limitations of the existing studies and the need for a comprehensive evaluation of ZSI based IPMSM drives, the main contributions of this paper are summarized as follows:

- Development of a vector-controlled IPMSM drive based on a ZSI to reduce the required DC-link voltage without using an additional DC–DC boost converter.
- Comprehensive performance evaluation of the proposed drive under different operating conditions, including steady-state operation, speed variation, load torque disturbance, and four-quadrant operation.
- Quantitative demonstration of DC-link voltage reduction capability, reducing the required voltage from 622 V in a conventional VSI-based drive to 300 V while maintaining satisfactory motor performance.
- Systematic evaluation of the proposed drive under different DC-link voltage levels, demonstrating its capability to maintain satisfactory speed regulation and torque performance over a wide range of input voltages.

- Validation of the electric drive system performance in terms of speed tracking, torque response, stator currents, and dynamic behavior.

The structure of this paper is as follows: after presenting the introduction in Section 1, the mathematical model of the PMSM has been given in Section 2. ZSC has been studied in Section 3. Section 4 examines the controller relations. Simulations results have been presented in Section 5. Finally, the conclusion is given in Section 6.

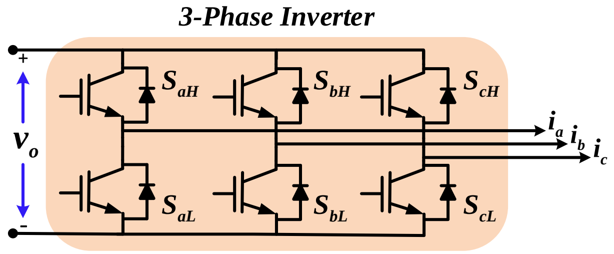

Fig. 1: Conventional six-switch voltage source inverter.

2. Permanent Magnet Synchronous Motor

The permanent magnet synchronous motor used in this paper is an interior permanent magnet (IPM) type. The stator voltage and flux equations of the d and q axis in the rotor flux have been expressed as follows [21].

$$\begin{aligned} v_d &= R_s i_d + \frac{d\psi_d}{dt} - p\omega_m \psi_q \\ v_q &= R_s i_q + \frac{d\psi_q}{dt} + p\omega_m \psi_d \\ \psi_d &= L_d i_d + \psi_m \\ \psi_q &= L_q i_q \end{aligned} \tag{1}$$

The electromagnetic torque expression and the equation of motion can be written as:

$$\begin{aligned} \tau_{em} &= \tfrac{3p}{2}\left(\psi_d i_q - \psi_q i_d\right) \\ \tau_{em} - \tau_{mech} - \tau_{damp} &= J\frac{d\omega_m}{dt} \end{aligned} \tag{2}$$

3. Converter

According to the following expression, in a conventional voltage source inverter, the root mean square (RMS) value of the output voltage is always less than the DC-link voltage [22].

$$\hat{V}_{ac} = 0.486 M v_o \tag{3}$$

An overview of a conventional voltage source inverter has been shown in Fig. 1. To eliminate this constrain, a boosting stage should be used before the inverter which will increase the cost, loss, and complexity of the converter structure [22].

Impedance Source Inverter

The converter used in this paper is a z-source impedance inverter proposed in [2].

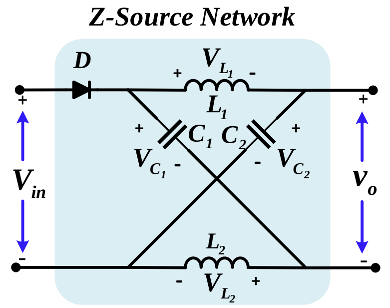

Fig. 2: Z-source network.

By controlling the duration of the shoot-through state in the impedance source inverter, any desired voltage greater than the input voltage can be created. The z-source network is shown in Fig. 2. Moreover, the relations governing the ZSI are expressed as follows:

$$v_o = BV_{in} \tag{4}$$

where

$$B = \frac{1}{1-2D_{st}} \geq 1 \tag{5}$$

and

$$\hat{V}_{ac} = M\ B\ \frac{v_o}{2} \tag{6}$$

As a result, by comparing two relations expressed in (3) and (6), which are respectively for the six-switch voltage source inverter and ZSI, in the impedance mode, a lower DC-link voltage is required to achieve the desired sinusoidal voltage amplitude when using ZSI.

To regulate the duty cycle of the shoot-through state, a simple boost switching control, as illustrated in Fig. 3, is employed [2]. In this approach, the shoot-through is managed by varying the modulation index, and the switching is implemented within the PWM framework.

4. Controller

The ZSI, shown in Fig. 2, is used as the converter of a vector-controlled drive system for an IPMSM. The block diagram of the control system is shown in Fig. 4. In this figure, the stator currents and the rotor angular position are measured. The controlled variables are the rotor angular velocity and the d-axis component of the stator current to indirectly control the flux linkage. Three proportional-integral (PI) controllers are used as the speed, d-axis current and q-axis current controllers. The manipulated variables are the d and q components of the stator voltage. The efficacy of the ZSI is illustrated in the control drive system.

TABLE 2: Parameters of the IPMSM in the case study

Parameters	Symbols	Values	Units
Number of pole-pairs	p	3	-
Rated torque	τ_n	6	N.m
Rated speed	ω_m	1000	RPM
Rated power	P_n	1500	W
q-axis inductance	L_q	57.1	mH
d-axis inductance	L_d	41.6	mH
PM flux linkage	ψ_m	0.483	Wb
Stator resistance	R_s	3.3	Ω
Damping coefficient	D	0.002	Nms/rad
Rotor moment of inertia	J	0.01	$kg.m^2$

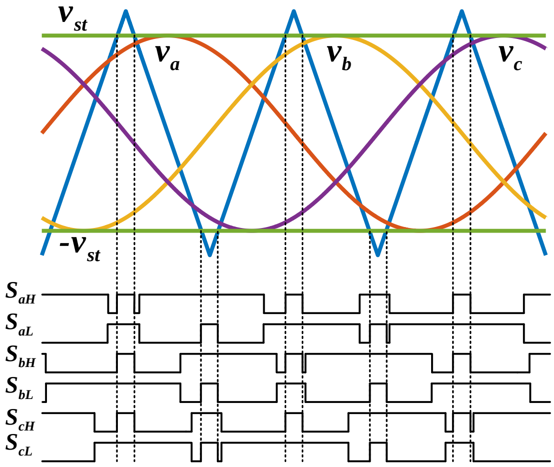

Fig. 3: Simple boost switching control strategy used to generate shoot-through signals [2]

TABLE 3 Parameters of the impedance network

Parameters	Symbols	Values	Units
Capacitor 1	C_1	470	μF
Capacitor 2	C_2	470	μF
Inductor 1	L_1	550	μH
Inductor 2	L_2	550	-
Modulation index	M	0.9	-
Boost factor	B	1.25	-
DC-link voltage	V_{in}	300	V
Shoot-through	D_{ST}	0.1	-
Switching frequency	f_{sw}	10	kHz

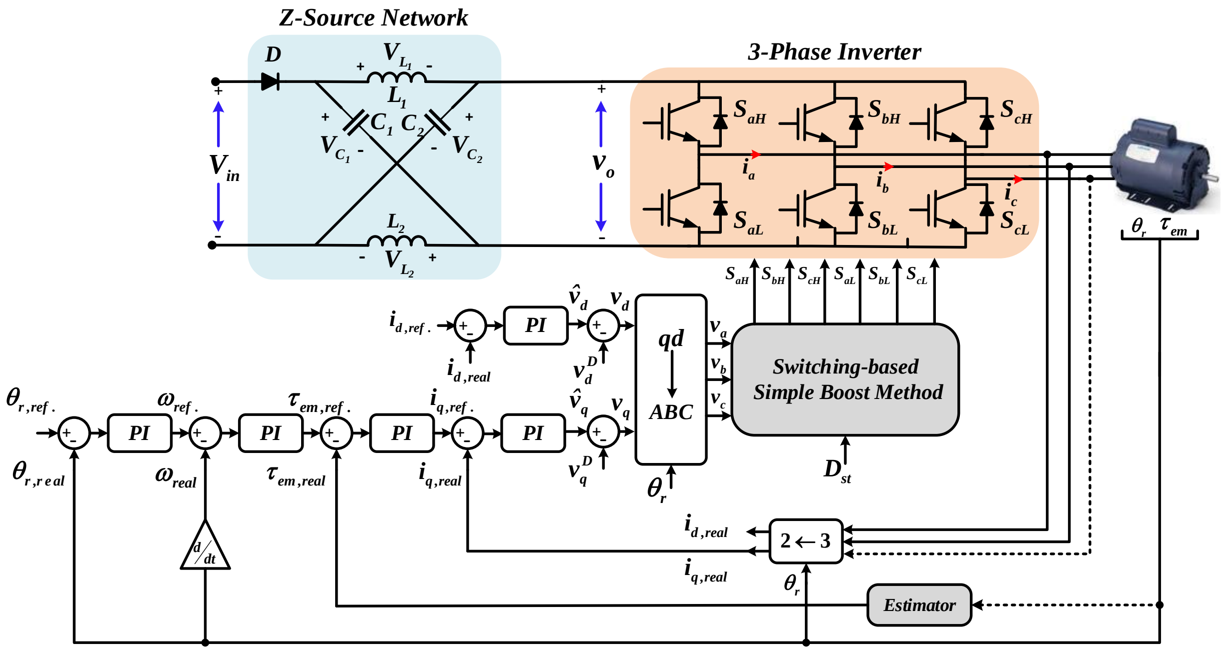

Fig. 4: Electric drive control system of permanent magnet synchronous motor with Z-source inverter.

Vector Controller

Based on the governing voltage equations of IPMSMs on the stator flux linkage reference frame, the d-axis component of the stator voltage is not only a function of the d-axis component of the stator current but also is a function of the q-axis component of the stator current. Similarly, it is the case for the q-axis component of the stator voltage which is a function of both d and q components of the stator current. Therefore, because the manipulated variables are the d and q components of the stator voltage, it is necessary to use a decoupling circuit [22].

$$\begin{cases} v_d = R_s i_d + \dfrac{d\psi_d}{dt} - \omega_m \psi_q \\ v_q = R_s i_q + \dfrac{d\psi_q}{dt} + \omega_m \psi_d \end{cases} \quad (7)$$

$$\rightarrow \begin{cases} v_d = \hat{v}_d + v_d^D \\ v_q = \hat{v}_q + v_q^D \end{cases}, \begin{cases} v_d^D = -\omega_m \psi_q \\ v_q^D = +\omega_m \psi_d \end{cases}$$

5. IPMSM Drive Evaluation

The ZSI based IPMSM drive system was modeled and simulated using MATLAB/Simulink. The developed simulation platform includes the mathematical model of the IPMSM, ZSI, shoot-through switching mechanism, PWM generation unit, and vector control scheme.

The IPMSM model was completely developed based on the mathematical equations of the actual machine in the rotating $d-q$ reference frame. The electrical and mechanical equations, including stator voltage equations, flux linkage relationships, electromagnetic torque equation and mechanical motion equation, were implemented to accurately represent the dynamic behavior of the motor. It should be emphasized that no predefined or built-in IPMSM model available in MATLAB/Simulink was used in this study; instead, the motor model was established based on the fundamental equations of the machine.

The motor parameters used in the simulation were obtained from a real IPMSM prototype. Fig 5 shows the photograph of the actual IPMSM considered in this study, while the corresponding electrical and mechanical specifications are presented in Table 2. These practical parameters, including stator resistance, d- and q-axis inductances, permanent magnet flux linkage, pole pairs, rated speed, and inertia, were directly used in the mathematical model to ensure that the simulation results represent the actual behavior of the motor drive system.

Based on the developed model, the ZSI based IPMSM drive was evaluated under different operating conditions to investigate its steady-state and dynamic performance.

To evaluate the efficacy of the vector controlled IPMSM using a ZSI, the electric drive system is simulated on an IPMSM. Table 3 illustrates the impedance source inverter parameters. The switching frequency of the converter is set to 10 kHz. A discrete time simulation with a time-step of 10 microseconds is carried out. Several test scenarios have been designed to prove the performance of the system and impedance source network. In the first scenario, motor performance has been studied in a steady state with applying the nominal load. Also, in this test, the behavior of the impedance source inverter is examined. In the second scenario, operational state of the motor is examined by changing the speed reference. In the third scenario, the transient state has been evaluated by changing the load torque. In the fourth scenario, four-quadrant operation of the motor under a constant load torque has been investigated. In the fifth scenario, operation of the IPMSM drive system has been investigated by applying input DC voltage variations and evaluating the effect of voltage disturbances on the impedance source inverter performance. Note that the parameters of the PI controllers are fixed in all of the test modes. For the speed control loop, the PI gains have been selected to be $k_p = 0.1$ and $k_i = 8$. For the i_{sd} control loop, k_p and k_i have been respectively set to 5, 50. For the i_{sq} control loop, the controller parameters have been set to $k_p = 50$ and $k_i = 100$.

The PI controller parameters were determined using a systematic trial-and-error tuning procedure. Initially, the controller gains were selected according to the dynamic characteristics of the IPMSM drive system and subsequently refined through successive simulation studies. During the tuning process, the proportional and integral gains were gradually adjusted to achieve an appropriate compromise between fast dynamic response, steady-state accuracy, and overall system stability. Particular attention was paid to reducing overshoot, minimizing settling time, eliminating steady-state error, and avoiding oscillatory behavior under different operating conditions.

It should be noted that the controller parameters were tuned only once and subsequently kept unchanged throughout all simulation scenarios. Therefore, the same PI gains were employed for steady-state operation, speed variation, load torque disturbance, and four-quadrant operation without any retuning or gain scheduling. This enables a consistent and unbiased evaluation of the ZSI based IPMSM drive and demonstrates that satisfactory performance can be achieved using a single set of controller parameters over the investigated operating range.

The selected controller gains were found to provide stable operation and satisfactory dynamic performance for all investigated operating conditions without requiring any controller parameter adjustment.

In the first scenario, the motor is examined at the speed of 1000 RPM with applying nominal torque of 6 Nm. Fig. 6 indicates the speed control, three-phases currents, i_q current control, i_d current control, developed torque of the motor under nominal load and speed, and load torque respectively. In this scenario, to achieve the nominal speed at full load, it is required to have the effective voltage amplitude of 220 V and a maximum of 311.1 V. To fulfill this need by using the ZSI with a modulation index of 0.642 and increasing coefficient of 3.52, the system requires the DC-link voltage 300 V and if a conventional six-switch voltage source inverter with modulation index 1 is used, it requires a DC-link voltage of 622 V. It is worth noting that in the conventional voltage source inverter if a modulation index other than 1 is selected, a higher DC-link voltage is needed. Fig. 7 depicts the voltage gain of the ZSC, the voltage at two ends of the capacitor, and inductor current. Note that D_{ST} is constant in all scenarios.

Also, this scenario indicates that the drive system maintains a well-regulated steady-state operation under rated conditions. The motor speed remains closely aligned with its reference value, while the electromagnetic torque effectively compensates for the applied load, confirming proper torque production capability. The stator currents exhibit balanced behavior with no noticeable distortion, which reflects stable inverter operation and appropriate current control. In addition, the regulated behavior of the current components (i_q and i_d) implies effective decoupling in the control scheme. The observed voltage boosting capability of the impedance source network enables the drive to operate under nominal conditions without imposing excessive stress on the DC-link, thereby demonstrating the practical advantage of the proposed inverter structure in steady-state operation.

In the second scenario, the motor performance has been studied in the transient state by applying the nominal load and changing the speed reference. To confirm this scenario, rating load of 6 Nm is applied to the motor at 0.5 seconds and it is shown that at the moment of applying the load, the speed control is performed well. Fig. 8 shows the results of the speed control, three-phase stator currents, phases swapping, i_q current control, i_d current control, developed electromagnetic torque, load torque respectively.

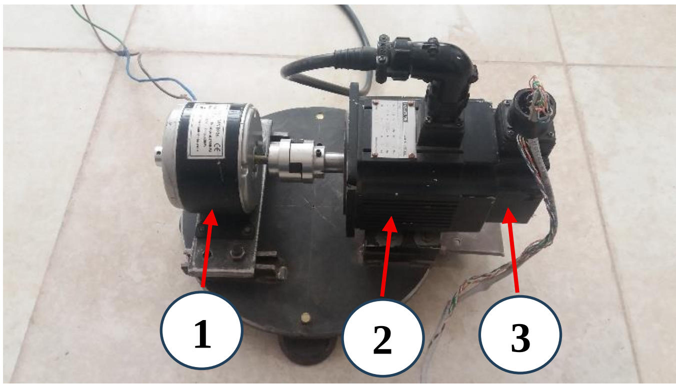

Fig. 5: Motor complex; 1) DC Generator; 2) IPMS Motor; 3) Encoder.

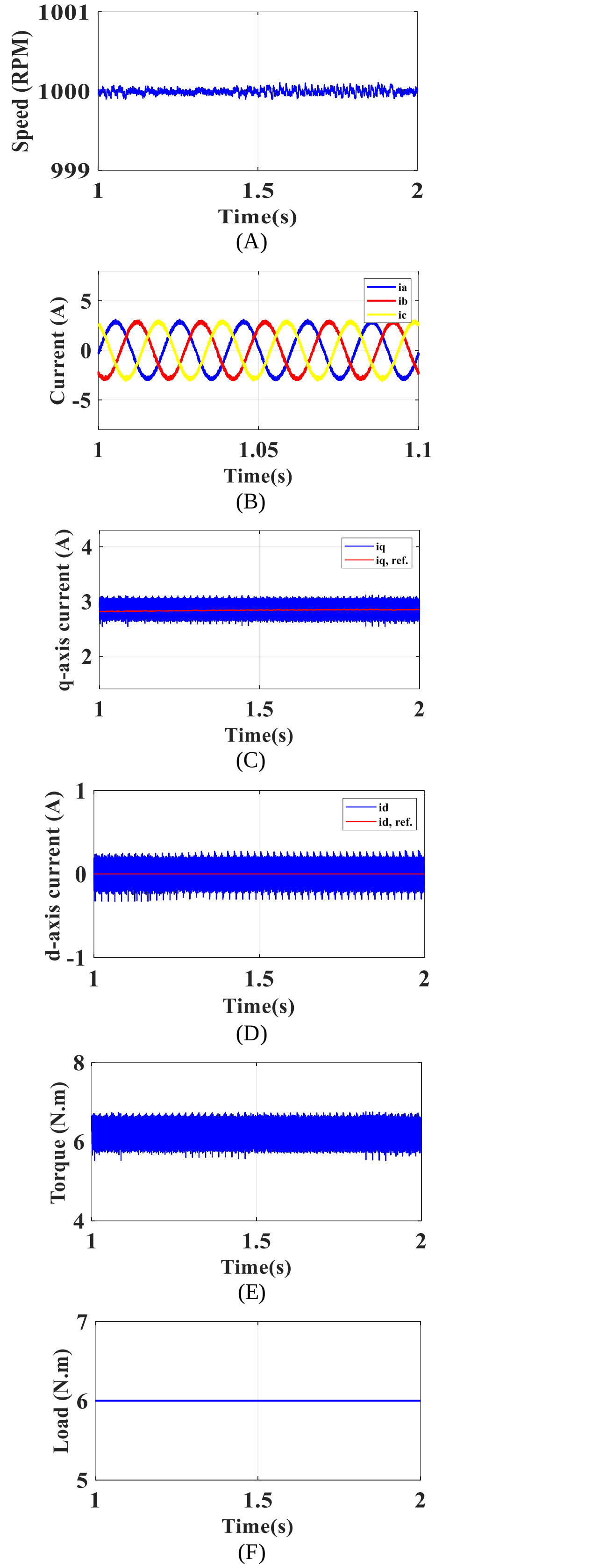

Fig. 6: Steady-state operating of the IPMSM with ZSI: (A) speed control under nominal load; (B) 3-phases currents of motor output; (C) q-axis current; (D) d-axis current; (E) developed electromagnetic torque; (F) load torque.

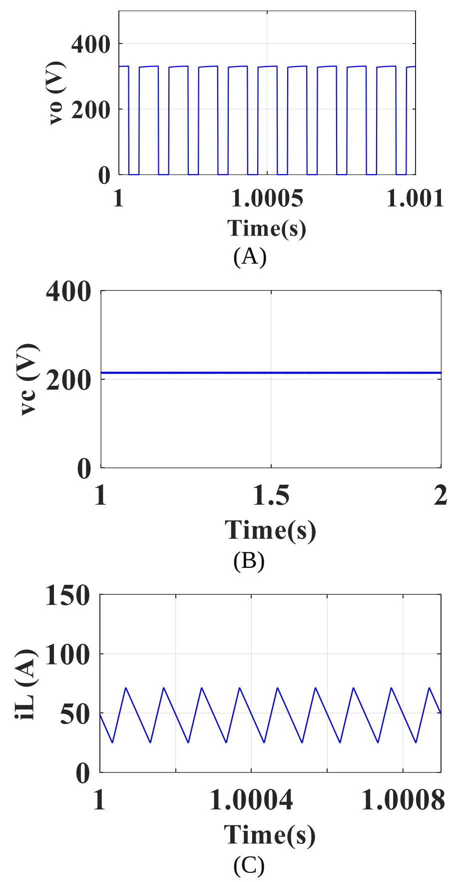

Fig. 7: Waveforms of ZSI in the nominal operating state and DC-link voltage of 300 Volts: (A) impedance network output waveform; (B) voltage waveform at two ends of the capacitor; (C) inductor current.

The results of the second scenario demonstrate that the drive system effectively handles transient conditions induced by changes in the speed reference. The motor rapidly adjusts to the new speed command while maintaining stable torque production, indicating the responsiveness of the control strategy. The three-phase currents remain well-balanced and retain smooth sinusoidal waveforms, reflecting proper current regulation even during dynamic operation. Moreover, the coordinated behavior of i_q and i_d current components confirms that the decoupling in the control loops is maintained under transient conditions. These observations highlight the capability of the proposed impedance source inverter to ensure reliable motor operation while accommodating sudden changes in reference speed.

In the third scenario, the motor performance has been studied in the transient response of the vector controller by changing the load torque. To confirm this scenario, first, the torque increases from 3 Nm to 6 Nm and subsequently it decreases from 6 Nm to 3 Nm. These variations of load torque are implemented during the time in which the rotor speed is kept constant at the nominal value of 1000 RPM. Fig. 9 shows the speed control, three-phase currents, i_q current control, i_d current control, developed electromagnetic torque of the motor under nominal load and speed of this scenario, and load torque respectively.

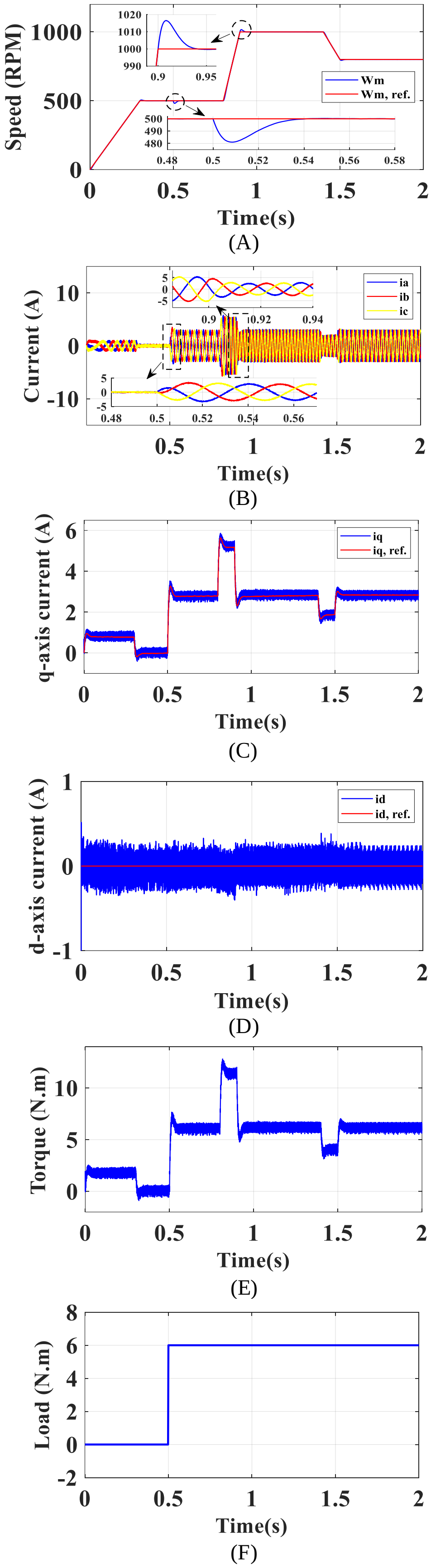

Fig. 8: Transient operating of the IPMSM with ZSI by changing speed: (A) speed control under nominal load; (B) 3-phases currents of motor output; (C) q-axis current control; (D) d-axis current control; (E) developed electromagnetic torque; (F) load torque.

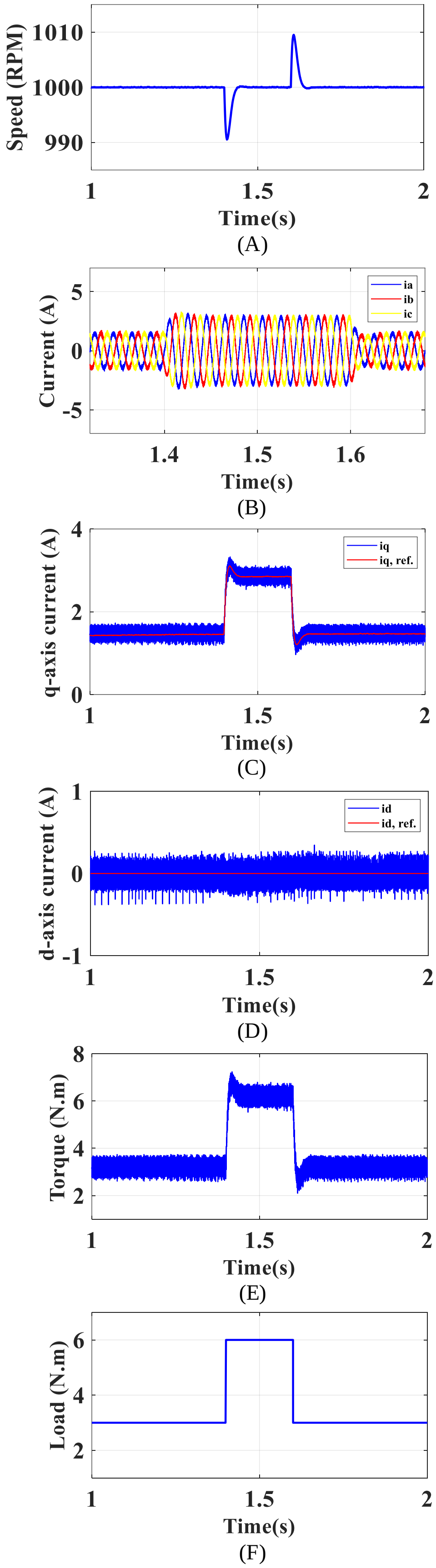

Fig. 9: Transient operating of the IPMSM with ZSI by changing load torque: (A) speed control; (B) 3-phases currents of motor output; (C) q-axis current control; (D) d-axis current control; (E) developed electromagnetic torque; (F) load torque.

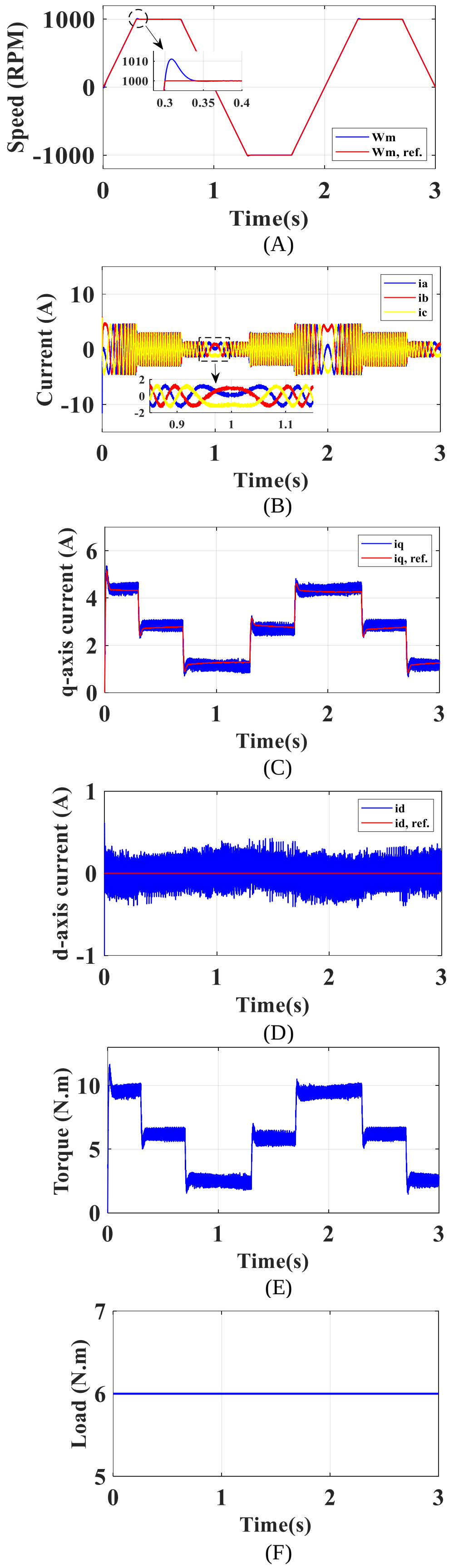

Fig. 10: Four-quadrant operating of the IPMSM with ZSI: (A) speed control under nominal load; (B) 3-phases currents of motor output; (C) q-axis current control (D) d-axis current control; (E) developed electromagnetic torque; (F) load torque.

In addition, this scenario demonstrates that the drive system effectively responds to variations in load torque while maintaining stable motor operation. The motor preserves its speed despite sudden increases and decreases in applied torque, indicating robust torque control and proper dynamic behavior of the vector control scheme.

The three-phase currents remain well-balanced and retain smooth waveforms throughout the transient events, reflecting consistent current regulation. Furthermore, the coordinated response of the i_q and i_d current components confirms that the decoupling of control loops is preserved even under rapid load changes. These observations highlight the capability of the proposed impedance source inverter to support reliable motor operation and maintain system stability under dynamic loading conditions.

In the fourth scenario, the four-quadrant operation of the vector controlled has been studied by changing the motor operating mode under load torque and rotor speed varying between 1000 RPM and -1000 RPM. Fig. 10 shows the results of the speed control, three-phase stator currents, phases swapping, i_q current control, i_d current control, developed electromagnetic torque, and load torque respectively. To verify this test, the reference speed reaches 1000 RPM in 0.3 seconds in a load torque state. After this mode, the reference speed decreases from 1000 RPM to -1000 RPM. During all the changes, the load torque is kept constant. This study has shown that when changing the direction of the motor rotating from right to left mode (moment of passing zero), the two phases change of the current are well done in the moment of 1 second. The results of this scenario in any area show that the real speed (torque) of the motor has followed the reference speed accurately and quickly by using the vector controller.

The results of the fourth scenario demonstrate that the drive system maintains accurate and stable performance across multiple operating regions, including full forward and reverse rotations under constant load torque. The motor quickly and precisely follows the reference speed and torque commands in all regions, indicating the effectiveness of the vector control strategy. The three-phase currents exhibit well-balanced behavior throughout the directional changes, and the phase swapping during zero-crossing is successfully managed without instability. Furthermore, i_q and i_d current components remain properly decoupled, ensuring consistent control performance during the entire operating range. These observations confirm that the proposed impedance source inverter, combined with vector control, is capable of supporting reliable and responsive motor operation under bidirectional and multi-region conditions.
In the fifth scenario, the motor performance is evaluated under different DC-link voltage levels while maintaining the rated load. To validate this scenario, the motor is initially operated with a DC-link voltage of 300 V. Then, the DC-link voltage is changed from 300 V to 400 V at 0.7 s, reduced to 200 V at 1 s, then to 100 V at 1.3 s, and finally to 50 V at 1.6 s. Fig. 11 shows the results of the speed control, three-phase stator currents, phase sequence, i_q current control, i_d current control, developed electromagnetic torque, and load torque, respectively. Also, Fig. 12 shows the DC-link voltage, ZSI output voltage, capacitor voltage, and inductor current of the ZSI during this scenario.

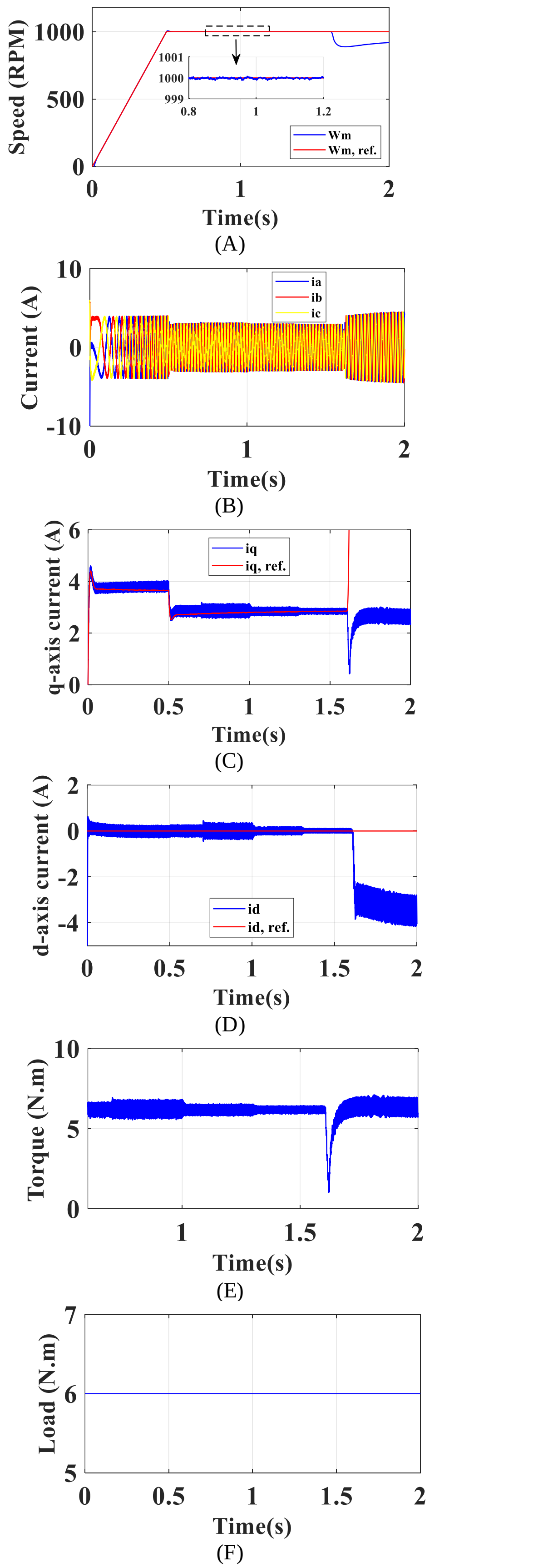

Fig. 11: Operation of the IPMSM drive with ZSI under input DC voltage variation: (A) speed control under nominal load; (B) 3-phases currents of motor output; (C) q-axis current control; (D) d-axis current control; (E) developed electromagnetic torque; (F) load torque.

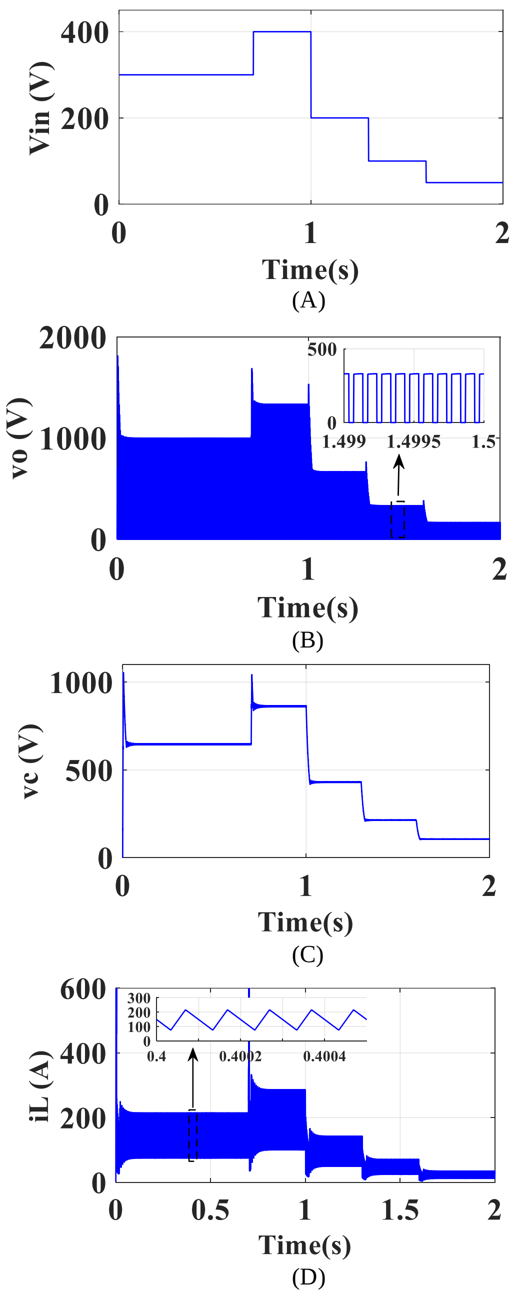

Fig. 12: Waveforms of ZSI in the DC-link voltage variations: (A) input DC voltage variation; (B) impedance network output waveform; (C) voltage waveform at two ends of the capacitor; (D) inductor current.

The obtained results confirm the effectiveness of the ZSI based IPMSM drive in maintaining stable operation under a wide range of DC-link voltage variations. As shown in Fig. 11, reducing the input voltage from the nominal value of 300 V to 200 V and 100 V does not significantly affect the motor speed tracking and torque response, demonstrating the capability of the z-source impedance network to compensate for the reduced input voltage through the shoot-through operation. Particularly, the operation with a 100 V input voltage highlights the voltage boost capability of this topology, where the motor drive maintains acceptable performance with a considerably lower DC-link voltage compared with a conventional voltage source inverter. However, further reduction of the input voltage to 50 V exceeds the practical voltage boost capability of the z-source network, resulting in insufficient DC-link voltage and degradation of the motor dynamic performance. Therefore, this condition represents the lower operating limit of the proposed drive system and emphasizes the importance of selecting an appropriate input voltage range to ensure stable operation.

Fig. 11 illustrates the effect of DC-link voltage variations on the performance of the IPMSM drive. The results show that the system maintains accurate speed tracking, stable electromagnetic torque response, and proper regulation of the stator currents when the input voltage is reduced from $300\ V$ to $100\ V$. This confirms the capability of the ZSI to compensate for the input voltage reduction through its shoot-through-based voltage boost capability. However, after applying $50\ V$ input voltage at $1.6\ s$, the inverter is unable to provide the required voltage level for proper motor operation due to the limitation of its voltage boost capability. Consequently, the drive system becomes unstable, which is clearly reflected in all waveforms, including speed response, stator currents, $d-q$ axis currents, and electromagnetic torque. Therefore, the obtained results demonstrate the effective low-voltage operation capability of this topology while identifying its practical lower voltage operating limit.

Fig. 12 presents the electrical waveforms of the ZSI during DC-link voltage variations. Moreover, the equal voltage across capacitors C_1 and C_2, as well as the identical current flowing through inductors L_1 and L_2, confirm the symmetrical operation and proper balance of the Z-source impedance network. The results show that the impedance network successfully performs the voltage boost operation by adjusting the output voltage according to the input voltage variations through the shoot-through operation. When the input voltage is reduced from $300\ V$ to $100\ V$, the ZSI is still capable of providing the required DC-link voltage for stable motor operation. However, when the input voltage reaches $50\ V$ at $1.6\ s$, although the inverter continues its voltage boosting operation, the generated DC-link voltage becomes insufficient to satisfy the motor voltage requirement. Consequently, the drive system becomes unstable, which confirms the practical lower operating voltage limit of the proposed topology.

6. CONCLUSION

In this paper, a vector-controlled IPMSM drive system based on a ZSI has been presented to achieve accurate speed and flux control while operating with a reduced DC-link voltage. The buck–boost capability of the ZSI eliminates the need for an additional DC–DC converter, resulting in improved reliability and reduced system complexity. A vector control strategy with decoupled d and q current regulation has been employed to achieve independent control of torque and flux, ensuring fast dynamic response and precise speed tracking. Simulation results under steady-state, transient, load disturbance, and four-quadrant operating conditions confirm stable speed tracking, effective torque control, and balanced stator currents. Furthermore, the DC-link voltage variation analysis demonstrates that the proposed system can maintain satisfactory motor performance with reduced input voltage levels, while identifying the practical lower voltage limit of the drive system. A comparison with the conventional voltage source inverter demonstrates that the proposed system significantly reduces the required DC-link voltage from $622\ V$ to $300\ V$ while maintaining high performance, making it a suitable solution for high-performance electric drive applications.

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