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Original Article

Modelling and Simulation of V/F Controlled Induction Machine Fed by Very Sparse Matrix Converter involving Space Vector Strategies

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Abstract - *Very Sparse Matrix Converters (VSMCs) are a reduced-switch version of conventional AC-AC conversion systems, but have not been extensively explored with respect to their influence on the dynamic performance of Induction Motor (IM) drives. In this study, the goal is to develop a closed-loop V/F controlled induction machine using a VSMC and to compare the performance of two modulation techniques, namely, Conventional Space Vector Modulation (CSVM) and Indirect Space Vector Modulation (ISVM), for such an application. To enable the system to be evaluated under the same operating conditions, a comprehensive two-axis mathematical model of the induction motor and converter system was implemented in Matlab/Simulink. The performance was evaluated under step changes in the reference and load torque, especially transient performance, such as settling time, rising time, peak overshoot, undershoot, and DC link voltage utilization. It was observed that ISVM contributed to better voltage transfer capability and faster dynamic response, whereas CSVM presented smooth torque evolution with less oscillatory behavior. The results presented here point to some practical compromises between the transient smoothness and response speed of the modulation strategies for VSMC-fed induction motors. The results provide a dynamic comparison approach for good modulation decisions for medium-performance industrial induction motors.*

Keywords - *CSVM, ISVM, VSMC, Space Vector Modulation, V/F Control.*

1. Introduction

Considering the need for bulky intermediate stages for power conversion, DC-AC and AC-DC, one of the advanced power electronic converter devices is a matrix converter, which allows direct AC-AC power conversion without using any energy storage devices. [1, 2]. The inherent characteristics of these are compact size, bidirectional power flow, increased reliability, and their ability to produce almost sinusoidal input and output waveforms with lower harmonic distortion. These properties render them very attractive for new applications in renewable energy systems, modern motor drives, and advanced power quality enhancement. At the same time, induction machines are still the backbone of electrical engineering because of their ruggedness, efficiency, and economic viability and are widely used for industrial automation, manufacturing, electric vehicles, and renewable energy conversions [3, 4]. The *V/f* control is commonly used for induction machines, which can be used to set a constant stator flux to ensure that the torque is stable across a wide range of speeds. Thus, matrix converter-driven induction machine represents a potential opportunity for small, reliable and energy-efficient electrical drive solutions in the future [5]. While SMCs offer many benefits, there are also a number of technical issues to deal with when using them with induction motor drives, due to the complex relationship between the switching states of the converter and the electromagnetic performance of the motor [6]. Although SMCs have several advantages, like small size and high-power density, the number of switching combinations is often limited. This restriction can cause harmonics and voltage distortions, which in turn can have a detrimental effect on machine performance. This distortion is manifested as undesired torque ripple, copper and core losses, and a decrease in drive efficiency, especially in high-performance industrial applications [7]. Because of the limited number of switching states in a sparse matrix, more advanced control methods, like field-oriented control or direct torque control, are much more difficult to implement because they generally require smooth and accurate voltage vector generation [8]. Moreover, the switching of SMCs can cause common mode voltages, current ripple, and Higher Electromagnetic Interference (EMI) levels, which require strong control techniques for effective mitigation. To solve these problems, it is necessary to develop effective modulation techniques to simultaneously reduce unwanted phenomena like harmonic distortion and torque ripples and make the most of the inherent benefits of SMCs.

Although there are some different modulation methods in the case of matrix converters, the comparative performances of these methods are yet not clearly understood, particularly if the matrix converter is used in Very Sparse Matrix Converter-fed induction motor drives under V/f control. In particular, the different modulation schemes and their trade-off in terms of dynamic response, steady state performance, utilization of the DC-link voltage, and transient performance for VSMC applications have not been characterized in a comparative way in an extensive way.

2. Literature Review

The analysis of matrix converters has gone beyond the issue of commutation safety and topology design to the development of advanced modulation methods designed to enhance the voltage gain and harmonic properties. The space vector methods are rapidly gaining popularity because they now have digital implementation and improved utilization of the DC link [9]. Recent research has proposed predictive, hybrid, and optimized switching arrangements to improve the steady-state quality of the waveforms and mitigate common-mode effects [10]. The approaches based on optimization report that "The main approaches, such as Model Predictive Control and Space Vector Modulation, are discussed as being able to achieve better dynamic performance, harmonic distortion reduction, and energy efficiency and that comparative analysis with traditional methods highlights the better efficiency and robustness of optimization-based methods in industrial drives, renewable systems, and high-performance applications [11]. An SVM scheme that is open-current-vector-based and proposed to convert the sparse matrix can achieve the peak common-mode voltage reduction by 42.3% without deteriorating the performance of the input and output waveforms or the voltage transfer ratio. This validates that the recent direction of research is to combine waveform-quality improvements with hardware-simplification objectives in the sparse/very-sparse family [12].

Sparse and very sparse realizations were introduced to simplify the hardware, which required fewer semiconductors and less AC-to-AC conversion. Such realizations simplify the implementation but restrict the redundancies in switching, thereby affecting the possible voltage vectors. Consequently, the modulation characteristics of classical converters cannot be applied to VSMC systems. In a recent comparative study of SVPWM versus SPWM on a three-phase matrix converter to a three-phase induction motor under closed-loop V/F control, the authors performed a Simulink study. In this study, the authors compared the torque, speed response, and total harmonic distortion of the identical plant, and it was found that the space-vector method outperformed the scalar method when a motor load is connected to the conversion device [13]. An analogous DTC-SVM scheme of an induction motor driven by a matrix converter found that the combination of DTC-MC with SVPWM was better in terms of simplicity, dynamic response, and torque response, and simulations confirmed the method, indicating a robust dynamic response, greatly reduced the motor torque ripple and improved speed control [14].

Due to its robust nature and relatively low calculation complexity, scalar V/F control is still used in many industrial induction motor drives. However, the literature mainly compares the modulation elements of VSI or indirect matrix converters, and the comparisons are generally made in terms of THD, voltage gain, or input power factor [10]. In 2021, Mugheri and Keerio [15] independently tested a fuzzy-PI controller in an application on a V/F-controlled induction motor and found that the performance of the simplified-rule fuzzy-PI controller was better than that of an open-loop constant V/F control and a traditional PI controller. In more modern advancements, Truong et al. [16] suggested a parallel-structure PI controller for V/F-controlled induction motors, wherein the coefficients Kp and Ki are not constant but are dynamically varied in real time by a fuzzy logic controller. They demonstrated that the system was more stable and responsive, and tracked the reference speed better than the conventional PI controller with fixed parameters.

Only limited attention has been given to the effect of different space vector strategies on the transient and dynamic response of an IM when supplied by a VSMC. Quantitative information regarding the rise time, settling behavior, torque recovery, and DC-link variation under realistic disturbances is rarely detailed.

3. Research Gap

Although there have been remarkable advancements in matrix converter modulation, most studies have focused on topological optimization, switching optimization, and the mitigation of harmonics. The validity of performance is commonly tested in terms of stable-state waveform quality or voltage transfer capability. Although these metrics are significant, they are insufficient to understand the behavior of a converter as it is applied to a real motor drive operating under dynamic disturbances. Specifically, the spatial aspect of space vector strategies is not often investigated in terms of its impact on the speed regulation properties when a VSMC is used. A lesser number of switches in the VSMC alters the available voltage vectors, significantly affecting transient torque production, load perturbation recovery, and reference tracking. However, there is limited quantitative evidence to describe these effects.

In addition, most comparative studies involving conventional and indirect space contracting techniques have been conducted on voltage-source inverters or conventional indirect-matrix converters. Their findings cannot be applied directly to VSMC structures owing to varying commutation directions and conduction limitations. Hence, there is an evident need for a systematic study that should assess the performance of CSVM and ISVM in a scalar-controlled induction motor drive with a VSMC, especially regarding the dynamic speed indices as opposed to harmonic factors alone.

The novelty of this work is that CSVM and ISVM are simulated as part of a common simulation platform under the same operating conditions. This method allows the direct and unbiased assessment of their dynamic influence on the behavior of induction motors, which has not been sufficiently treated in previous studies. This study differs from previous works, which mainly focused on the steady-state voltage quality and quantified key transient parameters and dynamic characteristics of the load and speed references. The analysis shows significant practical compromises: the ISVM improves voltage utilization and speeds up the response of the system, while the CSVM ensures smoother torque evolution with less oscillatory behavior. This type of comparative information is very useful for drive engineers to choose the best possible modulation strategy for their application in case priorities are set or a certain dynamic behavior is desired.

4. Indirect Matrix Converter Topology

The Indirect Matrix Converter is an advanced power conversion architecture that efficiently integrates the functions of a rectifier and inverter into a package. Unlike conventional AC-DC-AC converters, the IMC converter directly converts AC to AC without large intermediate DC-AC link capacitors and inductors. [17-19]. An IMC does not require any reactive energy storage components to operate, which can result in a smaller footprint, increased reliability, and useful life. The main benefits of the IMC design are the ability to generate sinusoidal input and output waveforms with a high power factor and low harmonic distortion. Advanced modulation techniques are used to realize these characteristics, which are also optimized with respect to the switching of bidirectional semiconductor devices [20]. Owing to its voltage control characteristics, size, and rate of change of the output voltage, this topology is particularly suitable for applications in renewable energy interface units, motor drives, and grid-connected power converters.

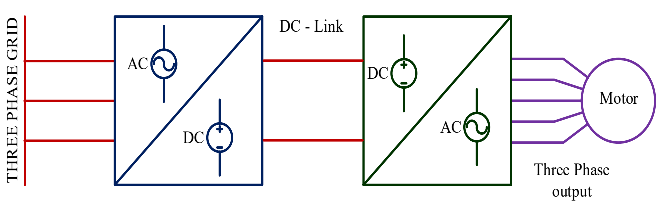


Fig. 1 Schematic block diagram of the indirect matrix converter

With its potential capabilities, IMC faces major challenges that must be overcome for large-scale industrial adoption. These difficulties are due to the difficulty of control algorithms, a somewhat large number of semiconductor devices, and possible problems of voltage commutation and switching transients [21, 22]. However, current studies on more effective modulation and protection methods are gradually making IMC a real competitor to traditional converter topologies. In principle, an IMC can be considered as a traditional inverter-based system, except that it does not use any physical DC-link energy storage devices. Instead, it uses a fictional intermediate DC-link bus to simplify the conversion process. The Schematic block diagram of the Indirect Matrix Converter topology is shown in Figure 1.

5. Different Topologies of Indirect Matrix Converter

The direct AC-AC matrix converter is generally recognized as having a relatively simple structure and good performance characteristics, such as a small size, ability to operate in bidirectional power flow, and generation of sinusoidal input and output waveforms. However, traditional PWM control methods and inherent difficulties in achieving safe and reliable switching commutation of two-way switches make their use difficult in industrial applications [23]. To solve these problems, a two-step conversion is used, and thus, the indirect matrix converter is developed. This has the advantage of using a rectifier and an inverter stage without the need for large energy storage elements. The fundamental advantages of the IMC are reduced modulation complexity, increased commutation resiliency, and increased operational flexibility; thus, it is a very attractive alternative for advanced AC drive systems and is applied in renewable energy sources.

5.1. The Structural Design and Working of the VSMC

The VSMC topology is an optimized ACAC conversion topology. The VSMC utilizes 12 transistors and 30 diodes to achieve the maximum working efficiency typical of standard direct and sparse matrix converters [24]. The VSMC significantly reduces the number of transistors compared with a Traditional Sparse Matrix Converter (TSMC), thus making the hardware implementation much simpler. However, the result of this transistor shrinkage is compensated by the increase in conduction losses, which can be ascribed to the addition of more diodes in the existing conduction paths.

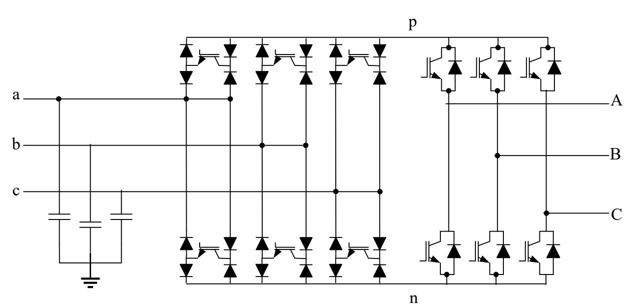


Fig. 2 Very sparse matrix converter

As illustrated in Figure 2, the architecture employs a diode bridge arrangement in the rectifier stage, which forms the fundamental part of its bidirectional switching cell. However, the inverter stage maintains a structural topology that is equivalent to that of a standard matrix converter. The VSMC uses one of the six cells of the Diode-Bridge Bidirectional Switching (DBBS) cells, thus ensuring a dependable two-way power flow while maintaining the important working features of the matrix converter technology.

6. Modulation Strategies for Matrix Converters

Since the early 1980s, many modulation schemes for matrix converters have been developed, as shown in early reviews. Among these is the SVM technique, which has become the most popular because of its computational efficiency, relative simplicity, and compatibility with modern digital control. The advent of the space-vector approach to the analysis and control of matrix converters in [25] was an important step in making SVM find wide application and optimization in this area. SVM allows the output voltage magnitude, waveform quality, and input displacement factor to be obtained in a refined and flexible manner, which is not affected by the output displacement factor. In practice, SVM is a pulse-width modulation technique that correlates voltage references to space vectors in a specified switching plane and thus determines the duty cycles of the converter switches. SVM is a vector-based technique that enhances the exploitation of the input voltage and does not introduce any harmonic distortion; thus, SVM is a potentially viable and powerful modulation technique that can be used by a matrix converter.

6.1. Conventional Space Vector Modulation (CSVM)

In three-phase Voltage Source Inverter (VSI) applications, such as high-performance motor drives and renewable energy systems, vector-based modulation schemes are used instead of Conventional Sinusoidal Pulse-Width Modulation (CSPWM). Space Vector Modulation (SVM) is a vector-based method in which sinusoidal references are directly used with a triangular carrier to generate the switching signals. In this method, 3ph voltages are mathematically converted into a two-axis stationary frame. (α-β), Moreover, represented as one space vector. Subsequently, within each sample period, the two neighboring active vectors and the zero vector are alternatively switched to obtain the desired output, depending on the magnitude and angular location of this vector. Thus, a higher DC-link voltage is used (approximately 15% higher than SPWM), and a much lower Total Harmonic Distortion (THD) at the inverter output is achieved [26]. Although SVPWM adds a little computational complexity, with the development of modern digital signal processors, it has become possible to apply it in real-time applications. Consequently, SVPWM is the most popular modulation technique in modern inverter-fed systems, which has better voltage quality, lower switching losses, and better dynamic performance than conventional PWM techniques. The CSVM design is a generalization of the SVPWM algorithm, which allows three-phase inverters to be effectively controlled by using three voltage vectors in the d-q reference frame [27]. The calculation of the commanded voltage vector in the CSVM involves a two-step process: first, the reference voltages are applied to the hexagonal vector space of the inverter, and then, the commanded voltage is projected onto this hexagonal region. At a single instance, the reference vector is in a sector bordered by three neighboring switching vectors. The CSVM algorithm involves the first step of finding the three nearest vectors, followed by synthesizing the desired voltage with the help of these vectors using the proper allocation of duty cycles. When applied in constant amplitude, the path of the reference vector is a circuitous path and is proportional to the generation of an equal three-phase voltage set at the inverter output. This is a vector-based synthesis that enables good control of the output voltages and phase relationships, thereby ensuring smooth operation of the load connected. The CSVM is a computationally intensive, systematic and efficient modulation framework; however, it is a useful control strategy in matrix converters and other enhanced AC-AC and AC-DC-AC power conversion systems.

$$v_{qs}^{s*} = \frac{2}{3} v_{ag}^{*} - \frac{1}{3} v_{bg}^{*} - \frac{1}{3} v_{cg}^{*} \tag{1}$$

The space-vector concept offers a sound mathematical base for the study and control of three-phase electric systems. This technique, which describes three-phase variables as one rotating vector in a complex plane, is much easier to handle mathematically than the traditional treatment of power conversion and provides a more intuitive set of control strategies when operating power-electronic converters and electric drives. In space-vector-based modulation, three-phase quantities are first converted to an equivalent two-phase representation, usually in the synchronously rotating d-q or stationary α-β reference frame. The subsequent reference frame, parameterized by its magnitude and angular position, summarizes the instantaneous condition of the apparatus. This reference vector is then used to calculate the modulation of the inverter output, which is reconstructed with two-phase components. This conversion, in addition to simplifying the control calculations, allows accurate voltage-vector generation, which results in better quality output waveforms, reduced harmonic distortion, and increased performance of variable-speed drives and contemporary power converters.

6.1.1. Switching States of CSVM

In CSVM, switching states are an essential part of the method used to generate the desired output voltage by varying the switching pattern of the inverter. The reference voltage vector is estimated during each switching period using a linear combination of the neighbouring zero and active voltage vectors. The algorithm works by considering eight possible switching states, six of which are active (vertices of a hexagon in the complex plane), and two of which are zero states (origin of the complex plane). A reference vector is rotated through the hexagon, creating a series of dynamically changing sectors with duty cycles defined for the reference, so that as the reference rotates, the sectors change sequentially. This process ensures accurate voltage vector curve tracking. CSVM enables accurate control of the output voltage amplitude, frequency, and phase, and minimizes harmonic distortion and optimizes the switching sequence to improve the utilization of the DC-bus voltage. This has resulted in the widespread use of CSVM as a modulation technique in motor drives, grid-connected inverters, and renewable energy conversion systems that demand high-quality output waveforms and good switching characteristics [28].

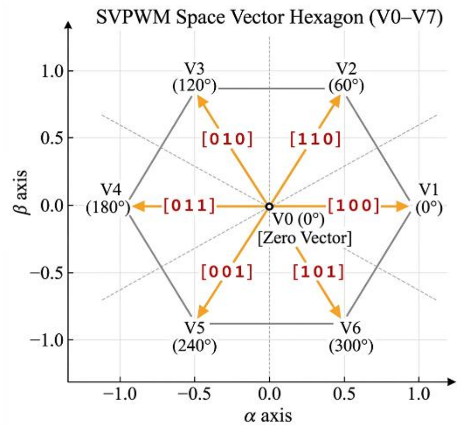


Fig. 3 Space-vector representation for a three-phase VSI under SVPWM

The switching state of the inverter, phase voltages, and line-to-line voltage of a three-phase VSI with the SVPWM scheme are shown in Figure 3. The values for each inverter leg can be chosen to be connected to either the positive or negative terminal of the DC link. In this way, the system can generate 8 different switching vectors. (V0-V7) over time. Of these vectors, V0 and V7 are zero vectors because all three phases are tied to the same DC-link voltage; thus, the line-to-line output voltage is zero. The other six vectors are vectors V1-V6, which are active (or voltage vectors) that form the vertices of a regular hexagon in the space-vector plane.

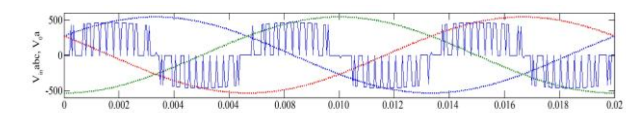
Normalizing the line-to-neutral voltages to the DC-link voltage and deriving the line-to-line voltages as the difference between corresponding phase voltages reveals a crucial insight. This correspondence illustrates that when an appropriate order of state switching is implemented, the SVPWM can produce nearly sinusoidal output waveforms that achieve excellent DC-link voltage utilization and less harmonic distortion than traditional sinusoidal PWM. The electronic switches of the inverter are employed in a 180° conduction mode, featuring six active switching states and two zero states, thereby maintaining only three active switches in either the upper or lower leg at any given time. Three bits are sufficient to form a binary coding scheme (2^3=8) to describe these eight switching states, as shown in Figure 4 (a)-(c). Owing to the complementary-switching principle, the status of either the upper or lower switches must be defined because turning on an upper switch implies that the corresponding lower switch is off. The VSI consists of six switches (S_1-S_6), where switches S_1, S_3, and S_5 are positioned in the upper arms, and their complementary counterparts S_4, S_6, and S_2 are positioned in the lower arms. Eight distinct switching patterns were generated by varying the on/off combinations of the three upper switches. These patterns directly shape the output voltages of the inverter, forming the basis for space vector synthesis in the SVPWM algorithm [29]. Line-to-line voltage vector $[V_{ab} V_{bc} V_{ca}]^t$ is represented in mathematical matrix form as.

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (2)$$

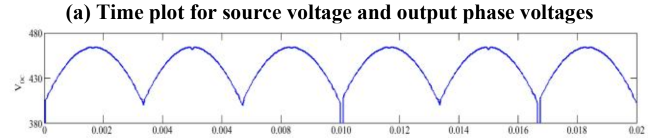
Line to neutral (phase) voltage vector $[V_{an} V_{bn} V_{cn}]^t$

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (3)$$

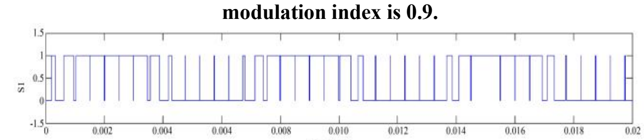
$$\eta_{Total} = \eta_{PV} \cdot \eta_{MPPT} \cdot \eta_{Inverter} \quad (4)$$



(a) Time plot for source voltage and output phase voltages



(b) Time plot for the DC link available for the inversion stage when the modulation index is 0.9.



(c) Switching the state of S1 during the inversion stage.
Fig. 4 Time plots and switching state for very sparse matrix converter with CSVM

6.2. Indirect Space Vector Modulation (ISVM)

The ISVM concept considers the matrix converter as an equivalent circuit in which the matrix converter is replaced by a virtual input rectifier, virtual DC link, and virtual output inverter. In this case, the modulation process consists of selecting appropriate switching functions to create the desired output voltage and adjust the input current parameters. Many modulation strategies have been proposed for matrix converters; however, space-vector-based techniques have come to the forefront as the most effective because they can optimize the use of voltages and reduce harmonic distortion [30, 31]. In the current study, the main emphasis was on the ISVM approach. Simply put, the algorithm is directly derived from the circuit model of the matrix converter (Figure 5), mirroring the functionality of a conventional back-to-back rectifier-inverter setup; however, it does not include an energy storage element, such as a DC-linked capacitor, in its circuit. Based on this conceptual model, the space-vector modulation plans used in the rectifier and inverter steps can be implemented, and these plans are well established. The ISVM scheme is a systematic and effective modulation method for different topologies of the Indirect Matrix Converter (IMC), by deriving the respective switching functions from this representation. The placement of the reference vectors v_o and i_i is in the S_{inv} and S_{rect} sectors of their corresponding hexagonal spaces; a total of 36 distinct location combinations are possible.

$$\begin{bmatrix} S_{Aa} & S_{Ab} & S_{Ac} \\ S_{Ba} & S_{Bb} & S_{Bc} \\ S_{Ca} & S_{Cb} & S_{Cc} \end{bmatrix}^t = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} . \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix}$$

$$= \begin{bmatrix} S_7.S_1 + S_8.S_2 & S_7.S_3 + S_8.S_4 & S_7.S_5 + S_8.S_6 \\ S_9.S_1 + S_{10}.S_2 & S_9.S_3 + S_{10}.S_4 & S_9.S_5 + S_{10}.S_6 \\ S_{11}.S_1 + S_{12}.S_2 & S_{11}.S_3 + S_{12}.S_4 & S_{11}.S_5 + S_{12}.S_6 \end{bmatrix}$$

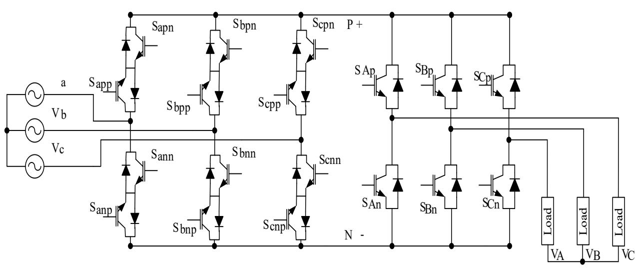


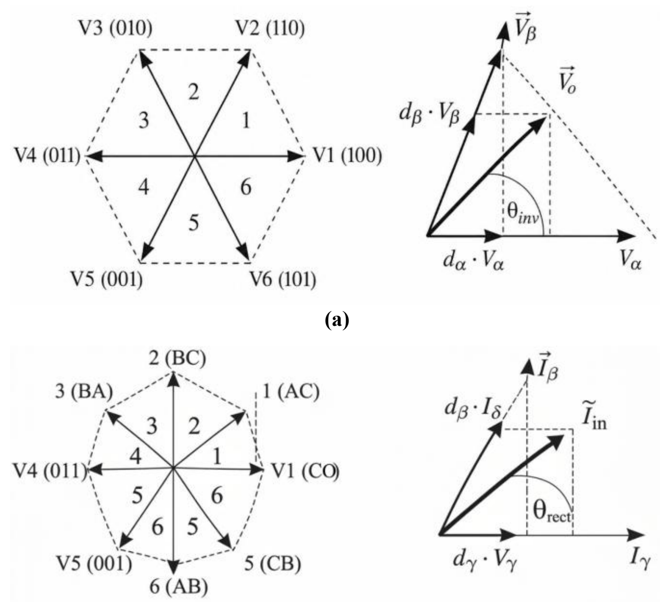
Fig. 5 Space vector pulse generation of VSMC

In the ISVM scheme used in the case of the Indirect Matrix Converter (IMC), four of the active states are used in each modulation cycle. The two reference vectors are associated with the inverter stage (a and b in Figure 6) and the other two with the rectifier stage (γ and δ in Figure 6).

Given the simultaneous operation of the inverter and rectifier, it is essential to consider all possible state combinations to achieve the desired output voltage synthesis and effective input current regulation. To achieve this, four duty cycles were defined in the IMC control formulation, as expressed in Equation (5).

The duty cycles are used to compute the distribution of the switching periods among the chosen active states to guarantee that the modulation scheme accurately reconstructs the reference vectors. In this equation, the input current modulation index is set at unity, which ensures that it uses the input source to its best advantage.

The scale of the equivalent DC-link voltage (V_{dc}) is determined by the condition of power balance that is inherent to the matrix converter, which thus links the rectifier and inverter stages of the virtual back-to-back architecture.



(a)

(b)

Fig. 6 Graphical representation of the inverter and rectifier hexagonal planes

The systematic assignment of duty cycles allows the Isolated Switched-Mode Converter (ISVM) to reproduce input currents in a sinusoidal form, control output voltages to any desired accuracy, and produce waveforms of high fidelity without any physical DC-link energy storage element. The dithering values of the conversion and inversion stages of the Integrated Multilevel Converter (IMC) are outlined as follows:

$$d_{\alpha\gamma} = m_v \cdot sin\left(\frac{\pi}{3} - \theta_{inv}\right) \cdot sin\left(\frac{\pi}{3} - \theta_{rect}\right)$$

$$d_{\beta\gamma} = m_v \cdot sin(\theta_{inv}) \cdot sin\left(\frac{\pi}{3} - \theta_{rect}\right)$$

$$d_{\alpha\delta} = m_v \cdot sin\left(\frac{\pi}{3} - \theta_{inv}\right) \cdot sin(\theta_{rect})$$

$$d_{\beta\delta} = m_v \cdot sin(\theta_{inv}) \cdot sin(\theta_{rect})$$

$$P_{in} = P_{dc} \Rightarrow V_{dc}I_{dc} = \frac{3}{2}V_{in}I_{in}\, cos(\varphi_{in}) \Rightarrow \quad (5)$$

$$V_{dc} = \frac{3}{2}V_{in}\frac{I_{in}}{I_{dc}}cos(\varphi_{in}) = \frac{3}{2}V_{in}m_C\, cos(\varphi_{in})$$

Improving operational efficiency is a key goal for the IMC discussed here, which utilizes an eight-branch switch-over symmetric switching scheme to coordinate five effective switching states within each modulation period. This design is specifically designed to limit switching losses by making the system operate in a balanced manner and to avoid gratuitous commutation. Figure 7 shows the ISVM scheme in the Simulink model. It was built using the Simscape Power Systems Toolbox, which provides a disclosed and modular representation of converter components. The circuit is made up of a switching array and an input filter, which are used to keep the input currents sinusoidal and minimize harmonics and an RL load at the output. This type of simulation framework provides a clear visualization of the ISVM work and an in-depth analysis of the system behavior under a range of operating conditions.

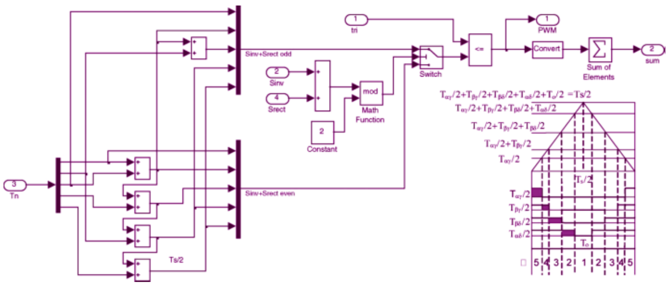


Fig. 7 PWM and signal generation via ISVM strategy in simulink

7. Induction Machine Control System

This is a control scheme that includes a VSMC in series with motor loads. This setup was used to study the performance of an induction motor with V/F speed control. In the simulation, the regulation of motor speed was assessed using two different modulation types: CSVM and ISVM in the V/F control. Among the various speed control techniques of the induction motor, such as pole changing, variation of supply frequency, rotor resistance control, stator voltage modulation, constant V/F control, and slip recovery control, the closed-loop constant V/F control method is widely used because of its simplicity and effectiveness, as well as its practical feasibility. In this method, the motor speed was the main control variable. A proportional-integral controller was used to receive an error signal generated from this. This controller produces a motor drive signal that will bring the motor speed back to the desired value (negative feedback). The controller also calculates a summary of the voltage components of the d-q reference frame, which is used in the space vector modulation scheme.

Table 1. Simulation parameters of the very sparse matrix converter and induction motor parameters

Parameter	Value
V_{rms}	220 V
IM Rating	3.73 KVA, 350 V, 50 Hz, 2p
R_S,L_s	[1.115Ω , 0.005974H]
R_R,L_R	[1.083 0.005974]
L_M	0.2037 H
J	0.02 N-m

A constant value is provided by dynamically changing the reference voltage and frequency, and keeping the V/F ratio constant to maintain a constant magnetic flux and ensure a stable production of torque in the motor. The proposed method was evaluated under both no-load and load conditions to confirm its efficacy in sustaining a constant speed and managing the performance of the motor used. Table 1 summarizes the simulation parameters applied to the VSMC and induction motor.

7.1. V/F Control of Three-Phase Induction Motor

The magnetic field produced in the stator winding of an induction motor is responsible for torque production. There is a direct proportionality between the applied stator voltage and the product of the stator flux linkage and the angular velocity of the rotating field. Thus, the stator flux is proportional to the ratio of the applied voltage to the supply frequency. The voltage and frequency must be changed in the same proportions to ensure a constant flux throughout the operating speed range. By maintaining this ratio, the motor can maintain an almost constant torque. This is the principle underlying the most popular step in induction motor speed control, that is, the constant volts-per-hertz (V/F) control strategy [32, 33]. The torque generated by an induction motor is, in practice, directly linked to the V/F ratio. Therefore, the constant-V/F method is efficient and simple for industrial motor drive applications; by maintaining a constant ratio of voltage to frequency, the motor can output a constant torque over a broad range of frequencies.

7.2. Induction Motor Drive Simulation

The closed-loop V/F speed control of an induction motor driven by a VSMC, employing CSVM and ISVM modulation as shown in 'Figure 8', makes use of a Very Sparse Matrix Converter and CSVM and ISVM modulation. In this system, the reference speed (ω_r*) is compared with the actual rotor speed (ω_r) measured by a speed calculator by using position/speed capture techniques. The resulting speed error is then fed to a Proportional-Integral controller, which then produces the required slip frequency (ω_{slip}) for speed control of the motor. The measured rotor speed (n) was used in conjunction with this slip frequency (s) to work out the stator supply frequency (f).

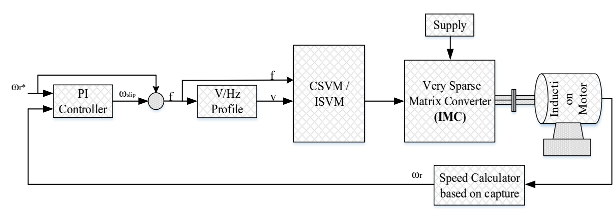


Fig. 8 System architecture for closed-loop V/F speed control of an induction motor driven by a VSMC

The *V/F* profile block guarantees an equal voltage rise in proportion to the frequency rise, which means that a near-constant *V/F* ratio is maintained to provide a constant torque potential over the entire operational speed range. The voltage and frequency signals are then used by the CSVM/ISVM modulation block, which produces the switching signals required in the very sparse matrix converter. The IMC amplifies the input signal and converts it to the desired output voltage and frequency to power the induction motor. This closed-loop feedback configuration provides stable operation, both no-loaded and loaded, and ultimately results in optimum speed control, better torque performance, and considerable reduction in harmonic distortion.

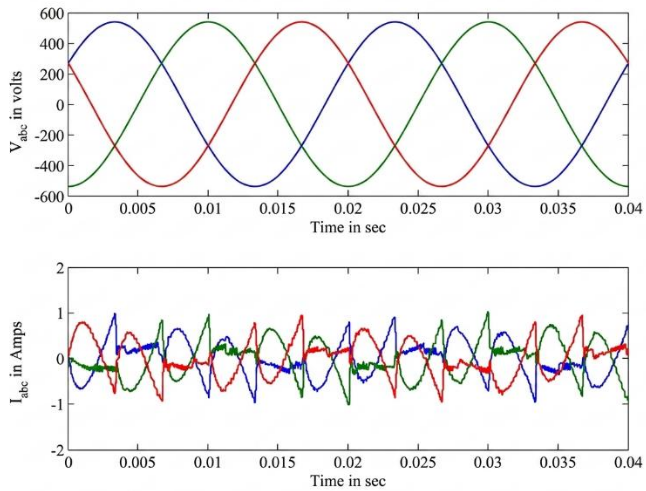


Fig. 9 VSMC Input voltage and current waveforms under CSVM

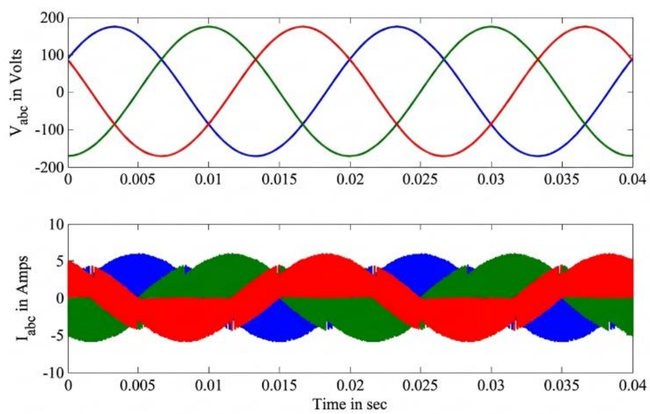


Fig. 10 VSMC Source voltage and current waveforms utilizing ISVM

The simulated waveforms of the input-source voltage and current of the VSMC in the CSVM are shown in Figure 9. The voltage profiles were synchronized, sinusoidal, and phase-shifted by 120°, verifying the proper synthesis of the input voltage. The existing profiles also exhibited slight distortion owing to changing events, but they were balanced and almost in phase with the voltage, which is an indication of a higher power-factor performance. The total harmonic distortion was quite small, which proves that the CSVM is effective in providing a high-quality input current. Figure 10 shows the Input-Source Voltage and Current Waveforms of VSMC operating with ISVM. The voltage profiles have sinusoidal, balanced phase properties similar to those achieved by the CSVM, and hence power the input side with adequate voltage control. In comparison, the present profiles are highly distorted and contain a higher harmonic content than the CSVM scenario. The currents are balanced, but the overall quality of the waveform is impaired by the new switching states and the complicated commutation of the ISVM.

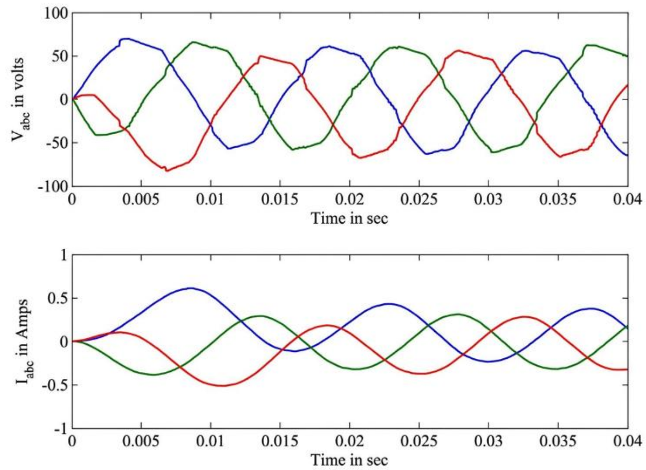


Fig. 11 Load-Side voltage and current response of VSMC under CSVM control

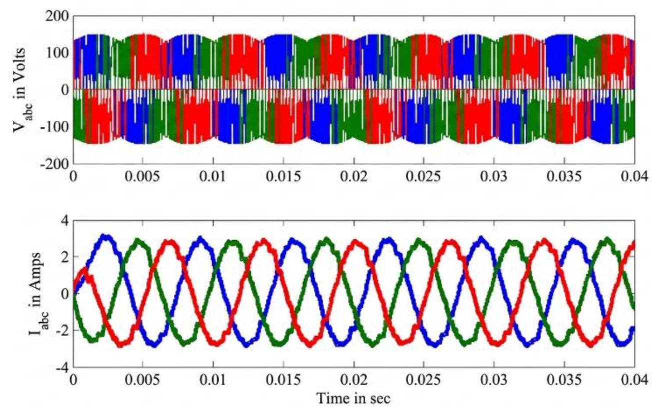


Fig. 12 Output performance of VSMC on load: voltage and current waveforms

As shown in Figure 11, the load-side voltage and current waveforms of the VSMC operating under the CSVM technique are displayed. The voltages were observed to be three-phase and sinusoidal with negligible distortion. The successful synthesis of the target load voltage is evidenced by the amplitude and phase shift values. The currents were mostly sinusoidal, balanced, and smooth with less harmonic distortion.

This performance results in less torque ripple and steady motor operation, thus proving the effectiveness of CSVM for speed control of induction motors. As presented in 'Figure 12', the load-side waveforms simulated for the VSMC operating with the ISVM method reveal quasi-sinusoidal output voltages with observable switching ripples. This is a sign of the switching transitions of the ISVM. Although switching ripple is present in the voltage signals, the load currents are balanced, which are nearly sinusoidal and have a higher amplitude than those of the CSVM. This implies that the ISVM can boost the existing drive capability at the cost of voltage quality.

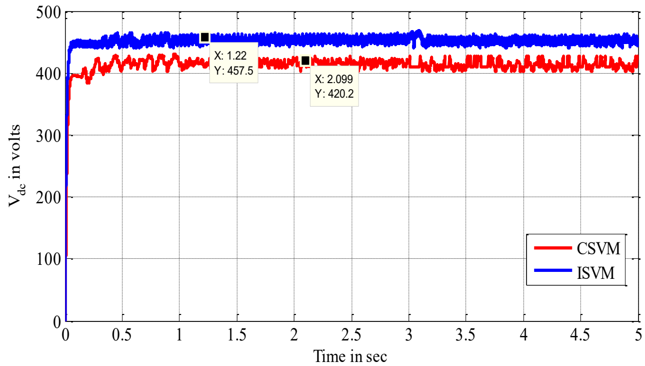


Fig. 13 Analysis of VSMC DC-Link voltage using CSVM and ISVM in simulation

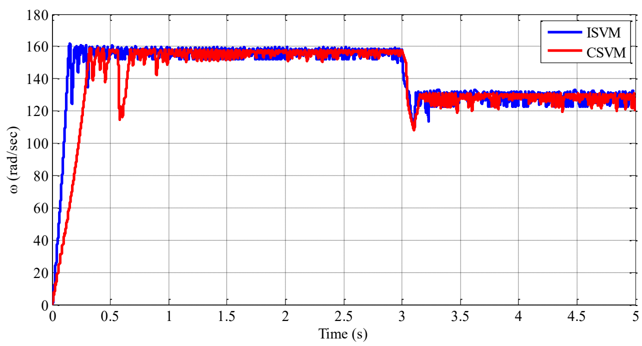


Fig. 14 Simulation of induction motor speed dynamics under V/F control: step changes in torque and reference (t=0s , ω = 157 rad/sec; t=1s, T=3 N-m & t=3s, ω = 130 rad/sec)

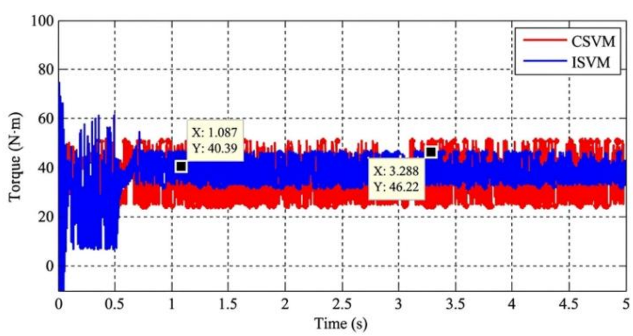


Fig. 15 Dynamic torque response of V/F controlled induction motor to speed and load fluctuations

As illustrated in Figure 13, a simulation of the DC-link voltage characteristics of the VSMC is presented, showcasing its behavior under both CSVM and ISVM. In both instances, the DC-link voltage was maintained close to its nominal value, signifying consistent converter operation. The CSVM was slightly lower in the DC-link compared with the ISVM, which was better in terms of voltage utilization capability when it was controlled by the ISVM. The two modulation techniques were found to stabilize rapidly after the transient phase, confirming that they are relevant to the dynamic operating conditions. Figure 14 shows the dynamic speed response of the induction motor running with a VSMC that contains CSVM and ISVM strategies. This is the response of the motor to step changes in the reference speed and load torque. Notably, the motor's speed went up to the reference value of 157 rad/s at t=0s and stabilized in approximately 0.3 seconds. Both modulation schemes were able to track the reference speed. A sudden change in the load torque to 3 Nm occurred at t=1s. The motor was given a small bump in speed, and the speed was immediately leveled, reflecting the robustness of the closed-loop PI-controlled V/F scheme. At t=3s, the reference speed was set to 130 rad/s, and both modulation methods were able to follow the new command with less than five overshoots. The ISVM had a smaller transient response than the CSVM, yet had more oscillations through the transition, and the CSVM had smoother tracking with fewer oscillations.

Figure 15 shows a simulated example of the torque response of the induction motor being fed by a VSMC under the V/F control scheme when using the CSVM and ISVM modulation strategies. The torque on the motor is sharp at the beginning as the motor speeds up to the reference speed. The ISVM generates a greater peak torque owing to its greater current driving ability, but the CSVM generates a more moderate increase. At the approximate time t = 1s, when a load torque of 3 Nm is introduced, the schemes are changed. The CSVM was shown to have smoother torque adaptation and smaller oscillations, whereas the ISVM had greater oscillations, which were then larger. At t = 3s, the reference speed was reduced, and the two methods restored torque balance; however, the ISVM displayed more transient oscillations than the CSVM.

Table 2. Simulated speed response characteristics of the VSMC-Fed induction motor using CSVM and ISVM strategies

Parameters / Modulation	DC link voltage (Volts)	Rise time (Sec)	Peak overshoot (%)	Peak time (Sec)	Settling time (Sec)	Undershoot (%)
CSVM	420.2	0.2051	0.76	1.027	0.323	26.30
ISVM	457.5	0.094	2.40	0.382	0.155	11.45

Table 2 lists the major dynamic performance parameters of the induction motor fed with VSMC using two modulation strategies: CSVM and ISVM. The parameters assessed were DC-link voltage, dynamic characteristics, and undershoot. Under the ISVM (457.5 V) as compared to the CSVM (420.2 V), the DC-link voltage was greater, which is an indication that the input supply was better utilized. The rise time of the ISVM (0.094 s) was much less than that of the CSVM (0.2051 s), which is the acceleration to the desired speed. However, the ISVM had a high peak overshoot (2.40%) compared to the CSVM (0.76%), indicating more oscillation among the transient conditions. Similarly, the ISVM has a lower peak time (0.382 s) and settling time (0.155 s) as compared to 1.027 s and 0.323 s, respectively. CSVM showed a higher value in terms of undershoot (26.30% as compared to ISVM 11.45%), which means that ISVM provided better recovery during drops in speed. These performance indicators are graphically compared in Table 2, and the shortcomings of each strategy are shown in relation to the others. The bar chart vividly reveals that the ISVM has a better speed dynamic, which is characterized by a higher rise and settling time, but the CSVM has better transient dynamics characterized by small overshoots and smooth transients.

8. Conclusion

This study focused on the performance characteristics of an induction motor fed by VSMC and the effect of CSVM and ISVM on its performance in a V/f-controlled induction motor drive. A thorough simulation analysis was performed, and unique performance profiles for each modulation strategy were identified. The indirect space vector modulation method exhibited a better dynamic response with significantly shorter rise and settling times, reduced undershoot, and improved DC-link voltage utilization. Conventional space vector modulation exhibited smoother transient operation but with a similar low undershoot performance.

Overall, the results indicate that the presented ISVM approach can provide a more powerful and efficient control solution for VSMC-fed Induction Motor (IM) drives and is well-suited to be implemented in high-performance industrial applications where fast response time and optimum utilization of the voltage are essential. The findings of this study contribute to the optimization of modulation techniques in the implementation of advanced motor-drive systems and suggest a way to achieve more efficient operation and dynamic control in industrial applications. Future studies may consider experimental validation of these simulation results and the inclusion of adaptive control algorithms further to improve the operation of ISVM in different circumstances.

Conflicts of Interest

"The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper."

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References

[1] Mahyar Khosravi et al., "Review of Model Predictive Control Strategies for Matrix Converters," *IET Power Electronics*, vol. 12, no. 12, pp. 3021-3032, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[2] Mohamed Azab, "A Review of Recent Trends in High Efficiency Induction Motor Drives," *Vehicles*, vol. 7, no. 1, pp. 1-50, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[3] Samson Shenglong Yu et al., "A DSE-based SMC Method of Sensorless DFIG Wind Turbines Connected to Power Grids for Energy Extraction and Power Quality Enhancement," *IEEE Access*, vol. 6, pp. 76596-76605, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[4] Hanan Mikhael D. Habbi, Hussein Jalil Ajeel, and Inaam Ibrahim Ali, "Speed Control of Induction Motor using PI and V/F Scalar Vector Controllers," *International Journal of Computer Applications*, vol. 151, no. 7, pp. 36-43, 2016. [Google Scholar]

[5] Mohamed Chebaani et al., "Extended Kalman Filter Design for Sensorless Sliding Mode Predictive Control of Induction Motors without Weighting Factor: An Experimental Investigation," *PLOS ONE*, vol. 18, no. 11, pp. 1-25, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[6] Xu Wu et al., "Direct Torque Control for Induction Motors based on Minimum Voltage Vector Error," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 5, pp. 3794-3804, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[7] Amir Masoud Bozorgi et al., "Modulation Techniques for Common-Mode Voltage Reduction in the Z-Source Ultra Sparse Matrix Converters," *IEEE Transactions on Power Electronics*, vol. 34, no. 1, pp. 958-970, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[8] Manjusha Vijayagopal et al., "Current Control and Reactive Power Minimization of a Direct Matrix Converter Induction Motor Drive with Modulated Model Predictive Control," *2015 IEEE International Symposium on Predictive Control of Electrical Drives and Power Electronics (PRECEDE)*, Valparaiso, Chile, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[9] Masood Moghaddami, Arash Anzalchi, and Arif I. Sarwat, "Single-Stage Three-Phase AC-AC Matrix Converter for Inductive Power Transfer Systems," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 10, pp. 6613-6622, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[10] S.M. Dabour, and E.M. Rashad, "Analysis and Implementation of Space-Vector-Modulated Three-Phase Matrix Converter," *IET Power Electronics*, vol. 5, no. 8, pp. 1374-1378, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[11] Akshay Sharma, and Vinod Kumar, "Advances in Optimisation-based Modulation and Control Techniques for Matrix Converters: A Review," *Journal of Information Systems Engineering and Management*, vol. 10, no. 53s, pp. 805-821, 2025. [CrossRef] [Publisher Link]

[12] Shanhu Li et al., "Open-Current Vector based SVM Strategy of Sparse Matrix Converter for Common-Mode Voltage Reduction," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 9, pp. 7757-7767, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[13] Prasopchok Hothongkham, Santisuk Sawangkla, and Sataporn Suathed, "Comparison of SPWM and SVPWM for Controlling Three-Phase Induction Motor Drive with Three-Phase Matrix Converter using V/f Method," *2025 28th International Conference on Electrical Machines and Systems (ICEMS)*, Busan, Korea, pp. 2893-2898, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[14] Ayad T. Mahmood, Khalaf S. Gaeid, and Takialddin A. Al Smadi, "Direct Torque Control Space Vector Modulation for Induction Motor Driven by Matrix Converter," *Tikrit Journal of Engineering Sciences*, vol. 31, no. 4, pp. 58-69, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[15] N.H. Mugheri, and M.U. Keerio, "An Optimal Fuzzy Logic-based PI Controller for the Speed Control of an Induction Motor using the V/F Method," *Engineering, Technology and Applied Science Research*, vol. 11, no. 4, pp. 7399-7404, 2021. [CrossRef] [Google Scholar] [Publisher Link]
[16] Truong Chi Trung et al., "Modern Scalar Control Applies Fuzzy Inference Technique in Motor Speed Control," *Journal of Transportation Science and Technology*, vol. 14, no. 6, pp. 24-33, 2025. [CrossRef] [Google Scholar] [Publisher Link]
[17] Annette von Jouanne, Emmanuel Agamloh, and Alex Yokochi, "Review of Matrix Converters in Motor Drive Applications," *Energies*, vol. 18, no. 1, pp. 1-28, 2025. [CrossRef] [Google Scholar] [Publisher Link]
[18] Manjusha Vijayagopal et al., "Direct Predictive Current-Error Vector Control for a Direct Matrix Converter," *IEEE Transactions on Power Electronics*, vol. 34, no. 2, pp. 1925-1935, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[19] Hui Wang et al., "Topology and Modulation Scheme of a Three-Level Third-Harmonic Injection Indirect Matrix Converter," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 10, pp. 7612-7622, 2017. [CrossRef] [Google Scholar] [Publisher Link]
[20] Yeongsu Bak, Eunsil Lee, and Kyo-Beum Lee, "Indirect Matrix Converter for Hybrid Electric Vehicle Application with Three-Phase and Single-Phase Outputs," *Energies*, vol. 8, no. 5, pp. 3849-3866, 2015. [CrossRef] [Google Scholar] [Publisher Link]
[21] Tole Sutikno, Rizky Ajie Aprilianto, and Hendril Satrian Purnama, "Application of Non-Isolated Bidirectional DC-DC Converters for Renewable and Sustainable Energy Systems: A Review," *Clean Energy*, vol. 7, no. 2, pp. 293-311, 2023. [CrossRef] [Google Scholar] [Publisher Link]
[22] Edisson Villa-Ávila, Danny Ochoa-Correa, and Paul Arévalo, "Advancements in Power Converter Technologies for Integrated Energy Storage Systems: Optimizing Renewable Energy Storage and Grid Integration," *Processes*, vol. 13, no. 6, pp. 1-32, 2025. [CrossRef] [Google Scholar] [Publisher Link]
[23] Tuyen D. Nguyen, and Hong-Hee Lee, "Dual Three-Phase Indirect Matrix Converter with Carrier-based PWM Method," *IEEE Transactions on Power Electronics*, vol. 29, no. 2, pp. 569-581, 2014. [CrossRef] [Google Scholar] [Publisher Link]
[24] Edivan Laercio Carvalho et al., "Three-Phase Bidirectional Isolated AC-DC Matrix-Converter with Full Soft-Switching Range," *IEEE Access*, vol. 11, pp. 119270-119283, 2023. [CrossRef] [Google Scholar] [Publisher Link]
[25] Alexandros Tsoupos, and Vinod Khadkikar, "A Novel SVM Technique with Enhanced Output Voltage Quality for Indirect Matrix Converters," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 2, pp. 832-841, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[26] Kotb B. Tawfiq, Peter Sergeant, and Arafa S. Mansour, "Comparative Analysis of Space Vector Pulse-Width Modulation Techniques of Three-Phase Inverter to Minimize Common Mode Voltage and/or Switching Losses," *Mathematics*, vol. 12, no. 18, pp. 1-21, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[27] Vinoth Jayakumar, Bharatiraja Chokkalingam, and Josiah Lange Munda, "Performance Analysis of Multi-Carrier PWM and Space Vector Modulation Techniques for five-Phase Three-Level Neutral Point Clamped Inverter," *IEEE Access*, vol. 10, pp. 34883-34906, 2022. [CrossRef] [Google Scholar] [Publisher Link]
[28] Gipyo Kim, Hyunjae Lee, and Jingeun Shon, "Enhanced Harmonic Reduction and Voltage Utilization Ratio Improvement in ANPC Inverters using an Advanced Hybrid SVPWM Technique," *Energies*, vol. 18, no. 7, pp. 1-14, 2025. [CrossRef] [Google Scholar] [Publisher Link]
[29] Lukas Wind et al., "Realization of a Complementary Full Adder based on Reconfigurable Transistors," *IEEE Electron Device Letters*, vol. 45, no. 4, pp. 724-727, 2024. [CrossRef] [Google Scholar] [Publisher Link]
[30] Quoc-Hoan Tran, and Hong-Hee Lee, "An Advanced Modulation Strategy for Three-to-Five-Phase Indirect Matrix Converters to Reduce Common-Mode Voltage with Enhanced Output Performance," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 7, pp. 5282-5291, 2018. [CrossRef] [Google Scholar] [Publisher Link]
[31] Ranju Bharti, Madhav Kumar, and B.M Prasad, "V/F Control of Three-Phase Induction Motor," *2019 International Conference on Vision Towards Emerging Trends in Communication and Networking (ViTECoN)*, Vellore, India, pp. 1-4, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[32] Zhe Zhang, and Ali M. Bazzi, "Robust Sensorless Scalar Control of Induction Motor Drives with Torque Capability Enhancement at Low Speeds," *2019 IEEE International Electric Machines and Drives Conference (IEMDC)*, San Diego, CA, USA, pp. 1706-1710, 2019. [CrossRef] [Google Scholar] [Publisher Link]
[33] Sifelislam Guedida et al., "Direct Torque Control Scheme for Less Harmonic Currents and Torque Ripples for Dual Star Induction Motor," *Romanian Journal of Technical Sciences - Electrical Engineering and Energy Series*, vol. 68, no. 4, pp. 331-338, 2023. [CrossRef] [Google Scholar] [Publisher Link]