

Performance Analysis of an Induction Motor Drive Based on Split-Source Inverter and Field-Oriented Control for Electric Traction Applications

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Abstract

The rise of electric vehicles has renewed interest in induction machines due to their robustness, low cost, and performance well suited to traction applications. This work presents a study on the modelling and control of an induction machine powered by a Split Source Inverter (SSI). The objective is to analyze the machine's performance under Field-Oriented Control (FOC), which allows decoupling between flux and electromagnetic torque. The developed models were simulated using MATLAB/Simulink. The results demonstrate a significant improvement in the machine's stability, accuracy, and dynamic response when FOC is combined with SSI compared to conventional power supply configurations.

Keywords

Induction machine; Split Source Inverter (SSI); Field-Oriented Control (FOC); PWM modulation; Electric traction.

1. Introduction

Electric vehicles impose increasing requirements in terms of power density, energy efficiency, and dynamic control of traction motors. In this context, the induction machine has become increasingly attractive for electric traction due to its robustness, moderate cost, and ability to withstand various operating conditions [1], [2]. At the same time, advances in power electronics and control computing now make it possible to achieve dynamic performances comparable to those of DC machines, while retaining the structural advantages of the induction machine [3].

DC-AC energy conversion for traction applications has seen the emergence of "single-stage" topologies that combine both boost and inversion functions without the need for a separate DC-DC stage. Among these, the Split-Source Inverter (SSI) has been proposed as an attractive alternative to the Z-Source Inverter. The SSI integrates a voltage-boosting function directly associated with the three-phase bridge and retains the same switching states as a conventional VSI, while requiring fewer passive components [4], [5], [6], [7]. These characteristics make the SSI a promising option for high-power-density on board converters [8], [9], [10], [11]. On the control side, Field-Oriented Control (FOC) remains the reference method for achieving flux-torque decoupling and precise speed-torque regulation in induction motors. Recent studies confirm the robustness of both indirect and direct FOC variants, while also highlighting growing interest in sensorless solutions (flux observers and speed estimators) to reduce cost and maintenance in embedded applications [12]. Improvements mainly focus on enhancing robustness against parameter variations and on estimating the flux angle using only stator measurements [13].

Several recent studies have combined these approaches—gain-type inverter topologies, FOC, and sensorless observation—to develop high-performance "single-stage" systems for traction electronics. Experimental comparisons and simulations show that the combination of SSI and FOC improves speed dynamics, reduces torque oscillations, and provides greater flexibility regarding the onboard supply voltage, which is crucial for electric vehicles powered by variable-voltage batteries [14]. Nevertheless, some challenges remain, including the optimization of PWM control strategies for the SSI, management of switching constraints, and experimental validation under real power conditions [15].

In light of the previously presented state of the art, the present work aims to deepen the study of the dynamic behavior of an induction machine associated with a Split-Source Inverter (SSI) and controlled by a Field-Oriented Control (FOC) strategy. More specifically, it focuses on three main aspects: the complete modeling of the induction machine in the rotating d-q reference frame, the integration and control of the SSI converter using Sinusoidal Pulse Width Modulation (SPWM), and the implementation of an FOC strategy equipped with an observer to achieve sensorless speed regulation. Simulations carried out in the MATLAB/Simulink environment aim to evaluate the dynamic performance, stability, and robustness of the combined IM + SSI + FOC system, to compare them with those of a conventional supply structure, and to identify prospects for optimization and experimental implementation in electric traction applications.

THPWM further reduces harmonic distortion. In this study, SPWM is chosen for its simplicity, stability, and compatibility with the Field-Oriented Control (FOC) strategy.

The capacitor voltage V_{DC} is given by:

$$V_{DC} = \frac{1}{1-D_{av}} V_{in} \tag{5}$$

Where V_{DC} is the input DC voltage and D_{av} is the average duty ratio.

The duty cycle D_{av} , determined by the selected modulation technique, varies according to the established equations, thereby influencing the effective voltage applied to the inverter bridge.

The modelling of the Split-Source Inverter (SSI) has demonstrated its ability to provide both voltage boosting and conversion within a single stage, offering simple control and good voltage quality. To fully exploit its performance in electric drive applications, it is combined with a Field-Oriented Control (FOC) strategy based on flux–torque decoupling, which enables fast and precise control of torque and speed while maintaining the robustness of the induction machine.

3. Field-Oriented Control (FOC)

Field-Oriented Control (FOC) is an advanced and efficient control method for induction machines, designed to reproduce behaviour similar to that of a DC machine [1]. Its principle is based on the decoupling between the magnetic flux and the electromagnetic torque, allowing independent and precise control of these two quantities [2].

The developed torque is expressed by the following relation:

$$T_e = \frac{3}{2} p \frac{M}{L_r} \phi_{dr} i_{qs} \tag{6}$$

Where p is the number of pole pairs, M the mutual inductance, and L_r the rotor inductance.

By keeping i_d constant, the flux is stabilized, while i_q is adjusted according to the torque demand, ensuring total decoupling between the two variables [16]. This characteristic makes the FOC control both fast, precise, and robust, even in the presence of disturbances or load variations. The FOC control structure consists of several processing steps. The stator currents (i_a, i_b, i_c) are first measured and then transformed into (i_d, i_q) components using Clarke and Park transformations. These components are then compared to their reference values i_d^*, i_q^* and regulated by proportional–integral (PI) controllers to generate the control voltages V_d, V_q . The control voltages are reconverted into three-phase signals through the inverse Park transformation and applied to the Split-Source Inverter (SSI) using Sinusoidal Pulse Width Modulation (SPWM) [14]. This closed-loop structure ensures precise control of torque and flux, fast dynamic response, and enhanced system stability. The combination of SSI and FOC allows achieving a variable, high-quality output voltage while improving electromagnetic torque stability and the overall efficiency of the drive. The functional diagram of the FOC shown in Figure 2 includes current measurement, Clarke-Park transformations, PI regulation, and generation of the control signals applied to the inverter. This structure guarantees accurate speed tracking, rapid dynamic response, and stable torque, fully meeting the requirements of electric traction applications [7].

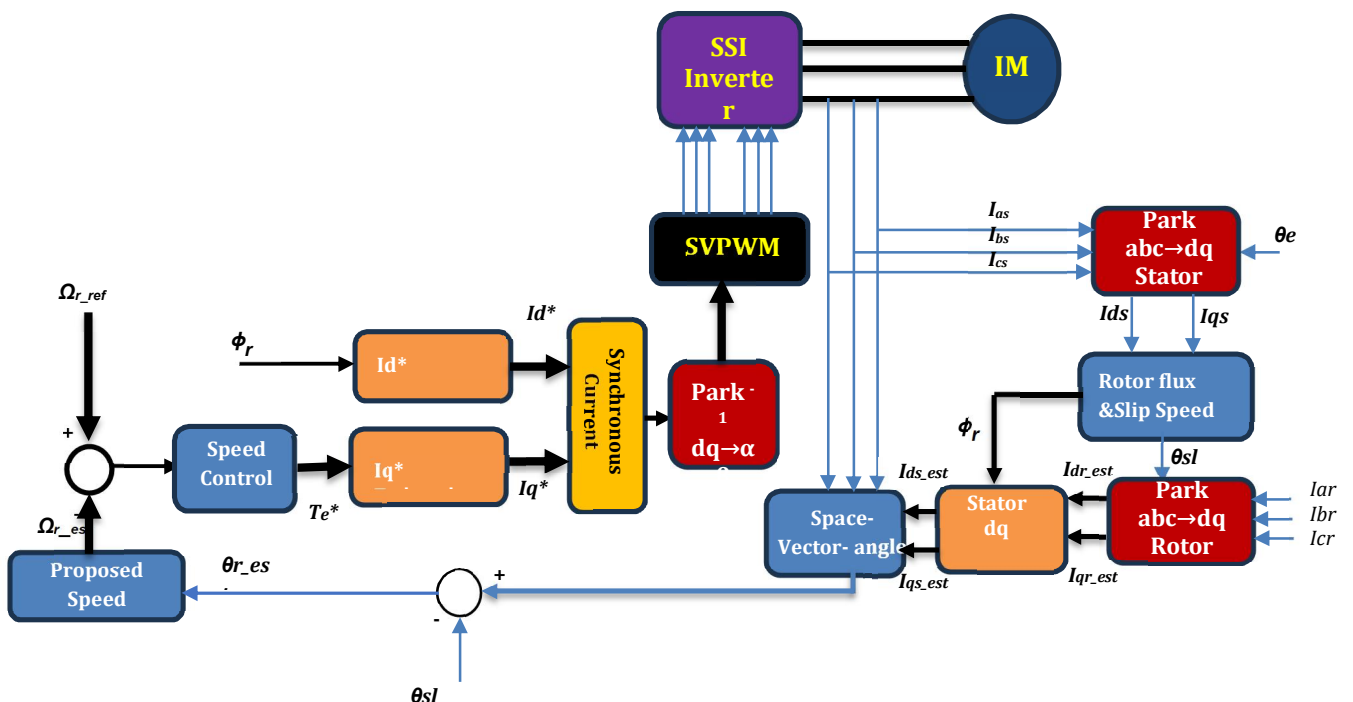


Fig. 2. Control diagram of an induction motor with SSI and FOC

4. Simulation Results and Discussion

This section presents and analyses the main results obtained from the complete model of the induction machine supplied by a Split-Source Inverter (SSI) and controlled using the Field-Oriented Control (FOC) strategy. The simulations were carried out in MATLAB/Simulink, considering the electrical and mechanical parameters of the machine as well as the dynamics of the SSI converter. The objective is to evaluate the accuracy of speed regulation, the stability of the electromagnetic torque, and the quality of the reference voltages and currents generated by the control system. Figure 3 illustrates the dynamic behaviour of the induction machine supplied by an SSI and controlled via a field-oriented control strategy. The displayed signals include the stator current, reference speed, rotor speed, and electromagnetic torque.

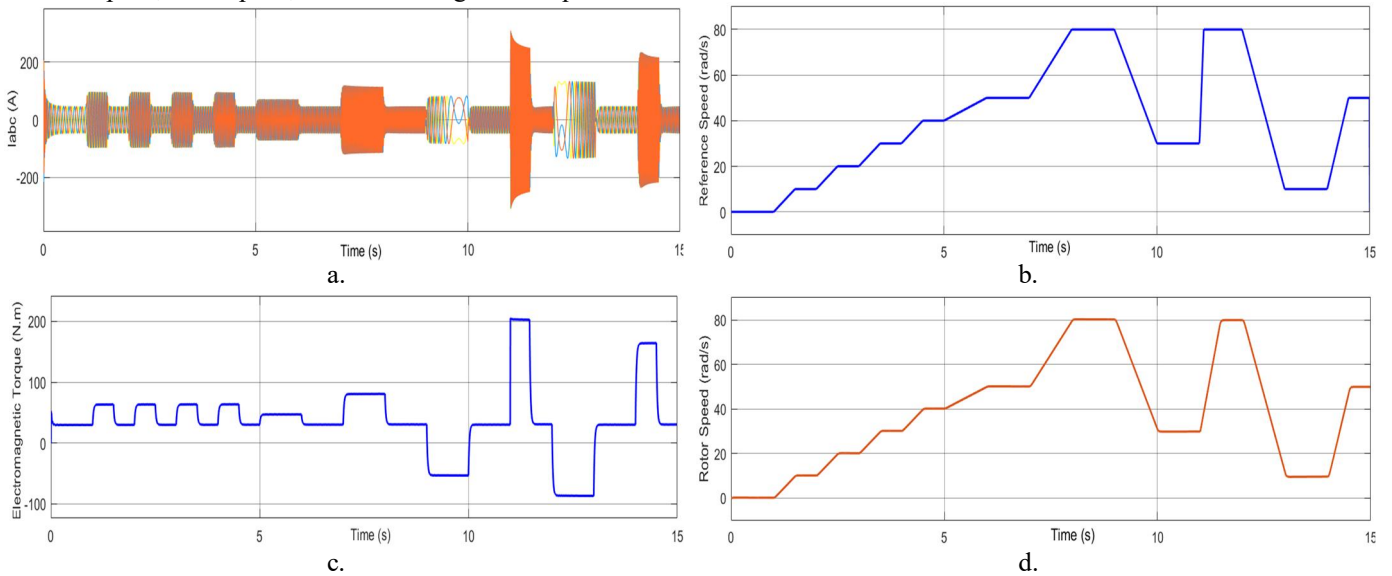


Fig. 3. Output results of the induction machine with SSI and FOC

Figure 3 illustrates the main simulated quantities of the induction machine supplied by a Split-Source Inverter (SSI) and controlled using the Field-Oriented Control (FOC) method. The three-phase stator current exhibits a nearly sinusoidal and balanced waveform, indicating good voltage quality from the SSI and a low harmonic distortion rate. During set-point variations, slight transient oscillations appear but are quickly damped, reflecting the system’s stability. The rotor speed closely follows the reference speed with a short response time and no significant overshoot, confirming the FOC control’s speed and precision. The electromagnetic torque varies according to speed changes, with transient peaks during acceleration and deceleration, then stabilizes in steady state. These results demonstrate the dynamic performance and robustness of the SSI-FOC combination, ensuring precise speed tracking, controlled torque, and smooth response, fully meeting the requirements of electric traction applications.

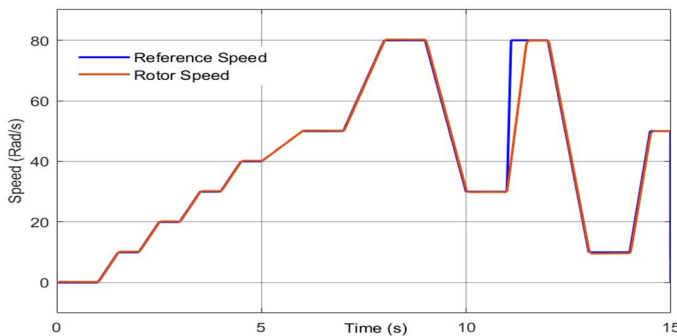


Fig. 4. Actual and reference speeds versus time for PI controllers based on FOC.

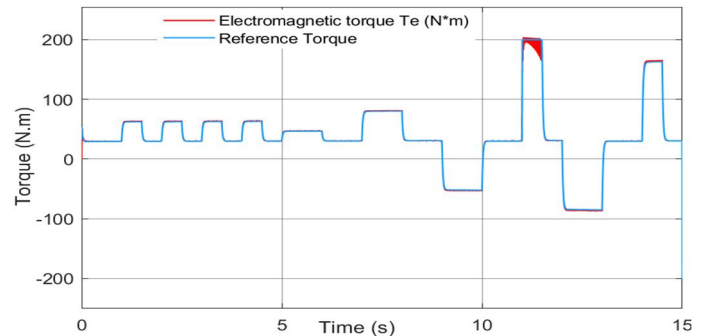


Fig. 5. Electromagnetic torque and its reference of the induction machine .

Figure 4 presents a comparison between the reference speed and the simulated rotor speed of the induction machine. It can be observed that the actual speed closely follows the imposed reference throughout the operating range. At each set-point change, the rotor speed quickly reaches the reference value with a very short response time and no significant overshoot, demonstrating the accuracy and stability of the FOC control. Speed variations, both during acceleration and deceleration; occur smoothly and without persistent oscillations, confirming the effective decoupling between flux and torque provided by the vector control. This fast dynamic response highlights the efficiency of the SSI-FOC combination, enabling precise speed control while maintaining stable operation, making this structure particularly suitable for electric traction systems that require rapid speed changes and well-controlled torque. Figure 5 shows the evolution of the electromagnetic torque of the induction machine supplied by a Split-Source Inverter (SSI) and controlled using the FOC method, along with its reference torque. According to the relation $P = \omega T_e$, the developed power directly depends on the sign and magnitude of the torque and speed. When $\frac{d\omega}{dt} > 0$, the power is positive $P > 0$,

and the torque is positive, corresponding to an acceleration phase of the machine. Conversely, when $\frac{d\omega}{dt} < 0$, the power becomes negative $P < 0$, indicating a negative torque and thus a deceleration phase with energy recovery. The actual torque reaches a maximum value of approximately 200 N·m, demonstrating the system's capability to provide high starting effort. The reference torque is also shown; the actual torque follows it with well-damped transient deviations, confirming the good stability and responsiveness of the FOC control combined with the SSI, as well as its ability to ensure efficient operation in electric traction, both in motoring and regenerative modes.

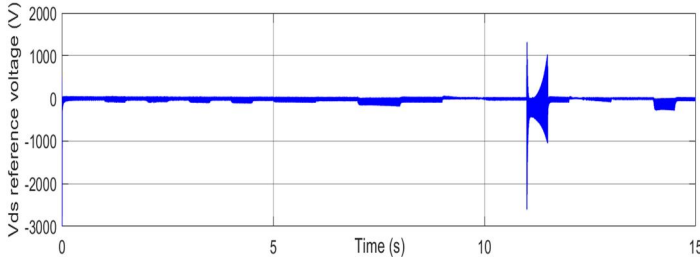


Fig. 6. Reference voltage V^*_{ds}

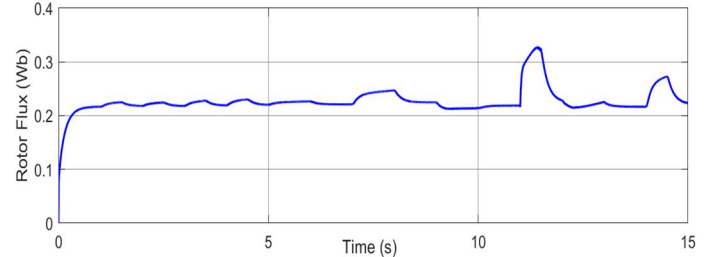


Fig. 8. Rotor flux

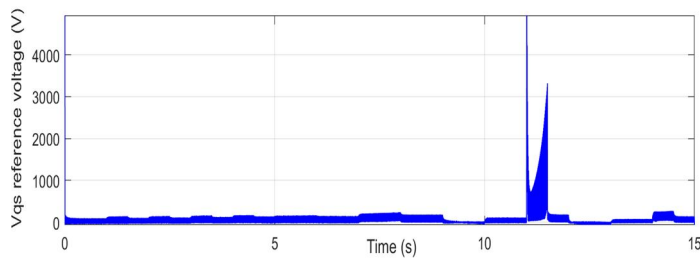


Fig. 7. Reference voltage V^*_{qs}

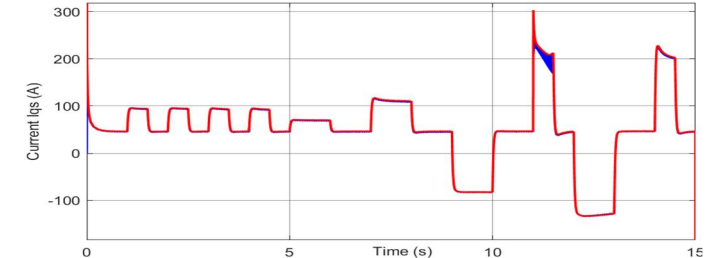


Fig. 9. Current I_{qs} and its reference I^*_{qs}

Figure 6 and figure 7 illustrates the evolution of the reference voltages generated by the FOC control of the induction machine supplied by a Split-Source Inverter (SSI). The V_{ds} component remains nearly constant, reflecting the maintenance of the rotor flux at a stable value, while V_{qs} varies according to changes in the speed reference, representing direct control of the electromagnetic torque. During transient conditions, V_{qs} exhibits brief peaks due to acceleration or braking before stabilizing in steady state. This behaviour demonstrates the effective decoupling between flux and torque, as well as the responsiveness and accuracy of the FOC control in generating the command voltages applied to the SSI.

Figure 8 shows the rotor flux of the induction machine, which stabilizes at approximately 0.22 Wb during normal operation. Brief disturbances are observed during speed transients, confirming the robustness of the FOC control in maintaining flux regulation.

Figure 9 shows the evolution of the measured current I_{qs} and its reference I^*_{qs} . The measured current closely tracks its reference throughout the operating cycle, confirming the accuracy and responsiveness of the current control loop. I_{qs} varies according to the speed profile, reaching a maximum of approximately 300 A during the strongest acceleration transient, in direct correspondence with the torque demand. The minor transient peaks observed during set-point changes are rapidly damped, validating the good dynamic response of the controller and the ability of the SSI-FOC system to ensure precise torque control of the induction machine.

5. Conclusion

The present work has enabled the study and simulation of an induction machine supplied by a Split-Source Inverter (SSI) and controlled using the Field-Oriented Control (FOC) strategy. The detailed modelling of the machine in the d-q reference frame, along with the implementation of FOC, demonstrated the effectiveness of flux-torque decoupling, allowing fast and precise speed regulation. The simulation results obtained in MATLAB/Simulink confirmed the system's stability, robustness, and dynamic performance. In particular, the rotor speed closely follows the reference with a short response time and no significant overshoot, while the electromagnetic torque effectively adjusts to load variations. Moreover, the combination of SSI and FOC ensures high-quality supply, low stator current distortion, and improved energy efficiency. These characteristics make this structure a promising solution for electric traction applications, where control accuracy, reliability, and energy reversibility are essential.

For future work, it would be interesting to extend this study to an experimental implementation and to explore intelligent or adaptive control approaches (such as PSO, fuzzy control, or sliding mode control) to further optimize the system's performance and robustness against parameter variations and external disturbances.

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Appendix

Table 1: Induction machine parameters (cage rotor machine) [16]

Parameters	Values
Rated power	100 kW
Rated voltage	350 V
Rated current	178 A
Rated speed	980 rpm
Number of pole pairs	3
Stator phase resistance	0.019 Ω
Rotor phase resistance referred to the stator	0.014 Ω
Stator inductance	10.9 mH
Rotor inductance	10.5 mH
Mutual inductance	0.034 H
Peak power	250 kW
Maximum torque	2400 N.m