

Robust Control of PMSM using Fully Synergetic Control with SVPWM and Real-Time Load Torque Estimation

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Abstract— This paper presents a synergetic control strategy for a Permanent Magnet Synchronous Machine (PMSM) drive, implemented and validated through detailed simulations in MATLAB/Simulink. The proposed approach integrates a load torque estimator to enhance system robustness and ensure accurate disturbance compensation and SVPWM to drive the inverter for better voltage quality. The control framework guarantees fast and precise tracking of both speed and current references, even under abrupt load variations. Simulation results show that the motor torque accurately follows step reference commands with minimal steady-state error and no overshoot, while the direct-axis current (I_d) exhibits smooth and stable behaviour with excellent reference tracking. The estimated load torque closely matches the actual disturbances, enabling effective compensation. Additionally, the three-phase stator currents remain balanced and sinusoidal throughout operation. The rotor speed rapidly converges to the reference without overshoot or chattering, demonstrating the high-performance capabilities of the synergetic controller. These results confirm the suitability of the proposed method for PMSM drives in applications requiring dynamic precision, disturbance rejection, and enhanced reliability.

Keywords— Synergetic control, PMSM, Load torque estimation, SVPWM.

I. INTRODUCTION

Permanent Magnet Synchronous Motors have gained significant traction in modern electric drive applications due to their high-power density, superior efficiency, and rapid dynamic response. These features make them ideal for high-performance systems such as robotics, Computer Numerical Control (CNC) machines, and aerospace applications [1]. Compared to Induction Motors (IMs), PMSMs eliminate rotor copper losses by employing permanent magnets, resulting in higher efficiency, particularly under partial load conditions [2]. Furthermore, PMSMs generate sinusoidal back-EMF, offering smoother torque and lower acoustic noise than Brushless DC Motors (BLDCs) [3].

However, PMSM performance is closely tied to accurate rotor position and load torque information. Sensor-based solutions increase cost and reduce system reliability. Sensorless control methods address this by eliminating mechanical sensors, but accurate real-time load torque estimation remains a challenge [4].

This paper proposes a synergetic control approach for PMSM drives, enhanced with a real-time load torque estimator. The proposed method ensures precise torque and speed regulation, improved dynamic behaviour, and robust operation under varying load conditions, making it well-suited for demanding industrial applications.

II. SYNERGETIC CONTROL AND PMSM

A. Concept of Synergy and Its Role in Control Theory

Synergy refers to the coordinated interaction of multiple components to produce a global effect greater than the sum of individual actions. This principle is evident across disciplines, from muscular cooperation in human motion to pharmacological and industrial systems where collective behaviour enhances performance [5].

In control theory, Synergetic Control builds on this concept by focusing on the collective behaviour of dynamic systems with interacting variables. Instead of controlling individual state variables separately, it defines a macro-

variable known as a synergetic manifold, that encapsulates the desired global behaviour. The control law is then designed to drive the system toward this manifold, ensuring coordinated, stable operation despite model uncertainties or external disturbances.

Synergetic Control offers several advantages:

- ✓ Robustness to parameter variations and external perturbations,
- ✓ A structured design methodology grounded in system dynamics,
- ✓ Flexibility to shape global system behaviour through macro-variable design.

These features make it particularly well-suited for nonlinear systems such as PMSMs, where coordinated control is essential for achieving high performance.

B. The synergetic control principles

In industrial settings, conventional PI controllers have been widely used for regulating electrical machines. However, their performance degrades under parameter variations, such as changes in stator resistance due to temperature fluctuations or faults. To overcome these limitations, adaptive control techniques were introduced, followed by Sliding Mode Control (SMC), which offers improved robustness. Nevertheless, SMC suffers from chattering, which can induce mechanical stress and undesirable oscillations in motor drives.

To resolve this, Kolesnikov introduced the Synergetic Control (SC) method in [6] and [7], which preserves the robustness of nonlinear control while eliminating chattering. SC has demonstrated promising results in various applications, particularly in power electronics and industrial systems such as battery chargers [8]. Its structured, model-based design and strong disturbance rejection capabilities make it a compelling choice for high-performance PMSM drive control.

Any nonlinear dynamic system of order n can be described as [9] :

$$\dot{x} = f(x, u, t) \quad (1)$$

Where:

- ✓ $x \in \mathbb{R}^n$ is the state vector,
- ✓ $u \in \mathbb{R}^m$ is the control input vector,
- ✓ And t is time,

The design of a synergetic controller involves the following steps:

Step 1: Definition of the Synergetic Macro-Variable Ψ , which is typically a linear combination or function of the system states, where the main control objective is to force the system to operate on the manifold $\Psi = 0$, which significantly reduces the system dynamics to a lower-dimensional subspace.

Step 2: Specification of Desired Dynamics for the Macro-Variable

The desired evolution of Ψ is imposed using a first-order differential equation:

$$T\dot{\Psi} + \varphi(\Psi) = 0 \quad (2)$$

Where:

- ✓ T is a design parameter (time constant),
- ✓ $\varphi(\Psi)$ is a nonlinear function satisfying: $\varphi(0)=0$ and $\varphi(\Psi) \cdot \Psi > 0$ for all $\Psi \neq 0$.

A common and simple choice is $\varphi(\Psi)=\Psi$, which leads to exponential convergence of the previous evolution equation and equation (2) becomes:

$$T\dot{\Psi} + \Psi = 0.$$

Step 3: Chain Rule Application

To connect the macro-variable dynamics to the system dynamics, we use the chain rule:

$$T \frac{\dot{\Psi}}{\dot{x}} \dot{x} + \Psi = 0 \quad (3)$$

Substituting (1) into (3), we obtain:

$$T \frac{\dot{\Psi}}{\dot{x}} f(x, u, t) + \Psi = 0 \quad (4)$$

Step 4: Solving for the Control Law

Solving equation (4) yields the control input u explicitly as a function of states, time, and the macro-variable:

$$u^* = g(x, \Psi, T, t) \quad (5)$$

This control law ensures that the system trajectories converge toward the manifold $\Psi=0$, and thus the reference tracking or regulation goal is achieved.

C. The mathematical model of the PMSM

To simplify the PMSM mathematical model, the following assumptions are made: uniform air gap with constant magnetic reluctance; equal stator inductances in d and q axes ($L_d=L_q=L_s$), valid for surface-mounted PMSMs with negligible saliency; and sinusoidal rotor magnetic field distribution ensuring sinusoidal back-EMF and flux linkage. These assumptions enable a tractable model for control design by using the rotating dq-reference frame, which converts three-phase stator quantities into two orthogonal DC components, simplifying the stator voltage equations.

$$\begin{cases} V_d = R_s I_d + L_s \dot{I}_d - p\Omega L_s I_q \\ V_q = R_s I_q + L_s \dot{I}_q + p\Omega L_s I_d + p\Omega \Phi_0 \end{cases} \quad (6)$$

And the mechanical equations:

- For the machine speed:

$$\frac{d\Omega}{dt} = \frac{T_{em} - C_r - f\Omega}{J} \quad (7)$$

- And for the electromagnetic torque will be:

$$T_{em} = \frac{3}{2} p \Phi I_q \quad (8)$$

In this model, R_s represents the stator resistance, L_s the stator inductance, Ω the mechanical speed, p the number of pole pairs, Φ_0 the permanent magnet flux, J the rotor inertia, f the viscous friction coefficient, and T_{em} the electromagnetic torque of the machine.

III. THE PROPOSED SYNERGETIC CONTROL APPROACH

During the control of the PMSM, the process is divided into two separate channels. The first channel is specifically dedicated to controlling the I_d current via the V_d voltage, while the second channel is responsible for speed regulation by controlling the machine's torque and speed through the I_q current then the V_q voltage (Figure 1).

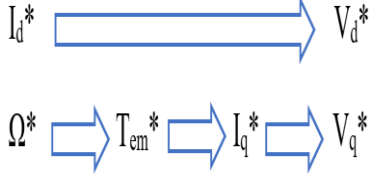


Fig. 1. PMSM control algorithm.

In the context of the PMSM, the rotor generates a constant permanent magnetic flux. As a result, it is not necessary to control the I_d current. However, in most situations, it is recommended to regulate I_d to be zero. This approach aims to minimize Joule losses, thereby enhancing the overall efficiency and performance of the system [10].

In all that follows, the asterisk (*) in the upper right corner of any symbol denotes the reference value of that symbol. The term ε_x represents the error of the variable x (the difference between the reference and real value). The symbols T_n , k_n , and k_{n+1} are synergetic control parameters..

A. Synergetic control for the I_d channel

The first step is the definition of the macro-variable as:

$$\begin{cases} \Psi_d = K_1 \varepsilon_d + K_2 \int \varepsilon_d dt \\ \dot{\Psi}_d = K_1 \varepsilon_d + K_1 \dot{\varepsilon}_d \end{cases} \quad (9)$$

Then the specification of the desired dynamics evolution

$$T_d \dot{\Psi}_d + \Psi_d = 0 \quad (10)$$

After that, the determination of V_d^* :

So, by the reformulation of the equation (6), it can be calculating the I_d current as the following:

$$\begin{cases} \dot{I}_d = V_d - R_s I_d + p\Omega L_s I_q \\ \dot{I}_d^* = V_d^* - R_s I_d^* + p\Omega L_s I_q \end{cases} \quad (11)$$

By the substitution of the equation (11) in the equation (10):

$$\begin{aligned} T_d (K_1 (V_d^* - R_s I_d^* + p\Omega L_s I_q - \dot{I}_d) + K_2 \varepsilon_d) \\ + K_1 \varepsilon_d + K_2 \int \varepsilon_d dt = 0 \end{aligned} \quad (12)$$

Finally, the resolution of the equation (12) leads to the V_d^* :

$$\begin{aligned} V_d^* = -\frac{K_2}{K_1} \varepsilon_d + \frac{1}{T_d} \varepsilon_d - \frac{K_2}{T_d K_1} \int \varepsilon_d dt + R_s I_d^* \\ - p\Omega L_s I_q + \dot{I}_d \end{aligned} \quad (13)$$

B. Synergetic control for the I_q channel

The control process of the I_q current loop will be exactly like the I_d current.

The macro-variables are:

$$\begin{cases} \Psi_q = k_3 \varepsilon_q + k_4 \int \varepsilon_q dt \\ \dot{\Psi}_q = k_3 \varepsilon_q + k_4 \dot{\varepsilon}_q \end{cases} \quad (14)$$

The dynamic evolution is:

$$T_q \dot{\Psi}_q + \Psi_q = 0 \quad (15)$$

The control laws are:

$$\begin{cases} \dot{I}_q = V_q - R_s I_q - p\Omega L_s I_d - p\Omega \Phi \\ \dot{I}_q^* = V_q^* - R_s I_q^* - p\Omega L_s I_d - p\Omega \Phi \end{cases} \quad (16)$$

$$\begin{aligned} T_q (K_3 (V_q^* - R_s I_q^* - p\Omega L_s I_d - p\Omega \Phi - \dot{I}_q) + K_4 \varepsilon_q) \\ + K_3 \varepsilon_q + K_4 \int \varepsilon_q dt = 0 \end{aligned} \quad (17)$$

The solution for the desired performances is:

$$\begin{aligned} V_q^* = -\frac{K_4}{K_3} \varepsilon_q + \frac{1}{T_q} \varepsilon_q - \frac{K_4}{T_q K_3} \int \varepsilon_q dt + R_s I_q^* \\ - p\Omega L_s I_d + \dot{I}_q + p\Omega \Phi \end{aligned} \quad (18)$$

C. The machine electromagnetic torque and speed loop

With a linear relationship between torque and the current I_q , there is no issue in determining the reference current I_q^* based on the reference torque:

$$I_q^* = \frac{2T_{em}^*}{3p\Phi} \quad (19)$$

Where the reference torque will be calculated by the speed synergetic controller as:

The Macro-variables are :

$$\begin{cases} \Psi_s = k_5 \varepsilon_\Omega + k_6 \int \varepsilon_\Omega dt \\ \dot{\Psi}_s = k_5 \varepsilon_\Omega + k_6 \dot{\varepsilon}_\Omega \end{cases} \quad (20)$$

The dynamic evolution is:

$$T_s \dot{\Psi}_s + \Psi_s = 0 \quad (21)$$

The control laws are:

$$T_s \left(k_1 \varepsilon_\Omega + k_2 \dot{\varepsilon}_\Omega \right) + k_5 \varepsilon_\Omega + k_6 \int \varepsilon_\Omega dt = 0 \quad (22)$$

$$\begin{aligned} T_s \left(k_5 \left(\frac{T_{em}^* - C_r - f\Omega}{J} - \dot{\Omega} \right) + k_6 \varepsilon_\Omega \right) + k_5 \varepsilon_\Omega + k_6 \int \varepsilon_\Omega dt = 0 \end{aligned} \quad (23)$$

The solution is:

$$T_{em}^* = -\frac{k_6 J}{k_5} \varepsilon_\Omega - \frac{J}{T_s} \varepsilon_\Omega - \frac{k_6 J}{T_s k_5} \int \varepsilon_\Omega dt + C_r + f\Omega + J\dot{\Omega} \quad (24)$$

D. The load torque estimation

In this study, the estimation of the load torque for a PMSM is achieved using an observer-based approach derived from the motor's electromechanical model. The electromagnetic torque is computed from the dq-axis currents using the well-known torque equation, while the mechanical dynamics are utilized to relate the torque balance to the load torque. Specifically, the estimated load torque $\hat{C}_r$ is obtained by subtracting the inertial and frictional torque components from the electromagnetic torque, according to the expression:

$$\hat{C}_r = \frac{3}{2} p \Phi I_q - f \Omega - J \frac{d\Omega}{dt} \quad (25)$$

However, in many practical scenarios, such as sensorless control or variable load conditions, the exact value of the load torque may be uncertain or completely unavailable.

To address this limitation, synergetic control treats unknown load torque as an external disturbance using dynamic synergetic manifolds that compensate for uncertainties without direct torque feedback. This robust approach maintains system stability and performance despite load variations. Combined with observer-based estimation, it enables reliable, sensorless PMSM operation ideal for electric vehicles and industrial applications facing disturbances and parameter uncertainties.

E. Space Vector Pulse Width Modulation SVPWM

The SVPWM is an advanced technique used to control three-phase voltage source inverters in applications such as electric motor drives. It operates by representing the three-

phase voltages as a single rotating vector in the $\alpha\beta$ (stationary two-axis) reference frame as shown in figure (2). The method divides the space vector plane into six sectors and approximates the desired reference voltage vector by time-weighted combinations of the nearest two active vectors and the zero vectors. SVPWM maximizes the DC bus utilization, reduces harmonic distortion, and provides smoother voltage output compared to traditional sinusoidal PWM. This results in improved performance, efficiency, and torque characteristics in AC motor control systems [11].

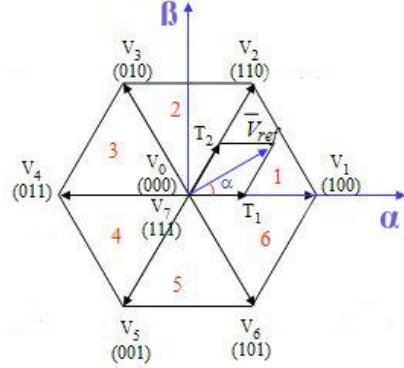


Fig. 2. SVPWM vectors.

The ultimate objective is to achieve robust speed control of the PMSM through synergetic control, incorporating SVPWM and a load torque estimator, as illustrated in Figure (3).

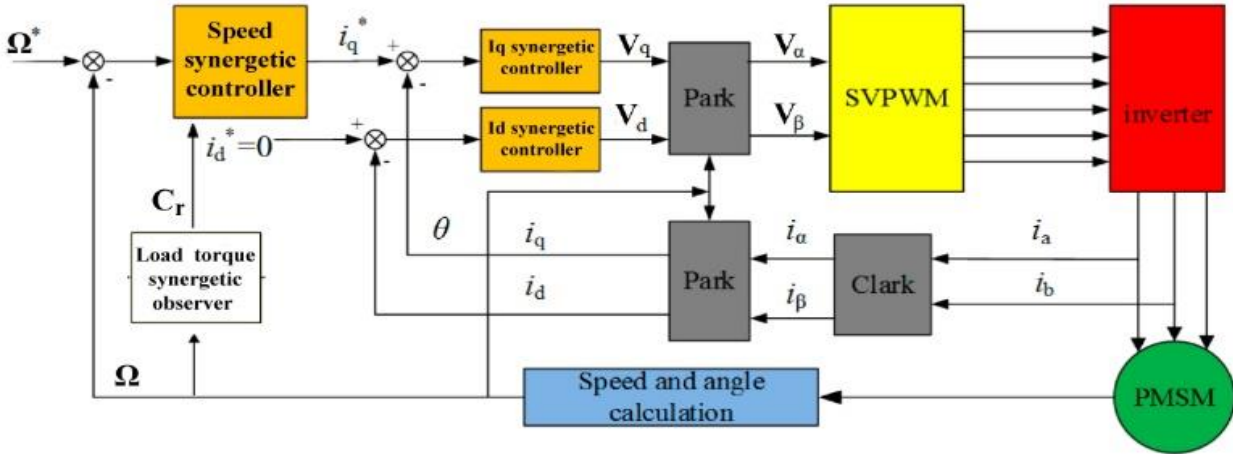


Fig. 3. The proposed control method.

IV. SIMULATIONS AND DISCUSSION

The simulation aims to demonstrate the effectiveness and robustness of the synergetic control strategy for PMSM through three stages. The first stage tests basic speed and I_d current regulation under constant load torque with step changes in reference values. The second stage introduces a varying load torque estimated by an estimator, assessing its accuracy and impact on control performance. The final stage

evaluates the system under dynamic speed profiles simulating automotive drive cycles, with zero I_d reference to reduce losses. These steps validate the controller's adaptability, precision, and energy efficiency for electric drive applications.

A. Synergetic control of PMSM under constant load torque $C_r = 2 \text{ N.m}$

The simulation results are illustrated in the next figures.

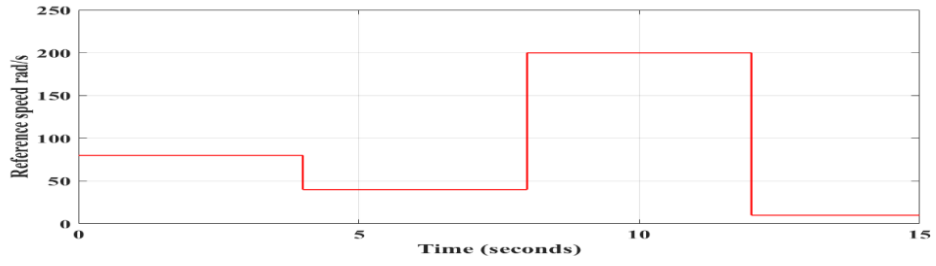


Fig. 4. Reference speed.

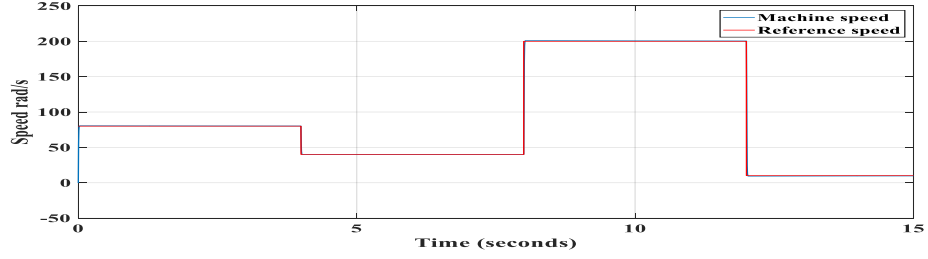


Fig. 5. Comparison of reference and machine speed.

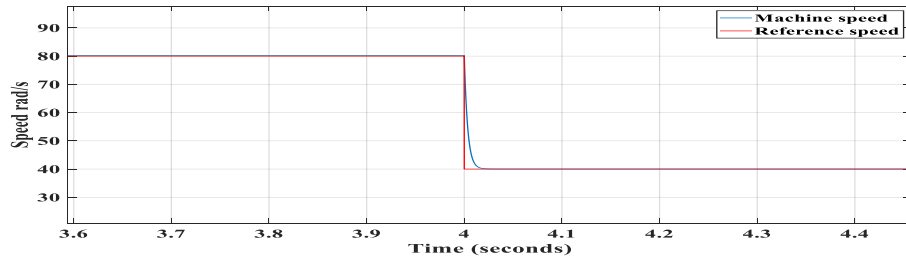


Fig. 6. Zoom of the previous figure ($3.6 \text{ s} < t < 4.5 \text{ s}$).

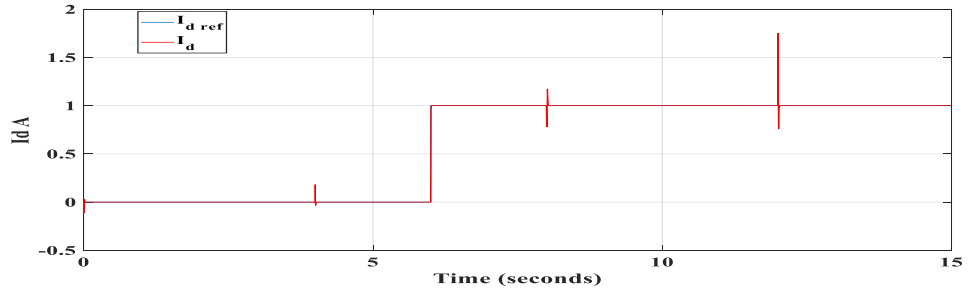


Fig. 7. I_d current with its reference.

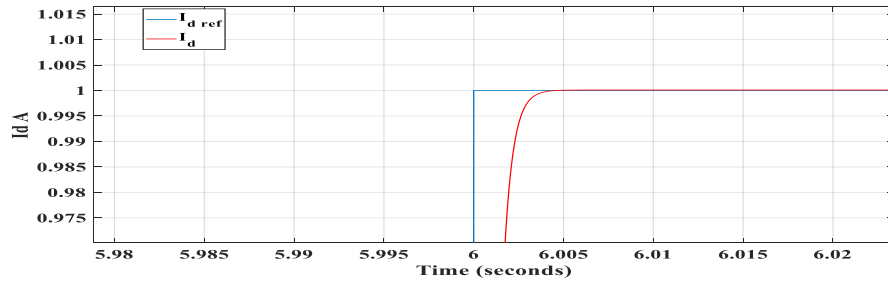


Fig. 8. Zoom of the previous figure ($5.98 \text{ s} < t < 6.025 \text{ s}$).

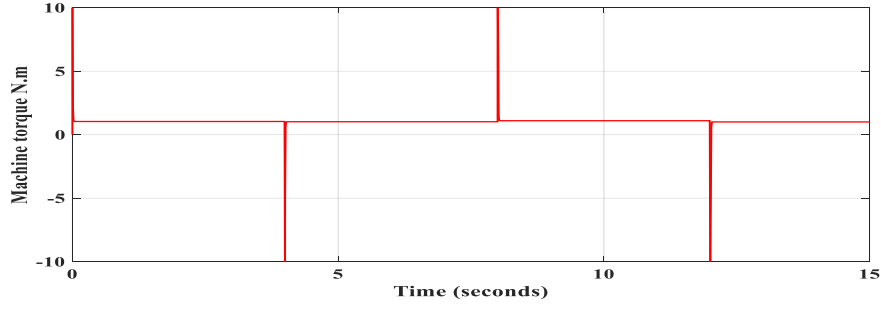


Fig. 9. Machine electromagnetic torque.

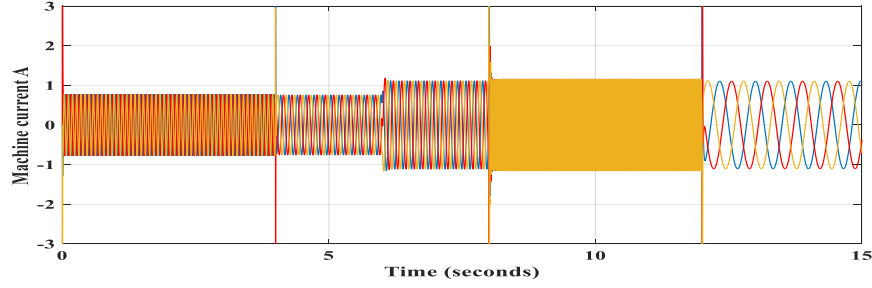


Fig. 10. Machine current.

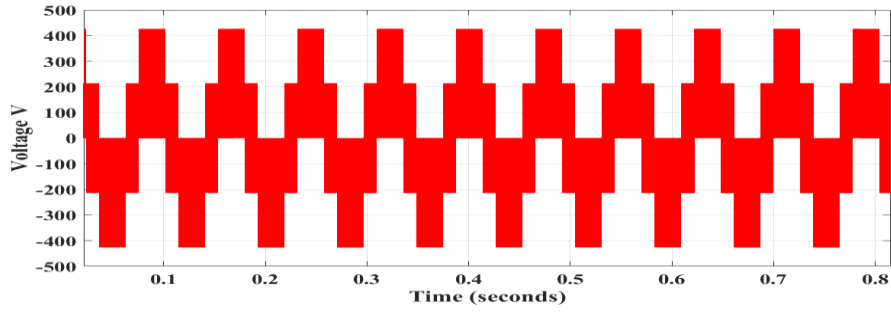


Fig. 11. Machine voltages (10 periods).

The simulation results confirm the effectiveness of the proposed synergetic control in regulating speed and I_d . Key findings include smooth and accurate speed tracking with fast response and no overshoot or chattering Figures (5) and (6), precise torque tracking under large steps, accurate d-axis current control with minimal steady-state error, stable sinusoidal stator currents, and high machine voltage achieved

via SVPWM. These outcomes highlight the controller's suitability for high-performance electric drive applications facing abrupt load and speed changes.

B. Load torque estimation

Now the load torque is changing dynamically to evaluate properly the estimator.

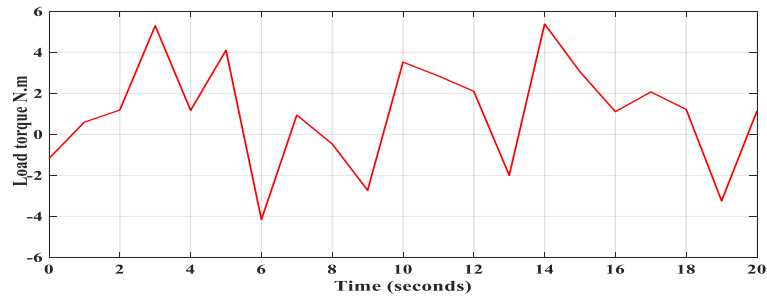


Fig. 12. Actual load torque.

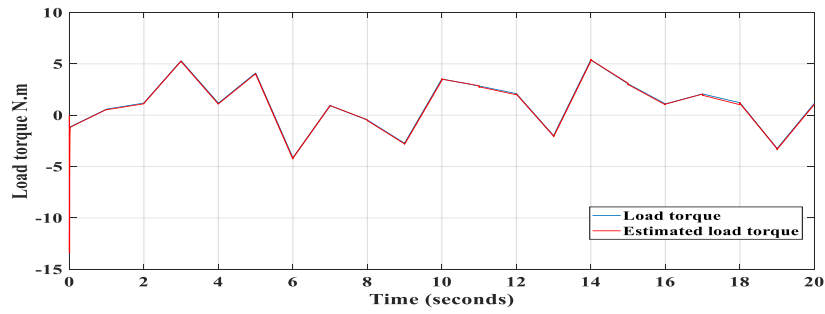
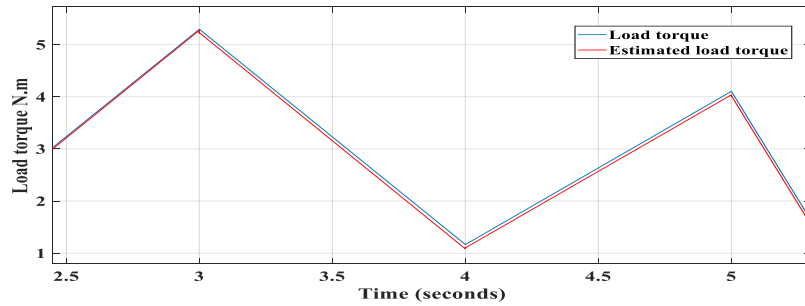


Fig. 13. Comparison of the actual and estimated load torque.


 Fig. 14. Zoom of the previous figure ($2.5 \text{ s} < t < 6 \text{ s}$).

The estimated load torque closely follows the actual load torque with very high accuracy. Therefore, it can be relied upon to calculate the load torque based on the machine speed and the I_q current. Consequently, the mechanical load torque sensor can be eliminated.

Moreover, when using torque control (synchronous control), even in the presence of faults or uncertainties in the estimated values or even in the absence of load torque data

the control strategy can still effectively handle the situation by treating the load torque as a disturbing term, this will be demonstrated in the upcoming simulation.

C. Synergetic control of the PMSM under dynamic reference speed with and without using load torque estimation

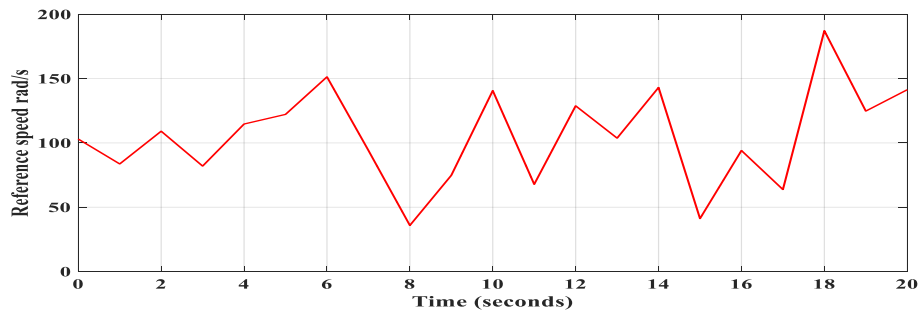


Fig. 15. Dynamic reference speed

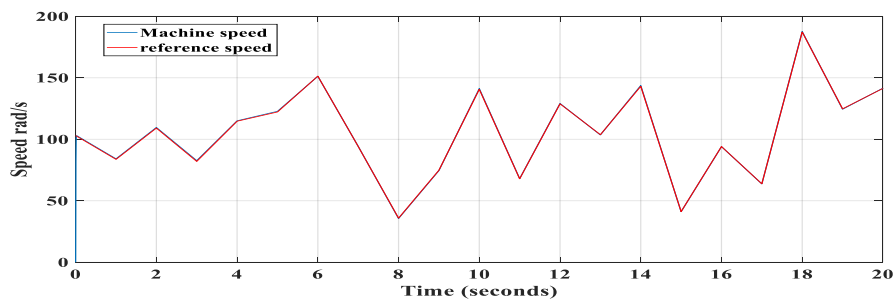


Fig. 16. Comparison of reference and machine speed.

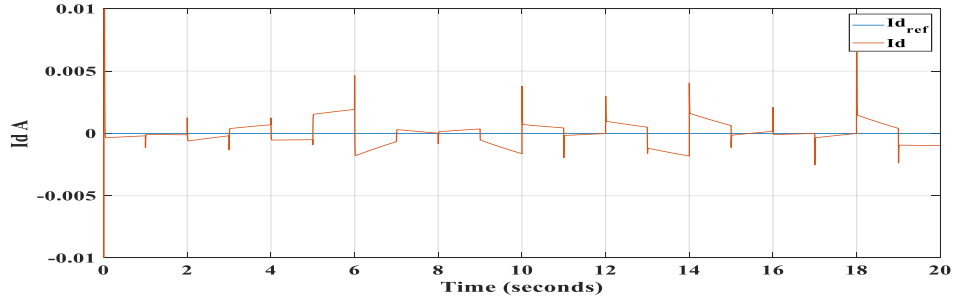


Fig. 17. I_d current with its reference.

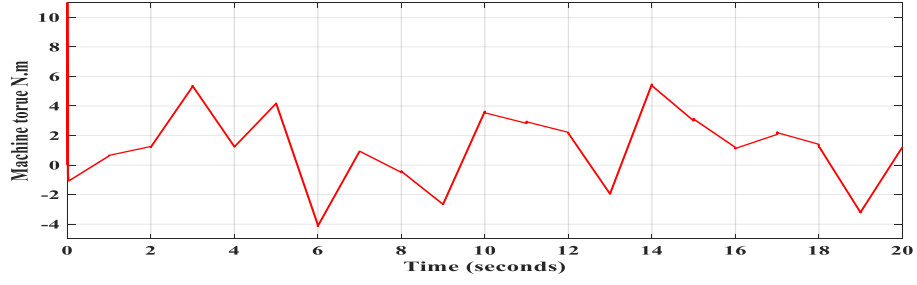


Fig. 18. Machine electromagnetic torque.

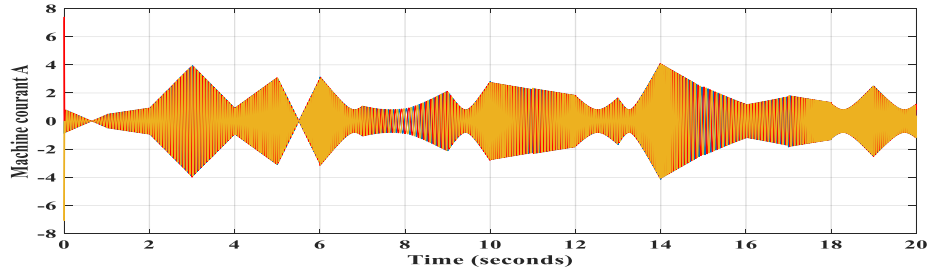


Fig. 19. Machine current.

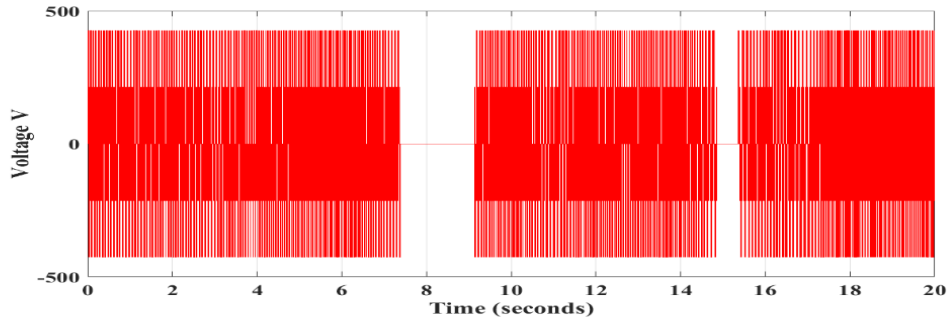


Fig. 20. Machine voltages.

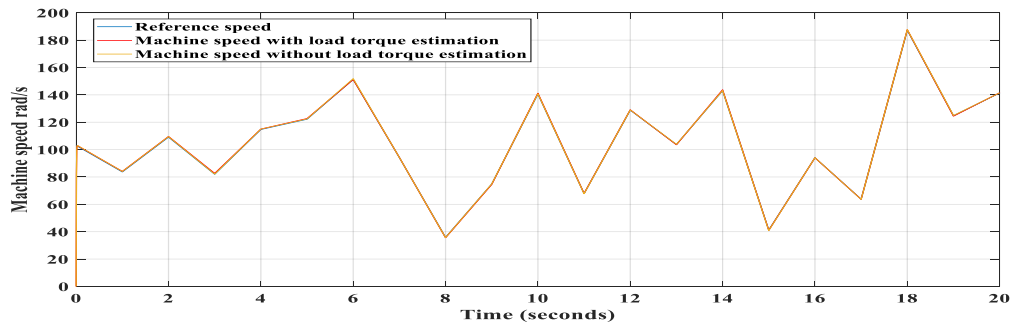
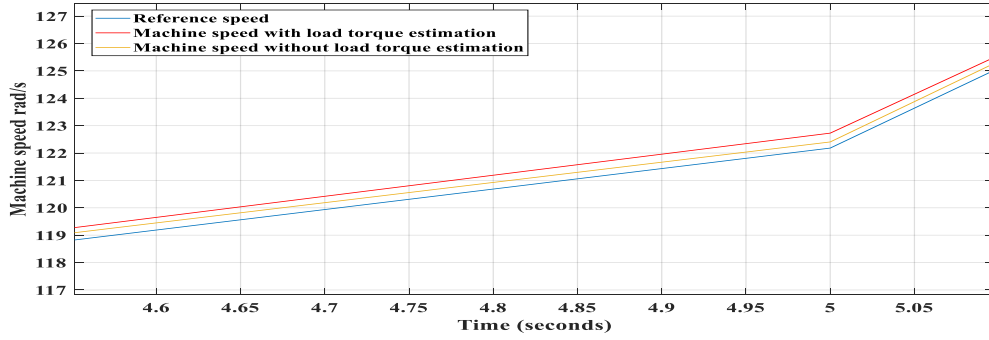


Fig. 21. Comparison of the speed control with using load torque estimation and without using it (compensated by the controller).

Fig. 22. Zoom of the previous figure ($4.55\text{ s} < t < 5.10\text{ s}$).

As in the previous two simulations, the synergetic control proved highly effective for controlling the PMSM. The machine speed accurately tracks the reference speed, even when the latter exhibits dynamic and rapid variations. The same applies to the load torque, which also varies dynamically, and to the i_d current, which tracks its reference precisely, very fast, without any instability overshoot or chattering phenomena.

In the last two figures, we present two different scenarios: in the first, the load torque is estimated using an estimator and provided as input to the speed synergetic controller; in the second, no torque estimation is used and the controller receives no load torque information. Despite this, the results remain very similar, with the machine speed closely following the reference. This confirms the robustness of the sensorless options control approach, which can effectively handle load torque as a disturbing term and incorporate its compensation within the control structure.

V. CONCLUSION

A synergetic control strategy combined with load torque estimation and SVPWM was successfully applied to a PMSM drive and validated via MATLAB/Simulink simulations. The system demonstrates fast, accurate tracking of speed and current references without overshoot or chattering. The SVPWM ensures smooth, balanced three-phase currents, while the torque estimator effectively compensates for load disturbances. These results confirm the proposed method's suitability for high-performance and robust electric drive applications.

ANNEX I

TABLE I. SIMULATION PARAMETERS

Type of parameters	designation	symbol	value
	Stator resistor	R_s	$3.45\ \Omega$
	Stator inductor	L_s	1.2 mH
	inertia	J	0.00154 N.m.s/rad
	Rotor permanent magnetic flux	ψ_{d0}	0.55 Wb
Synergetic control	T_d, T_q, T_s		5000
	K_1, K_3, K_5		0.05
	K_2, K_4, K_6		50

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