A New Synergetic Scheme Control of Electric Vehicle Propelled by Six-phase Permanent Magnet Synchronous Motor

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Abstract. *Electric Vehicles (EVs) are a promising alternative to conventional vehicles powered by internal combustion motors, offering the possibility of reducing CO_2, pollutants, and noise emissions. As known, the control of such an electric vehicle takes into account several phenomena governing its behavior, which is a complicated problem because of the non-linearities, unmeasured disturbance, and parameters uncertainty of this system. This problem is one of the important challenges facing controller designers. Various control techniques have been proposed to enhance Ev's performance. On this basis, in this research, a new synergetic scheme of electric vehicles propelled by Six-Phase Permanent Magnet Synchronous Motor (PMSMs) is developed. The synthesis of the proposed Synergetic Controller (SC) is based on the selection of four-manifolds of stator current of PMSMs. The SC provides fast response, asymptotic stability of the closed-loop system in wide range operating condition, and decrease the size of modeled system. Also, the principal feature of SC is that it supports parameters variation. Furthermore, to illustrate the improvements and the performances of the proposed controller, a comparison study between various nonlinear controllers such as Integral Action in Sliding Mode (ISMC), Super Twisting Sliding Mode (STSM), using a dynamic model of the lightweight vehicle under New European Driving Cycle (NEDC) was done. The obtained simulation results under several operating conditions show the efficiency and superiority of the proposed control compared with nonlinear controllers; also, it demonstrates the feasibility of the proposed control approach for real systems.*

Keywords

Electric Vehicle (EV), Integral action in Sliding Mode (ISMC), six-phase Permanent Magnet Synchronous Motor (PMSM), Super Twisting Sliding Mode (STSM), Synergetic Control (SC).

1. Introduction

With the rapid development of the economy and people's living standards, the total amount of vehicles is continuously increasing. Currently, the most common vehicle type is still the Conventional Vehicles (CVs) powered only by an Internal Combustion Engine (ICE). Hence, many social issues come, such as excessive consumption of oil resources and serious environmental pollution [1]. Nowadays, transport-related air pollution is a severe matter of concern, particularly in populated urban areas. In general, 25 % of worldwide CO_2 emanations are due to transportation. Besides CO_2, SO_x, and NO_x are also produced [2]. The above issues have aroused worldwide attention and brought great challenges to the automobile industry [3]. In this regard, significant use of electrified vehicles is needed to replace conventional internal combustion engine-based vehicles [4]. Recently, due to advantages of energy conservation and environmental protection, the new energy Electric Vehicles (EVs) have attracted lots of attention as green transportations [5] and [6], therefore become, electric vehicles have turned into the key authentic and logical research around the globe in the 21st century [4].

Driven EVs are powered by electric motors through transmission and differential gears depending on the transmission solution adopted [7] and [8]. The most widely used electric motor for traction application is the Permanent Magnet Synchronous Motors (PMSMs) [9]. This is because of the reality that a permanent magnet enables these motors to achieve high torque densities which make this machine very small [10] and [11]. High power density to volume ratio [12]. Also, it has the advantage of high efficiency, high torque density, and maintenance-free which are satisfied with EV rigorous requirements [13] and [14].

As the electric vehicle is a complex physical system composed of several subsystems, the modeling of each subsystem is a difficult task that requires extensive kinematic and dynamic studies of the vehicle. As well as the control of the electric vehicle by considering several phenomena governing its behavior such as nonlinearities, unmeasured disturbance, and parameters uncertainty of this system, calls for the use of powerful, insensitive, and robust control techniques. Therefore, several works have reported speed and position control with different driving and control techniques [15].

Vector control provides good dynamic performance for EVs in wide speed ranges and operates the motors with optimum stable torque. This technique is based on linear controllers such (Proportional Integral controller - PI, Proportional-Integral-Derivative controller - PID). The main advantages of linear controllers are simplicity of implementation and ease of synthesis. However, they have insufficient robustness against an unmeasured disturbance and parameters uncertainty of the controlled system.

One of the most popular techniques currently consists of the use of fuzzy logic for the control of nonlinear systems [16] and [17]. It is a type of automatic control based on heuristic reasoning that can approximate any nonlinear function with a given degree of precision. It does not require an exact mathematical model of the system or complex calculations. The design of the control is simple because it relies on the designer's understanding of the basic physical properties of the system and it is based on qualitative linguistic control rules. The choice of suitable fuzzy rules, membership functions, and their definitions in the universe of discourse invariable involve painstaking trial-error.

This has led to a strong interest in the synthesis of non-linear control techniques, robust and capable of overcoming this problem. Due to the feature of high accuracy, simplicity, and robustness, Sliding Mode Control (SMC) has become popular as an efficient and powerful strategy for controlling complex, nonlinear, and high order dynamic systems [18] and [19]. In relay or switched systems, there exists an undesired oscillation or fluctuation that has a low amplitude and high frequency, named chattering [20] and [21]. This harmful phenomenon is generated by the presence of unmodeled or parasitic dynamics (sensors, actuators, and data not included in the ideal model) and switching imperfections. Chattering is considered as an inherent feature of SMC systems and can be visualized as an infinite number of commutations infinite time interval about the sliding manifold, which causes degradation in the performance of the systems, e.g., high heat losses in electrical power circuits, high wear of mechanical parts and low control accuracy [19]. The chattering is a major obstacle in the implementation of SMC, which makes it the disadvantage of the control based on SMC [21]. This must be solved to improve the control performance.

Recent works are focused on eliminating and reducing the chattering effects. Among these works, the discontinuity term was replaced by sigmoid and smooth function in reference [22] and [24], but this solution leads to lower control accuracy and an increase in error. In references [23] and [25] Higher-Order Sliding Modes (HOSM) proposed, the control performances were enhanced, however, the select controller parameters remain the drawback of this technique. In reference [26] and [27] first order and second order SMC are proposed, the chattering phenomenon was minimized but a low pass filter provides unavoidable time delays in the controlled values which required a compensation technique [26] and [27]. In another study, the backstepping control was proposed, it presents a recursive procedure that combines between the choice of the Lyapunov function and the synthesis of the control law. This method transforms the control law synthesis problem for the overall system into a control sequence synthesis for small systems. By exploiting the flexibility of the latter, backstepping can respond to problems of regulation, tracking, and robustness with less restrictive conditions than other methods. Also, the integral sliding mode control was developed, its advantage is chattering reduction, however, may cause a big steady-state error.

Nevertheless, from the previous studies, it has been concluded that the methods don't allow total minimization of the chattering phenomenon. On this basis, a novel technique for adaptation of non-linear system is the synergetic control suggested by [28].

The synergistic control is similar to the sliding mode control technique by a common methodology, namely the imposition of a dynamic preconceived by the designer without the drawbacks of the first-mentioned will be used. Extensively in the work of this paper.

Synergetic control is a method of state-space formed based on modern mathematics and synergetic. Russian scholar Kolesnikov [29] put forward it in 2000 based on the synergetic theory, used to describe and analyze the highly nonlinear and complex system of multiple subsystems [30]. To achieve this goal, one has first to choose pertinent macro-variables and then elaborate manifolds that enable the desired performance to be reached. Macro-variables can be functions of two or more state variables [31]. First of all, it is well suited for digital control implementation, because it requires a fairly low bandwidth for the controller, a second advantage is that it operates at the constant switching frequency and it does not have the chattering problems of sliding-mode control so that it causes less power filtering problems [32], a third advantage is that it can help not only reduce the size of a modeled system but also ensure the stability of the power system in general, and ease of implementation in practice highlighted this relatively new control approach.

This research concerns the design of a new and robust synergetic scheme of electric vehicles propelled by Six-Phase Permanent Magnet Synchronous Motor.

The outline of this paper is as follows: the second part presents the modeling of six-phase PMSM. In the third part, nonlinear techniques such as sliding mode controller, sliding mode with integral action controller, and super twisting controller were developed. The fourth part details the design of the proposed controller and its application on six-phase PMSM. In the fifth part, the application of the proposed control scheme on the model of the real electric vehicle under the driving cycle profile is presented. A simulation survey, which illustrates the powerful performance of the suggested control scheme is presented in part sixth. In the last part, the Conclusion and perspectives are given.

2. System Description

In this section, the asymmetrical six-phase PMSM motor is fed by a dual three-phase Voltage Source Inverter (VSI) with a common DC power supply, as shown in Fig. 1 [33].

Six-phase machine drive system which has a permanent magnet synchronous motor whose stator winding is spatially shifted by 30 electrical degrees with isolated neutral points which are fed by two three-phase voltage source inverters, in this study, a six-phase PMSM with two three-phase winding is adopted where ABC winding is spatially 30 electrical degrees phase led to def winding. The phase voltage and flux linkage equations in the stationary reference frames for ABC winding and def winding of six phases PMSM are given [34]:

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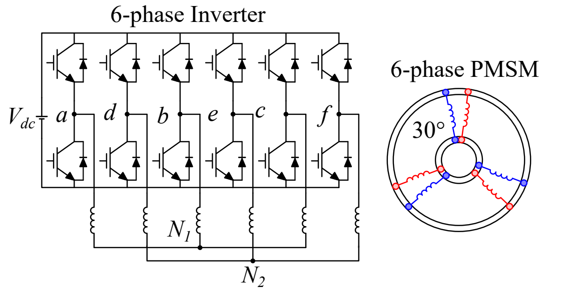


Fig. 1: The asymmetrical six-phase PMSM motor drive system.

$$
\begin{aligned}
V_{abc} &= R_s i_{abc} + \frac{d}{dt}\left(\varphi_{abc}\right), \\
V_{def} &= R_s i_{def} + \frac{d}{dt}\left(\varphi_{def}\right), \\
\varphi_{abc} &= L_{abc} i_{abc} + L_{abcdef} i_{abcdef} + \varphi_{fa\ bc}, \\
\varphi_{def} &= L_{def} i_{def} + L_{defa\ bc} i_{defa\ bc} + \varphi_{fdef}.
\end{aligned}
\tag{1}
$$

The machine model of a six-phase PMSM can be described in a synchronous rotating reference frame as follows [35] and [36]:

$$
\begin{aligned}
\frac{d}{dt} i_{d1} &= \frac{1}{L_{d1}}\left[-R_s i_{d1} + \omega_e L_{q1} i_{q1} + V_{d1}\right], \\
\frac{d}{dt} i_{d1} &= \frac{1}{L_{d1}}\left[-R_s i_{d1} - \omega_e\left(L_{d1} i_{d1} + \varphi_f\right) + V_{q1}\right], \\
\frac{d}{dt} i_{d1} &= \frac{1}{L_{d1}}\left[-R_s i_{d2} + \omega_e L_{q2} i_{q2} + V_{d2}\right], \\
\frac{d}{dt} i_{d1} &= \frac{1}{L_{d1}}\left[-R_s i_{d1} - \omega_e\left(L_{d1} i_{d1} + \varphi_f\right) + V_{q1}\right., \\
\omega_e &= \frac{P}{2}\omega_r.
\end{aligned}
\tag{2}
$$

Developed torque can be represented by the following equation:

$$
\begin{aligned}
T_e = 1.5&\left[\left(L_{d1} i_{d1} + \varphi_f\right) i_{q1} + \left(L_{d1} - L_{q1}\right) i_{d1} i_{q1}\right] + \\
&+ \left(L_{d1} i_{d1} + \varphi_f\right) i_{q1} + \left(L_{d1} - L_{q1}\right) i_{d1} i_{q1}.
\end{aligned}
\tag{3}
$$

Mechanical dynamic equation of six phases PMSM is:

$$
T_e = J\frac{d\omega_r}{dt} + B\omega_r + T_L. \tag{4}
$$

2.1. Decoupled Control

The aim of this control is to reach a simple model of the six-phase PMSM which accounts for the separate control of the main variables i and φ, as similar as the DC machine. The Six-phase PMSM works on the basic principle based on vector control in which both $i_{d1} = i_{d2} = 0$, we replaced the laws of decoupled control in Eq. (3); consequently, the equation of torque can be simplified as follow:

$$T_e = K_t\left(i_{q1+}i_{q2}\right) = K_t i_q^*, \tag{5}$$

where

$$K_t = \frac{3}{2}\frac{P}{2}\varphi_f. \tag{6}$$

3. Design of Nonlinear Controllers

In this section, we will briefly present the design of nonlinear controllers such as Sliding mode control with Integral action, and Super Twisting Sliding mode controller.

3.1. Sliding Mode Control with Integral Action

In EV conditions, the difference with traditional internal combustion vehicles is the torque and speed adjustable range. EV has a wider speed adjustable range that could improve the speed quickly and can work in the high rotate speed condition. With the above characteristics, EV needs a motor that has good speed and torque tracking performance [37].

To reduce the effect of chattering, we Propose to add an integral term in the sliding surface also the discontinuous function is replaced by a saturation function, which consists in determining a border band around the sliding surface, thus ensuring the smoothing of the control and maintaining the state of the system in this band. The control law then becomes [38] and [39]:

$$U_n = \begin{matrix} \dfrac{k}{\varepsilon_s}S(x) & \text{si } |S(x)| < \varepsilon_s \\ k\,\mathrm{Sign}(S(x)) & \text{si } |S(x)| > \varepsilon_s \end{matrix}. \tag{7}$$

In this control an integral term is added to the sliding surface, which means that the trajectories of the system begin on the same sliding surface, causing the reach phase to be eliminated [40] and [41], also to improve transient performance and steady-state accuracy, and to overcome drawbacks of the conventional SMC method [42]:

$$S = e + w\int e dt. \tag{8}$$

The error in the speed and current are defined as the difference between the actual value and the reference value as follow:

$$\begin{cases} S(x) = (\Omega - \Omega_{ref}) + w_1 \displaystyle\int (\Omega - \Omega_{ref})\,dt, \\ S(x) = (i_d - i_{dref}) + w_2 \displaystyle\int (i_d - i_{dref})\,dt, \\ S(x) = (i_q - i_{qref}) + w_3 \displaystyle\int (i_q - i_{qref})\,dt, \end{cases} \tag{9}$$

where w_1, w_2 and w_3 are positive constant.

3.2. Super Twisting Sliding Mode

This algorithm was proposed in [43], and was developed for the control system of relative degrtooto to eliminate the phenomenon of reluctance [44]. The state trajectory of the S and S phase plane is shown in Fig. 2 [45]. The super-twisting algorithm defines the control law, $u(t)$ as a combination of two terms. The first defines the discontinuous term time derivative while the second is a continuous function of the sliding variable. The STSM control laws are given as follows [46] and [47]:

$$u = -K_p|y|^{\mathrm{r}}\,\mathrm{sign}(y) + u_1, \tag{10}$$

$$\frac{du_1}{dt} = -k_i\,\mathrm{sign}(y), \tag{11}$$

where the K_p and K_i are positive gains, r is a positive constant, variable is $s = y$.

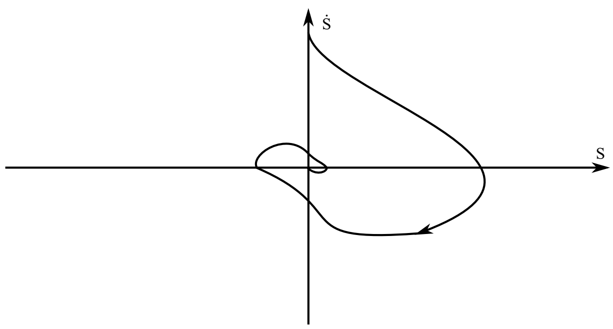


Fig. 2: Phase plane trajectory of the super-twisting algorithm.

The super-twisting algorithm does not need any information on the time derivative of the sliding variable. The choice of $r = 0.5$ assures that sliding order 2 is achieved [48].

3.3. Proposed Synergetic Controller For EV

Introduced in the last decades, synergetic control has rapidly gained acceptance not only by the robust control community but also by the industrial partners, as illustrated by its implementation in power electronics and its industrial application in battery charging [31] and [49]. The SACT is essentially a nonlinear control method using the directional self-organizing principle. Manifold is an important concept in the theory of synergetic control. It can reduce the system order by constructing a proper manifold. The control goal is not only to make the closed-loop systems satisfy specific transient characteristics but also to keep them asymptotically stable near the attractor. By establishing the mathematical model of the system and combining it with a synergetic control algorithm, the corresponding nonlinear system controller can be designed [50].

Let us consider an nth order nonlinear dynamic system described by Eq. (12):

$$\dot{x} = f(x, u, t). \tag{12}$$

In which x represents the state vector, u represents the control input vector and $f(x, u, t)$ represents a nonlinear function. The synergetic controller synthesis procedure is completely analytical, which consists of the following steps [51] and [52].

The first step in the design of a synergetic control resides in the training of macro-variables defined as a function of the state variables of the system in the form of an algebraic relationship between these variables that reflect the characteristics of the requirements of the design. From an initial state of any kind to a state of desired balance said: the manifold:

$$\Psi = \Psi(\mathrm{x}, \mathrm{t}). \tag{13}$$

With Ψ is a macro-variable and $\Psi(x, t)$ a function given by user. The control will force the system to operate on the manifold $\Psi = 0$. The designer can select the characteristics of this macro-variable according to the control specifications.

In the second step, the fixing of the dynamic evolution of macro-variable of the manifolds ($\Psi = 0$) by an equation, the functional equation, defined by the following general form [28]:

$$\begin{aligned} &T\dot{\Psi} + \Psi = 0, \\ &\text{with } T > 0. \end{aligned} \tag{14}$$

T: designates the designer chosen speed convergence to the desired manifold. Differentiating the macro-variable Eq. (13) along Eq. (12) leads to Eq. (15):

$$\dot{\Psi} J = \frac{d\Psi}{\mathrm{dx}} \dot{X}. \tag{15}$$

Combining equation Eq. (12), Eq. (14) and Eq. (15), we thus obtain:

$$T \frac{d\Psi}{\mathrm{dx}} f(x, n, t). \tag{16}$$

Synthesize the control law (evolution in time of the control output) according to Eq. (16) and the dynamic model of the system, leads to Eq. (17):

$$u = u(x, \Psi(x, t), T, t). \tag{17}$$

From the Eq. (15), it can be seen that the control depends not only of the state variables of the system, but also of the macro-variable and the control parameter T. In other words, the designer can choose the characteristics of the controller by selecting a suitable macro-variable and a time constant T.

The procedure summarized above can be easily implemented as a computer program for automatic synthesis of the control law. Moreover, the synergetic control system can be global stability, parameters insensitivity and noise suppression by suitable selection of macro-variables.

3.4. Synergetic Control Design For Six-Phase PMSM

The method described in the previous paragraph requires that we define the same number of macro-variables as control channels in the system. In other side we have four main control components in the model based on field-oriented control (V_{d1}, V_{q1}, V_{d2} and V_{q2}), therefore we submit four manifolds (Ψ_1, Ψ_2, Ψ_3 and Ψ_4) defined as follows:

$$\begin{gathered} \Psi_1 = i_{d1}, \\ \Psi_2 = k_1\left(\omega_r - \omega_r ref\right) + k_2 i_{q1} + k_3 \int \left(\omega_r - \omega_r ref\right) dt, \\ \Psi_3 = i_{d2}, \\ \Psi_4 = k_4\left(\omega_r - \omega_r ref\right) + k_5 i_{q2} + k_6 \int \left(\omega_r - \omega_{rref}\right) dt, \end{gathered} \tag{18}$$

where k_1, k_2, k_3, k_4, k_5 and k_6 are the controller parameters.

$$\begin{gathered} 0 = \mathrm{T}_1\left(l_{d1}\right) + i_{d1}, \\ 0 = \mathrm{T}_2\left(k_1\dot{\omega}_r + k_2 l_{q1} + k_3\varepsilon\right) + k_1\varepsilon + k_2 i_{q1} + k_3 \int \varepsilon dt, \\ 0 = \mathrm{T}_3\left(i_{d2}\right) + i_{d2}, \\ 0 = \mathrm{T}_4\left(k_4\dot{\omega}_r + k_5 l\dot{q}2 + k_6\varepsilon\right) + k_4\varepsilon + k_5 i_{q2} + k_6 \int \varepsilon dt, \end{gathered} \tag{19}$$

with $T_1 > 0$, $T_2 > 0$, $T_3 > 0$ and $T_4 > 0$.

Solving Eq. (19) above for V_{d1}, V_{q1}, V_{d2} and V_{q2} we get:

$$\begin{gathered}
V_{d1} = R_s i_{d1} - \omega_e L_{q1} i_{q1} - \frac{L_d}{T_1} i_{d1}, \\
V_{q1} = \frac{R_s}{L_q} i_{q1} + (L_d i_{d1} + \varphi_f) \frac{\omega_r}{L_q} - \frac{k_1}{k_2 J} (T_e - T_L - B\omega_r) - \frac{k_3}{k_2}\varepsilon - \frac{k_1}{T_2 k_2}\varepsilon - \frac{1}{T_2} i_{q1} - \frac{k_3}{T_2 k_2} \int \varepsilon dt, \\
V_{d2} = R_s i_{d2} - \omega_e L_{q1} i_{q2} - \frac{L_d}{T_3} i_{d2}, \\
V_{q2} = \frac{R_s}{L_q} i_{q2} + (L_{d1} i_{d2} + \varphi_f) \frac{\omega_r}{L_q} - \frac{k_4}{k_5 J} (T_e - T_L - B\omega_r) - \frac{k_6}{k_5}\varepsilon - \frac{k_4}{T_4 k_5}\varepsilon - \frac{1}{T_4} i_{q2} - \frac{k_6}{T_4 k_5} \int \varepsilon dt.
\end{gathered} \tag{20}$$

4. Application Model of EV

In this section, we present a real electric vehicle profile to obtain the speed and torque to be used as testing of the effectiveness, robustness and performances of the controllers.

4.1. Synergetic Control Design For Six-Phase PMSM

To evaluate the longitudinal dynamic behaviour of the vehicle, it is implemented the equations proposed by Gillespie [53] for a conventional vehicle propelled by means of an engine/powertrain system with some available transmission ratio. Nevertheless, the equations are adapted for an EV configuration. The model is based on the movement resistance forces as the rolling and climbing resistance, aerodynamic drag and vehicle acceleration [54]. The Fig. 3 Shows the forces applied to the vehicle are:

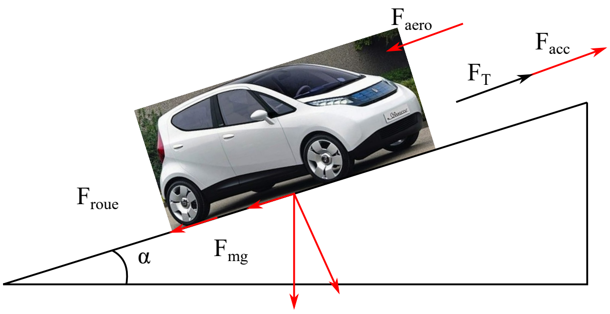


Fig. 3: Forces applied on electric vehicle.

The forces acting on the vehicle itself are rolling resistance of the tires, aerodynamic drag, and gradient force [55].

$$\begin{cases} F_{resistant} = M_{VE} \cdot g \cdot (C_0 + C_1) \cdot V_{VE}^2, \\ F_{grad} = M_{VE} \cdot g \cdot \sin\alpha, \\ F_{aero} = 0.5 \cdot \rho \cdot C_{\mathrm{X} \cdot \mathrm{V}_{\mathrm{VE}}^2}. \end{cases} \tag{21}$$

And the force of acceleration is giving by:

$$\mathrm{F}_{\mathrm{acc}} = \mathrm{M}_{\mathrm{VE}} \cdot \mathrm{r} \cdot \frac{\mathrm{d}\Omega_{\mathrm{roue}}}{\mathrm{dt}}. \tag{22}$$

The power of electric vehicle is gives as follow:

$$P_{VE} = F_T V_{VE}. \tag{23}$$

$$\begin{gathered} P_{VE} = (M_{VE} \cdot g \cdot (C_0 + C_1) \cdot V_{VE}^2 + \\ + M_{VE} \cdot g \cdot \sin\alpha + 0.5 \cdot \rho \cdot C_x \cdot V_{VE}^2 + \\ + M_{VE} \cdot r \cdot \frac{d\Omega_{\mathrm{roue}}}{dt}) V_{VE}. \end{gathered} \tag{24}$$

The parameters of the EV are shown in the Tab. 1.

Tab. 1: Parameters of EV.

Parameter EV	Quantity
EV weight	820 kg
Force of gravity	$9.81\ \mathrm{m \cdot s^{-2}}$
Radius of the wheel	0.33 m
Density of the air	$1.2\ \mathrm{kg \cdot m^{-3}}$
Front surface (S)	2.75
Coefficient of air penetration($\mathrm{C_x}$)	0.3
Coefficient of rolling resistance in the dynamic state ($\mathrm{C_0}$)	$1.6 \cdot 10^{-6}$
Coefficient of rolling resistance to static state ($\mathrm{C_1}$)	0.008
Slope of the road (α)	2.5 %

4.2. NEDC Drive Cycle

The driving profiles depend on a considerable parameter set such as traffic condition, topography and characteristics of the driver [56]. In this work the EV performance is evaluated under the NEDC driving cycle presented in Fig. 4.

NEDC consists of four repeats of a low-speed urban cycle plus one cycle of highway driving. NEDC is obviously a highly-stylized cycle, incorporates constant decelerations, accelerations and speed periods [41]. In our study we use low speed urban cycle (200 s).

The Fig. 5 represented the global synoptic diagram of proposed synergetic control scheme for EV propelled by PMSM.

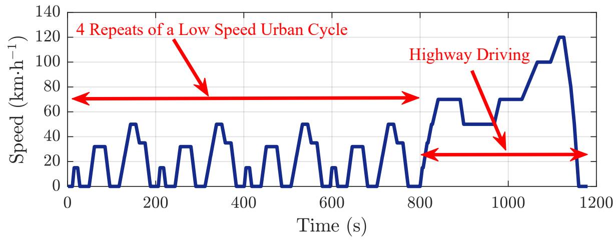


Fig. 4: NEDC Driving Cycle.

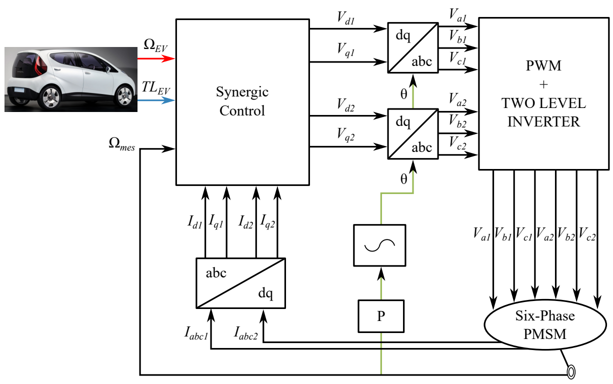


Fig. 5: Synoptic diagram of proposed synergetic control scheme for EV propelled by PMSM.

5. Simulation Results and Discussion

In order to illustrate the benefits provided by the suggested controllers, several simulation tests have been carried out for several of operating conditions. The parameters of the test motor are giving in App. B.

To appreciate the robustness of suggested controllers, various simulation tests were carried out such as variation of speed consign, and variation of load torque in fact, the reference speed is set to 50 rad·s^{-1} at $t = 0$, and 100 rad·s^{-1} at $t = 0.25$ s, also for the load torque is 30 N·m at $t = 0$ s and changed to 120 N·m at $t = 0.4$ s.

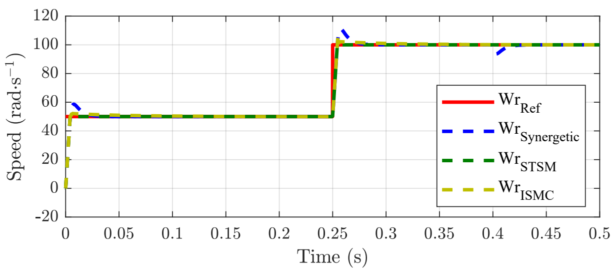


Fig. 6: Performance of proposed scheme control with Integral action in SMC & super twisting SM and synergetic controller.

In the first part, in order to show the dynamic and static performances of suggested control, we present the performance of different controllers ISMC, STSM and synergetic control without EV.

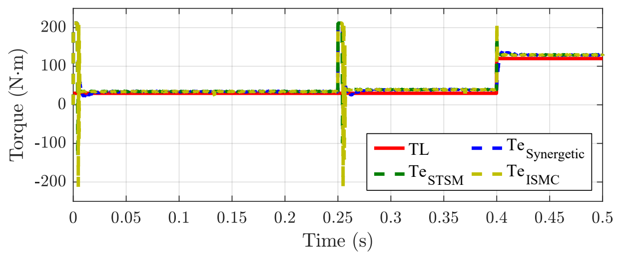
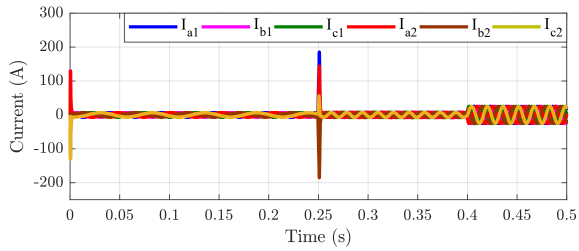
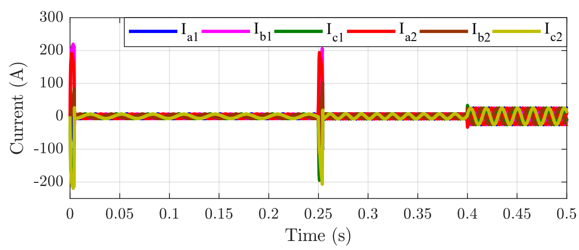


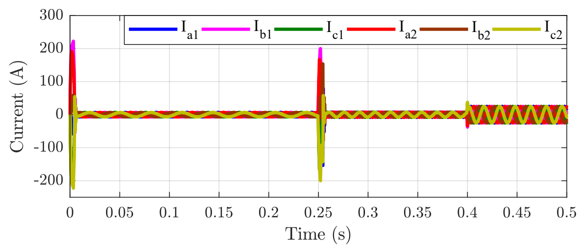
Fig. 7: Performance of proposed scheme control with Integral action in SMC & super twisting SM and synergetic controller.



(a) Synergetic control.



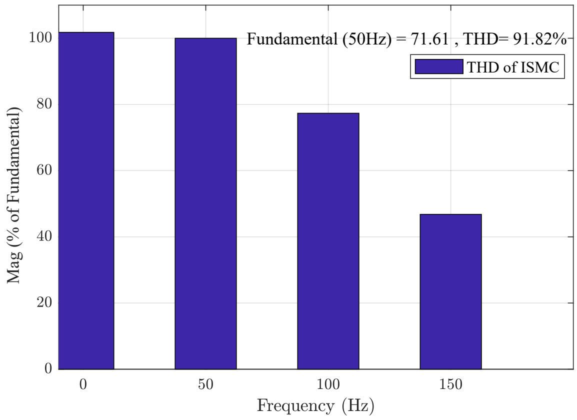
(b) STSM control.



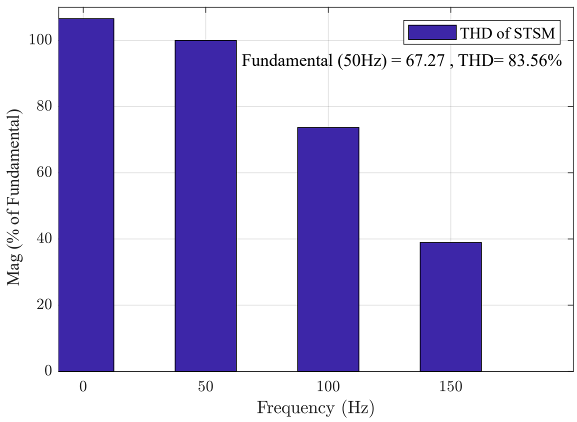
(c) ISCM control.

Fig. 8: Performance of stator current.

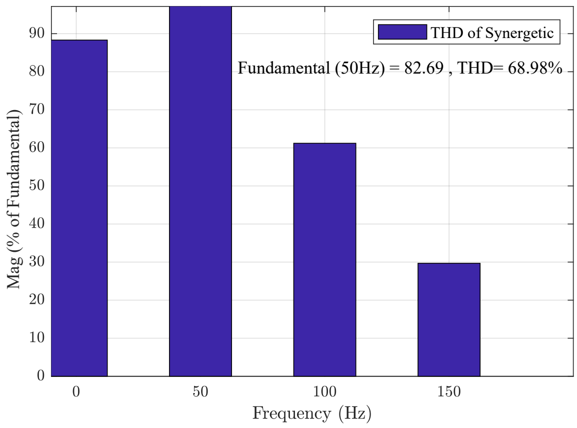
From the obtained results in Fig. 6, Fig. 7 and Fig. 8. One can notice that the Synergetic control and STSM has been verified theirs strong robustness and high performance compared with ISMC control in term of speed and torque and currents. In fact, the three controllers ISMC, STSM and Synergetic are fast in dynamic response and rejects also the ISMC has presented an overshoot measurable compared to other controllers. In addition, the synergetic controller proves good performance in the rejection of load torque, and the minimization of torque ripple and accuracy according to FFT analysis which showing in Tab. 2 and Fig. 9.



(a) ISMC.



(b) STSM.



(c) Synergetic control.

Fig. 9: FFT analysis of Electromagnetic torque for different controllers.

Tab. 2: THD analysis results for different controllers proposed.

	ISMC	STSM	SC
Torque	91.81 %	83.56 %	68.98 %
Quadrature current	91.84 %	83.55 %	68.73 %

Table 3 shows the comparative analyses between the proposed speed synergetic controller with ISMC, STSM controllers, we can comment on the following points:

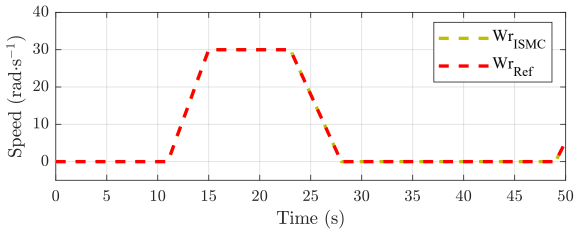
1. The proposed controller is faster response time and very small tracking error compared to the STSM, and keep it advantage even in reversal speed.

2. Torque ripple is the lowest in the Synergetic control compared to both ISMC and STSM.

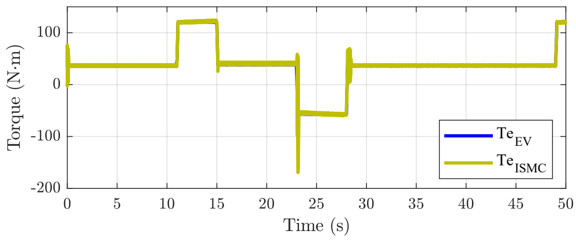
3. Faster torque response time when to load application. Moreover, the overshoot in current at this time is weak in the Synergetic control.

Tab. 3: Comparative analysis of the various controllers.

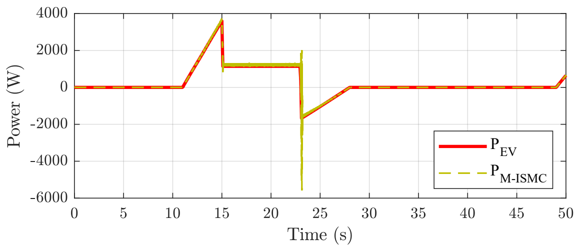
Controller	Response time	Torque ripple	Reversal of the speed	Overshoot current
ISMC	2.67 ms	5.9 %	5.335 ms	33.65 A
STSM	3.1 ms	4.32 %	6.038 ms	28.93 A
SYN	2.7 ms	3.1 %	5.33 ms	27 A



(a) Speed response.



(b) Torque response.

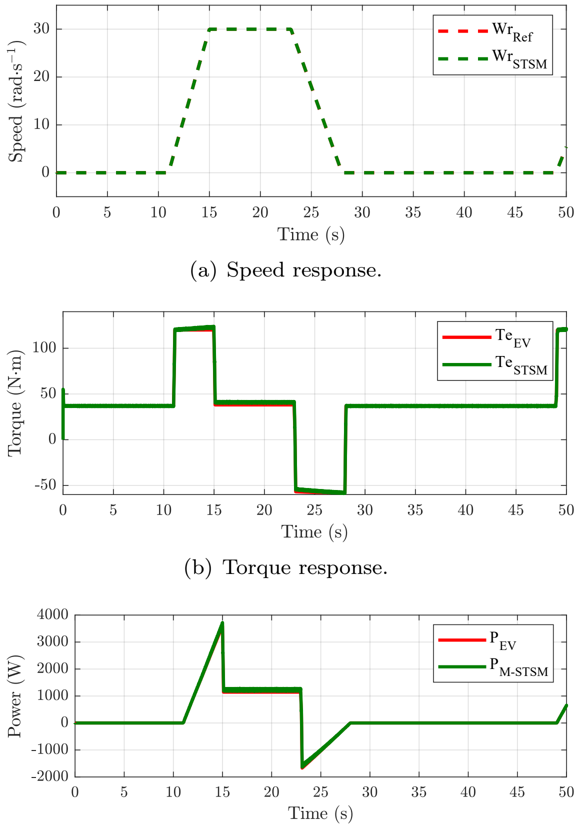


(c) Power response.

Fig. 10: Performance of EV with ISMC.

In the Second part, to confirm the effectiveness of the proposed controllers and check their performance and robustness, we tested the presented controllers under a real model of lightweight electric vehicle under NEDC driving cycle.

From the obtained Fig. 10, Fig. 11 and Fig. 12, it's obviously one can observe that the quantities developed by the PMSM (torque and speed) follow the instructions of the commands from the driving cycle initially, in fact, the ISMC shows a measurable ripples and errors in acceleration and deceleration phase which limit both dynamic performance and accuracy of system. For STSM, one can see a considerable error and ripple in the acceleration and decelerations phases which can limit the dynamic performance but remain better than the ISMC. Moreover, the synergetic control follows the instructions of the commands very well in acceleration and deceleration phases and less error and low ripple compared to ISMC and STSM as presented in Fig. 12, this performance improvements the dynamic response and the accuracy and it directly affect the comfort of the vehicle.



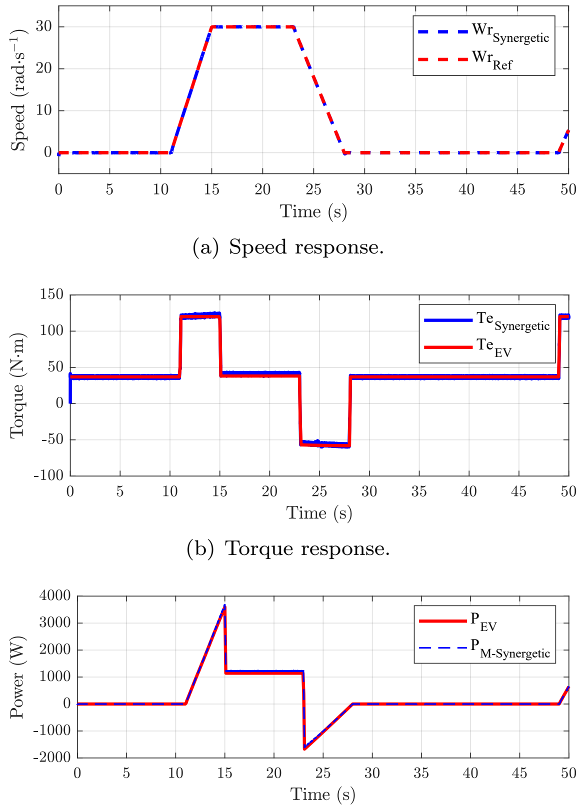
(a) Speed response.

(b) Torque response.

(c) Power response.

Fig. 11: Performance of EV with super twisting SM.

The comparisons of electromagnetic torque THD between different nonlinear controllers and proposed drive system are given in Fig. 9. In the ISMC, the torque THD are up around 91.81 %, and 83.56 % for STSMC. However, the proposed scheme control reduces very well the electromagnetic torque THD to around 68.98 %, and minimize the chattering phenomena.



(a) Speed response.

(b) Torque response.

(c) Power response.

Fig. 12: Performance of EV with synergetic controller.

6. Conclusion

A novel efficient synergetic scheme control of electric vehicle propelled by six-phase permanent magnet synchronous motor was developed. The special merit of this suggested controller is that does not require the linearization of the model of controlled system, and it can be easily implemented. In addition, it is well suited for digital control implementation or practice because it requires a low bandwidth for the controller. Another advantage is that it operates at constant switching frequency and it does not have the chattering problems of sliding-mode control, so that it causes less power filtering problems.

Based on this work, we have integrated novel model synergetic control of EV propelled by PMSMs to minimize the chattering phenomenon and to enhance the robustness system control against uncertainty parameters. From simulation results, it can be concluded: That synergetic control can increase the robustness of the scheme control. In fact, the synergistic controller proves high dynamic and static performance in terms load torque rejection, and reduction of the vibration torque caused by chattering phenomenon. Besides, the obtained results show superior performance of the proposed algorithm as conjunction with previous nonlinear techniques in way of minimization of chattering phenomenon and good robustness.

Our future work includes:

- To complete the chain of EV, we are working to associate a modern battery which ensure a long autonomy like NMC 21700, and develop new control strategies of DC-DC converter.
- On other hand, to reduce the cost and complexity of presented drive system, we are working also to estimate some state of control system such as load torque, electromagnetic torque, speed by integration of an Algebraic observer as robust estimation method.
- Implementation of proposed control scheme in real system.

Author Contributions

K.K. encouraged M.K.B.B. to realization about synergetic control in electric vehicle applications by using dual PMSM. Starting from the basic of synergetic control theory and compared this control with others robust controls. K.K. and M.K.B.B. fictive the original idea, the design and the conception ideas of the work offered, M.K.B.B. developed the synthesis of synergetic control which is based on the select of four manifolds of stator current of PMSMs. The SC provides fast response, asymptotic stability of the closed-loop system in wide range operating condition, and decrease the size of modeled system. Furthermore, to illustrate the improvements and the performances of the proposed controller, both authors used a dynamic model of lightweight vehicle under NEDC driving cycle, M.K.B.B. carried out the simulations of this technique. He wrote the manuscript with the support of K.K., they analyzed the results and provided a commented of the results obtained. The design and implement the research, Contribution to the discuss, analysis of the results presented and the writing the final version of this manuscript has been done by all authors.

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Appendix A Nomenclature

- V_{ds1}, V_{qs1}, V_{ds2}, V_{qs2} = stator voltage in the dq frame;
- i_{ds1}, i_{ds2}, i_{qs1}, i_{qs2} = stator current components;
- φ_{abc}, φ_{def} = stator flux components;
- φ_f = magnet flux components;
- R_s = per phase stators resistances;
- L_{d1}, L_{d2}, L_{q1}, L_{q2} = per phase stators leakages inductances in dq frame;
- J = inertial moment;
- B = viscous friction coefficient;
- Ω_e = stator pulsation;
- Ω_r = rotor angular speed;
- T_{em} = electromagnetic torque;
- T_L = load torque;
- P_n = nominal power;
- SC = Synergitic Control;
- $STSM$ = Super Twisting Sliding Mode;
- $ISMC$ = Integral Action Sliding Mode;
- S = Sliding mode surface100;
- k = sliding mode gain;
- w_i $(i = 1, 2, 3)$ = integral action in sliding mode gain;
- k_p, k_i = STSM gain;
- L_r = per phase rotor leakage inductances;
- K_t = mechanical constant coefficient;
- Ω_s = stator pulsation;
- Ψ_i $(i = 1, \ldots, 4)$ = manifolds;
- K_i $(i = 1, \ldots, 6)$ = synergetic control gain;
- T_i $(i = 1, \ldots, 4)$ = time constant of synergetic control;
- $NEDC$ = New European Drive Cycle;
- PVE = Electric Vehicle Power;
- FT = Force Total applied on EV;
- VVE = speed of EV;
- MVE = weight of EV;

Appendix B AC Driver Parameters

- $R_S = 1.9$ Ω;
- $L_{d1} = L_{d2} = 8.35 \cdot 10^{-4}$ H;
- $L_{q1} = L_{q2} = L_{d1}$;
- $P = 4$;
- $J = 0.015$ KG·M^2;
- $B = 0.0954$ N·M·S·RD^{-1};
- $\varphi_f = 0.353$ Wb;
- $VDC = 800$ V;
- $Pn = 12$ KW;
- $Te = 120$ N·m;
- $n_N = 100$ rad·s^{-1};