EXPONENTIAL SLIDING MODE CONTROL OF ELECTRICAL VEHICLE WITH LOAD OBSERVER FOR DISTURBANCE COMPENSATION

Abdelmadjid Guerouad, Mohamed Bourahla, Mustapha Benghanem and
Abdelhaq Amar Bensaber

*Applied Power Electronics Laboratory -LEPA- University of sciences and the
technology of Oran -Mohamed Boudiaf - (USTO-MB) BP 1505 EL M'naouer
Oran, Algeria*

abdelmadjid.guerouad@univ-usto.dz, bourahmed.usto.dz@gmail.com,
mbenghanem69@yahoo.fr, abs.abdelhak@gmail.com

Abstract— Electric vehicle components work as nonlinear systems where electromechanical parameters change considerably, thus, nonlinear control is an interesting solution such as sliding mode control (SMC), which provide outstanding results, and yet it suffers from the chattering phenomena. In this paper, the speed control of permanent magnet synchronous motor (PMSM) applied for electrical vehicle traction is achieved, the proposed control method merges the flexibility of the linear extended state observer (LESO) and SMC robustness to contribute with some important characteristics such as chatter-free performance, heftiness, robustness and secure power system operations. Simulation results obtained by Simulink/Matlab of the system proven the ability of this last one in reducing the chattering.

Keywords— Permanent magnet synchronous motor (PMSM), Sliding mode control (SMC), Exponential reaching law (ERL), Linear extended state observer (LESO)

1. INTRODUCTION

Recently the demands on the electrical vehicles (EVs) has increased due to the expanding awareness of the global warming problem related to the fossil fuel consumption [1], but it is still less common than the conventional vehicles [2], which implies that the development of the EV is critical and at any level, especially in the electrical machine drive because it is one of the most essential sections of the EV's technologies [3].

The Permanent magnet synchronous motors PMSM is one of the most suitable machines for the EVs due to the many advantageous that it is present, particularly the high-power density, which is an important factor in the EV design [4]. Generally, the control of the speed of the PMSMs is carried out via the proportional integral (PI) controller, this controller assures an optimal performance, and doesn't require advanced calculation speed. But in the extreme conditions such as high temperature and high speed, the machine suffer from certain uncertainties and parametric variations, that leads to the variation of the mathematical model, under these conditions the performance of the PI decrease, because it can't adapt to these drawbacks [5].

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Meanwhile, the application of the nonlinear control is increasing, and it is involving several domains, because of the development of the power electronics and the microprocessors particularly with the digital signal processors (DSPs), furthermore, the nonlinear control algorithms provide a respectable performance and robustness against the disturbances. Likewise, the PMSM control has benefited from this non-linear control algorithms, and an advantageous work has been done through the application of these algorithms, such in [4] where a backstepping control is applied for PMSM speed control, and an adaptive control is tested in [6], and a disturbance observer-based control is adapted in [7].

The sliding mode control (SMC) is a powerful nonlinear control algorithm and has outstanding results, due to its robustness against the internal parameters variation and the external disturbances [8], the SMC has been applied successfully in the work of [9] and in [10]. But to profit from the disturbance rejection feature of the SMC, a control gain should be chosen high enough to contain the error in the sliding surface, which will engender the chattering phenomena by exciting a high frequency dynamic, to solve this problem, several efforts have been done, such as in [11] where a high order sliding mode controller is applied, this technique has proven a good efficiency but it demand a higher calculation speed, another technique is used in [12]–[13], where a novel exponential reaching law has been selected instead of the conventional control gain, the application of this technique has shown the ability of this technique to eliminate the chattering after a certain reaching time that depends on the value of the error. However, in the both previous papers the sliding mode control with the exponential reaching law (SMCERL) produces more satisfying results when associated with the adequate observer.

This paper applies a novel combination between the aforementioned SMCERL, with the linear extended state observer LESO, which is a simple and an impressive estimator that is commonly used in the estimation of the lumped disturbances, which is basically the internal dynamics of the system and the external disturbances, and does not include the identified linear system dynamics [14], previous works validate its precise observation of the disturbances with a faster converging estimation, such in [15] where it was combined with an integral sliding mode controller, and in the work of [4]–[6], it was used for the online observation of the unknown load torque and friction effects.

The first section of this paper is dedicated for the adequate mathematical model of the PMSM, the second section deals with the proposed controller, it is divided in two parts, the first one illustrates SMCERL, then the LESO estimator is presented and adapted with the SMCERL for the feed-forward compensation in the second part, the simulation results are presented in the fourth section, followed by concluding remarks in section five.

2. MATHEMATICAL MODEL OF THE PMSM

The mathematical attitude of the surface-mounted PMSM model where ($L_d = L_q = L$), and in the well-known $d-q$ reference through the park transformation is described in the following equations [7]:

$$\frac{di_d}{dt} = -\frac{R}{L}i_d - p\omega i_q + \frac{1}{L}v_d \quad (1)$$

$$\frac{di_q}{dt} = -\frac{R}{L}i_q - p\omega i_d - p\frac{1}{L}\phi_f\omega + \frac{1}{L}v_q \quad (2)$$

$$\frac{d^2\theta}{dt^2} = \frac{d\omega}{dt} = \frac{3p\phi_f}{2J}i_q - \frac{1}{J}(T_L + B\omega) \quad (3)$$

Where i_d , i_q and v_d , v_q describes the stator currents and voltages in the $d-q$ reference, L is the stator inductance, ω and θ are the rotor angular velocity and

position respectively, p is the number of pole pair, R represents the stator resistance, ϕ_f is the permanent magnet flux, and J is the moment of inertia, B refers to the viscous friction coefficient, and T_L is the load torque.

3. THE SLIDING MODE CONTROL ALGORITHM

3.1. THE SMC WITH THE EXPONENTIAL REACHING LAW

The SMC is considered as a Variable Structure Control (VSC), and it is based on the Lyapunov theory [16]. If the controlled system is approved to be controllable and observable, the SMC can be established through three steps. First a sliding surface has to be chosen, then the existence of a reaching law has to be verified, and finally the control law is designed in such a way that it guarantee the convergence of the system's trajectory toward the sliding surface [17].

The purpose of this method is to control the PMSM speed ω , and the sliding surface is chosen as the speed error e_ω of the system:

$$S = e_\omega = \omega_{ref} - \omega \quad (4)$$

$$\dot{S} = \dot{e}_\omega = \frac{d\omega_{ref}}{dt} - \frac{d\omega}{dt} \quad (5)$$

By replacing the derivative of the motor speed (3), in (5):

$$\dot{S} = \dot{e}_\omega = \frac{d\omega_{ref}}{dt} - \frac{3p\phi_f}{2J} i_q - \frac{1}{J} (T_L + B\omega) \quad (6)$$

The control law should guarantee the stability of the system, and according to the SMC methodology, it must ensure the convergence of the system toward the sliding surface, therefore the switching function is usually adopted with the equal reaching law as follows:

$$S = -k \operatorname{sgn}(S) \quad (7)$$

Here k is the SMC control gain, it is proportional to the chattering level, and to the reaching time value, so in order to reduce the chattering level, the reaching time will also be reduced, thus the exponential reaching law is adopted, where it adapts to the variation of the system state and the sliding surface, in the control gain as follows:

$$\dot{S} = -eq(x_1, S) \operatorname{sgn}(S) \quad (8)$$

Where:

$$eq(x_1, S) = \frac{k}{\xi + \left(1 + \frac{1}{|x_1|} - \xi\right) e^{-\delta|S|}} \quad (9)$$

Considering that x_1 is the system state, and $k > 0$, $\delta > 0$, and $0 < \xi < 1$

$$\begin{cases} \lim_{|S| \rightarrow \infty} eq(x_1, S) = \frac{k}{\xi} \\ \lim_{|S| \rightarrow 0} eq(x_1, S) = \frac{k|x_1|}{1+|x_1|} \end{cases} \quad (10)$$

The exponential reaching law approach uses a control gain that adapts flawlessly with the system state and the sliding surface, which is indicated in the previous equation, the control gain evolve between two values, the first one is (k/ξ) and the second one is $(k|x_1|)/(1+|x_1|)$ respectively according to the error, this will eliminate the error faster and diminish the reaching time when the error is large, and when the error gets slighter the control gain follows its value in order to limit the chattering level.

The exponential reaching law is applied by using (8) in (6), and the control law becomes:

$$i_{qref} = \frac{2J}{3p\phi_f} \left[eq(x_1, S) \operatorname{sgn}(S) + \frac{d\omega_{ref}}{dt} + \frac{1}{J}(T_L + B\omega) \right] \quad (11)$$

The Lyapunov function is selected as $V = \frac{1}{2}S^2$, and by tacking in consideration the equations (6) and (8):

$$\begin{aligned} \dot{V} &= S\dot{S} = S \left(\frac{d\omega_{ref}}{dt} - \frac{3p\phi_f}{2J}i_q + \frac{1}{J}(T_L + B\omega) \right) \\ \dot{V} &= S(-eq(x_1, S)\operatorname{sgn}(S)) \\ \dot{V} &= -|S|eq(x_1, S)\operatorname{sgn}(S) \leq 0 \end{aligned}$$

And this demonstrates the stability of the control law, and the convergence of the sliding surface to zero in a limited time.

3.2. THE PROPOSED LESO BASED COMPOSITE CONTROLLER

The novel ERL technique reduces the value of the chattering level and improve the performance of the SMC. Still, the unknown disturbance has a considerable impact in the control law, which will influence the value of k , and increase the chattering. Thus employing a disturbance estimator for the feed-forward compensation of the unknown disturbance will enhance the performance of the SMCERL [12]–[13].

The unknown load disturbance is usually composed of the internal dynamics of the system and the external disturbances, and the LESO is well known for estimating both, thus the LESO is applied in this approach, which utilises the estimation of the unknown disturbances as the new extended state of the system [10]–[14].

The derivative of the rotor angular velocity (3) can be written as:

$$\dot{\omega} = \tau_L + b_0 i_{qref} \quad (12)$$

First we consider b_0 as the estimation of $\frac{3p\phi_f}{2J}$, and τ_L is the unknown load torque that includes the tracking error of the current i_q along with the friction and the modelling errors all combined.

Where:

$$\tau_L = -\frac{1}{J}(T_L + B\omega) + \frac{3p\phi_f}{2J}(i_q - i_{qref}) + \left(\frac{3p\phi_f}{2J} - b_0\right)i_{qref} \quad (13)$$

In order to proceed with the design of the LESO several assumptions must be presumed, the estimated load torque is considered to be time varying, unknown, and uniformly absolutely bounded, which will guarantee the existence of a solution for the estimation error dynamics, as follows:

$$0 \leq |\tau_L| \leq l \quad (14)$$

The load torque is considered as an extended state, so that the LESO is designed as:

$$\begin{cases} x_1 = \omega \\ x_2 = \tau_L \end{cases} \quad (15)$$

$$\begin{cases} \dot{x}_1 = x_2 + \frac{3p\phi_f}{2}i_{qref} \\ \dot{x}_2 = \dot{\tau}_L \end{cases} \quad (16)$$

According to [6], a second order linear extended state observer can be established for (16), as follows:

$$\begin{cases} \dot{z}_1 = z_2 - 2\rho(z_1 - \omega) + \frac{3p\phi_f}{2J}i_{qref} \\ \dot{z}_2 = -\rho^2(z_1 - \omega) \end{cases} \quad (17)$$

Where $(-\rho)$ represent the desired double pole of the LESO, with $(\rho > 0)$, z_1 indicate the estimation of ω , and z_2 is the estimation of τ_L .

Finally, the estimation of the unknown load torque z_2 is added to the final control law for the feed-forward compensation as follows:

$$i_{qref} = \frac{2J}{3p\phi_f} \left[eq(x_1, S) \operatorname{sgn}(S) + \frac{d\omega_{ref}}{dt} + \frac{B\omega}{J} - z_2 \right] \quad (18)$$

The Lyapunov function $V = \frac{1}{2}S^2$ proves the stability of the proposed control law according to the stability criteria.

4. SIMULATION RESULTS

The following figure introduce the block diagram of the proposed control system, where the simulation of the speed regulation system is carried out with MATLAB/SIMULINK.

Fig. 1 The block diagram of the control system

Fig. 2 introduce the simulation the SMCERL with a conventional PI controller, where the desired speed is set up to 3000 rpm, and a furious variation of the load torque of 6 Nm is applied between $t=0.5$ sec and $t=1.5$ sec, the load torque is added to analysis the attitude of each controller in presence of disturbance.

The results prove the superiority of the SMCERL over the PI controller, as we can notice that the dynamic response under the PI control is much slower than SMCERL, while the SMCERL tracks almost perfectly the reference, the response time is less than 0.01 sec while the conventional PI controller took more than 0.08 sec to reach the desired speed, the overshoot of PI controller is more than 35 rpm when the load is added, while the SMCERL recover faster, and the overshoot is less than 10 rpm.

Fig. 2 Simulation of SMCERL with the conventional PI controller

However, with a closer look the drawback of the SMCERL becomes clearly noticeable as Fig. 3 proves, we can see that exponential reaching law technique helps reducing enormously the chattering phenomena and increases the rapidity of the system's response but the chattering is not null yet.

Fig. 3 Simulation of the SMCERL

Before integrating the LESO with SMCERL, first the simulation of the LESO estimation of the load variation is presented in Fig. 4, where we can observe clearly the precision of the LESO in tracking the real load torque.

Fig. 4 Simulation of the LESO load torque estimation

Fig. 5 Simulation of SMCERL with the LESO integrated

The proposed controller in this paper is compared with the SMCERL in Fig. 5, where the same desired speed and load torque are applied as in Fig. 2, the speed curves demonstrate the enhancement made by the addition of the LESO in matter of disturbance rejection and chattering reducing, as we notice in Fig. 5 that the proposed controller has a faster response than the SMCERL with more than 0.002 sec, and the chattering level becomes barely noticeable due to the feed forward compensation of the unknown disturbance.

5. CONCLUSION

In order to ensure the high performance, and the heftiness of the system against the unknown disturbances, a novel nonlinear control algorithm based on the combination

between the distinguished SMCERL, with the LESO has been applied in this paper. In order to control the speed of PMSM dedicated for electrical vehicle propulsion; first the SMCERL algorithm is tested without a disturbance observer, simulation results proved the ability of the exponential function to phase out the chattering level when the error is not important; In the second part the LESO was introduced as a disturbance observer, the load estimation of the LESO is added to the control law for the feed-forward compensation, by this means the load disturbance is anticipated and the chattering was eliminated regardless the value of the error caused by the external disturbances, with a higher efficiency.

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