Optimizing the Performance of Electric Vehicle Induction Motors through Synergistic Control

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Abstract

This paper seeks to present innovative control algorithms for extending the high-speed operation of Induction motors, widely used in Electric Vehicle (EV) applications. Previously, a Model Predictive Control (MPC) based flux weakening method to push the motor operation beyond the rated speed. This method enhances various metrics such as steady-state speed attainment time and torque ripple. However, several issues with this method such as speed, torque, and flux ripples, and chattering lead us to a novel Sliding Mode Control (SMC) approach. This SMC method amalgamates an exponential component and constant rate component to significantly improve both speed and torque regulation. It also significantly reduces the chattering and further enhances the steady-state speed attainment. Furthermore, we use a Nonlinear Disturbance Observer to boost the performance of the sliding mode control method and, small dynamic disturbance observer to enhance it's resilience to parameter uncertainties.

Keyword: Electric Vehicle, Induction Motors, Sliding Mode Control.

1. Introduction

Electric vehicles [1], [2], [8] are expected to deliver an enormous economy, with the considerable torque, dynamic reactivity with a good dependability. High power efficiency operating for low torque and low speed range (especially urban driving) is one of the most crucial issues in electric vehicles [2]. In electric vehicles [2], [8], motor selection is the most significant part, and there are a lot of types motor that can be used in these vehicles [2], [8]. One of these motors is the induction motor, which is particularly widely used in electric vehicle applications. When induction motors are fed uncontrolled large initial current, little dynamic responsiveness or big inaccuracy in output parameters (torque and speed) occurs. Advanced control techniques, including vector control, should be employed to alleviate the aforementioned constraints. Similar to individually stimulated direct current (DC) motors, the torque and flux control of alternating current (AC) motors may likewise be accomplished independently of each other utilizing current components. In DC motors, flux may be regulated with field current, and torque can be controlled with armature current. In an induction motor, on the other hand, there is no two-phase current readily accessible, which will enable the flux and torque to be adjusted individually. In induction motors, three-phase sinusoidal currents flow, which include amplitude, frequency, and phase information. In vector control techniques, three-phase currents may be divided into two components that are perpendicular to each other using Park transformations, as in DC motors. In direct torque control (DTC), torque and flux are sought to be maintained at reference levels within the defined hysteresis bands. By adopting vector control, both of the problems described are overcome, and the torque and speed of the motor may be regulated individually. In this article, DTC, which has good performance in induction motor control, is applied. DTC was advocated by Takahashi and Noguchi. The benefit of this system is that DTC reacts extremely fast to fluctuations in torque, and speed references are reacted to promptly by DTC. In torque and speed references. In addition, the absence of axis transformation and minimal dependency on motor settings are significant benefits. Since there is no axis transformation, the processing speed of the motor control algorithm is great. The main shortcoming in DTC is ripples in motor parameters such as speed, current, and torque. The requirement of running the induction motor at a speed over its specified speed is of major relevance, particularly for various industrial applications and electric vehicles [2], [8]. When regulating the induction motor in the flux weakening zone, three criteria must be verified. Changes in motor characteristics and operating circumstances should minimally influence the controller's functionality. The motor reference parameters (speed and torque) should be followed with the least degree of error throughout the acceleration and deceleration operations. Especially in acceleration and deceleration, the ripple in the reference voltage might be considerable. The reference voltage ripple in the flux weakening area should be small. When the issue of control in the flux weakening area is investigated in the literature, it is obvious that the research is evaluated under four categories. The first of these heads is the traditional 1/ωr control approach. With this technology, speed control may be carried out in the flux weakening zone of both DTC and field-oriented controlled (FOC) induction motors. However, current and voltage restrictions are disregarded in this manner. The second control technique in the flux weakening area is the voltage-closed loop PI controller. Many research has been done utilizing this strategy. Since this approach involves closed-loop control, adding a PI controller to the flux weakening controller makes the system rather complicated, despite the minimal dependency on the motor parameters. Also, employing a PI controller increases the issue of raising the back electromotive force. In this instance, an ant windup controller needs to be added to the system, and this structure increases the complexity of the flux weakening controller. Another option is the model-based method. There is few research in the literature employing this strategy. The performance of this approach is adversely influenced by changes in motor characteristics. The final of the control mechanisms in the flux weakening area is the look-up table. Although this approach delivers the largest torque output, the control process is constrained to a preset table and is reliant on the motor settings. MPC is often a highly effective and successful control approach among current control systems. Compared to other control techniques, MPC deals with the current and future states of the system to be managed, whereas traditional control methods deal with the present and past states. Thus, MPC control creates less steady-state error than other control approaches. The flux weakening applications of the MPC approach are extremely rare in the literature, and in these investigations, the d-axis of the stator current or voltage was adjusted. MPC was utilized for control in the flux weakening zone, however in this research, motor control was conducted using FOC, and current components were regulated in the flux weakening region. Since torque control in FOC is handled as an open loop, it is extremely reliant on motor parameters. In addition, its reaction to changes in reference values (speed and torque variations) is relatively sluggish.

The induction motor (IM) has been extensively employed in applications that need great torque control precision across a broad speed range, such as electric automobiles. Considering the control techniques for IM, one approach that has lately been adopted is model predictive control (MPC) because to its high edibility and simplicity. The primary principle of MPC is to utilize a model of a plant to forecast the behavior of system variables within a time horizon. In this method, by minimizing a cost function utilizing the idealized and projected behavior, an optimum control performance may be attained by choosing the control input to the system. However, the conventional MPC leverages the model of the IM to create the controllers. So, it might affect the performance of the controller owing to the parameter inaccuracies. Recently, various MPC solutions have been introduced in order to boost the resilience against parameter mismatches in the machines. Ordinary MPC applies the nonlinear model, considering the Taylor representation of IM for each equilibrium point. A predictive torque control for IM combines a combined integral sliding mode observer and an adaptive Luenberger observer. A model-free predictive current control (MFPCC) based on the ultra-local model. The complete controller simply requires the input and output data without the requirement for the motor settings. A model-free control is also presented, where the control signal is determined by the sampling current and the current error. In linear extended states, observers are deployed for this job. The robust MPC considering a generalized proportional-integral observer is provided. The stated results are good despite the IM parameter problems. The deadbeat predictive current control (DPCC), which leverages the error between the measured currents and the anticipated currents to adjust for the in-sequence of machine parameter mismatches. This approach offers high resistance against parameter incompatibilities. Aiming to lower the inaccuracy of the stator current forecast, deploy the Luenberger observer to accomplish this purpose. The robust deadbeat-based current control proposed has good dynamic performance and high resilience in the experimental testing compared to PI. current control and the standard deadbeat.

This paper proposes a unique technique to flux weakening control in electric induction motors by applying model predictive control (MPC) inside a direct torque control (DTC) framework. Unlike prior studies that largely focused on minimizing flux ripple using MPC on current components, this study combines MPC directly with DTC to boost dynamic responsiveness. By immediately acquiring reference values for speed and torque control inside the flux weakening zone, this technique circumvents the restrictions of traditional field-oriented control (FOC). Notably, DTC's inherent quicker dynamic response benefits in accomplishing speedy modifications to reference values. The MPC algorithm analyzes numerous factors, including current and voltage constraints, in addition to flux limitations. This comprehensive approach results in a more sophisticated control system, allowing accurate and economical operation across different operating situations. Furthermore, the suggested solution overcomes issues related with acceleration and deceleration operations, limiting inaccuracies in speed tracking and lowering ripple in the reference voltage. Simulation and experimental investigations demonstrate the usefulness of this technique, proving its potential for boosting induction motor control performance. Overall, this study proposes a complete method that combines the characteristics of DTC and MPC, enabling considerable advances in flux weakening control for electric induction motors.

2. Dynamical modelling of electric vehicle

The figure. 1 shows a hybrid car with a gasoline engine, battery, and electric motor. The engine powers a generator, while the battery and motor connect through a controller. The controller manages power flow for both battery and generator to drive the wheels.

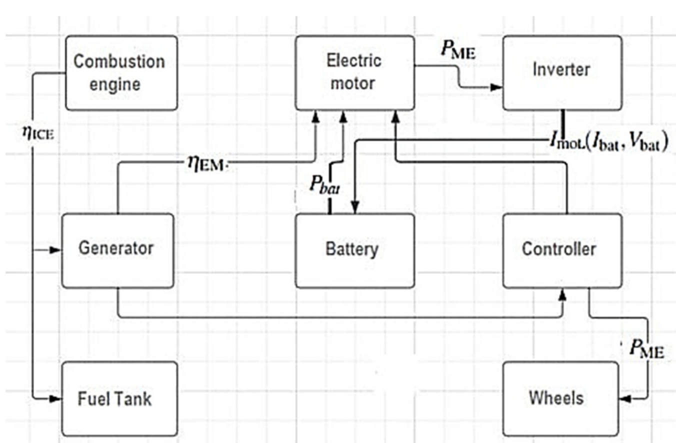

Fig. 1. The schematic diagram of a dynamic electric vehicle [15]

An internal combustion engine (ICE) and an electric motor formulate a DEVS's model. Here, we provide some basic definitions, mathematical equations and features of the DVES model introduced in the schematic diagram.

2.1 Internal Combustion Engine: The internal combustion engine is the power output of the engine; it is equal to the product of the efficiency and the power input from the fuel source.

$$P_{ICE} = \eta_{ICE} * P_{fuel} \tag{1}$$

2.2 Electric Motor: The electric motor in electric vehicles plays an important role. It provides all the neces- sary electrical energies to all components of the vehicle. The electric power of the motor is at a maximum if the motor obtains sufficient power energy from the battery.

$$P_{EM} = \eta_{EM} \cdot P_{bat} \tag{2}$$

2.3 Total Power Output: The total power output to the vehicle is the total sum of the power of the internal combustion engine P_{ICE} and the total power of the electric motor P_{EM}.

$$P_{total} = P_{ICE} + P_{EM} \tag{3}$$

2.4 Energy Storage System Model: A battery that stores and provides electrical energy to the electric motor makes up the energy storage system of a DEVS.

$$SOC(t) = \frac{E_{bat}(t)}{E_{max}} \tag{4}$$

The battery energy is given by

$$E_{bat}(t) = \int_{t_o}^{t} P_{bat}(t')dt' + E_{bat}(t_0) \tag{5}$$

Where, where "P_{ICE}" is the internal combustion engine power; "η_{ICE}" is the efficiency of engines; "P_{fuel}" is the power output of fuel sources; P_{EM} is the electric motor power output; η_{EM} is efficiency of electric motor; P_{bat} is the power output of battery; $E_{bat}(t)$ is the battery stored energy at time t; $SOC(t)$ is the battery state of charge at time t; E_{max} is the capacity of maximum battery storage energy; $P_{bat}(t)$ is the battery initial energy stored; $P_{bat(t)}$ is power output of the battery at time t, and t_0 is the initial time.

2.5 Vehicle Dynamics Model: A mathematical model, based on DEVS principles, predicts a vehicle's motion and acceleration.

The vehicle acceleration equation is represented by

$$a = \frac{P_{total}}{m \cdot g} - \frac{1}{C_r \cdot g} - \frac{1}{C_d} \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v^2 \tag{6}$$

The vehicle speed v(t) at time t

$$v(t) = \int_{t_0}^{t} a(t')dt' + v(t_0) \tag{7}$$

Where, a is the vehicle acceleration; m is the mass; g is the acceleration caused by gravity; C_r is the rolling resistance coefficient; C_d is the aerodynamic drag coefficient; ρ is the air density; A is the frontal area; v is the speed, t_0 is the initial time and $v(t_0)$ is the vehicle initial speed.

The engine model, the model of the energy storage system, and the model of the vehicle dynamics are the three primary parts of the DEVS model. To model the behavior and operation of the Electric Car, several elements are combined.

3. Design of Sliding mode control for Dynamical modelling of electric vehicle

Sliding Mode Control (SMC) is a nonlinear control technique that has gained popularity due to its ability to provide accurate, robust, and easy-to-implement control solutions. The SMC approach involves designing a sliding surface and a control law that ensures the system state converges to the sliding surface. Once the sliding surface is reached, the system state remains in a close neighborhood of the surface, ensuring robustness and stability. The SMC approach has been widely used in various applications, including motor control. In this study, we propose the design of an SMC system for tracking the speed of a IM. The IM speed control loop is modeled as a first-order system, allowing us to employ a Lyapunov-based SMC approach to design a robust and stable speed controller.

3.1 Design and Implementation:

The SMC system is designed based on the following steps:

1. Define the sliding surface: The sliding surface is defined as the error between the reference speed and the actual rotor speed, i.e., e = $\omega ref - \omega e$.
2. Design the sliding mode controller: The SMC controller is designed using the Lyapunov stability concept, ensuring the stability and robustness of the system.
3. Implement the SMC controller: The SMC controller is implemented in the feedback loop, using the estimated load torque and system states.

3.2 Observer-Based Load Torque Estimation: To improve the performance of the system and compensate for load torque disturbances, an observer-based load torque estimation scheme is embedded in the feedback line. The observer estimates the load torque based on the error signal and system states, allowing the SMC controller to adapt to changing system conditions.

4. Simulation Results and discussions

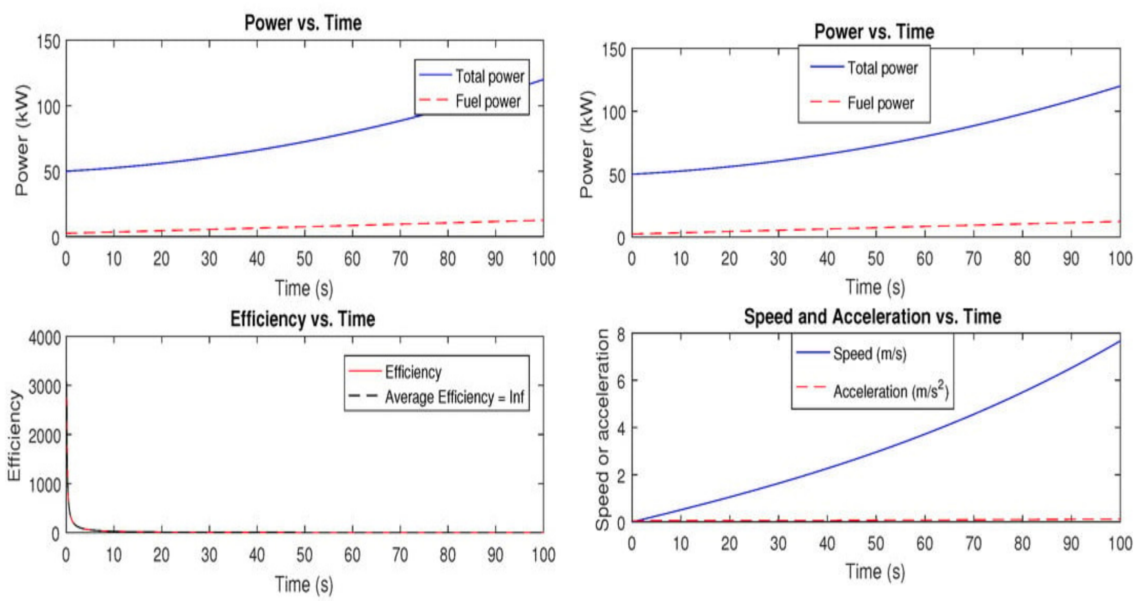

Fig. 2 The vehicle's performance and the effect of various parameters over time

Figure 2 illustrates the relationship between power, fuel consumption, and efficiency during vehicle travel. As speed increases (plot 2), total power (plot 1) rises, reflecting the engine's increased workload. Fuel consumption (plot 1) also climbs steadily. However, acceleration (plot 2) eventually diminishes as fuel depletion reduces engine power. Finally, efficiency (plot 3) initially rises with speed but plateaus. The black dashed line represents the ideal constant-speed efficiency. As fuel nears depletion, efficiency drops due to power loss, impacting both speed and acceleration. These results highlight the dynamic interplay between vehicle performance and factors like speed, fuel consumption, and efficiency. Figure 3 explores how battery parameters influence maximum energy storage (MESC). While higher collective capacity, voltage, and charge/discharge current increase MESC (plots 1-2, 4), temperature has a complex effect (plot 3).

Larger batteries, higher voltages, and moderate temperatures all favor higher MESC. However, excessively high currents can lead to power losses and reduced MESC.

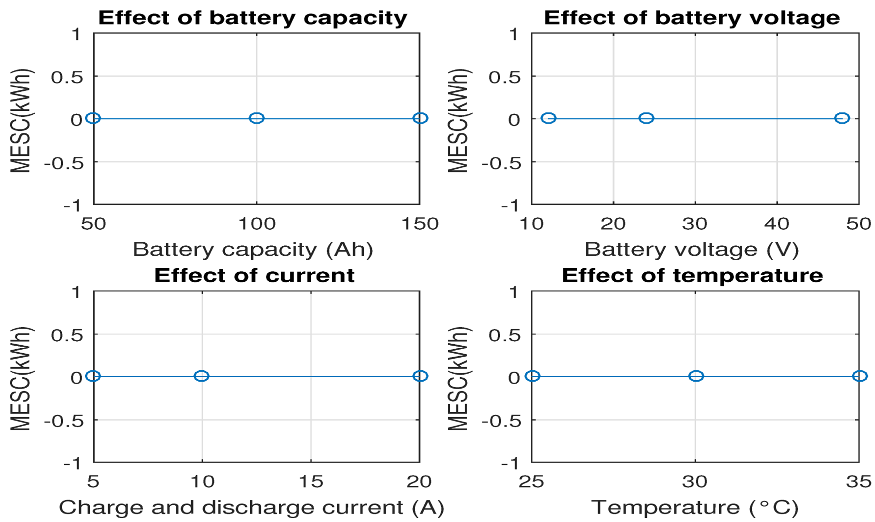

Fig. 3 the maximum energy storage capacity of the battery under different parameters

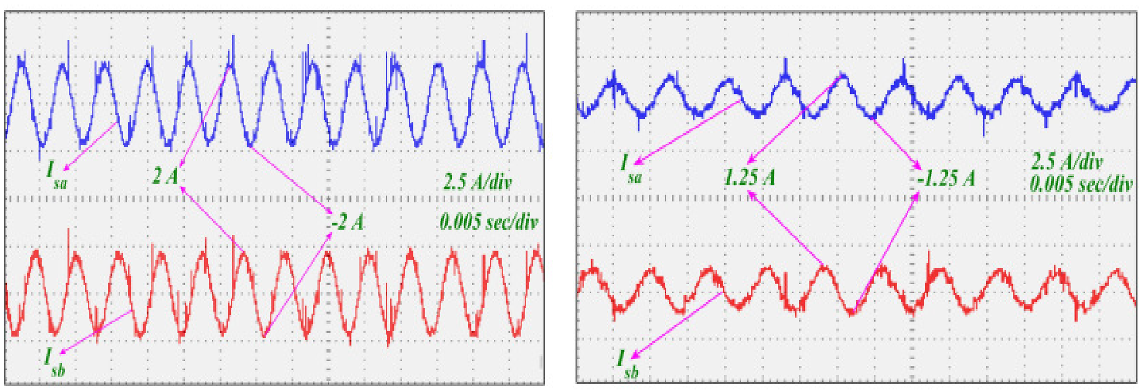

Fig. 4. Stator currents for the flux weakening region. (a) Classical flux weakening control. (b) SMC-based flux weakening control

From figure 4, the SMC-based approach shows enhanced torque surges family member to the traditional change deteriorating control within the induction electric motor's wearing down domain name. This difference emphasizes a remarkable compromise in using SMC possibly compromising torque level of smoothness for various other benefits like durability or quick vibrant reaction. Such monitoring highlight the requirement for refined design choices considering efficiency metrics versus each various other in search of ideal system actions. This relative evaluation brightens the unique qualities and also effects of utilizing SMC-based techniques in induction electric motor control, notifying future advancement plus improvement initiatives in the area.

Conclusion

This paper proposes two control formulas to prolong the broadband procedure of Induction Motors for Electric Cars (EVs). While the Model Predictive Control (MPC) technique properly raises rate as well as minimizes torque ripple it experiences staying problems. To resolve this a unique Sliding Mode Control (SMC) system is presented, integrating a rapid plus continuous price part for remarkable rate together with torque law with reduced babble. In addition, a Nonlinear Disturbance Observer is utilized to support the SMC's efficiency, as well as a little vibrant disruption onlooker improves its durability versus criterion variants. This incorporated strategy guarantees substantial developments in broadband procedure of Induction Motors for EVs.

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