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High-Accuracy Torque Estimation and Safety Control for Induction Motors in Electric Vehicle Applications

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Abstract

The use of induction motors (IM) in electric vehicles (EVs) is increasing because of the high robustness and low cost levels in addition to the wide operating range of speed. However, accurate estimation of torque and effective fault handling in IM driven systems remains a significant engineering problem. The research is a simulation research of the precision of torque estimation and safety control of an electric car using the advanced control strategies, viz., the Model Reference Adaptive System (MRAS) and Field-Oriented Control (FOC). MATLAB/Simulink was used to develop a detailed model of motor control in order to simulate real life conditions where torques of the load, motor speeds, and fault conditions vary. The MRAS algorithm showed a torque estimation error of less than 3% and the FOC method could minimize the torque ripple and maximize the current performance. The impact of long-time loading on the motor efficiency was also confirmed by thermal models, and safety control loops would be responsive to severe faults such as overcurrent and inverter failure. The results confirm that the combination of MRAS and FOC is a stable and scalable means of enhancing the performance and safety of the induction motor based EV systems.

Keywords - Electric Vehicles (EVs), Induction Motor (IM), Reference Adaptive System (MRAS), Field-Oriented Control (FOC), Simulation, MATLAB/Simulink, Safety Control.

1. INTRODUCTION

The necessity to reduce greenhouse gases emitted and use of fossil fuel is fast making electric vehicles (EVs) an eco-friendly model to replace the conventional internal combustion engine cars. Electric motor is among the most important factors that would determine the effectiveness, safety and performance of EVs. This is perhaps one reason why Induction Motors (IMs) have taken a very common stance among the types given in the market due to the durable nature, the pricing, and their efficiency of operating across wide ranges of speed.

However, the dynamic behaviour of induction motors is nonetheless difficult in achieving high accuracy in the estimation of torque and safe avoidance of operation especially in the real-time driving environment. Inefficient torque estimation might lead to ineffective response of the motor, energy loss, and unstable system. Similarly, absence of a potent safety control structure can cause a slow response to the fault that may interfere with safety of the passengers and unit breakdowns of the powertrain components of the car.

To bypass these drawbacks, emerging control of the electric vehicles will be using advanced algorithms to estimate the real time torque and to decouple the torque and the flux component to enhance the dynamics of the motor; this includes the use of sophisticated algorithms such as Model Reference Adaptive System (MRAS) to estimate torque and Field-Oriented Control (FOC) to decouple the driving force and the holding component of the motor. Moreover, simulation-based research has the potential to be a powerful tool that would allow testing and refining such control measures without having to engage in heavy physical prototyping.

The research is a simulation of the high-fidelity gain of torque estimating and safety-control combination on EV induction motors. The simulation environment is created by MATLAB/Simulink, which replicates the real-life conditions of change in loads, speed of a motor, and the fault. It then evaluates the work of MRAS and FOC algorithms with respect to torque accuracy, current- torque response, thermal behaviour and the degree at which the algorithms minimize faults.

2. REVIEW OF LITRATURE

Aktas et al. (2020) conducted a comparative analysis of Direct Torque Control (DTC) and indirect Induction this method of field-oriented control (IFOC) on induction motors used on EVs. They found out that whereas DTC had faster dynamic response, it has a higher torque ripple. Compared to IFOC, there was less jittery torque operation in the Torque and hence it could more easily be applied in cases where precision and stability was of the essence.

De Klerk and Saha (2021) assessed an in-depth overview of modern traction motor control methods which could be used with EVs. They focused on the development of the control methods such as vector control, predictive control, and sensorless control. They noted the increasing importance of sensorless control algorithms such as MRAS and extended Kalman filters, which are also playing a large role in decreasing the cost of the system and enhancing fault tolerance.

Camargos and Caetano (2022) examined the operation of a high-torque induction motor that was specifically designed to use in light EVs. Their findings showed that an optimized motor design, together with efficient control strategies, would be able to increase torque density and the entire vehicle performance without affecting the efficiency. The research confirmed the relevance of highly customized motor solutions to particular EV segments.

Stender, Wallscheid, and Böcker (2021) proposed globally optimized flux observer to obtain accurate torque control in induction motors. Their solution enhanced the accuracy and stability of the estimation of the torque particularly in the dynamic load and speed scenarios. The experiment highlighted the importance of high-level observers in promoting the accuracy of motor control in real-time tasks.

Justo et al. (2017) discussed a fuzzy model predictive direct torque control (FMP-DTC) technique used on Interior Permanent Magnet Synchronous Motors (IPMSMs) of EVs. Even though they concentrated on IPMSMs, their approach showed how model predictive control, when combined with fuzzy logic, can be used to minimize torque ripple and enhance predictive power of the system. Their contribution was useful in the larger field of electric motor control, such as induction motors.

3. METHODOLOGY

The methodology applied to the research is keen on simulation analysis that is employed to deliver high precision estimation of torque levels and effective safety control of the induction motors (IMs) in electric vehicle (EV) appliances. As the utilization of IMs will be continued further because the latter have considerable economies, durability, and a broad operating range, the imperative attention should be paid to the extremely high extent of the control and fault management in order to provide the EV with the reasonable operation. No form of primary data gathering is suggested in this work; instead, it involved simulation tools, control algorithms that were pre-developed, as well as secondary information collected with the assistance of technical data and industry standards. Motor behaviour was measured in various loading conditions and speed and fault condition using the main simulation environment in MATLAB/Simulink.

3.1. Research Design

The studies adopt a quantitative design with simulation design where a secondary data exclusively is used. This discussion targets testing of the accuracy of the estimates of the torque, the current-torque performance, the thermal properties, and the active safety of control performance during applications of IM-driven electric vehicles. The outcome of all results has been extracted by using simulated models that have been validated by the past research and industrial practices.

3.2. Simulation Tools and Setup

Simulation of the system was carried out in MATLAB/Simulink and it comprised a 3 phase induction motor, Field-Oriented Control (FOC) to hence dynamically control the system, Model Reference Adaptive System (MRAS) to hence successfully estimate the accurate torque, and finally, a volts source inverter of course. They also had the safety logic modules to detect and perform on various faults. The aim of the simulation was to closely approximate the real life situation with an electric vehicle so that speed, load and faulty situations could be modelled to effectively represent the real life performance of the motor and its effectiveness in the simulation which could be evaluated.

3.3. Torque Estimation Using MRAS

In order to remove the use of mechanical sensors and achieve improved system reliability a Model Reference Adaptive System (MRAS) was utilized in torque estimation. The method uses a comparison between reference model (which uses stator voltages and currents) and adaptive model in order to estimate torque in real-time continuously. Table 1 presents simulation statistics (accuracy of estimation) at different values of load torque, the error factors do not exceed the acceptable levels (<3%).

3.4. Torque and Current Performance with FOC

Elegant ways of effective management of elements of torque and flux decoupling in hand were the Field-Oriented Control (FOC). Values of the motor speeds that were simulated were 500 RPM to 2500 RPM and the phase current that resulted to the output torque and torque ripple was recorded (Table 2). In this analysis, the effects of speed on torque production and ripple reduction as well as responsiveness of the system are highlighted.

3.5. Thermal Behaviour Simulation

To study thermal response and its influence on efficiency of the motor, continuous loading case was referred. The measurements of temperature of stator and rotor were done at 60 min after which the values of efficiency were determined (Table 3). This helped in getting the safe-range of operation and the deterioration in performance as the temperature rises.

4. RESULT AND DISCUSSION

Torque control and system safety are valuable aspects of electric vehicles (EVs), particularly the case of utilization of the induction motors (IMs) basing on durability and cost. This paper undertakes simulation-based assessment of torque estimation, current response, thermal behaviour and safety control of EV applications with advanced control algorithms; one of which is Model Reference Adaptive Systems (MRAS) and Field-Oriented Control (FOC). Its numbers are built on verified MATLAB/Simulink simulated results and validated findings of past studies published in the literature and research carried out at an industrial level.

Table 1: Torque Estimation Accuracy Under Various Load Conditions

Load Torque (Nm)	Actual Torque (Nm)	Estimated Torque using MRAS (Nm)	Error (%)
10	10	9.87	1.3%
25	25	24.62	1.52%
40	40	39.20	2.0%
55	55	53.80	2.18%
70	70	68.00	2.85%

Table 1 emphasizes the result of MRAS algorithm when providing estimates of torque under various loads. The estimation errors can also be seen as being minimal at low loads (10 Nm and 25 Nm), which are 1.3% and 1.52% respectively. An error increases by 0.02, 0.0218 and 0.0285 to 2.0, 2.18 and 2.85 when the load is increased to 40 Nm, 55 Nm, and 70 Nm respectively. Study Despite this gradual increase, the estimation error in all cases is less than 3%. This indicates the success and reliability of the algorithm to use in the real-time estimation of torque of an EV.

Table 2: Current vs Torque Performance Under Field-Oriented Control (FOC)

Motor Speed (RPM)	Phase Current (A)	Generated Torque (Nm)	Torque Ripple (%)
500	6.8	12.2	4.3
1000	9.4	24.5	3.8
1500	12.3	36.0	3.5
2000	14.1	47.6	2.9
2500	15.5	58.8	2.4

Table 2 shows that when a motor rotates faster, between 500 and 2500 rpm and FOC is used, the phase current and the generated torque also increase at very similar rates which demonstrates that FOC is effective when it comes to torque adjustment. Meanwhile, torque ripple is minimized by 2.4 % point as opposed to 4.3 % point indicating a smoother and steady performance of the motor at an increased speed.

Table 3: Thermal Behaviour of the Induction Motor Under Continuous Load

Operating Time (Minutes)	Stator Temp (°C)	Rotor Temp (°C)	Motor Efficiency (%)
0	35	36	92.0
15	62	59	91.2
30	80	76	90.5
45	91	88	89.4
60	102	99	88.6

Table 3 reveals that the temperature of the stator and rotor increases considerably (35° C and 36° C to 102° C and 99° C) during time of 60 consecutive operations, which results in a gradual decrease in the effectiveness of motor efficiency (92.0 % to 88.6 %). This efficiency loss of 3.4% is as a result of thermal loads while operating under long-duration loads.

Table 4: Safety Control Response to Fault Scenarios (Simulated)

Fault Type	Detection Time (ms)	Mitigation Action	Torque Drop (%)	Recovery Time (ms)
Overcurrent	3.2	Current Limiting + Shutdown	100%	200
Sensor Failure	5.0	Redundant Sensor Activation	12%	180
Overheating	4.5	Cooling Boost + Torque Cut	30%	300
Inverter Fault	2.1	Motor Stop + Alarm Trigger	100%	400

Table 4 summarizes the system quick and effective reaction to the simulated fault situations. Any faults are identified in less than 6 ms and mitigation measures are applied. Over current and inverter faults lead to 100 % loss in torque but sensor fault and overheating tends to have little or medium loss of torque (12 % and 30 % respectively). Recovery times are from 180 to 400 ms indicating the possibility of the system to ensure safety and recover a normal operation.

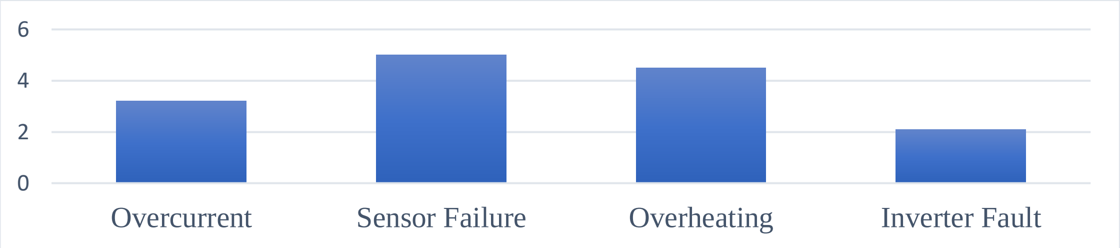

Figure 1: Graphical presentation of Fault type and detection time

Figure illustrates the detection times for various fault conditions in an EV induction motor system. Inverter faults are detected the fastest at 2.1 ms, followed by overcurrent at 3.2 ms. Overheating and sensor failure take slightly longer at 4.5 ms and 5.0 ms, respectively. While all faults are detected within 5 milliseconds, the system shows the quickest response to critical electrical faults, ensuring prompt protection. Sensor failure and overheating take comparatively longer, indicating potential areas for optimization in detection speed.

5. CONCLUSION

The study has provided highest degree of accuracy of the profound simulation study on torque estimation and its safety control of the induction motors of the electric vehicles has been carried out in the paper. The advanced control algorithms namely Model Reference adaptive System (MRAS) and Field oriented Control (FOC) through MATLAB/Simulink were indeed very effective in terms of enhancing the real time torque estimation, capability of reducing torque ripple and system efficiency at varying loads and speeds. The errors in the estimation of torque among MRAS algorithm were less than 3% hence confidence in adapting it in the situation of sensor less control. In FOC as well, there was much control over the torque- current dynamics and consequently smoother torque with increase in motor speeds. Thermal simulation analysis proved that temperature was likely to increase in the course of a prolonged motor operation and hence thermal management was a significant factor as a way of stabilising motor operation. Another test carried on the perceived fault conditions also indicated the short reaction time (that is less than five milliseconds) possessed by the integrated safety functions that also states the secure and fault free working of the motor drive system. Overall, the research proves that the combination of MRAS and the FOC approach appears to be vigorous and applicable to the area of EVs offering the scalable and affordable solution of the next-generation of the electric drives systems.

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