PHOTOVOLTAIC-FED MOTOR DRIVE SYSTEM FOR NEXT-GENERATION ELECTRIC VEHICLES

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Abstract: The growing demand for zero-emission, environmentally friendly Electric Vehicles (EVs) is driven by both current and anticipated energy crises, supported by government policies and evolving market trends. Addressing this need, the present study proposes a novel control strategy for an induction motor drive system in EVs, primarily powered by solar PhotoVoltaic (PV) panels. The system employs Field-Oriented Control (FOC) technology to ensure precise motor control, enhanced performance, and reduced energy losses. To enable real-time monitoring and control, an Internet of Things (IoT) based system is integrated, providing valuable insights into the motor drive's operation and energy consumption. The incorporation of solar PV energy offers a sustainable, long-term alternative to conventional grid-powered sources. The FOC technique further ensures efficient and reliable motor drive operation under varying load conditions. Overall, the synergy of solar energy, advanced motor control, and IoT monitoring presents a highly efficient and eco-friendly solution for future EV applications.

Keywords: Field-oriented control, electric vehicle, internet of things, photovoltaic and induction motor.

I. INTRODUCTION

With economic progress, vehicles have become increasingly common in households worldwide. However, the rapid expansion of the automotive industry has led to pressing challenges, most notably fuel shortages and air pollution. EVs, with their zero emissions, low noise, and high efficiency, are gaining widespread recognition, supported by national policies aimed at sustainable transportation. In recent years, global demand for EVs has surged dramatically, prompting major automotive manufacturers to release their own models of new energy vehicles. A key component of EV development is the design of robust and efficient motor controllers especially in China, which currently leads the global EV market thanks to strong governmental support and rapid growth in EV production and sales.

EVs offer a cleaner, more efficient alternative to traditional internal combustion engine vehicles and have drawn increasing attention as the demand for sustainable transport solutions grows. However, several barriers to widespread adoption remain, including limited driving range, long charging times, and dependence on non-renewable grid power. Induction motors (IMs) have become the preferred choice in a wide array of industrial and automotive applications due to their robust construction, simple design, low maintenance requirements, and strong reliability. They are widely used in industrial control systems as well as in new energy vehicles. Advances in AC motor control theory have enabled the development of servo systems using AC motors that match the performance of traditional DC systems, unlocking the full potential of IMs. Traditionally, IMs were either directly connected to the grid or operated using scalar control methods such as the voltage-to-frequency (V/f) technique. While straightforward, these methods are limited in dynamic performance and are sensitive to motor parameters such as starting torque, inertia, and the number of pole pairs.

Many modern applications demand variable-speed operation, which is poorly supported by traditional scalar control methods, particularly under transient conditions. While scalar vector control provides speed variation in steady states, it does not address performance during dynamic load changes and may lead to over-currents and overheating. The rapid advancement of electrical drive systems has highlighted the need for more precise and responsive control techniques, particularly in applications requiring accurate speed and position control. The IoT enables interconnectivity and data exchange among physical devices, facilitating intelligent automation with minimal human intervention. With IoT integration, manual monitoring and control of induction motors can be replaced by automated condition monitoring systems, improving efficiency and reliability.

This study presents a novel approach for managing a solar PV-powered induction motor drive system for EV applications. FOC is employed to regulate the induction motor (IM) with high precision, ensuring optimal performance and energy efficiency under varying load conditions. An integrated IoT-based monitoring system enables real-time observation and remote control of the motor drive system, enhancing system intelligence and reliability. The combination of solar PV energy, FOC-based motor control, and IoT monitoring offers a sustainable and efficient solution for future electric mobility.

II. LITERATURE SURVEY

EVs have emerged as a promising solution to reduce dependence on fossil fuels and the environmental pollution they cause. In recent years, the integration of solar PV technology and other renewable energy sources into EV systems has gained significant attention to enhance autonomy and sustainability. Research in this domain spans several key areas including system design, control strategies, and performance optimization. One prominent area of focus is the development of efficient power conversion systems that facilitate solar PV integration with EVs. For instance, a solar-powered EV charging station with bidirectional power flow management was proposed in [1], demonstrating the feasibility of reducing grid dependency through solar energy.

Control strategies play a critical role in maximizing the efficiency of EVs integrated with solar PV. In [2], various Maximum Power Point Tracking (MPPT) algorithms were evaluated to optimize energy capture from PV systems for EV charging. EVs are powered exclusively by electric current, with the motor driven by energy stored in batteries, which may be charged through the grid or renewable sources. A DC-DC converter is essential to regulate power between the PV panels and the battery, while the electric motor facilitates propulsion. As highlighted in [3], EVs can be powered independently using various external sources, including PV panels, onboard generators, or hybrid energy collection systems.

The evolution of EV technology spans more than 150 years, with milestones in 1832, the 1960s, and the present era. Early models lacked rechargeability, whereas modern EVs feature sophisticated management systems [4]. The potential for zero-emission transportation becomes fully realizable when EVs are powered by renewable sources. With global urbanization, rising disposable income, and increasing vehicle ownership, the number of EVs is steadily growing [5]. EVs offer several advantages, including lower operating and maintenance costs, and contribute positively to environmental and public health.

From a practical standpoint, research such as [6] aims to identify optimal configurations of batteries, DC-DC converters, and motors through real-world EV analysis. Emission control strategies for renewable energy-based charging stations are also being explored. Induction motors (IMs), known for their ruggedness, reliability, and low cost, are widely used in AC motor drives across various performance levels [7]. These motors require minimal maintenance and operate effectively even in harsh environments.

Governments around the world are enacting measures to improve air quality and reduce greenhouse gas emissions [8]. Despite significant progress, EVs accounted for only 1.5% of vehicles worldwide as of 2023, indicating considerable room for further adoption. Since 2011, EV usage has steadily increased. Traditional induction motor control methods, such as variable stator voltage-frequency ratio (V/f) control, are simple and cost-effective but suffer from poor dynamic performance and high slip power losses [9]. Efficient machine operation requires effective flux control, particularly under dynamic conditions [10].

Variable frequency control techniques such as V/f and slip frequency control offer reasonable steady-state performance and are relatively easy to implement [11]. However, to fully realize the potential of EV systems, continual improvements in both mechanical and electrical subsystems are necessary. While mechanical enhancements can improve vehicle design [12], optimizing the electric powertrain—especially the motor drive system—is crucial for achieving greater efficiency and range [13]. EV motors are subject to more stringent performance requirements than those used in conventional industrial applications.

FOC has emerged as a preferred method for managing induction motors in EVs. FOC allows independent control of torque and magnetic flux, ensuring efficient operation across a wide range of speeds and load conditions. In [14], a FOC-based strategy was shown to significantly outperform traditional control approaches in EV traction motor applications.

Several comprehensive reviews have addressed advanced motor control techniques. For example, [15] evaluated direct torque control strategies for IMs, while [16] explored various control approaches to improve the energy efficiency of electric propulsion systems. A major theme in such research is the reduction of energy losses. Although [17] presents a detailed review of power electronics and motor drives used in different EV types, it omits in-depth discussion of motor traction control. Similarly, while [18] surveys the current state and future directions of EV propulsion systems, it lacks coverage of control mechanisms. In contrast, [19] provides an extensive overview of EV systems and associated technologies.

The integration of sensor networks, human factors, and information-aware controller design was discussed in [20] to improve operational safety and efficiency. The integration of IoT technology into EVs offers real-time monitoring and control capabilities. Users can track charging processes and receive real-time updates on battery status and energy consumption through IoT-enabled platforms. The combination of solar PV, FOC motor control, and IoT-based monitoring holds significant promise for enhancing the autonomy, efficiency, and sustainability of EVs. However, further research is required to explore these synergies in depth and develop fully integrated, scalable solutions for widespread deployment.

III. PROPOSED SYSTEM

A sustainable and effective solution for EV applications is achieved by integrating solar PV technology, FOC for motor control, and an IoT based monitoring system. This combination of renewable energy and intelligent control enhances the autonomy, efficiency, and environmental impact of EVs. The widespread adoption of three-phase AC induction motors in both industrial and electric mobility applications highlights their reliability and performance. In a three-phase AC induction motor, sinusoidal stator phase currents at a specific frequency create a rotating magnetic field within the stator housing. This magnetic field induces a current in the rotor due to the relative motion and changing flux, generating torque. The interaction between the stator-generated magnetic field and the induced rotor current results in rotational motion, which drives the motor. Figure 1 illustrates the IoT-based FOC-controlled induction motor drive system used in this study.

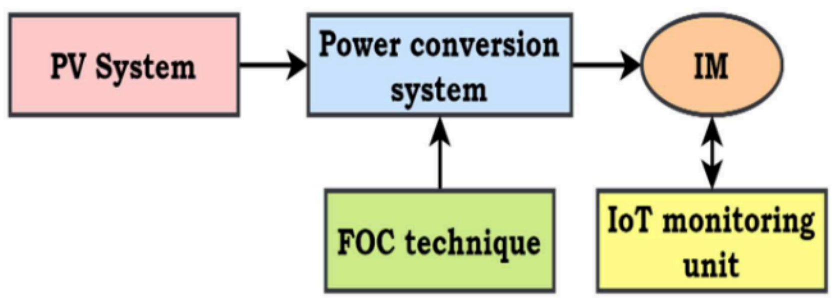

Fig. 1 IoT based FOC Controlled induction Motor Drive

EVs can harness solar energy by utilizing PV panels mounted on the vehicle to convert sunlight into electrical power. A power conditioning unit regulates and adapts the current and voltage output from the solar PV system to match the EV's power requirements. The induction motor drive system in EVs is controlled using the FOC method, which allows precise adjustment of motor torque and magnetic flux. This enables efficient operation across a wide range of speeds and load conditions. By enhancing energy efficiency, the FOC technique also contributes to extending the vehicle's driving range. An IoT based monitoring system is integrated into the EV to provide real-time control and observation of the motor drive system. The IoT system collects key performance data such as motor efficiency, energy consumption, and battery State Of Charge (SOC). This data enables remote management and optimization of the EV's propulsion system. Through a web interface or mobile application, users can access detailed insights into EV's operational status, facilitating informed decisions for energy usage and vehicle performance.

A. FOC Method for Induction Motor Control

The FOC technique offers an excellent dynamic response and allows the motor drive to react effectively during transient conditions. In this method, the phase currents i_a, i_b, and i_c of the stator are measured, although i_c can be calculated using the current balancing principle when only i_a, and i_b are available. Under FOC, the motor operates smoothly and quietly, with superior speed control and dynamic performance compared to traditional voltage/frequency (V/f) regulation methods.

A high-performance Digital Signal Processor (DSP) is used to implement the FOC algorithm. The DSP enables decoupling of the induction motor's torque and flux components, making the control similar in behavior to that of a separately excited DC motor. The core of FOC lies in transforming the three-phase time-varying system into a two-coordinate (d-q) time-invariant reference frame. This transformation simplifies control by enabling the use of two constant input references: one aligned with the d-axis (flux-producing component) and the other with the q-axis (torque-producing component).

The control structure continuously processes real-time data, allowing precise control over motor operation in both steady-state and transient conditions. In the rotating d-q reference frame, the complex behaviour of the AC induction motor is simplified to DC-like quantities, making it easier to implement and manage high-performance motor control. The stator voltage equations in the d-q reference frame, which form the foundation for implementing the FOC algorithm, are expressed as:

$$v_{ds} = \frac{d\varphi_{ds}}{dt} + i_{ds}R_s - \varphi_{qs}\omega_e \quad (1)$$

$$v_{qs} = \frac{d\varphi_{qs}}{dt} + i_{qs}R_s - \varphi_{ds}\omega_e \quad (2)$$

where, v_{ds}, v_{qs} are d and q-axis stator voltages, i_{ds}, i_{qs} are d and q-axis stator currents, φ_{ds} , φ_{qs} are d and q-axis stator flux linkages, R_s is the resistance of stator, ω_e is the synchronous electrical angular speed. The proposed FOC strategy incorporates several key components, including proportional-integral controllers for current regulation, Clarke and Park transformations for converting three-phase currents into a two-axis rotating reference frame, and space vector pulse width modulation for inverter switching control. To ensure accurate transformation and synchronization, a rotor flux angle estimator—implemented using either a sensor or observer—is employed.

This control architecture is well-suited for high-performance applications such as EVs, industrial drives, and robotics, offering rapid transient response, high torque precision, and reduced torque ripples. By aligning the control reference frame with the rotor flux vector, FOC enables independent and precise control of torque and flux. This decoupling improves the system's efficiency and dynamic performance under varying load conditions. MATLAB/Simulink simulation results validate the effectiveness of the proposed control method. The

FOC-based system demonstrates superior performance in torque control, dynamic response, and overall reliability when compared to traditional scalar control methods, such as voltage/frequency (V/f) regulation. These improvements make the proposed FOC approach a compelling solution for modern, energy-efficient EV propulsion systems.

B. Induction Motor Monitoring Using IoT unit

To enable real-time management and monitoring of the EV's motor drive system, the proposed architecture integrates an IoT based monitoring framework. The EV is equipped with multiple sensors that continuously track key parameters such as motor speed, voltage, current, temperature, and battery state of charge. This sensor data allows the EV's performance to be monitored and adjusted in real time. An embedded microcontroller or gateway unit processes the incoming sensor data and transmits it using wireless communication protocols (such as Wi-Fi, LTE, or LoRa) to a central server or cloud platform. This centralized system receives, stores, and analyzes the data, enabling remote monitoring and control of the EV's motor drive system from virtually any location via a web interface or mobile application.

The data collected provides valuable insights into the EV's operational status and energy efficiency. When combining with machine learning algorithms, the system can predict maintenance needs, optimize performance, and enhance energy usage patterns. Users can personalize settings such as charging schedules and energy-saving modes to extend driving range and minimize energy waste. Figure 2 illustrates the IoT-based monitoring architecture for the induction motor used in the EV system.

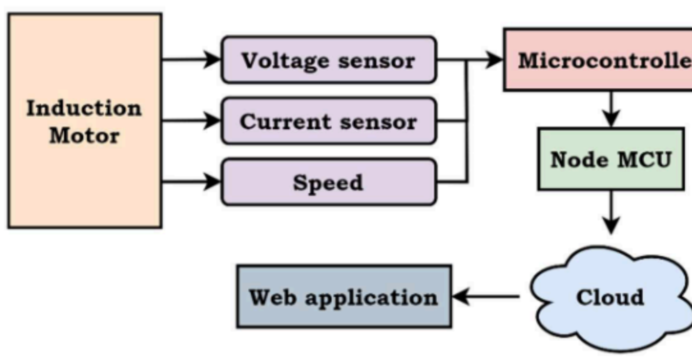

Fig. 2 IoT monitoring of induction motor

The microcontroller unit implemented using an Arduino UNO board processes sensor data based on predefined instructions. This processed data is then transmitted to a NodeMCU module, which serves as the communication gateway. The NodeMCU displays the data locally and simultaneously uploads it to a cloud-based platform, specifically ThingSpeak, for remote access and real-time monitoring. Gateways such as the NodeMCU can be built using hardware, software, or a hybrid combination, depending on the application requirements.

In EVs, the motor drive is a critical component required for propulsion. It must deliver precise speed and torque control without compromising efficiency or reliability. Continuous monitoring of parameters such as vibration, current, and temperature is essential to detect abnormalities and prevent system failure. According to an IEEE survey, 44% of motor faults originate in the bearings and

24% in the stator. Bearing failures are often indicated by increased vibration and temperature, typically caused by improper installation or inadequate lubrication. Therefore, a combination of current sensors, temperature sensors, and vibration sensors is employed to detect and diagnose these faults in advance.

IV. RESULTS AND DISCUSSIONS

The proposed system integrates solar PV energy, FOC for induction motor control, and IoT-based monitoring was developed and tested in the context of an EV application. The integration of solar PV energy significantly enhanced the energy efficiency of the EV motor. By supplementing the battery pack's power supply, the solar PV panels contributed to a reduction in the overall energy consumption of the EV. Furthermore, the use of the FOC technique optimized the induction motor drive's performance by maximizing torque output and minimizing power losses, resulting in improved operational efficiency. Key parameters such as rotor speed, voltage, and current were continuously monitored using IoT-based technology. Figure 3 presents the rotor speed profile of the induction motor as measured through the IoT monitoring system.

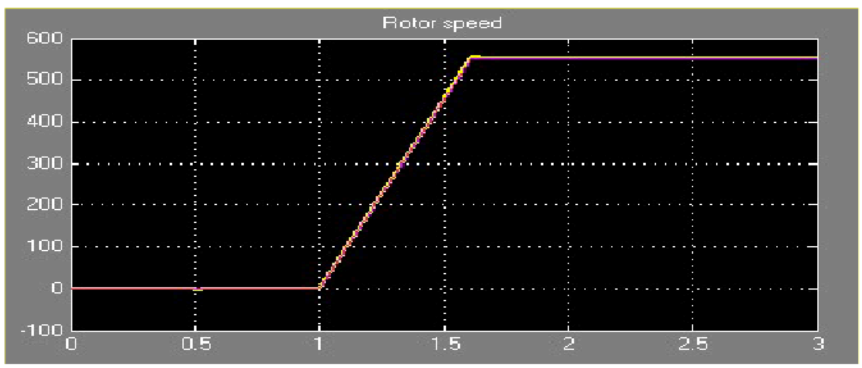

Fig. 3 Induction Motor Speed

The speed of the induction motor is monitored and reaches 550 RPM after 1 second. The integration of solar PV energy extends the EV range, enabling longer trips between charging intervals. Real-time data from the IoT monitoring system such as battery state of charge and energy consumption allows users to adjust their driving behaviour to maximize range. Figure 4 illustrates the MATLAB simulation of the FOC-controlled induction motor drive system.

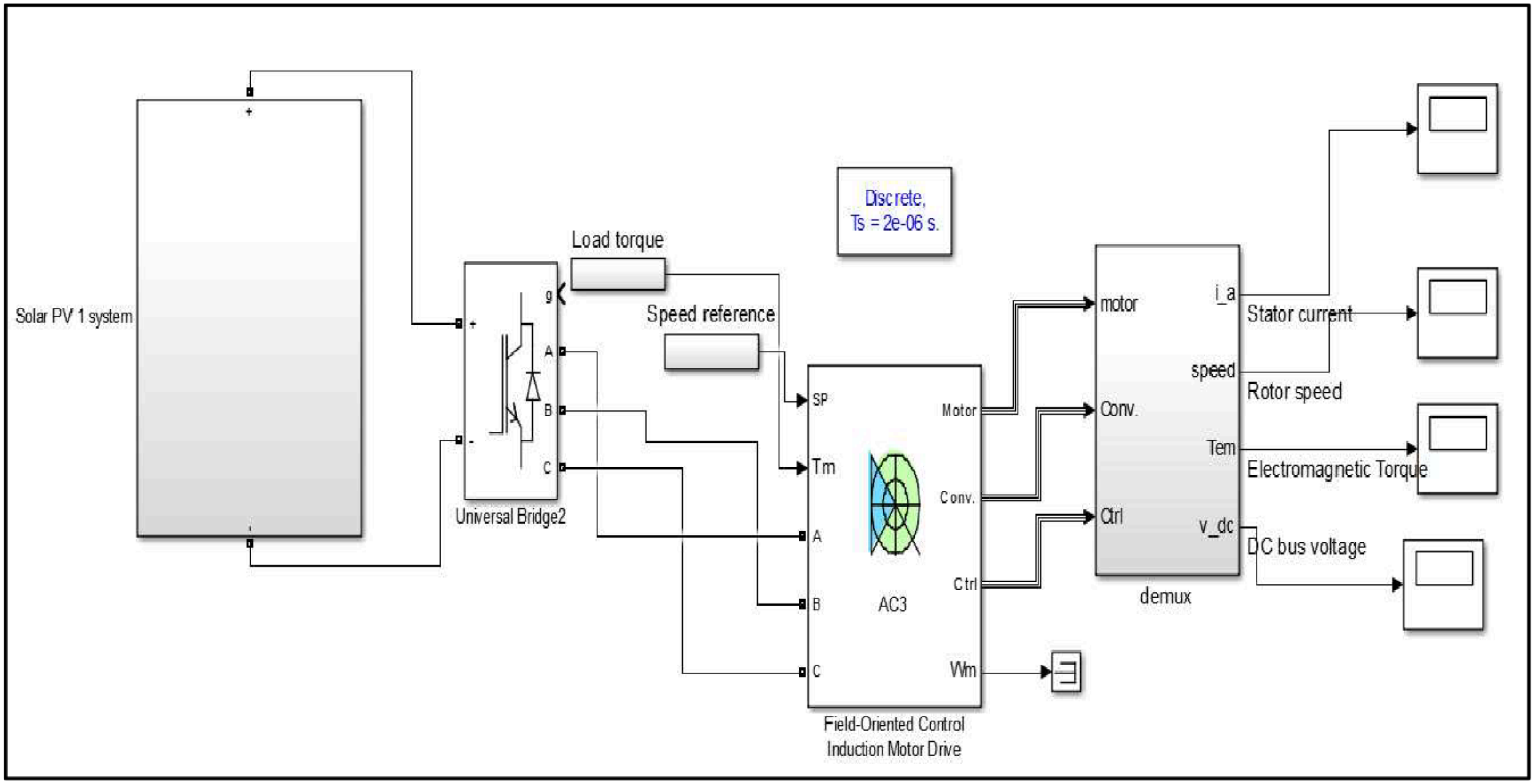

Fig. 4 Simulation of FOC-controlled induction motor drive

The FOC algorithm maintains a constant speed by dynamically adjusting the supply voltage and frequency to the motor based on load variations. Voltage regulation ensures optimal operation and prevents overvoltage or undervoltage conditions. To meet the motor's torque and speed demands, the FOC controller modifies both the amplitude and phase of the supply voltage. It also regulates the stator current to ensure optimal torque generation while preventing overheating. The FOC controller adapts the stator current's amplitude and phase based on real-time speed and load conditions. Figure 5 shows the DC bus voltage, and Figure 6 illustrates the stator current of the induction motor.

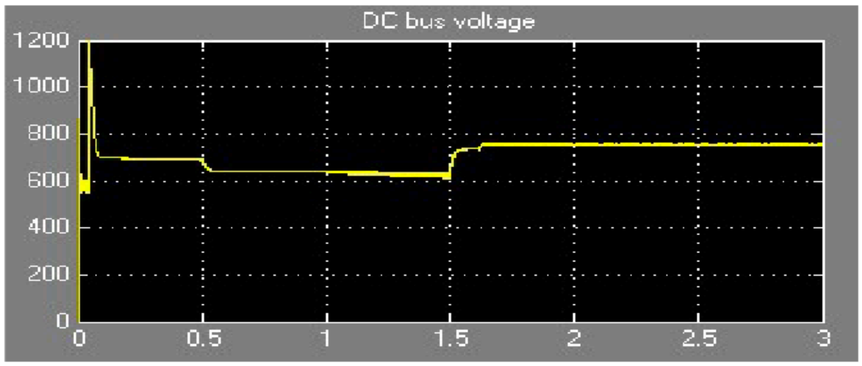

Fig. 5 DC bus Voltage

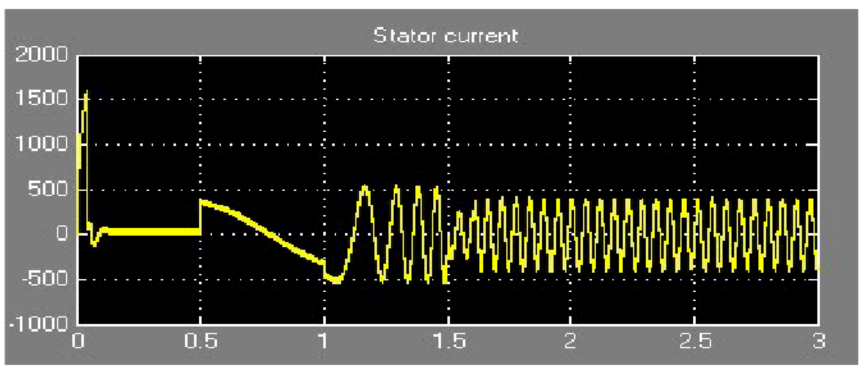

Fig. 6 Stator Current Monitored by IoT

V. CONCLUSIONS

The proposed system has demonstrated effectiveness in enhancing energy savings, extending driving range, and promoting overall sustainability through evaluation and implementation. The integration of solar PV energy significantly increases the EV's range while reducing dependence on grid-based power, thereby lowering greenhouse gas emissions and minimizing the vehicle's environmental impact. The use of FOC optimizes the performance of the induction motor drive system, resulting in improved energy efficiency and increased torque output. The incorporation of an IoT-based monitoring system allows real-time measurement of key motor parameters, potentially replacing conventional predictive control techniques. This real-time feedback enables early detection of motor faults, operational disruptions, and component degradation, thereby enhancing system reliability and reducing maintenance needs. While further research and development are essential to optimize the system's scalability and efficiency for large-scale deployment in the EV sector, the integration of solar PV energy, FOC motor control, and IoT monitoring marks a significant advancement toward sustainable and intelligent transportation solutions.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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