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Design and implementation of IoT-based soft starter for induction motor

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ABSTRACT

The practical application of the induction motor is an essential part of electrical engineering. A direct connection of the motors to the mains voltage negatively affects both the motor itself and the mains system as a whole due to high starting current values, as a result, more accidents and shortening the drive system service life. This article discusses the development of designing and implementing of soft starter single-phase IM to reduce the inrush current using the firing angle reduction technique with remote monitoring and control using the ESP32 (node MCU) and Arduino Due microcontrollers. The integration of IoT-based tools software such as VS Code, enables the remote monitoring and control of motor features. Testing shows that the system effectively facilitates remote motor control, providing a flexible and accessible learning environment with minimum starting current, solving the inrush current problem facing IMs. The proposed soft starter gives three cases of firing angle reduction that show a percentage reduction in starting current for these cases (case I, case II, and case III) are 51%, 54% and 64%, respectively. Case III has a maximum starting current is 2.2 A compared to 6.2 A for direct connecting of IM to the power supply (DOL).

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1. INTRODUCTION

Electric motors are used in many industries. They account for about half of the overall consumption of electricity (more than 40% of consumed electrical energy in the world, it is largely used in electrical systems and networks like pump drives and fans [1]. But they have many challenges like high accelerating torque and large starting currents (about 5 to 7 times the rated current of the motor [2]. In high torque acceleration, the motor reaches the full load motor speed in a very short time, and this may damage the operation safety of the load [3]. Also, the high inrush current may cause various problems that affect the electrical installation [4]. A correlation was found between starting current and the load of the motor and since a motor usually requires a larger starting current to overcome inertia [5]. Soft starters mitigate these issues by gradually ramping up the voltage, thereby reducing the starting current and extending the motor's service life [6], [7]. Some researchers produce a soft starter to drive a 10 kV/19,000 kW 3-phase induction motor [8].

The soft starters used in induction motors deal with the challenges posed by high starting currents. Earlier, such as [6], found that gradually increasing the voltage will reduce inrush current and enhance system reliability [6], [9]. According to this, later works developed protective features for soft starter designs. For instance, a researcher used a microcontroller-based soft starter with overcurrent detection using Arduino ATMega16 [10]. In parallel, the IoT has transformed how motor control systems are monitored remotely.

Shukla *et al.* [11] show an IoT-based motor starter that enables wireless communication to monitor voltage and current parameters in real time, thus enabling remote diagnostics. Similarly, a researcher used an ESP32 module for real-time monitoring of industrial machines, providing a cloud connection for condition monitoring [12], [13]. On the design of the main circuit of the soft starter algorithm side, advanced strategies such as fuzzy proportional integral derivative (PID) control are applied to enhance the soft start process. A fuzzy PID control approach was proposed that minimizes both inrush current and torque pulsations [14]. Additionally, some research used multi-zone AC voltage converters as soft starters, and show improved voltage control and harmonic reduction [15] the proposed soft starter applied seamlessly transitions from direct frequency converter (DFC) to phase control, improving efficiency and current limiting without motor parameters requirement in [16], artificial neural network (ANN)-based soft motor acceleration control reduces inrush current using an open-loop design with fewer sensors [17]. For wireless monitoring of data, some used tools like ESP32, LabVIEW, Wokwi, and Adafruit IO for Remote three-phase motor wiring to enhance engineering remote education, safety, and accessibility [18]. Researchers used a programmable logic controller (PLC) and DIAView for the same purpose [19]. Meanwhile, the motor can be controlled after the voltage, current, and temperature of the induction motor have been monitored remotely with the Blynk IoT application [20].

IoT applications have been extended to include many scientific areas, such as evaluating the production equipment in power electronics like the smart earth leakage circuit breaker [21]. Others present a comprehensive model for the power consumption of wireless sensors [22], also IoT in healthcare, achieving interoperability of high-quality data acquired by IoT medical devices [23]. Furthermore, the internet of things enhanced business processes with, namely, IoT-enhanced BPs, which make use of IoT devices to carry out the tasks required to achieve a process's goal [24]. Others used the internet of things in forestry and environmental sciences [25].

While previous studies have dealt with different aspects of soft starting and IoT monitoring separately, this work integrates both of them into a unified system. We design a soft starter circuit using a zero-cross detector (ZCD) circuit, a triode for alternating current (TRIAC) driver, TRIAC, and an Atmel Due microcontroller, along with a split-core current transformer (SCT) and tachometer sensors. By integrating the Arduino integrated development environment (IDE) with Visual Studio Code, plot real-time data for starting current and motor speed, testing different firing angles, and selecting the best according to performance. Also, test sensor calibration by using Excel to plot the terminal output and CT reading. Finally, to enhance the system's usability in real-world industrial settings, the integration of a NodeMCU enables remote data transmission and control over the internet. This proposed research provides a robust soft starter design and offers real-time monitoring and remote control, solving the existing gap in the current literature review.

2. METHOD

2.1. Soft starter circuit design

The soft starter circuit in this study is designed to gradually increase the voltage applied to single-phase induction motors so that it reduces the inrush current and mechanical stress during startup. The components of the circuit include: ZCD Circuit (The ZCD circuit is responsible for accurately detecting the moment when the AC voltage crosses zero). TRIAC Driver and TRIAC (The TRIAC driver receives the trigger signal from the microcontroller and amplifies it to a level suitable for driving the TRIAC. By adjusting the firing angle of the TRIAC, the circuit can regulate the effective voltage supplied to the motor during startup. Microcontroller **(**the Atmel Due microcontroller (Atmel Due) forms the core of the control system. It processes the signals from the ZCD circuit and various sensors, calculates the appropriate firing angles, and generates the trigger pulses for the TRIAC driver. Also, the microcontroller saves sensor data like current and speed for monitoring and calibration. Sensor modules include a current transformer (SCT-013 100 A) to measure the motor's current. Its output is applied to the microcontroller. Tachometer (SJA12-10N1) The tachometer provides the motor's revolutions per minute (RPM). NodeMCU For remote monitoring via IoT, a NodeMCU module is integrated with the Atmel Due. The NodeMCU collects buffered sensor data from the microcontroller and transmits it over the internet. This data is then plotted in real time on the VS Code terminal for the first 20 seconds, where start and stop commands are also available for remote control. Single-phase IM as a load. Circuit breaker for protection 12, 9, and 3.3 V DC power supply to supply voltage to the tachometer, due microcontroller, and NodeMCU respectively. Figures 1 and 2 show the wiring diagram and the experimental diagram of the proposed system, respectively.

2.2. Firing angle testing and calibration

Different firing angle styles were tested to evaluate the soft starter's performance under various conditions. The procedure involved programming the microcontroller to adjust the firing angle over a known range. Then, recording the corresponding motor current and RPM for each firing angle. Then exporting terminal outputs from VS code to Excel with 4 times repeating of results, this could ensure analyzing the data and verifying sensor readings, and allow for the calibration of the CT and the speed sensor. And finally, selecting the firing angle rhythm that provided the smoothest startup performance. Additionally, the CT output was measured under various load conditions, the corresponding voltage readings were exported to Excel, and the readings were also repeated 3 times.

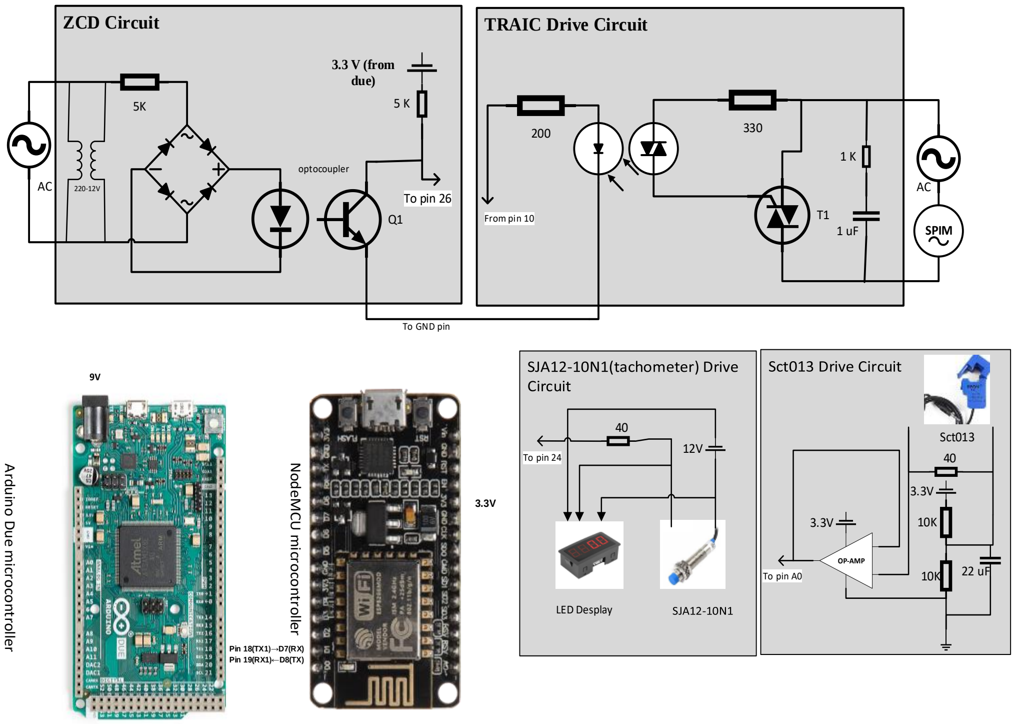


Figure 1. The wiring diagram of the proposed system

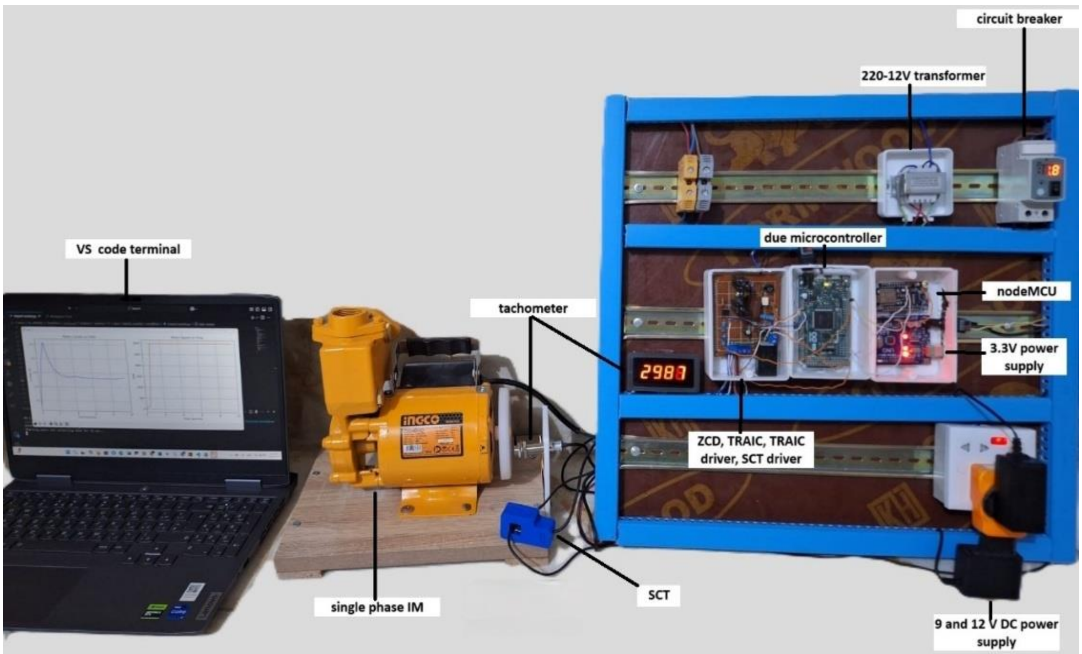


Figure 2. The experimental diagram of the proposed system

2.3. Integration of Arduino IDE with VS Code for real-time data plotting

For real-time visualization of motor performance, the project uses VS Code as a development environment integrated with the Arduino IDE. This integration was achieved through wired, where Serial Communication Setup was used. The microcontroller was programmed to send sensor data (e.g., starting current and RPM values) by serial communication. VS Code's built-in serial monitor was configured to capture these data streams in real time, and then the received data was plotted. Custom scripts within VS Code parsed the serial data, ensuring that the readings were displayed in a readable format, which allows for export and calibration using Excel. And wireless by integration of NodeMCU with Atmel Due for remote data transmission and control. To enable remote monitoring and control of the soft starter system, a NodeMCU module was integrated with the Atmel Due microcontroller. The NodeMCU's software includes routines to check for data from the Due. In addition to transmitting sensor data, it also supports remote control commands (such as start and stop signals) received over the network. These commands are sent from a remote interface (VS Code terminal) and then forwarded by the NodeMCU to the Due via the serial1 communication. Connect D7 NodeMCU RX to pin 18, TX1 in DUE, and D8 NodeMCU TX to pin 19, RX1 in DUE. This bidirectional communication allows for both real-time data monitoring and remote control of the soft starter system.

3. EXPERIMENTAL RESULTS

To validate the performance of the proposed soft starter system, the results were analyzed in several ways. During the soft start tests, sensor data were captured by the microcontroller and transmitted to the VS Code terminal. Figures 3 and 4 display the starting current root mean square value (RMS) and speed of the motor in revolutions per minute (RPM) for direct on line (DOL) and soft starting circuit, respectively. These graphs illustrate how the current initially spikes when the motor is directly connected, and how it is significantly reduced when using the soft starter with optimized firing angle.

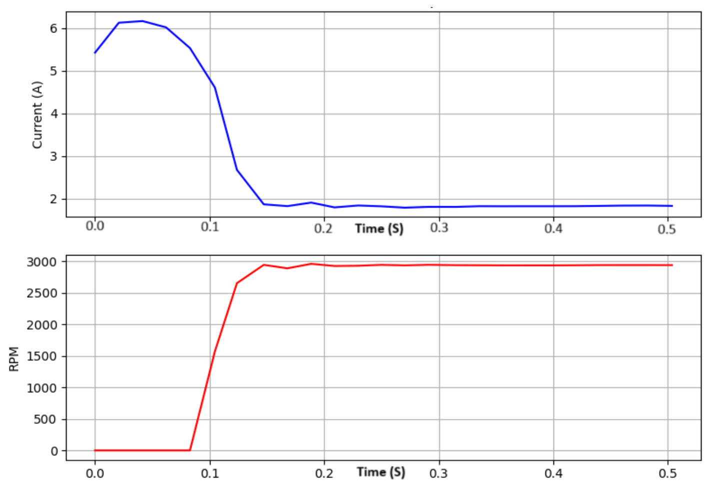


Figure 3. DOL RMS current and speed in RPM

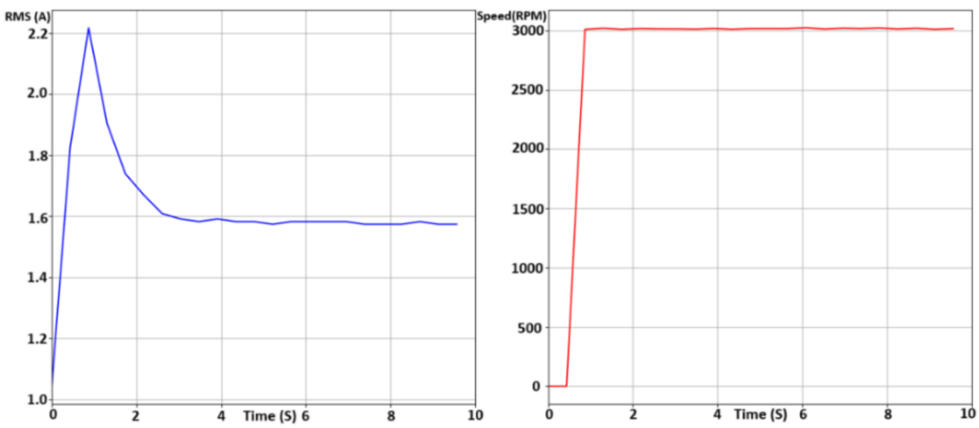


Figure 4. Soft starter RMS current and speed in RPM

Varying the firing angle in predetermined increments and recording the corresponding motor response. Figure 5 shows the motor current waveforms profiles for three different firing angle cases. Case I is shown in Figure 5(a), the firing angle slowly decreases with 0.09 degree per cycle, while in case II in Figure 5(b) the firing angle decrease with 0.09 degree per cycle with condition states that if the current exceeds 2.2 A the firing angle pauses decreasing for 1 second, as stated in (1).

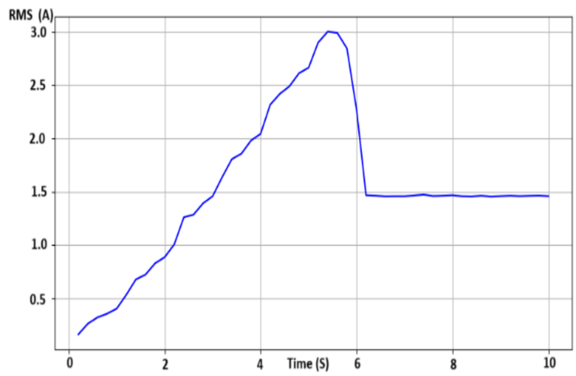
$$a_{k+1} = \begin{cases} a_k - 0.09^0 & I_k < 2.2A \\ a_k & I_k > 2.2A \end{cases} \quad (1)$$

Finally, case III is shown in Figure 5(c) the firing angle will reduce 0.4 degree per cycle and if the current does not exceed 2 A and it increasing with 1 degree per cycle if it exceeds 2 A, this happens until motor current fall below 2 A then it continues reducing the firing angle with same value (0.4 degree per cycle), as shown in (2).

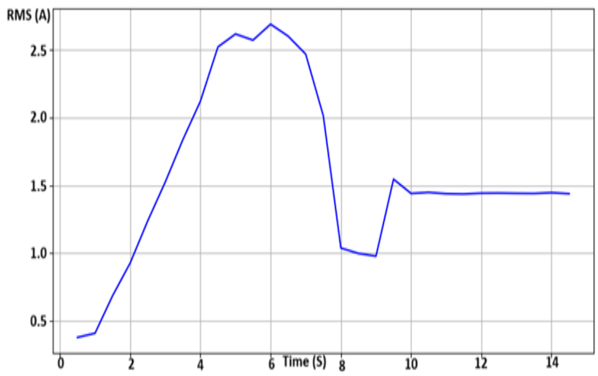
$$a_{k+1} = \begin{cases} a_k - 0.4^0 & I_k < 2.0A \\ a_k + 1.0^0 & I_k > 2.0A \end{cases} \quad (2)$$

Where $a_{k+1} = next\ firing\ angle, a_k = present\ firing\ angle, I_k = present\ RMS\ current$. The optimal setting is identified by the smoothest current waveform, as seen in case III. Based on (3) the percentage reduction in starting current for case I is 51%, in the same way can conclude that the II and III is 54% and 64%, respectively.

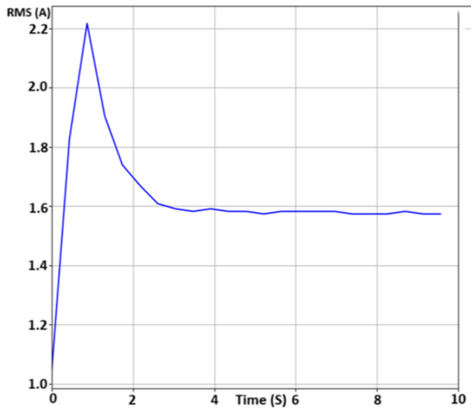
$$Reduction\% = \frac{I_{DOL.max} - I_{Soft\ start.max}}{I_{DOL.max}} \quad (3)$$



(a)



(b)



(c)

Figure 5. Motor RMS current waveforms profiles for three different firing angle cases: (a) motor RMS current for case I, (b) motor RMS current for case II, and (c) motor RMS current for case III

Current sensor calibration for the purpose of calibrating the data from VS Code and further verifying sensor readings, VS Code program provides the ability to export the samples in the terminal to

Excel. The reading was repeated 4 times to ensure proper calibration results, which allowed for the calibration of the current transformer. Figure 6 shows calibration results of RMS current for the data shown in Figure 5(c) at four different iterations.

The current transformer (CT) output was measured under various load conditions, the corresponding voltage readings were exported to Excel. The calibration curve as shown in Figure 7 plots the CT output voltage against known load values and the results are repeated 3 times. The curves show 5.7%, 6.1%, and 5.4% error, respectively which are considered acceptable values for real time measurements rate of error.

The study shows that the suggested system reduces peak starting current (2.2 A) as compared with DOL, which is reached about 6.2 A. As a result less motor stress and more stability for the power network, as shown in case III. The system shows smooth acceleration for the same case, because the speed reaches its steady state at 1 second, as compared with DOL which requires 0.15 seconds only. Also, IoT integration using a NodeMCU microcontroller provides successful remote monitoring and control of the motor. Besides, the system offers improvements for the existing systems because in previous systems used either design a soft starter or IoT based control of induction motor while in the proposed system its includes both.

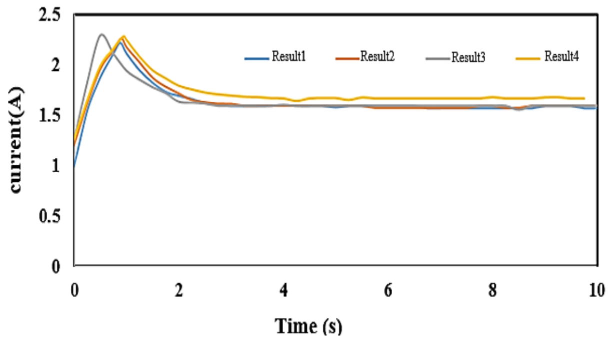


Figure 6. Calibration of SCT sensor at different iterations

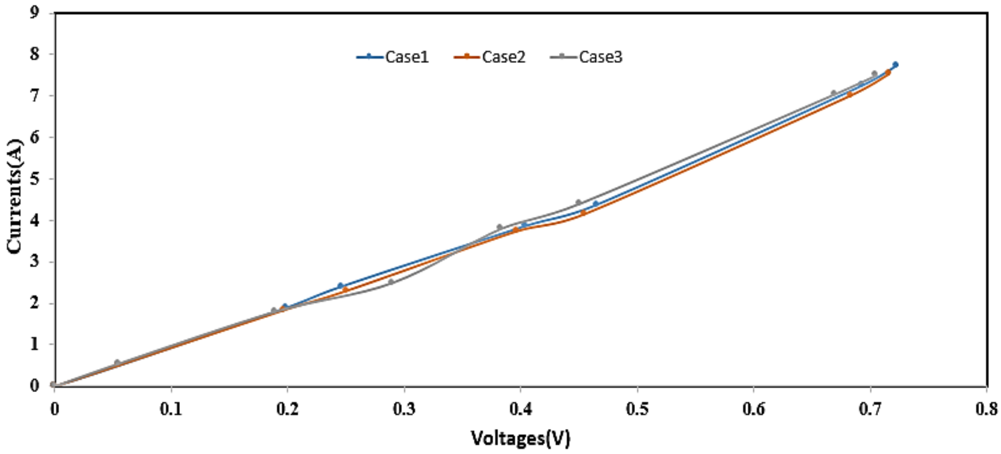


Figure 7. Calibration of SCT sensor at different loads

4. CONCLUSION

This article presented a complementary design and implementation of IoT-enabled and controlled single-phase induction motors. The system includes a ZCD circuit, TRIAC driver, TRIAC, and an Atmel Due (microcontroller) with sensor modules for rms current and rpm speed, show obvious decreasing in the inrush current and smoother motor acceleration compared to DOL starts. The calibration of sensors data is done using VS Code and Excel ensuring accurate measurement of current and RPM, while the NodeMCU enables effective remote monitoring and control. The experimental results show that the optimized firing angle minimizes current spikes at the starting period, so that enhancing both motor long life and operational efficiency. This technique not only with current research but also extends to integrating IoT capabilities into motor control applications. Future work should focus on refining the latency of communication between the NodeMCU and the microcontroller, automating and advancing the sensors calibration process, and searching for more advanced control algorithms to further optimize the soft starter performance that can give better results.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Laith Najem Abood Khudhur	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓
Amer Abdulmahdi Jabbar Chlaihawi	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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