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Improving Robustness and Dynamic Performance of Sensor less Vector-Controlled IM Drives with ANFIS-Enhanced MRAS

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ABSTRACT- The Model Reference Adaptive System (MRAS) enables effective speed control of sensorless Induction Motor (IM) drives at zero and very low speeds. This study aims to enhance the resilience and dynamic performance of MRAS by integrating an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller into sensorless vector-controlled IM drives. To address issues related to parameter uncertainties, load variations, and disturbances, the combination of MRAS and ANFIS is investigated. The ANFIS controller improves the dynamic performance by adapting its parameters based on the error between estimated and measured rotor speeds. This allows for better tracking of the reference speed and smoother drive operation. The proposed MRAS scheme with ANFIS reduces the sensitivity of the sensorless control system to parameter variations, such as changes in motor parameters or load torque, thereby enhancing stability. The primary goal of this system is to maintain stability and reduce the impact of parameter variations on the sensorless control system. The performance of the proposed system is evaluated using the MATLAB platform and compared with existing systems. Results indicate that the ANFIS-enhanced MRAS offers superior dynamic performance and robustness, making it a viable solution for applications requiring precise speed control and high reliability.

Keywords: Sensorless Vector, Model Reference Adaptive System, Induction Motor Drive, Adaptive Neuro-Fuzzy Inference System Controller, Neural Networks.

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1. INTRODUCTION

One of the most widely utilized motors in applications these days is the AC induction motor. With the ability to transfer between 70 and 80 percent converts all electrical energy into mechanical form, induction machines represent the most significant class of industrial electrical machines. In the realm of electric cars, the training of Induction Motors with SMC has gained significant importance [1-2]. Numerous investigations have substantially demonstrated the efficiency of the SMC, which is resilient against disruptions and fluctuation in parameters [2-3]. In the event of extremely powerful oscillations, which result in the chattering phenomena, it is still limited [3,4,6]. A mechanical sensor must be installed to measure the speed of both the electrical vehicle and the induction machine [7-8]. Nevertheless, there is an additional expense associated with the addition of this sensor that may be comparable to the machine's cost. It follows that a good way to solve this issue would be through sensor less control. Low speed, however, presents a challenge for speed estimate [9]. Researchers and engineers have known since the early work on the order sensor-less with state observers that under some operating situations, especially at low speeds, the control's performance declines [10].

The purpose of the ANFIS controller is to enhance the sensor less vector-controlled IM drive's dynamic performance by adjusting its settings in response to the discrepancy between the observed and estimated rotor speeds. Better monitoring of the reference speed and more seamless drive system functioning are guaranteed by this adaptive technique. Additionally, the sensor less control system's sensitivity to parameter variations such as adjustments to motor settings is decreased by the suggested MRAS scheme with ANFIS.

2. METHODOLOGY

The usage of Neural Networks removes the requirement for a precise mathematical representation of a system, but selection of count of hidden layer neurons are a challenging task since it mostly affects the performance of system. Fuzzy logic controller is a non-linear optimizer, it can be used to a substitute for PI controller, but it requires human expertise and experience for the design of the controller. To overcome the drawbacks and limitations of fuzzy and NN controllers discussed so far, the ANFIS controller is proposed under this manuscript. The benefits of both fuzzy and ANN controllers are combined in the ANFIS controller, it acts as a robust controller. Induction Motor (IM) drives must be controlled to satisfy industry requirements for torque and speed. These devices do, however, have a commutator that corrodes, sparks, and needs regular repair. The advancement of digital signal processing and power semiconductor technology has made AC motor drives competitive substitutes for DC motor drives. However, because IM is a singly stimulated machine, controlling it is challenging. The workflow model shown in the below *figure 1*.

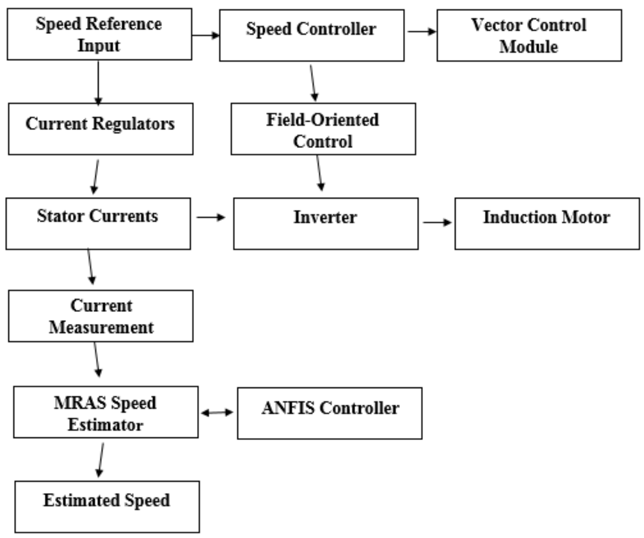

Figure 1. Workflow Model

System Workflow

- *Initialization*: The system initializes the MRAS and ANFIS controller with initial parameters.
- Input Measurement: Stator currents and voltages are measured and fed into the vector control module.
- *Vector Control Execution*: The vector control module processes the inputs to generate the required current components for torque and flux control.
- *MRAS Speed Estimation*: The MRAS uses the stator current measurements to estimate the rotor speed, comparing the reference and adaptive model outputs to generate an error signal.
- *ANFIS Adaptation*: The ANFIS controller receives the error signal and adjusts the adaptive model parameters to minimize the error.
- *Speed Control*: The speed controller generates torque commands based on the difference between the reference speed and the estimated speed.
- *Inverter Operation*: The inverter converts these commands into appropriate voltages to drive the IM.
- *Performance Monitoring*: The system continuously monitors performance metrics and compares them to evaluate improvements over traditional systems.

3.1 System Design and Integration

3.1.1 Model Reference Adaptive System (MRAS) Setup

Using stator current measurements and preset motor settings, the reference model models the optimal dynamic behavior of an induction motor (IM). In order to reduce the error with the reference model, the adaptive model continually modifies its parameters to estimate the rotor speed. The error signal that results from the variations between the reference and adaptive models is used by the adaptation process.

3.1.2 Adaptive Neuro-Fuzzy Inference System (ANFIS) Implementation

Input Layer Design: Inputs to the ANFIS include the error between estimated and measured rotor speeds, stator currents, and any other relevant operational variables.

Fuzzy Inference System (FIS) Development: The FIS is designed with fuzzy rules and membership functions that capture the non-linearities and uncertainties of the control process.

Neural Network Integration: The neural network layer in ANFIS updates the parameters of the FIS based on learning algorithms, which adapt to changes in the input-output data.
Output Layer Configuration: The output layer generates control signals that adjust the adaptive model parameters in MRAS, aiming to minimize the error signal and enhance system performance.

3.1.3. Modeling of IM Drive

The modeling of IM is necessary for torque and flux control [28]. By using the stationary reference frame the motor is modeled. By using the dynamic modeling the performance characteristics of motor is analyzed. The modeling of IM considered the variables like voltage, current, frequency, and speed. The stator and flux connection matrix is defined as follows: k num rotor bars and k num stator circuits in the common IM.

$$[V_{Sta}] = [R_{Sta}][I_{Sta}] + \frac{d[\zeta_{Sta}]}{dt} \quad (1)$$

$$[V_{Rot}] = [R_{Rot}][I_{Rot}] + \frac{d[\zeta_{Rot}]}{dt} \quad (2)$$

$$[\zeta_{Sta}] = [L_{l,Sta}][I_{Sta}] + [L_{l,Rot}][I_{Rot}] \quad (3)$$

$$[\zeta_{Rot}] = [L_{l,Sta}][I_{Sta}] + [L_{l,Rot}][I_{Rot}] \quad (4)$$

Where, V_{Sta} is denoted as the stator voltage, R_{Sta} is denoted as the stator resistance, I_{Sta} is denoted as the stator current, ζ_{Sta} is denoted as the stator flux, V_{Rot} is denoted as the rotor voltage, R_{Rot} is denoted as the rotor resistance, I_{Rot} is denoted as the rotor current, ζ_{Rot} is denoted as rotor flux, $L_{l,Sta}$ is denoted as stator leakage resistance, $L_{l,Rot}$ is denoted as the rotor leakage resistance

$$[I_{Sta}] = [I_{Sta1} I_{Sta2} \cdots I_{Sta,k}]^T \quad (5)$$

$$[I_{Rot}] = [I_{Rot1} I_{Rot2} \cdots I_{Rot}]^T \quad (6)$$

$$[V_{Sta}] = [V_{Sta1} V_{Sta2} \cdots V_{Sta,k}]^T \quad (7)$$

If IM refers, squirrel-cage machine then $[V_{Rot}] = 0$, $[L_{Rot,Sta}] = [L_{Sta,Rot}]^T$. The mathematical modeling in α-β axis of IM is defined as follows,

$$\frac{d\zeta_{\alpha Sta}}{dt} = -R_{Sta} I_{\alpha Sta} + v_{\alpha Sta} \quad (8)$$

$$\frac{d\zeta_{\beta Sta}}{dt} = -R_{Sta} I_{\beta Sta} + v_{\beta Sta} \quad (9)$$

Flux linkage of the stator is described by,

$$\zeta_{Sta} = \frac{L_{Mag}}{L_{Rot}} \zeta_{Rot} + \frac{I_{Sta}}{\gamma L_{Rot}} \quad (10)$$

$$\gamma = \frac{1}{(L_{Sta} L_{Rot} - L_{Mag}^2)} \quad (11)$$

3.2. Improve Dynamic Performance of ANFIS based MRAS System for Sensor-less Vector Controlled IM Drive

In this section, proves the better dynamic performance of ANFIS based MRAS system for sensorless vectors controlled induction motor drive. Premise and consequence are the two distinct parameter groups in the ANFIS framework. Determining these parameters using an optimization technique is known as ANFIS training. Jang introduced a mixed learning strategy for training in his initial ANFIS model. In this method, the least squares estimation (LSE) method is used to find the consequence parameters, while gradient descent (GD) is used to discover the premise parameters. Since its creation, ANFIS has been used to model and identify a wide range of systems, with positive outcomes. Choosing the right optimization technique for training is crucial to using ANFIS effectively. Derivate-based algorithms (GD, LSE, etc.) and non-derivative-based algorithms (heuristic algorithms, as GA, PSO, ABC, etc.) are are used in ANFIS training.

However, a recent trend toward heuristic-based ANFIS training algorithms for improved performance has been noted. It appears to be suggested in hybrid algorithms that are heuristic and derivative based at the same time. The heuristic and hybrid methodologies used in ANFIS training are studied within the parameters of this study to aid researchers in their investigation. Furthermore, an evaluation of the final state of ANFIS training is conducted with the intention of illuminating future research endeavors pertaining to ANFIS training.

3.2.1. Neuro-Fuzzy control

The presentation of the Neuro-Fuzzy ANFIS combines Neural networks' capacity for learning with the knowledge representation of fuzzy logic to provide concepts for controlling and observing different aspects of the IM system parameters. This work presents the construction of the control strategy employing the concepts of the ANFIS control scheme for the regulation of the speed observer. The error and the error change are inputs used by the ANFIS controller. The second controller ANFIS's Vsq.n, the third controller ANFIS's speed observer, and the first controller ANFIS's modified reference Vsd.n are the outputs. The neural network block is linked to the rule base block. The NN is trained to choose the appropriate collection of rule bases using the back propagation algorithm. The ANFIS controller receives the inputs that have been fuzzified using the fuzzy sets. The back-propagation algorithm has the benefit of being simple to comprehend and having a wide range of successful applications [11]. This method is based on error back propagation and computes the weight changes layer by layer, beginning with the previous layer and working backward [12]. For control, the error back-propagation training algorithm-based neuro-fuzzy system is employed [13]. The final approach uses a mean square error cost function reduction through the use of the gradient descent search strategy.

4. RESULT AND DISCUSSION

Figure 2 displays the real-time experimental setup. From which, the linearized IMD with ANFIS and proportional integral torque controller can be examined. Real-time validation is performed on the proposed ANFIS-based linearized controlled IMD system. The real motor line voltages and currents are measured using Hall-effect current and voltage sensors. An A/D channel transmits the data to the DSP board. Speed encoders measure rotor speed. The DSP board yields the hysteresis current controlled the signals of pulse width modulation, which must be fed to the switches of the 3-phase voltage source inverter. An induction motor is attached to a direct current -motor shaft for obtaining the load perturbation necessary for analysing the torque. Next, the armature-circuit's load-shaft is altered by increasing resistance. An oscilloscope is used to observe all test variables, except for current. The design of the ANFIS controller does not require any human intervention for the development of fuzzy rules. Gbell membership function is used for 2 inputs namely error, difference of the error is exposed in *figure 3*.

Figure 2. Experimental set-up

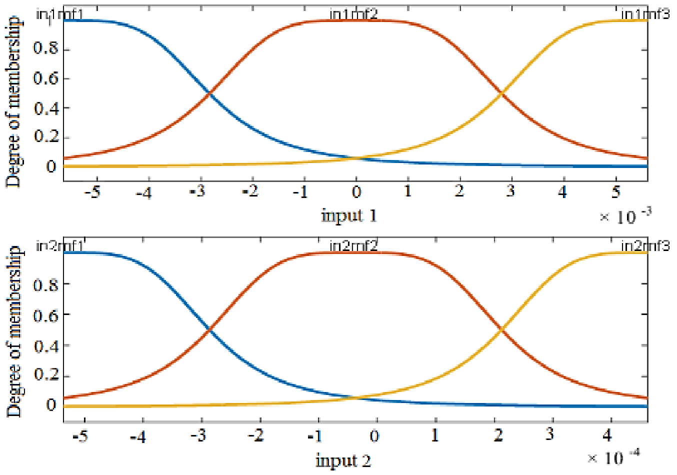

Figure 3. Membership functions of inputs

Here, the ANFIS controller Training stage is displayed in *figure 4* and *figure 5* shows the completion of training and its output. Finally, the developed ANFIS structure and surface viewer are depicted in *figure 6* and *figure 7* respectively.

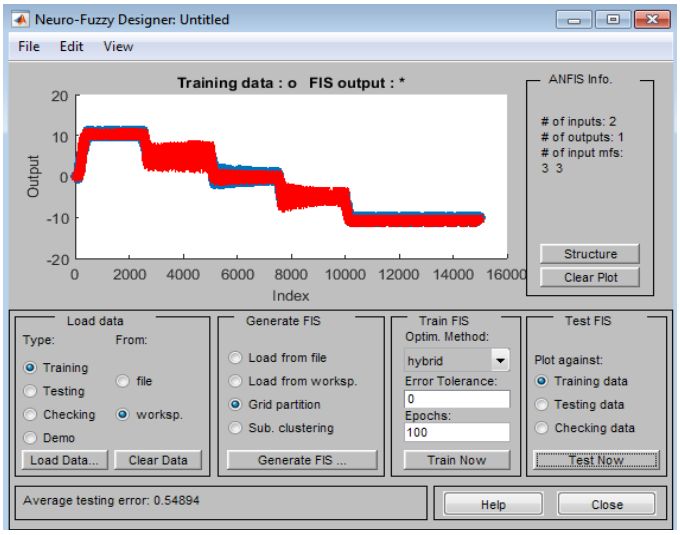

Figure 5. ANFIS training

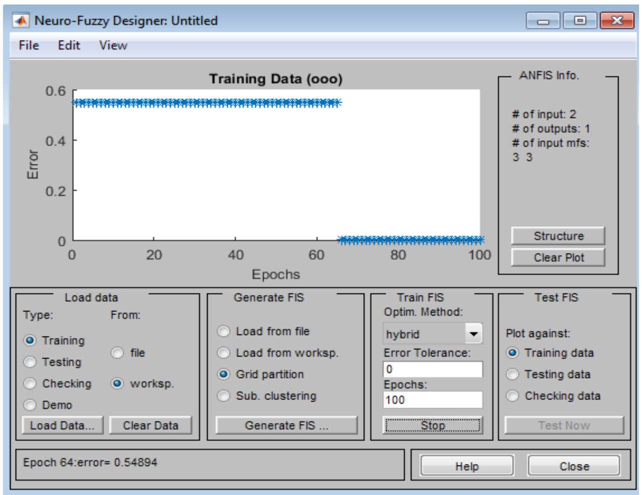

Figure 6. ANFIS training output

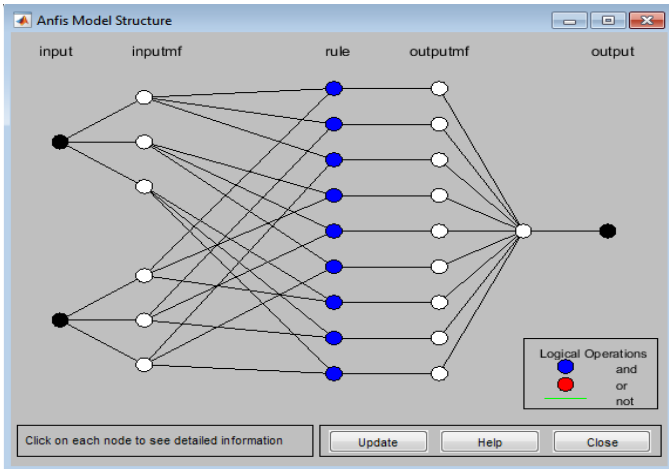

Figure 7. ANFIS structure

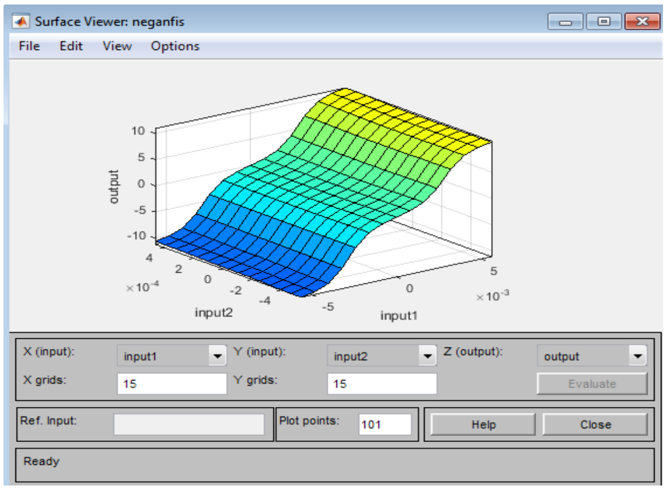

Figure 8. ANFIS surface viewer

Here, the ANFIS based MRAS scheme is applied at sensorless vector controlled IM drive and efficiency is estimated. Furthermore, the dynamic characteristics, robustness properties are presented, and then it is associated by using PI controller. The PI controller design coefficients are selected by trial, error method in like as, the output settled as is rapidly probable. The values are K_p= 0.9, K_i=8.1. *Table 1* illustrates the ratings and parameters of the IM.

Table 1. Ratings and Parameters of the IM

Parameter	Values
Nominal Power P	0.75 kW
Frequency f	50 Hz
Voltage V	416 V
Rotor Resistance R_r	7.5297 Ohm
Stator Resistance R_s	12.6 Ohm
Stator leakage Inductance L_{ls}	0.01671 H
Rotor leakage Inductance L_{lr}	0.01671 H
Pole Pairs P	2
Mutual Inductance L_m	0.53713 H
Moment of Inertia J	0.01225 kg m^2
Rated Torque T_e	5.1 Nm
Rated Speed N	1415 rpm
Rated Current I	1.8 A

The proposed ANFIS controller has two main objectives namely better dynamic performance like minimum settling time, peak overshoot, and robustness. Then, the proposed ANFIS based sensorless vector controlled IMD simulated using MATLAB/SIMULINK. Here, the speed overshoot and the settling time minimized below diverse operating regions including low and zero speed regions. To study this performance of ANFIS controller, four important tests performed on test drive, likened with a conventional PI controller. Here details and explanations of the tests presented.

Table 2. Comparison of simulation and experiment results

Techniques	Efficiency (%)	
	Experimental results	Simulation results
PI based MRAS	98.75	98.901
ANFIS based MRAS	99.146	99.764

Table 3. Comparison of Torque and flux ripple

Switching techniques	Performance comparison			
	Reference torque	Torque ripple		Flux ripple
		Nm	Pu of mean torque	
DTC drive	1.0	0.7431	2.32	0.0199
	1.3	0.59	0.91	0.0144
	1.5	0.6156	0.8347	0.0136
	1.7	0.7855	1.13	0.0145
ANFIS	1.0	0.1962	0.2290	0.0135
	1.3	0.2084	0.1740	0.0136
	1.5	0.2499	0.27	0.0130
	1.7	0.2383	0.2072	0.0134
PI	Test 150rpm at no load	0.2019	0.2064	0.0127
	Test 250rpm at 50% load torque	0.2007	0.2055	0.0133
	Test 350rpm to 0 to -50rpm	0.1987	0.1999	0.0116
	Test 4 ± 25 rpm speed reversal	0.1977	0.1995	0.0105
ANFIS	Test 150rpm at no load	0.2012	0.2057	0.0117
	Test 250rpm at 50% load torque	0.20044	0.2045	0.0103
	Test 350rpm to 0 to -50rpm	0.1975	0.1991	0.0101
	Test 4 ± 25 rpm speed reversal	0.1966	0.1987	0.0109

Table 4. Comparison of settling time

Parameter	PI Controller	ANFIS Controller
Speed (50 rpm)	0.61	0.49
Speed error (zero rpm)	0.69	0.49
Estimated speed (49.5rpm)	0.61	0.49

Advanced work proposes a comparison between fuzzy and ANFIS based speed control algorithms, taking into account the speed's settling time. The MATLAB program has allowed the results to be compared in a virtual environment. Among the methods without sensors is the FOC. The suggested MRAS speed observer completes the speed estimation procedure; the sensor-less initiates it. The induction motor's estimated speed is set to 500 rpm, and with the aid of the suggested controller fuzzy and ANFIS-based MRAS with FOC controller, the motor's real speed is also 500 rpm. Induction motor settling time is reduced to 1.3 seconds while utilizing a fuzzy-based controller. Based on this analysis and implementation, MATLAB/Simulink is used to create an artificial network-based MRAS speed observer with FOC controller, which regulates the motor speed and shortens its settling time.

5. CONCLUSION

This manuscript, the performance, robustness, stability are improved by the MRAS with ANFIS controller is proposed. The major aim of the manuscript is improve the stability, robustness and reduces the sensitivity of the sensorless control system to parameter variations, such as changes in the motor parameters or load torque. The performance of the proposed system is implemented by MATLAB platform and compared with existing system. The efficiency of ANFIS based MRAS in experimental result is 99.146% and simulation result is occurred 99.764%. The efficiency of PI based MRAS in experimental result is 98.75% and simulation result is occurred 98.901%. The proposed ANFIS based MRAS is high efficiency than other techniques. The settling time of the ANFIS controller in speed (50 rpm) is occurred 0.49 and PI controller is 0.61. The settling time of the ANFIS controller in speed (zero rpm) is occurred 0.49 and PI controller is 0.69. The settling time of the ANFIS controller in estimated speed (49.5 rpm) is occurred 0.49 and PI controller is 0.61. The settling time of proposed ANFIS controller is occurred 0.49, which is low error, when compared to the existing sytems.

6. FUTURE RESEARCH WORK

The future study outlines a new design technique that combines an ANFIS controller with an induction motor drive based on decoupled feedback linearization. Using a DSP TMS320F2812 processor, the entire drive system was built, modeled, and experimentally explored in a real-time hardware setup. When it comes to beginning, load perturbation, and speed reversal, the feedback linearized induction motor drive with ANFIS controller has a strong and quick reaction with much less speed and torque ripple than the PI-torque controller. Nonetheless, during all of these actions, the DC-link capacitor voltage remains evenly balanced without the need for an additional controller. Additionally, the flux responses are kept almost constant during these processes. The ITAE performance index shows positive results when the ANFIS-torque controller is used, which can replace the conventional PI-torque controller.

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Conflicts of Interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

Author Contributions

For the individual contribution of research author and co-authors as follows: "Conceptualization, Govindharaj I and R. Rampriya; methodology, Govindharaj I; Hardware, Govindharaj I; validation, Govindharaj I, R. Rampriya, and Dinesh Kumar K; formal analysis, Balamurugan S; investigation, R. Rampriya; resources, Govindharaj I; data curation, Yazhinian S; writing—original draft preparation, Govindharaj I and Balamurugan S; writing—review and editing, Govindharaj I; visualization, Anandh T; supervision, R. Rampriya.

Data Availability

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

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