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RESEARCH ARTICLE

Emulation of Wind Turbine System using Fuzzy Controller-based Vector Controlled Induction Motor Drive

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Abstract

This project presents a new approach for simulating wind turbines by using a Vector Controlled Induction Motor Drive (VCIMD) system enhanced with a Fuzzy Logic Controller (FLC). The goal of this system is to optimize the performance and efficiency of wind energy conversion. By accurately controlling the induction motor drive through vector control, the dynamic characteristics of wind turbines can be realistically emulated, allowing for a more true-to-life representation of real-world conditions. Integrating a Fuzzy Logic Controller provides intelligent adaptive control capabilities to improve stability and response. This synergistic combination of VCIMD and FLC not only enables efficient power generation but also ensures robust operation across varying wind conditions. The project investigates the dynamic interaction between these technologies, providing a comprehensive solution for wind turbine emulation that shows great potential for advancing renewable energy research and development. The findings from this study contribute to ongoing efforts to optimize wind energy systems for greater reliability and sustainability.

Keywords: Vector controlled motor drive (VCMD), Induction motor, Wind Turbine, Fuzzy Logic Controller (FLC).

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1. Introduction

In recent years, there has been growing interest in renewable energy sources as a result of increasing worries about environmental sustainability and the depletion of non-renewable resources. Among these sources, wind power has emerged as one of the most promising and widely accepted forms of renewable energy. Wind turbines are typically utilized to harness wind energy by converting the kinetic energy of wind into electrical power. However, the unpredictable and fluctuating nature of wind makes operating wind turbines challenging [1] - [3], [12] - [13]. To optimize energy conversion and increase wind turbine efficiency, various control strategies have been implemented. One such strategy uses fuzzy logic controllers, which are known for handling nonlinear and

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uncertain systems [4] - [8]. This research paper discusses the project titled 'Emulation of Wind Turbine System using fuzzy controller-based vector controlled Induction Motor Drive'. The project aims to emulate a wind turbine system utilizing a fuzzy logic controller-based vector-controlled induction motor drive and analyze its performance compared to a conventional control strategy.

Efficient and reliable electric power generation from wind that follows modern grid requirements needs research and development of advanced control methods. The wind energy industry is also providing many jobs, leading to major economic growth [9] -[11]. Therefore, it is critical that how wind energy systems operate and are controlled is taught to engineers to develop skilled professionals for the industry. Hence, to enable research and education, it is important to develop controlled test systems that can mimic large wind turbines using small electric machines, without relying on actual wind [12] -[15]. A wind turbine can be emulated either using a DC motor or induction motor drive. Although DC motors have advantages for control, they are bulky, expensive, and require frequent maintenance due to brushes and commutators. The generator could be various types used in the field. Around 50% of generators used employ doubly-fed induction generators (DFIG) [13], [16] - [18]. Their large market share is mainly because the converters used for their control have lower rating, cost and losses. Hence, this work considers DFIG as the generator and induction motor as the prime mover in the test system, for testing the proposed controllers. However, the proposed control designs should work for any motor and generator types.

Previous work explained emulating linear and nonlinear mechanical loads using two coupled induction motors [6] -[14]. One method estimates the wind turbine torque based on wind speed and blade pitch angle, and directly applies it as a torque reference to the induction motor controller. Since the inertia of the motor used for emulation is usually much lower than the wind turbine, compensating for inertia difference is critical for accurate emulation. Most methods in literature account for the inertia difference with an additional loop called inertia compensation. The torque compensation from this loop depends on the combined inertia and friction of the motor-generator; it requires differentiating speed, making the loop highly noise-sensitive. This emulation approach can have stability issues in digital implementation. To reduce instability, some methods filter the acceleration response or use state-space designs, though not validated experimentally. Some inertia compensation schemes ignore friction terms, enabling simple proportional control, but give steady-state errors. The existing wind turbine emulation method has issues with stability and parameter sensitivity. It becomes unstable when emulating a turbine with over twice the inertia of the test system. This work first proposes a simple control for inertia emulation that is experimentally shown to be stable and less parameter sensitive. However, it requires feedforward torque compensation for disturbance rejection. The proposed advanced control has very good disturbance rejection and low sensitivity to parameters. Two control designs for this structure are explained. This paper improves on prior work by additionally discussing the simple control and another advanced control design, along with extensive simulation and experimental results comparing all the proposed methods.

2. Material and methods

The project makes use of MATLAB/Simulink software to model and analyze various control systems, since it is a robust tool for this purpose. The materials required for the project are a computer with MATLAB/Simulink installed, data sheets for the induction motor drive, and a fuzzy logic toolbox.

2.1. Induction motor drive

Discussing induction motor drive systems, need to understand how induction motors work. In brief, induction motors are 3-phase, self-starting AC electric motors that run at a constant speed. Their velocity is decided through the frequency of the electricity deliver and the wide variety of windings withinside the motor. In the past, it was not possible to vary the speed of induction motors as needed, which limited their use even though they had advantages compared to DC motors. However, with advancements in power electronics such as thyristors, transistors, IGBTs, and GTOs, variable speed induction motor drives were developed. While these drives are more expensive than DC drives, induction motors are being used more often and replacing DC motors because of their benefits.

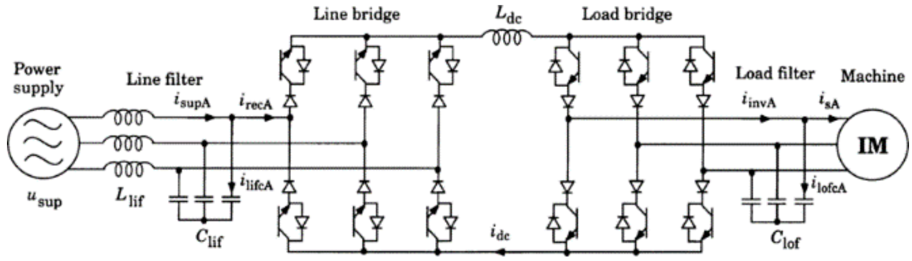

Figure 1: Schematic image of induction motor drive.

The simulation involves these steps:

2.2. Modeling the induction motor drive

First, a mathematical representation of the induction motor drive will be developed based on its data sheets. This model will simulate the motor's performance under different conditions. The simulation was carried out using MATLAB/Simulink software. The wind turbine system was modeled using a mathematical representation of a wind turbine coupled with an induction motor and a generator. The fuzzy controller was designed based on the input-output relationships of the system and was implemented using the fuzzy toolbox in MATLAB. The fuzzy controller was then integrated into the vector control of the induction motor to achieve the desired output. The simulation was performed for both the fuzzy controller and the conventional controller, and their performances were compared in terms of power output, speed regulation, and efficiency.

2.3. Designing the fuzzy controller

The fuzzy controller will be designed utilizing the system's inputs, outputs, and governing rules. It will use control signals from the motor model and wind speed data to optimize the system's functioning. The experimental setup consisted of a wind turbine simulator, an induction motor, and a generator. The wind turbine simulator was designed to generate varying voltage signals to simulate different wind speeds. The fuzzy controller was implemented using an Arduino microcontroller and was connected to the induction motor through a three-phase inverter. The conventional controller was also implemented using an Arduino microcontroller. The performance of the two controllers was measured in terms of power output, speed regulation, and efficiency.

Fuzzy logic allows reasoning with vague real-world data using the concept of fuzzy sets, which have partial memberships unlike binary sets. FLCs are especially useful when the inputs and outputs are not well-defined or vary over time. FLCs can reason about the uncertainty in inputs to produce robust, adaptive control actions. They are often applied where conventional methods are impractical due to system complexity or lack of models. FLCs can be easily implemented in software or hardware, making them popular for real-world control tasks. They have been successfully used in automotive engineering, robotics, consumer electronics, medical equipment, traffic control, financial modeling, and more [16] - [20].

2.4. Integrating and simulating

The fuzzy controller will be combined with the induction motor drive model, and the simulation will run for various wind speeds. The system's performance will be evaluated on parameters like torque, speed, and power output.

3. Existing system

3.1. Wind turbine emulation

The mechanical power generated by the wind turbine, P_T, depends on the wind speed v_{wind}, the area covered by the blades A, and the air density ρ, as shown in the equation. The energy coefficient C_p is a characteristic of the end velocity ratio λ and the pitch perspective β. J_{TG} and B_{TG} represent the combined inertia and viscous friction of the wind turbine generator system (WTGS). A vector-controlled squirrel cage induction motor (SCIM) drive is used to emulate the wind turbine. The torque reference for the SCIM drive is expected to be determined using the wind turbine model. However, the transfer function of the mechanical subsystem of the motor generator set (MGS) which emulates the WTGS, $G_{MG}(s)$, is different, as shown in the equation. Here, J_{MG} and B_{MG} represent the combined inertia and viscous friction of the MGS. The motor inertia J_M is substantially different from and much lower than the turbine inertia J_T. Also, the friction coefficient B_M of the motor differs from the friction coefficient B_T of the turbine. Therefore, the produced torque needs to be suitably adjusted so that the emulated speed ω_{emu} tracks the actual speed ω_{act}, as shown. This modification of torque from the turbine torque T_T to the motor reference torque T_M is called inertia compensation, as illustrated in the block diagram of a wind turbine emulator.

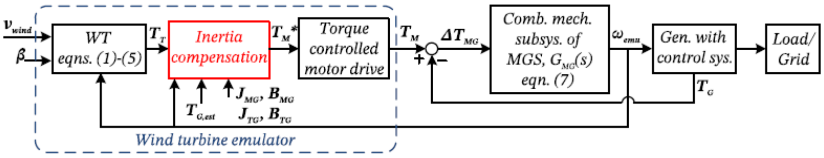

Figure 2: Block diagram of a wind turbine emulator with inertia compensation.

3.2. Inertia compensation scheme

The current inertia compensation method uses the difference between the inertia of the turbine generator (J_{TG}) and motor generator (J_{MG}), as well as the difference between the damping of the turbine generator (B_{TG}) and motor generator (B_{MG}), to calculate the compensation torque (T_{comp}). This T_{comp} is then subtracted from the obtained electromagnetic torque (T_T) to determine the torque reference (T_M) for the torque-controlled drive. This compensation approach is quite sensitive to the mechanical parameter values. Using a differentiator to generate T_{comp} can also introduce noise issues. Instability has also been reported when the inertia of the emulated wind turbine generator system (J_{TG}) is more than twice that of the motor generator system (J_{MG}). Ideally, the acceleration term in T_{comp} should match the acceleration term in T_T in the block diagram, but a one sample delay between them from the digital implementation is said to cause instability. The emulation transfer function is obtained by discretizing the system using a sampling period T_s. Applying Jury's stability test gives a stability condition. Simulations confirm this stability condition. For a step change in the turbine generator torque (T_{TG}), the response is stable when $J_{TG} = 1.0J_{MG}$ but unstable when $J_{TG} = 2.0J_{MG}$.

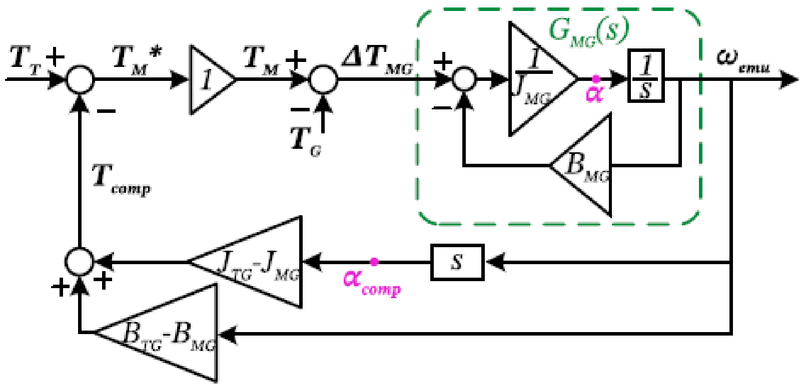

Figure 3: Existing inertia compensation scheme.

Disadvantage of this existing is the inertia compensation loop becomes highly sensitive to noise. The digital implementation of this emulation approach leads to stability issues.

4. Proposed system

4.1. 1 – DOF control of inertia

The proposal suggests using a one-degree-of-freedom control method to imitate inertia in order to improve stability and decrease the impact of parameter variations. From the perspective of control systems, wind turbine emulation can be regarded as the process of controlling the emulated speed, ω_{emu}, to match the actual speed, ω_{act}. Therefore, the regulation occurs within a closed feedback loop, as depicted in Figure 4. The value ω^*_{emu} is calculated by subtracting T_G from T_T and then multiplying the result by the gain, k. Because the current T_G is not present, we can estimate the values of i_{sd}, i_{sq}, i_{rd}, and i_{rq}, which represent the stator and rotor current components on the d and q axes of the DFIG. The controller $C(s)$ is designed with a proportional-integral (PI) structure in which the zero z_c of the controller cancels out the pole p_{pl} of the plant. The root locus diagram in Figure 6(a) demonstrates the representation of the open loop poles and zeros, as well as the desired closed loop pole, p_{cl}. In order for the closed loop pole to be in the desired location, the Bode plots of the emulated and actual transfer functions appear identical and cannot be distinguished from each other. However, the Bode diagram representing the disturbance transfer function shows that there is inadequate rejection of disturbances due to a high gain across a broad range of frequencies. The wind turbine emulator accurately tracks the simulated unit step accelerating torque and confirms the analytical result for the proposed 1-DOF. The system's ability to reject disturbances when there is a sudden change in T_G is not very good, unless there is a feedforward of $T_{G,\text{est}}$. However, when implementing feedforward compensation, the ability to reject disturbances is greatly enhanced. The wind turbine emulator successfully simulates and accurately tracks the changes in turbine generator and wind speed during step adjustments. As demonstrated, a control system with only one degree of freedom and no feedforward compensation from $T_{G,\text{est}}$ exhibits limited ability to reject disturbances effectively. The precision of tracking is influenced by the correctness of the parameter estimations of J_{MG} and B_{MG}, which will be illustrated later on. The suggestion provided is to utilize 2-DOF control for wind turbine emulation in order to enhance the ability to reject disturbances and reduce the impact of parameter variations.

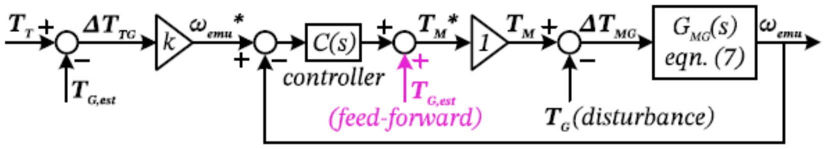

Figure 4: Proposed 1 – DOF control of inertia emulation.

4.2. 2 – DOF control of inertia

The 2-degree-of-freedom control system uses a desired input signal called r_{emu} that comes from ΔT_{TG} and passes through a pre-filter $F(s)$, as shown in the Figure 5. The goal in designing the controller $C(s)$ is to get both high bandwidth and strong disturbance rejection so it can accurately track r_{emu}.

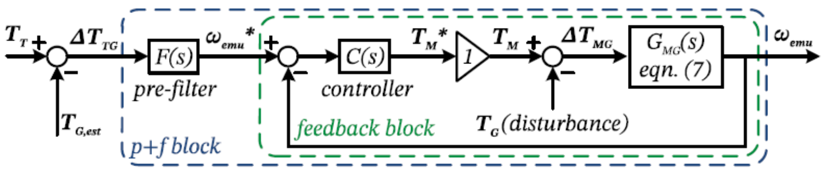

Figure 5: Proposed 2 – DOF control for inertia emulation.

4.3. Proposed 2 – DOF design 1

The design I uses a controller called $C(s)$, which is a lead-lag compensator. It has 2 degrees of freedom. The controller zero, z_c, is positioned at the desired location of the closed loop pole, and then a controller pole is placed at $s = p_c$ to maintain causality. Here, p_c is greater than p_{pl}. The value of the controller gain, k, needs to be set to a high value in order for the dominant closed loop pole, p_{cl1}, to be very close to z_c, effectively cancelling it out. The additional closed loop pole, p_{cl2}, is positioned further towards the left on the negative side.

The feedback block's bandwidth can be maximized by placing the closed loop pole at $s = p_{cl2}$, which is the only effective option. The pre-filter pole, p_{pre}, is employed to eliminate z_c. Therefore, p_{cl1} has become the primary pole in the closed loop system involving the $(p + f)$ block, and it is situated near the intended pole position. The selection of the gain value, k, depends on the desired bandwidth of the feedback block and the desired level of steady state error. The value of the open loop gain of the feedback block, $G_{\text{ol}}(s)$, is the amount of amplification or attenuation that occurs in the feedback system.

4.4. Proposed 2 – DOF design 2

In the prior design for a 2-degree-of-freedom (DOF) system, it was necessary to utilize a high controller gain, k, to minimize the steady state error. Implementing a PI controller structure $C(s)$ ensures that the steady-state error is eliminated.

The controller $C(s)$ and its zero location z_c are part of the 1-DOF control. Similar to the 2-DOF design I, the pre-filter pole p_{pre} is positioned at the desired closed-loop location along with the gain k_{pre}. Because p_{pre} cancels z_c, the magnitude of the open loop transfer function at the gain crossover frequency ω_{gc} is affected. The desired bandwidth determines the k value that can be selected.

4.5. Design verification

The frequency response plots of the emulation and disturbance transfer functions with the proposed 2-DOF design I are presented above. This shows that the emulation transfer function's frequency response closely matches that of the actual transfer function $G_{TG}(s)$; divergence only starts at a much higher frequency than the desired pole location. It illustrates that the proposed 2-DOF design I with $k = 65$ provides substantially better disturbance attenuation over a wide frequency range compared to 1-DOF control. The emulation and actual transfer functions' frequency responses are nearly indistinguishable across a broad frequency band as depicted. This shows that the disturbance rejection given by 2-DOF design II is considerably higher than that of the proposed 2-DOF design I with $k = 65$. With the proposed 2-DOF design I, the simulated system has lower steady-state error for $k = 65$ than for $k = 15$.

5. Expected outcomes

The anticipated results of this project involve gaining a thorough comprehension of the dynamic behavior and control needs of a wind turbine system. The effectiveness of the fuzzy controller in controlling a wind turbine system will be determined by comparing the results from both simulation and practical experiments. This comparison will provide valuable insights. The project may also create opportunities for additional studies on the utilization of fuzzy logic controllers in renewable energy systems.

6. Simulation results and validation

The results obtained from the simulation will be assessed and compared to the performance of a traditional wind turbine without the fuzzy controller. The comparison will depend on various performance metrics such as torque and power output. The productivity and effectiveness of the controller will be determined based on these measurements. The control signals from the motor will be quantified and contrasted with the simulated results. Any discrepancies will be investigated to improve the accuracy of the simulation. Figure 6. shows the simulation result of proposed 1-DOF Inertia compensation (Actual Speed, w_{act} and Emulator Speed, w_{emu}). Figure 8 shows the simulation result of proposed 1-DOF Inertia compensation with 15% inaccuracies in T test. Figure 8 shows the simulation result of proposed 1-DOF Inertia compensation with 12% inaccuracies in T test and Figure 9. shows the simulation result of proposed 2-DOF Inertia compensation (Actual Speed, w_{act} and Emulator Speed) w_{emu}.

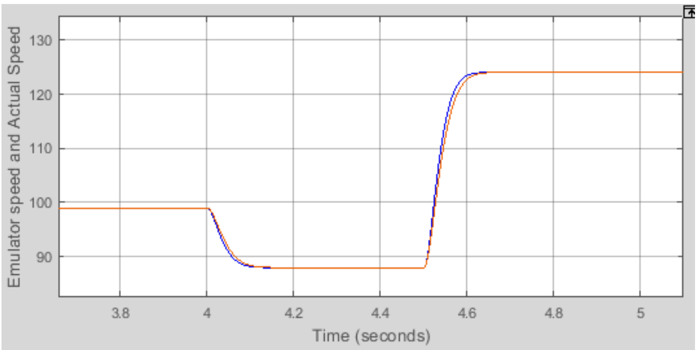

Figure 6: Simulation result of proposed 1-DOF Inertia compensation (Actual Speed, w_{act} and Emulator Speed, w_{emu}).

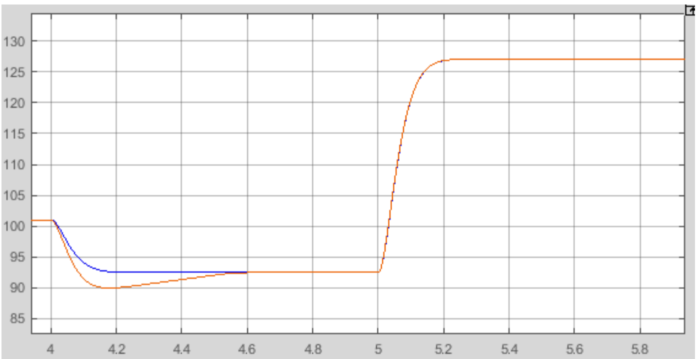

Figure 7: Simulation result of proposed 1-DOF Inertia compensation with 15% inaccuracies in T test.

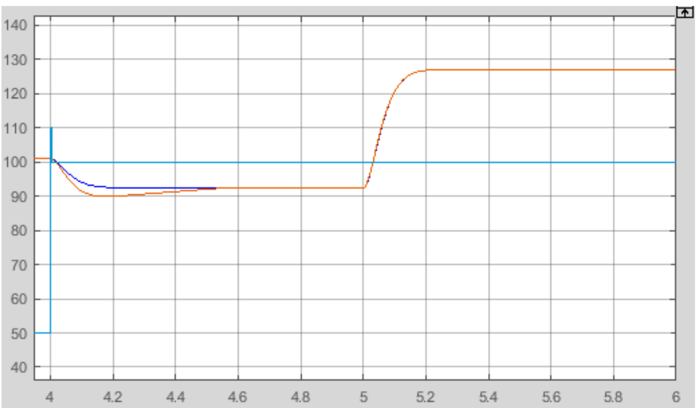

Figure 8: Simulation result of proposed 1-DOF Inertia compensation with 12% inaccuracies in T test.

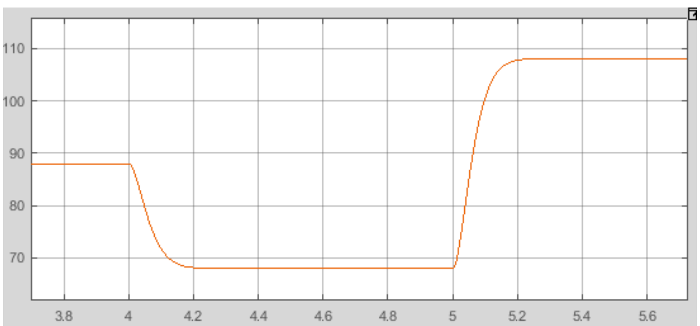

Figure 9: Simulation result of proposed 2-DOF inertia compensation (Actual Speed, w_{act} and Emulator Speed) w_{emu}.

7. Conclusion

This paper discusses the single degree of freedom (1-DOF) and two degree of freedom (2-DOF) control techniques for simulating a wind turbine utilizing a squirrel cage induction machine (SCIM) with significantly lower inertia without stability problems. The proposed methods overcome the noise and instability issues of current approaches by implementing closed-loop control for inertia emulation. The paper first shows the design and performance of 1-DOF control. To improve its poor disturbance rejection capability, a feedforward of the DFIG torque estimate is added to the controller output. In addition, 2-DOF control is proposed to increase robustness to parameter uncertainties, while still providing good disturbance rejection. The torque required by the 1-DOF or 2-DOF controller is provided by a vector controlled SCIM drive, which acts as the emulated wind turbine driving the DFIG. Simulations and experiments on a 7.5 kW DFIG coupled to a 5 kW SCIM validate the performance of the proposed 1-DOF and 2-DOF control-based wind turbine emulators. The wind turbine emulation scheme based on the proposed 2-DOF design II has zero steady state error, high bandwidth tracking, very low parameter sensitivity, and good disturbance rejection.

Declarations and ethical statements

Conflict of interest: The authors declare that there is no conflict of interest.
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Artificial Intelligence usage statement: During the preparation of this manuscript, the authors utilized ChatGPT solely for language refinement and grammatical corrections. The authors carefully reviewed and revised the generated content and take full responsibility for the accuracy, integrity, and originality of the final manuscript.
Availability of data and materials: The data and/or materials that support the findings of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

G V Nagesh Kumar: Conceptualization, Methodology, Validation. **R Veda Sai**: Implementation, Writing–Review & Editing. **T Mahitha Reddy**: Implementation, Writing–Review & Editing. **S K Shajid**: Implementation, Writing–Review & Editing. **Kusuma Boora**: Editing & Visualization.

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