Model predictive control based frequency regulation of microgrid with integration of distributed energy resources

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ABSTRACT

Power generation sector has become more prevalent in the use of renewable energy sources resulting in more complex and non-linear network. Microgrids are becoming the best alternative solution in remote areas where the distribution network is infeasible. However, the intermittent nature of distributed renewable energy resources can result in a generation and demand mismatch instigating frequency variation which is a crucial concern. Thus, modern power system requires increasing intelligence and flexibility to cope up with the generation-load mismatch. Efficient control techniques are of vital importance in maintaining the frequency near the nominal value, and the selection of the controller is crucial in maintaining the reliable, effective, and steady functioning of the power system. The present study demonstrates frequency control in islanded microgrid with disruptions in load demand using the model predictive control by efficiently managing the energy storage with integration of large-scale renewable energy sources. The effectiveness and superiority of the proposed model predictive controller (MPC) is presented by comparing its performance with proportional integral controller and proportional integral tuned with adaptive neuro fuzzy inference system (ANFIS) through simulations in MATLAB environment.

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1. INTRODUCTION

A microgrid is a small energy zone that can function in both islanded and grid-connected mode while integrating various distributed energy resources [1]. Distributed resources include controllable sources such as diesel generators, fuel cells, and batteries, as well as renewable sources like solar and wind energy systems. The microgrid encounters frequency and power fluctuations as a result of the variable and uncertain nature of renewable sources, as well as generation and load demand mismatch [2]. If a microgrid is connected to the grid, the associated electrical power system can provide loads. Otherwise, distributed generation must operate in an isolated mode while dealing with fluctuations in load and variable renewable energy sources, necessitating strict microgrid management to ensure frequency and voltage stability and maintain high-quality power delivery to clients. However, developing a dynamic power balance between generation and demand is challenging, as electrical power has become a deregulated entity. Consequently, the analysis and development of improved frequency controller units have become crucial in addressing the issue of power generation and consumption mismatches, which can lead to frequency fluctuations and negatively impact the efficiency and reliability of microgrid power flow [3].

From the perspective of primary regulation, frequency droop characteristics are commonly employed to manage system frequency [4]-[8]. However, in contrast to a vast interconnected system, the system inertia of an isolated microgrid is significantly lower. Consequently, because of growing penetration of renewable energy resources, power generation may experience rapid fluctuations. However, energy storage systems are a likely solution that can counteract the adverse effects of reduced inertia. The reserve power in the energy storage devices helps to increase the microgrid inertia leading to greater load frequency stability [9]-[12]. Thus, to reasonably control greater surge currents, a high-power density storage device such as flywheel energy storage super capacitor energy storage can be used with battery energy storage devices. Moreover, the electrical vehicle when integrates as vehicle-to-grid (V2G), balances the energy flows [13] and provides frequency support to the grid [14]. In these circumstances, the standard control techniques may not be sufficiently cope as with the quick swings in output power from renewable energy sources, resulting in significant and frequent deviations from the nominal operating frequency point. Standard proportional-integral (PI) controllers are simple, user-friendly, and cost-effective. Nonetheless, their main drawbacks are poor dynamic response, limited accuracy, and extended settling time. Therefore, it is crucial to investigate and develop the improved frequency controller units in such situations.

The choice of an effective controller is a critical factor in analyzing the load frequency control of large power system networks, especially with the integration of renewable and energy storage devices. Intelligent controllers utilizing optimization techniques such as metaheuristic approaches like particle swarm optimization (PSO) [15], [16], teaching learning [17], fuzzy logic controllers [18]-[20] metaheuristic approaches like grasshopper optimization were proposed for frequency control [21]. The frequency deviation of a standalone microgrid was mitigated with a deep learning-based method employing thermostatically controlled load management [22].

It has been suggested that linear quadratic regulators are the optimal controllers [23], [24]. However, their implementation requires knowledge of all system states throughout operation, which can be challenging in complex power networks due to the large number of variables that influence performance. Observer-based control is becoming more widely acknowledged as a remedy for this problem. An observer estimates the system's variables, and a well-liked state estimation algorithm, like the Kalman filter, can be used to estimate these variables efficiently [25]. Model predictive control (MPC) is a technique of optimal control that seeks to minimize an objective function for a constrained dynamical system over a finite, receding horizon. It is rapidly becoming a viable alternative for managing voltage regulation, frequency control, power flow, and optimizing economic operations. The impact of predictive control for two area system for a standalone microgrid is presented [26]. MPC is the intelligent controller suitable for the rapid response, robustness against load variations, and uncertainty in parameters [27]-[30].

The primary aim of this study is to examine the frequency response of a microgrid when subjected to sudden load perturbations. The key contribution of this study lies in:

- Analysing the impact of energy storage devices on frequency regulation support in a microgrid, taking into account the stochastic behaviour of renewable energy sources.
- Developing a frequency control system for damping frequency oscillations in low voltage microgrids using a MPC technique, while simultaneously estimating the states of parameters with a Kalman filter approach. The results of this study have been validated against traditional controllers.

The remaining of this paper is organized as follows: section 1 represent introduction, section 2 presents modelling of microgrid, section 3 represents the controller design, section 4 shows the results and further leads to discussion, and finally the conclusion.

2. MODEL DESCRIPTION

The test system of the microgrid in the islanded mode considered in this study is presented in Figure 1. Numerous components of microgrid model such as diesel engine, battery energy storage, flywheel energy storage system, solar, and wind turbines are considered for this study [31]. The incremental power frequency dynamics of the microgrid which serves an area with change in load demand represented as ΔPL. The surplus power ΔPm-ΔPL is accounted for, by increasing the rate of rise of kinetic energy and increased load consumption which is expressed by (1) respectively.

$$\Delta P_m - \Delta P_L = \frac{2HP}{fo} \frac{d\,\Delta f}{dt} + D\,\Delta f \tag{1}$$

Where ΔPm is the change in microgrid power which consist of sum of the powers of all the distributed energy sources and storage device connected to system; D is the damping constant which represents the ratio of percentage change in the load to that of percentage change in the frequency in per unit MW/Hz; and H represent the inertia constant of the rotating masses. The various distributed energy resources connected to the microgrid are represented by their respective transfer function [32], [33] as indicated in Figure 2.

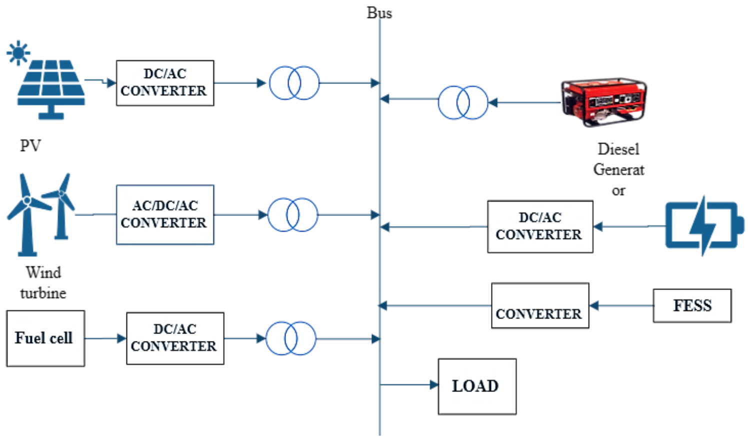


Figure 1. Microgrid structure

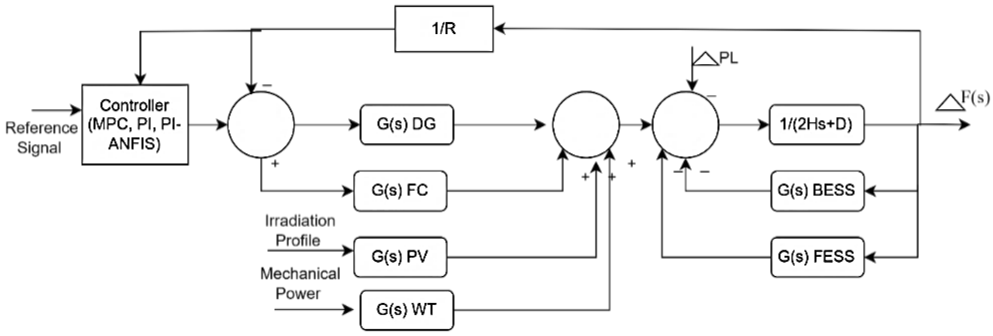


Figure 2. Block diagram of microgrid

3. METHODS FOR FREQUENCY CONTROL

The purpose of load frequency control is to maintain the frequency within acceptable limits while subjecting disturbance in load. The conventional techniques like droop control, tie line control is ineffective. An efficient controller is crucial for successful frequency regulation as its primary function is to reduce the error signal so that the frequency deviation becomes close to zero and the frequency of the system returns close to the nominal value in the specified time which is possible with the intelligent controllers such as MPC and proportional integral tuned with adaptive neuro fuzzy inference system (ANFIS).

3.1. PI controller

The PI controller is a proportional integrals control in which the control signal is proportional to both the error signal and the integral. The mathematical representation for the proportional-integral controller is as (2).

$$u(t) = kp + ki \int e(t)dt \qquad (2)$$

The response of the PI is better as compared to the proportional and integral control used separately. Although its response is sluggish but it can be enhanced if it is tuned with neural networks, fuzzy networks, and even linearizing the model based on the trial and error method, Zeigler -Nicholas method, and particle swarm-based approach [32].

3.2. PI tuned with ANFIS

ANFIS offers the ability to combine the merits of neural network and fuzzy inference systems into a single framework. Adaptive neuro fuzzy inference system is based on the set of fuzzy if and then rule that modifies its structure in response to information or data presented during the learning phase, whether internal or external. The ANFIS was fed with the desired or target response. The discrepancy between the preferred response and the system output results in an error. The system is then updated with this error, and the parameters are logically changed until the system performance is deemed acceptable, this process is repeated. The ANFIS can be trained using different optimization methods [33]-[35].

3.3. Proposed model predictive controller

The model predictive controller is a multivariable control system that simultaneously regulates the output by considering all interactions between system variables while simultaneously grappling with system constraints. This type of controller is particularly useful in situations in which a high level of precision and adaptability is required. By considering the relationships between all relevant variables, the model predictive controller is able to make more informed decisions and achieve more accurate results which are generally difficult to control using conventional techniques. There are several variations of the MPC technique, with the main difference being how the objective function can be formulated or how system model is obtained. Nevertheless, all these strategies utilize system model for generating a control signal to minimize the objective function [36], [37]. The structure of model predictive control is shown in Figure 3.

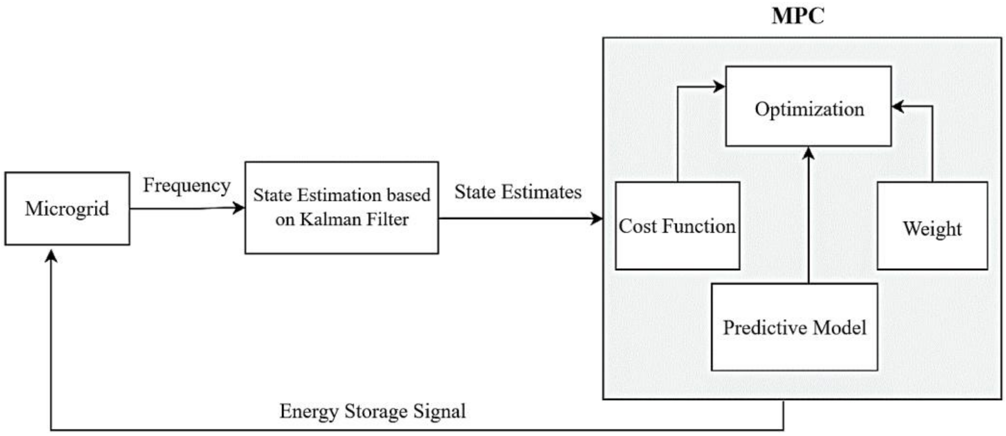


Figure 3. Model predictive control

The states of the system had been estimated based on the observer-based control approach Kalman filter. The Kalman filter is an iterative process for estimating the state of the system when inputs are uncertain and its quickly estimates the true values. It is a recursive method that uses system prior state measurements and control inputs to estimate the present system state [38]. The state space representation and objective function which is combination of the linear quadratic and the Kalman filtering approach is represented by (3)-(6).

$$\dot{x} = A\,x(t) + B\,u(t) + Dw \tag{3}$$

Where w represents the difference between the change in power due to energy storage devices and load demand and u(t) represents the input control signal. A is state matrix, C is control output vector, and B and D are coefficient matrix.

$$y(t) = \Delta f = C\,x(t) \tag{4}$$

$$J(N1, N2, Nc) = \sum_{j=N1}^{N2}[\Delta w(t+j,t)]^{\,2} + \alpha 1 \sum_{j=0}^{Nu} \Delta u_1(t+j-1)^2 + \alpha 2 \sum_{j=0}^{Nu} \Delta u_2(t+j-1)^2 \tag{5}$$

$\alpha 1$ and $\alpha 2$ are the weighing factor; N1 and N2 are the minimum and maximum costing horizon; Nc represents the control horizon; Δu_1 and Δu_2 are the control signals to the DG and fuel cell, respectively; and w(t+j) represents the reference over the future horizon N.

Control signal constraints for the output are added to the objective function. These constraints are represented by (7) to (9).

$$u_{min} \le u(t+j) \le u_{max} \tag{6}$$

$$y_{min} \le y(t+j) \le y_{max} \tag{7}$$

Where:

$$u(t) = u(t-1) + \Delta u(t)$$
$$u(t+1) = u(t-1) + \Delta u(t) + \Delta u(t+1) \tag{8}$$

Solution of the objective function (5) gives the optimal result over the horizon N while subjected to the constraints specified by (6) and (7). The performance index of the frequency changes which is integral time square of the error in the frequency signal can be expressed by (9), which determines the effectiveness of the controller. The detailed step by step algorithm of MPC is depicted through Figure 4.

$$P_I = \int_0^T |\Delta f|^2 \, dt \tag{9}$$

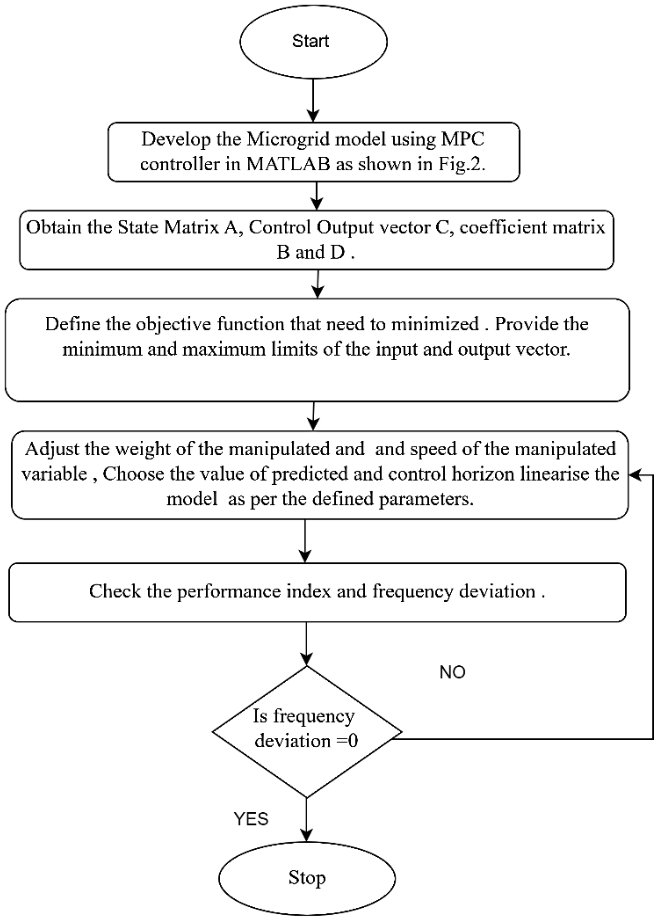


Figure 4. Flowchart of MPC controller

4. RESULTS AND DISCUSSION

The microgrid depicted in Figure 1 was developed using MATLAB Simulink 2022. The nature of the wind and solar energy profiles was assumed to be stochastic, whereas the variation in load demand was regarded as a step change with an amplitude of 1 p.u. The parameters of distributed energy resources for the microgrid design are depicted in Table 1. Figure 5 illustrates the PV output, wind power fluctuations, and load demand disruption.

The frequency response of the microgrid was analyzed with and without energy storage devices equipped with PI controllers shown in Figure 6(a). The response from the figure indicates that the frequency deviation overshoot and undershoot are more pronounced when the battery and flywheel energy storage are not considered, and the system's response is slower owing to its longer settling time. However, the results show that the incorporation of energy storage devices in microgrid provides the frequency support and improves the response. Furthermore, Figure 6(b) presents a comparative analysis of the frequency deviation using controller PI, PI adjusted with ANFIS, and model predictive control while incorporating the battery energy storage system (BESS) and flywheel energy storage system (FESS) which clearly depicts that the model predictive controller outshines the conventional PI controller and PI tuned -ANFIS. In comparison, the PI controller without tuning exhibits poor response, as indicated by its larger oscillations in the frequency response in Figure 6(b). For PI controller, the transient time is relatively larger which shows its poor response as it takes approximately 7.2 seconds to settle down to steady state.

Table 1. Data for the distributed energy resources

Parameter	WTG	PV	FC	DG	BESS	FESS	LOAD
Rated power (kW)	100	30	70	160	45	45	210

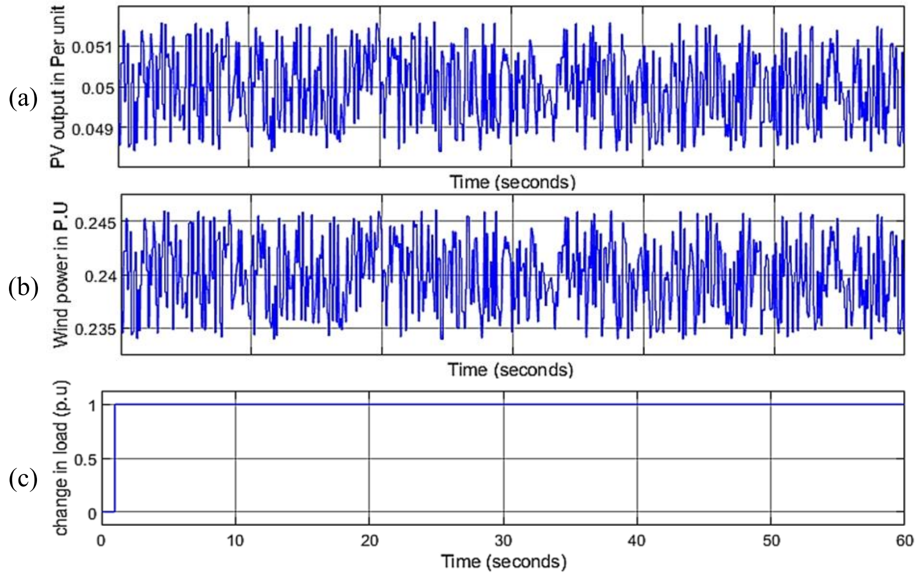
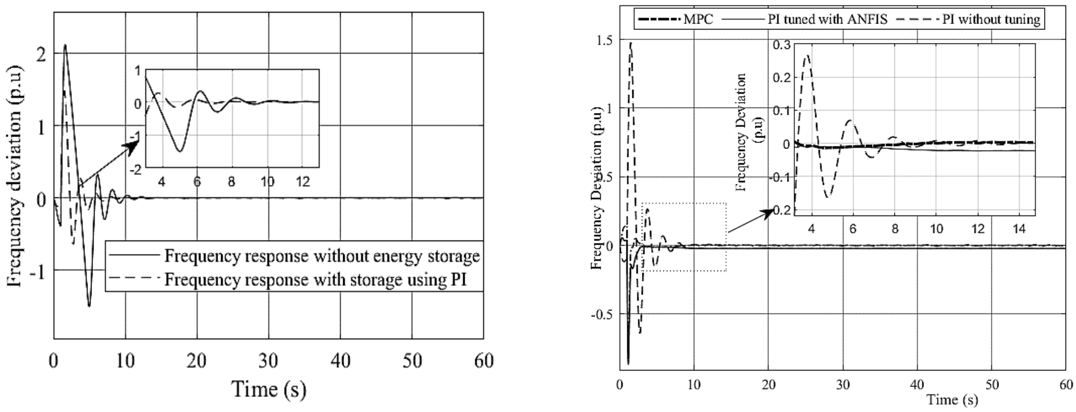


Figure 5. Per unit variation in solar, wind, and load demand: (a) stochastic variation of solar, (b) variation in wind output, and (c) step change in load



(a) (b)

Figure 6. Frequency response: (a) effect of energy storage and (b) performance with different controllers

The response of the PI controller is enhanced when it is trained using ANFIS as its steady state error reduces and the transient time reduces to about 3 seconds. The parameters selected for the ANFIS-based PI are listed in Table 2. The variation in training error with maximum epochs and testing of output versus input is represented in Figure 7.

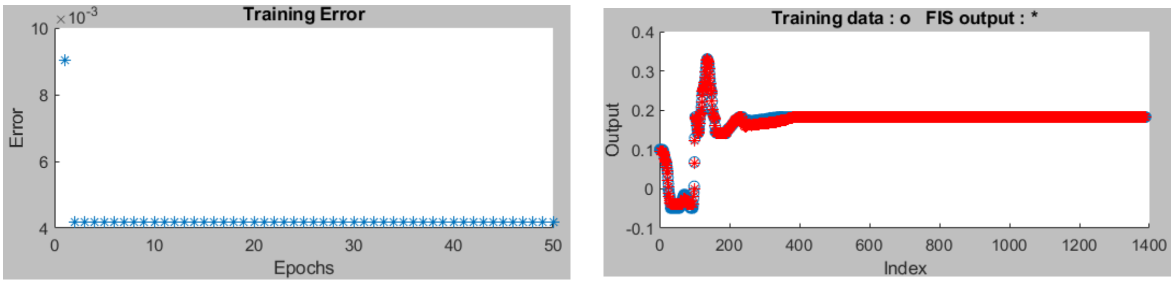
Although PI tuned with ANFIS represents a smaller transient time but the deviation in frequency is not completely eliminated. Moreover, training with neural networks has certain limitations, like choosing appropriate membership functions, dimensionality issues, which can sometimes affect the performance. In contrast, the MPC results in almost zero frequency deviation and the oscillations in frequency deviation response take much less time to settle down to its nominal value after experiencing a step change in load demand, it has less transient time less than as compared to other controllers as depicted in Figure 6(b), it dampens the oscillations quickly and the frequency settles to nominal value of 50 Hz within acceptable timeframe. The comparative results with the existing literature based on methods using sources of energy integration and performance index parameters are depicted in Table 3, which shows the effectiveness of the proposed work.

Table 2. ANFIS parameters

S.No	Parameters
Membership function	Triangular
Fuzzy rules	10
Nodes	44
Training sample	1389
Maximum epoch	50

Table 3. Comparison with the related work

Reference	Configuration	Sources of energy	Method used	Performance index
[31]	AC microgrid	Microturbine, PV, FC, BESS, FESS, CHP	PSO-fuzzy	0.00015
[30]	Islanded microgrid	WT, PV, DG, AE, FC, BESS, FESS	PSO-MPC	0.0001274
[39]	AC microgrid	DG, FC, BESS, FESS, WT	PSO-ABC	0.00011
[40]	Standalone microgrid	DG, FESS, BESS, FC	GA	0.00018
[41]	Hybrid network	DG, WTG	QOHSA	0.000153
Proposed work	Islanded microgrid	DG, FC, BESS, FESS, PV, WT	KF-MPC	0.00012



(a) (b)

Figure 7. ANFIS results: (a) training error and (b) FIS output

5. CONCLUSION

In this study, the dynamic behavior of the microgrid was analyzed with different types of controllers while simultaneously considering the variable nature of renewable energy sources and incorporating the energy storage devices like battery energy storage and flywheel energy storage. The integration of energy storage devices plays a vital role in addressing the low inertia issue resulting from the utilization of renewable energy sources. However, selecting an efficient controller is of paramount importance. In this regard, the model predictive controller (MPC) offers an optimal solution, and the Kalman filter further enhances the performance of the MPC controller by promptly estimating its state vector. The performance of the microgrid with the Kalman filter-based MPC outperforms both PI and PI trained with ANFIS.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Sarbjeet Kaur	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓			
Surbhi Gupta	✓				✓					✓		✓	✓	

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

The authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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