Resonant converter for fast-charging applications

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ABSTRACT

Resonant converters (RCs) are gaining attention from the research community due to their significant contributions to the architecture of electric vehicle (EV) charging infrastructure. The primary part of RC is responsible for enabling constant-current (CC) charging, which helps lower inrush current, decrease losses, and improve efficiency. While the load current stays constant during charging using the CC approach, the source current grows linearly with charging time. However, pulling a high source current increases the rating of the inverter switches, which stresses them, raises their temperature, increases heat sink demand, and causes conduction loss—all of which are undesirable. Consequently, the rated CC is provided by the P2 topology of RC, which has a lower peak current source than other topologies and will improve charger performance. However, this assertion must be verified by mathematical modeling, design with theoretical calculations, specifications, and MATLAB simulation before execution. By providing a constant load current of 5 A at a DC source voltage of 200 V, the P2 RC and the conventional LCL RC are designed to compare source current values.

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1. INTRODUCTION

Wide-ranging output choices, little voltage strain, high operating frequency, magnetic integration, electrical separation, small electromagnetic interference (EMI) and harmonic pollution, high efficiency, and high energy density are just a few of the many advantages that make LLC resonant converters popular in electronics-based industries. This research presents detailed evaluations of the benefits and drawbacks covers three of the most used topologies for LLC resonant converters [1]. Because of their many topologies, unique and practical characteristics, broad range of power electronics applications, including high-voltage power supply, welding, inductive power transfer, power factor correction, capacitor charging, induction heating, and more, resonant converters have been the subject of much research [2]. For many power electronics applications, resonant converters (RCs) have also been considered as a good substitute because of their gentle switching, small size, high efficiency, and high frequency functioning. Three to four reactive components are present in many resonant immittance converter topologies [3], [4].

Because of many different topologies, unique and practical features, and an extensive variety of submissions in the fields of power electronics, including power factor correction, capacitor charging, induction heating, welding, inductive power transfer, high-voltage power supplies, and more, resonant converters have been the subject of intense research [2]. Also, RCs have been considered a feasible option for various power electronics applications because of their soft switching, high-frequency operation, high efficiency, and compact size. A maximum of three and four reactive elements are found in many resonant immittance converter topologies [3], [4]. The benefits of parallel resonant converters (PRC) and series resonant converters (SRC) are combined in hybrid resonant converters for power electronic applications, offering a broad range of operating conditions. [5]. Applications requiring impulse power make use of the capacitor charging power supply (CCPS) such flash lamps, medical sterilization, rock crushing, and electromagnetic rail guns, among many other application areas. A full bridge converter along with series phase-shift with parallel input and output for CCPS is designed and examined in this work [6]. Additionally, a thorough analysis of the industrial uses of LLC resonant converters is led, with a focus on solar systems, electric vehicle (EV) charging, power supply for LED lighting drivers, and liquid crystal display (LCD) televisions [1]. For hybrid DC systems, three-port resonant topologies such as LCC, LLC, and LCL are crucial because they offer soft switching operation with zero (ZVS) for active switches and zero current switching (ZCS) for diode rectifiers, which increases system dependability and efficiency. CC and CV modes are also used for battery charging. By reducing reactive losses, resonant capacitors further improve performance by removing DC bias [7], [8].

This article suggests a new AOC approach that overcomes the disadvantages of the traditional CC charging strategy of lengthy charging times and the CP charging approach of high resonant current stress by utilizing an LCC resonant converter's capacity to achieve a higher average output current. These speeds up the charging process all the way through [9]. Based on state plane analysis, this study examines the relationship between switching frequency and output voltage when maintaining a fixed limiting value for the resonant current [10]. This study presents a design methodology and analytical formulation for a parallel-resonant inverter with load-independent ZCS**.** Despite changes in load, the suggested inverter maintains a consistent output voltage amplitude and ZCS [11]. Power factor pre-regulation is another crucial element for enhancing power quality and reducing losses, particularly in EV chargers and CCPS. By utilizing fewer components and offering more effective energy conversion, the bridgeless isolated half-bridge converter architecture permits inherent power factor correction [12].

This study suggests a three-phase wye-wye coupled CLLLC resonant converter as the basis for a bidirectional onboard charging system. A three-phase wye-wye linked CLLLC resonant converter at the back and a bidirectional totem pole converter at the front make up its two-stage design. Pulse frequency modulation is used by this three-stage, rear-stage, wye-wye connected CLLLC resonant converter to confirm a constant output voltage and current for the charging system [13]. This analyses the design and operation of a series resonant converter, which is employed as a constant current power source with controllable output current [14]. To prevent high-voltage striking arcs, a high-voltage DC power supply that uses series resonant constant current charging is designed [15]. a reconfigurable resonant converter with a low component count is recommended in [16] for CV and CC battery charging for electric vehicles, ZVS-capable single-stage full-bridge converters can handle large voltage ranges and high-power levels, which makes them appropriate for intricate AC-DC or DC-AC transitions under changeable load circumstances [17]. By using resonant frequency instead of switching frequency, interleaved topologies in pulse frequency modulation (PFM) converters decrease current ripple and disperse load current across many phases [18].

Asymmetric CLLC resonant converters, on the other hand, provide bidirectional power transmission with adaptive soft start techniques that prioritize current limitations and permit seamless operation under a range of load circumstances [19]. Due to its benefits, which include continuous linearity, low charging time, high efficiency, low heat management system, and less losses, the constant current (CC) charging strategy has outperformed the constant voltage (CV) charging technique [20]. The disadvantages of simultaneous charging using separate voltage-fed LLC resonant converters include two-stage conversion losses as well as higher expenses, volume, and control complexity. This work addresses these problems by integrating LLC resonant converter with an isolated quasi-Z source inverter for a single-stage conversion at a variable voltage level for a simultaneous charging system [21]. The C2L3 resonant topology is used to achieve a fair balance between those measures. High accuracy and quick speed are guaranteed by the suggested equalizer, which hybridizes constant current (CC) and constant voltage (CV) balance in numerous equalization stages [22].

This paper suggests a bidirectional wireless power transmission system design for a power bank. The proposed design is based on circuits for detecting AC current, voltage, and phase, bidirectional AC–DC and bidirectional DC–DC circuits, and an MSP430L MCU functioning as a controller. Design given in [23] might improve power banks' mobility while achieving BWPT based on the simulation findings. In this work, P2 resonant configuration is considered for fast-charging applications with constant current output for different load conditions.

2. OBJECTIVES OF THE WORK ARE AS FOLLOWS

Power converters work on the idea of resonance in which capacitive and inductive reactance's cancel each other out which are known as resonant immittance converters, or resonant converters (RC). This results in decreased energy loss and increased efficiency. Using techniques like ZVS and ZCS, RCs provide soft switching by lowering switching losses and EMI. Regardless of load variations, the resonant converters may provide a constant output current. They are especially well-suited for high-frequency applications because they improve overall performance while enabling the decrease of passive component size. RCs may be generally divided into three groups such as series, parallel, and hybrid (both series and parallel combinations). The P2-RC, which is a hybrid configuration, offers great flexibility, healthier load regulation, and improved efficiency under various operating circumstances: i) To derive mathematical modeling of the P2 resonant converter; ii) Design P2 resonant converter parameters; and iii) To analyze and evaluate P2 resonant converter for constant current applications.

3. P2 RESONANT CONVERTER

Figure 1 shows the block diagram for this proposed work. An inverter running at the P2 resonant converters at resonance frequency (P2-RC) transforms the system's input direct current (DC) into alternating current (AC). Two inductors (L1, L2), and two capacitors (C1, C2) in this converter function under resonant circumstances to transmit power effectively and with the fewest possible losses. Soft switching is feasible during resonant frequency operation, which lowers switching losses and boosts system effectiveness.

Besides, the P2 RC works as an active impedance-matching network between the source and the load, destabilizing the system at dynamic loads and providing stability under static loads. The output of the P2 RC is an AC voltage that gets transformed to a DC voltage using a diode bridge rectifier. In addition, a controller reconfigures the switching frequency of the inverter's output to keep it at the resonant frequency and achieve a constant current output w.r.t to load changes. From design consideration, the P2 RC provides good and efficient working ability for CC applications.

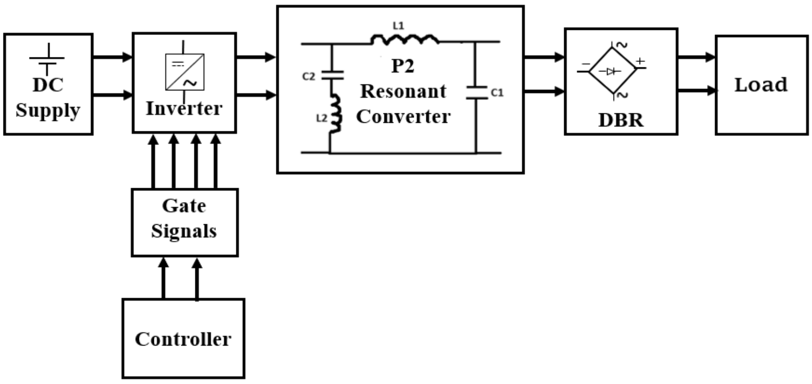


Figure 1. Block diagram of P_2 resonant converter

3.1. Mathematical modelling of proposed converter

To comprehend the properties of any RC topology, mathematical modeling is necessary. This entails determining the expressions for fundamental parameters such as characteristic impedance (Z_C), load current (I_2), source current (I_1), voltage gain (M), and current gain (H), among others, and monitoring the LICC condition [24], [25]. First, a Π-structured P2 RC operated with Resistive or Capacitive loaded with an impedance of Z_2 is selected. The structure's branch reactance's are X_1, X_2, and X_3, represented in Table 1. From the LICC condition, if it is rearranged then the design constraints are $L_1 = L_2$, $C_1 = 2$ C. Therefore, it becomes as Resonant frequency = $\omega = \frac{1}{\sqrt{l_1 c_1}} = \frac{1}{\sqrt{c_2(l_1+l)}} = \sqrt{\frac{c_1 - c_2}{l_2 c_1 c_2}}$.

3.2. Design and analysis of P2 resonant converter

Although numerous resonant converters have been projected in the literature for various applications, this specific design focuses on two key factors: enhancing voltage gain and minimizing input power drawn. One such converter is P2 RC, which offers load-independent constant current output and soft-switching capability, with a voltage gain of approximately 2.5. The component values for the two resonant inductors and capacitors used in the proposed Π-type resonant converter were derived from the mathematical analysis presented in the previous section. Table 1 summarizes the additional parameters of the converter. The design aims to achieve a voltage gain of 2.5 times higher than the input voltage and deliver a constant load current of 5 A (I avg). The P2 RC is designed to determine the RC elements (L1, L2, C1, C2) for 5 A of load current with 200 V DC input to the inverter at a switching frequency of 25 kHz as shown in Table 2. Table 3 shows the fundamental parameters such as characteristic impedance (Z_C), load current (I_2), source current (I_1), voltage gain (M), and current gain (H) according to the input specifications mentioned in Table 1.

Table 1. Mathematical modeling of P2 RC

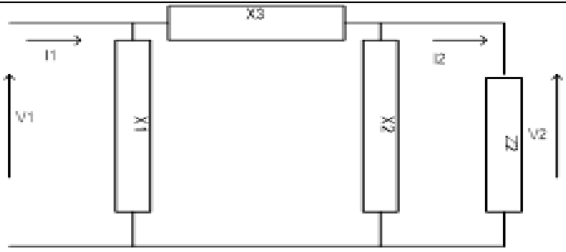
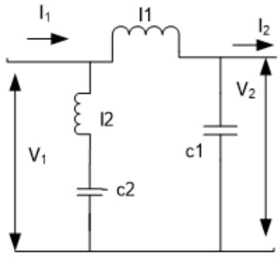
	Nominal-∏ Structure	P2 element form
Circuit diagram		
LICC	$X_1 = X_2 = -X_3$	$X_1=(\frac{1+S^2L_2C_2}{SC_2})=X_2=(\frac{1}{SC_1})=X_3=(SL_1)$
Voltage Gain	$M = \frac{Z_2X_2}{X_2X_3+Z_2(X_2+X_3)} = \frac{Z_2}{X_3}$@LICC	$M=\frac{V_2}{V_1}=\frac{Z}{S^2(ZL_1C_1)+SL_1+Z} = \frac{Z}{X_3}$
Current Gain	$H = \frac{X_1X_2}{X_1X_2+X_2X_3+Z_2(X_1+X_2+X_3)}$ $= \frac{X_2}{Z_2}$@LICC	$H=\frac{I_2}{I_1}=\frac{S^2(L_2C_2)+1}{S^2ZC_1C_2(L_1+L_2)+S^2C_2(L_1+L_2)+SZ(C_1+C_2)+1} = \frac{X_1}{Z}$
Load Current	$I_2 = \frac{X_2V_1}{X_2X_3+Z_2(X_2+X_3)}$ $= \frac{V_1}{X_3}$@LICC	$I_2=\frac{MV_1}{Z} = \frac{V_1}{S^2ZL_1C_1+SL_1+Z} = \frac{V_1}{X_3}$
Source current	$I_1 = \frac{V_1[X_1X_2 + X_2X_3 + Z_2(X_1 + X_2 + X_3)]}{X_1[X_2X_3 + Z_2(X_2 + X_3)]}$ $= \frac{Z_2V_1}{X_1X_3}$@LICC	$I_1=\frac{I_2}{H} = \frac{V_1[+Z(X_1X_2X_3)]}{S^2ZL_1C_1+SL_1+Z} = \frac{V_1Z}{S\left(\frac{L_1+S^2+L_1+L_2C_2}{C_2}\right)} = \frac{V_1Z}{X_1X_3}$
ZC	$Z_C = B_{@\omega=\omega_O} = \lvert X_3(\omega_O)\rvert$@LICC	$Z_C = \sqrt{\frac{L}{C}}$

Table 2. Specifications and design of P2 resonant converter

Specifications and design	
I_o = Avg load current = 5 A	I_2 = RMS of load current = Form factor*I_o = 5.55 A
V_{DC} = DC input voltage to inverter = 200 V	V_1 = Fundamental AC voltage=$\frac{2\sqrt{2}}{\pi}V_{DC}$=180 V
F = Switching frequency = 25 KHz	$L_1 = L_2$=Resonant inductors=$\frac{V_1}{2*\pi*f*I_2}$=2.06e^{-4} H
R_o = Load resistance = 100 Ω	C_1 = Resonant capacitors = $\frac{1}{\omega^2L_1}$ = 1.963e^{-7} F
t_c = Charging time = 50 msec	C_2 = Resonant capacitors=$\frac{C_1}{2}$ = 9.815e^{-8} F

Table 3. Theoretical calculations of P2 resonant converter

Theoretical calculations
$X_1 = X_2 = X_3$ = Branch impedances = 32.42 Ω
Z = AC load impedances = $\frac{8R_o}{\pi^2}$ = 81.05Ω
V_O = Load voltages = I_oZ = 405.25V and I_2 = AC load current = $\frac{V_1}{X_3}$ =5.55 A
M = Voltage gain = $\frac{Z}{X_3}$ = 2.5, and H = Current gain = $\frac{X_3}{Z}$ = 0.4
I_1 = AC source current = $\frac{I_2}{H}$ = 13.875 A and I_{1peak} = Peak source current = $I_1 * \sqrt{2}$ = 19.6222 A

4. RESULTS AND DISCUSSION

The P2 RC is operated with resistive and capacitive load in the MATLAB environment. As P2 RC is used to claim a load-independent constant current, the different loads are applied and verified with theoretical and simulation results. The gate signals of S1, S2, S3, and S4 of the inverter with 25 kHz operating frequency are shown in Figure 2. Figure 3 displays the MOSFET voltage and current waveforms of the switch's (S1) inverter's switching characteristics.

4.1. Analysis of P2 RC with resistive load

After applying the above gate pulses to the inverter, with 200 V of DC input voltage with a resistive load of 100 Ω applied, the inverter output voltage and current waveform are shown in Figure 4. The inverter output is applied as input to RC, its output waveforms are shown in Figure 5. The output of P2 RC is given as input to the DBR, its output voltage and current waveforms of the DBR with 100 Ω are shown in Figure 6. All the results shown above for a single resistive load of 100 Ω, for other values of resistive load results are tabulated in Table 4.

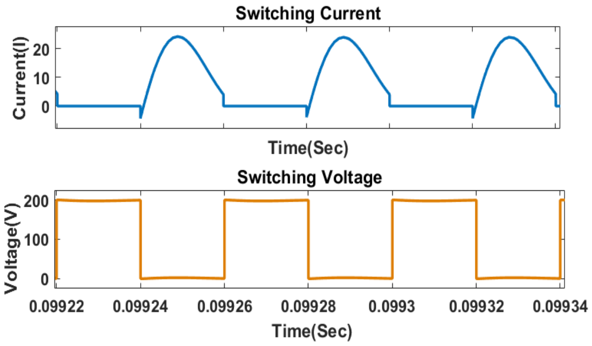


Figure 2. Gate signals for inverter switches

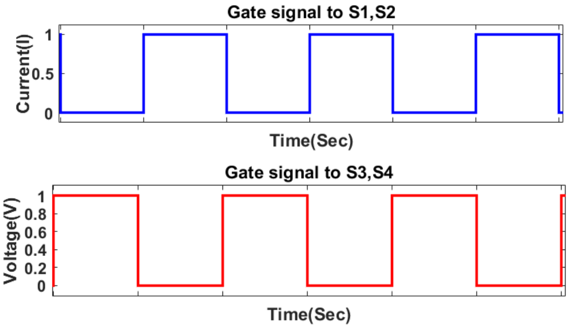


Figure 3. MOSFET switching characteristics of current and voltage

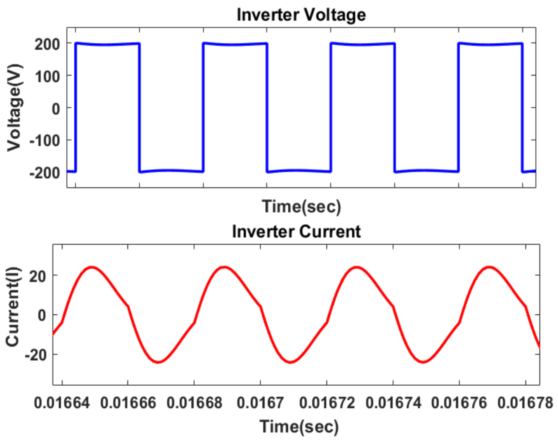


Figure 4. Inverter output at 100 Ω load

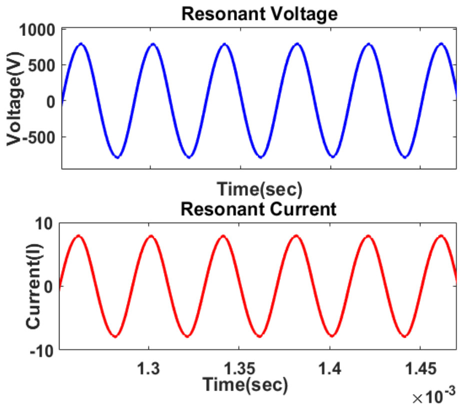


Figure 5. Resonant output at 100 Ω load

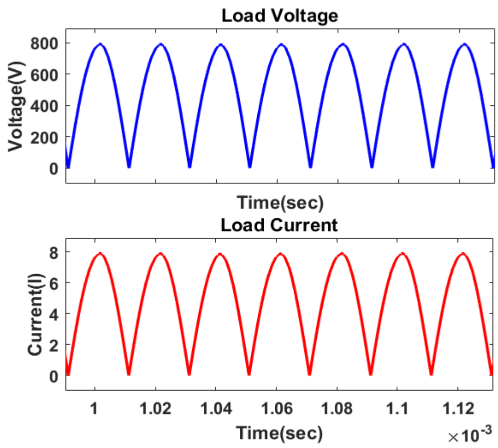


Figure 6. DBR output at load 100 Ω

From Table 3, it is concluded that the current output (I avg) is constant irrespective of any value of resistive load. Because all three stages work in together, the system produces a constant current at the DBR output. The DBR efficiently transforms the energy into a unidirectional current, the resonant P2 circuit efficiently transfers energy while shaping the waveform into a sinusoidal shape, and the inverter supplies a stable voltage input. Under various load scenarios, its integrated design reduces ripple and preserves current stability.

Table 4. P2 RC for different resistive loads

R-load	$V_{PEAK\ INV\ O/P}$ (V)	$I_{PEAK\ INV\ O/P}$(A)	$V_{PEAK\ RC\ O/P}$ (V)	$I_{PEAK\ RC\ O/P}$ (A)	$V_{PEAK\ DBR\ O/P}$ (V)	$I_{PEAK\ DBR\ O/P}$ (A)	I_{AVG}
100 Ω	200 V	100 A	800 V	8 A	800 V	8 A	5.06 A
200 Ω	200 V	150 A	1500 V	8 A	1600 V	8 A	5.06 A
300 Ω	200 V	180 A	2400 V	8 A	2400 V	8 A	5.06 A
400 Ω	200 V	200 A	3000 V	8 A	3100 V	8 A	5.06 A
500 Ω	200 V	220 A	4000 V	8 A	4000 V	8 A	5.06 A

4.2. Comparative analysis

The P2 RC is modeled, designed, and simulated for various resistive loads in the above sections. A comparative analysis is carried out through theoretical and simulation results tabulated in Table 4. Claims of the work:

- The output voltage is improved by 2.5 times, tabulated in Table 4.
- The P2 RC is compared with LCL RC to claim the input peak source current as shown in Figure 7. The P2 RC has 3.1 A and LCL has 3.7 A of current at t=50 msec, which shows that P2 RC in place of an LCL results in a 20% decrease in peak source current. The claim is that the "proposed novel P2 RC draws less peak current from source".

In Table 5. Voltage gain, current gain, source current, and load currents are validated with mathematical analysis and simulation results at a resistive load of 100 ohms.

4.3. Analysis of P2 RC with capacitive load

The same circuit is implemented with different capacitive loads and charging time considered as 50 ms. Here, the average load current (I_O avg) = $C\frac{dv}{dt}$ where C is load capacitance dv is the change in voltage, and dt is runtime fixed at 50 m seconds. A load profile voltage waveform of a capacitive load of 66 F is shown in Figure 8. The different capacitive load results are tabulated in Table 6.

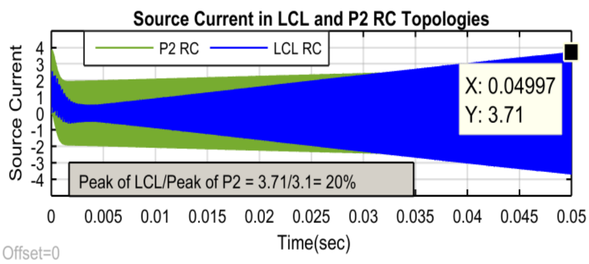


Figure 7. Source current comparison for P2 and LCL RC

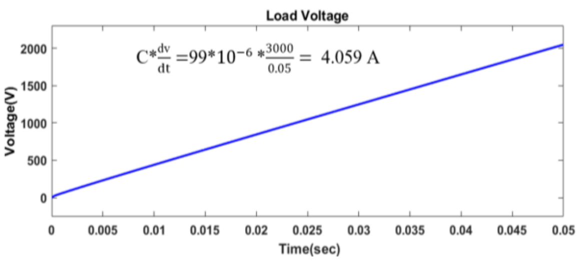


Figure 8. DBR output at load 99µF

Table 6. C- load conditions of P_2 resonant converter

C-load	Voltage across the capacitor (V_C)	Time in milliseconds	Average load current(mA)
33 µF	6080 V	50	4.012
66 µF	3060 V	50	4.039
99 µF	2050 V	50	4.059

Table 5. Comparative analysis

At a resistive load of 100 ohms		
Parameters	Theoretical value	Practical value
Voltage gain	2.499	2.497
Current gain	0.4	0.4
I_1 (source current)	13.87	13.78
I_2 (load current)	5.55	5.54

5. CONCLUSION

The P2 RC is a mathematical model of the proposed charger of 5 A, which was validated with theoretical and simulation results by applying 200 V DC at a frequency of 25 kHz. It is easy to see the charger's unique features, such as its high gain of 2.5, linearity in load voltage, and constant current feature as per designed. Since P2 RC has been shown to lower peak source current by 20% when compared to traditional LCL, this topology has been used for CC charging. The proposed work is validated with resistive and capacitive loads; need to validate with a battery to claim as a 5 A CC charger.

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AUTHOR CONTRIBUTIONS STATEMENT

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Kankipati Shravya	✓		✓	✓	✓	✓			✓	✓	✓		✓	

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 data supporting this study's findings are available on request from the corresponding author, [KS], upon reasonable request. The data, which contains information that could compromise the privacy of research participants, is not publicly available due to certain restrictions

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