Dynamic Wireless Charging Using Dynamic Frequency Tuning with Sliding Mode Control

Mahdi Salimi
Faculty of Engineering and Science
University of Greenwich, London, UK
m.salimi@gre.ac.uk

Pedram Asef
Department of Mechanical Engineering
University College London, London, UK
pedram.asef@ucl.ac.uk

***Abstract*— This paper presents a novel sliding mode control (SMC) based on a dynamic frequency tuning strategy for capacitive wireless power transfer (CWPT) chargers to ensure maximum power transfer and efficiency optimization under continuous misalignments in harsh environments, such as dynamic wireless charging for ground vehicles and offshore vessels. In the realm of maritime applications, complex matching networks like LCLC are known for their stability against misalignment. However, they struggle with efficient power transfer when coupling capacitance varies widely. Our proposed controller dynamically tunes the operating frequency to maintain resonance, ensuring the elimination of reactive power and the maximization of power transfer. Rigorous simulations validate the controller's effectiveness under severe misalignments, confirming that the promising SMC effectively compensates for parameter uncertainties and outperforms conventional approaches in adverse working environments.**

Keywords—Capacitive wireless power transfer, severe misalignment, dynamic charging, sliding mode controller

I. Introduction

Wireless charging is emerging as a critical solution for next-generation power transfer applications, including electric vehicles (EVs), electric vessels, and aircraft. These applications demand efficient, high-power, reliable, and maintenance-free charging systems to eliminate physical connectors. Moreover, dynamic wireless charging not only alleviates range anxiety but also boosts safety and convenience within automated charging infrastructures. This cutting-edge technology stands out as the perfect solution for contemporary transportation systems, paving the way for more efficient and practical onshore and offshore charging scenarios [1].

For on-the-go charging[2] of ground EVs and offshore wireless charging for vessels can be considered dynamic charging conditions, especially given the challenging maritime environment. Capacitive wireless power transfer (CWPT) is gaining attention as a viable alternative to inductive wireless power transfer (IWPT), primarily due to its superior performance under misalignment conditions [3]. Unlike inductive chargers, which experience efficiency drops under misalignment,, capacitive chargers leverage cascaded LC matching networks to provide a relatively flat frequency response around the resonant frequency, enabling robust and stable operation without requiring additional control loops. In EVs, cascaded LC networks significantly boost voltage gain, allowing effective power transfer even with small coupling capacitors, which is crucial for applications with limited chassis space [4]. However, cascaded LC matching networks still struggle to deliver efficient and high-output power to meet the requirement of fast chargers if they have to work under significant and continuous misalignments. While CWPT for EVs often relies on complex LC compensation networks, capacitive chargers for vessels can benefit the availability of large couplers. This advantage simplifies the compensation topology, as the coupling capacitance can be directly compensated using a series inductor (L-type compensation) at a reasonable operating frequency. The absence of matching networks on the vessel side reduces onboard weight and volume, making this pioneering approach highly favourable for maritime applications. Additionally, when coupler capacitance and L-type compensator are properly tuned, the series LC branch effectively acts as a short circuit at the resonant frequency, allowing maximum power transfer through the CWPT system.

Despite CWPT advantages, the L-type resonant topology is highly sensitive to frequency variations [5]. Even minor changes in the coupling capacitance can significantly shift the equivalent impedance of the LC branch, leading to a drastic drop in transferred power. This poses a major challenge for practical implementation in electrified vessels, where significant misalignments and continuous coupling variations are inevitable. Without an effective frequency tuning mechanism, L-type compensation may not be viable despite its inherent benefits. To enhance misalignment tolerance, the frequency tuning for a coaxially overlapped coupler combining capacitors and coils was introduced in 2024 [6] to eliminate the need for additional compensation components. By leveraging the complementary properties of different transmission paths, the CWPT system enables efficient power transfer across a broad coupling range. A frequency-tracking approach is implemented to sustain resonance despite misalignments, with experiments demonstrating 82.7% power transfer at 500 W under 40% unidirectional displacement. However, this approach depends on precise system parameters and lacks the adaptability of a closed-loop controller, making it vulnerable to parameter uncertainties that play a critical role in real-world applications. Hence, the output power significantly drops when the misalignment exceeds 40%.

To tackle these challenges, this paper introduces a sliding mode control (SMC) approach for dynamic frequency tuning in CWPT systems. The proposed controller continuously adjusts the operating frequency to maintain resonance across a wide range of conditions, ensuring that the coupling capacitance and L-type inductance function as a short circuit. This facilitates maximum power transfer while eliminating reactive power, thereby optimizing system efficiency by suppressing reactive current. Unlike conventional methods that require precise parameter values, the proposed SMC is inherently robust against uncertainties and can effectively counteract continuous and severe misalignments, even beyond 50%. The stability and robustness of the system are proved through Lyapunov theory, demonstrating that the controller can sustain optimized operation despite variations in coupling capacitance. Additionally, the controller exhibits a fast dynamic response, making it well-suited to handle real-time misalignment variations.

II. CAPACITIVE WIRELESS POWER TRANSFER SYSTEMS

The CWPT block diagram, shown in Fig. 1, is designed for applications with limited coupling capacitance, such as EVs, where the maximum accessible capacitance is restricted to a few hundred pF. The matching networks in Fig. 1, consisting of LC branches, serve two main functions: (1) reducing the required inductance for resonant operation and (2) enhancing voltage and current gain. The matching network on the primary side boosts voltage gain, while the secondary side increases current gain to improve the transferred power.

One of the key advantages of LCLC-based matching networks is their relatively flat impedance profile around the resonant frequency. Unlike sharp resonant peaks, this characteristic allows the system to continue transferring power despite variations in coupling capacitance due to misalignments. With an LCLC matching network on both sides, the wirelessly transferred power depends on the coupling capacitor [7]. During misalignments, when the coupling capacitance decreases, the transferred power also declines. Consequently, compared to the nominal condition (no misalignment), the transferred power experiences a reduction. Fig. 2 illustrates the dynamic variation of output power in an LCLC-based matching network [8] under different levels of misalignment.

As presented in Fig. 2, it can be reported that if the coupling capacitance is highly limited, such as in EVs, and if the maximum misalignment remains within 25%, an LCLC-based matching network remains a viable solution despite its complexity. Conversely, in harsher environments, such as electrified maritime applications, where harsh and continuous misalignments are expected, a closed-loop frequency tuning becomes essential. The controller ensures that the system preserves resonant operation despite rapid fluctuations in the coupling capacitance, thereby maintaining power transfer. Designing a closed-loop controller for frequency tuning of an LCLC-based matching network is challenging due to the presence of multiple state variables. Monitoring state variables, such as capacitor voltage, becomes more difficult as voltage gain increases. Additionally, implementing high-voltage LC branches in a vehicle raises concerns regarding safety, weight, and complexity. On the other hand, in certain applications where coupling capacitance is not as limited, such as electrified vessels with larger available surfaces, significant coupling capacitance can be achieved. In such cases, the use of LCLC matching networks for voltage gain enhancement is unnecessary. Instead, a simple L-type compensation network on the primary side might be sufficient to maintain resonant operation, eliminating the need for additional matching networks on the secondary side. Under resonant condition, the L-type matching network forms a series resonant circuit with the coupling capacitor, effectively acting as a short circuit. This allows the input voltage to be transferred directly to the load side. Consequently, the transferred power depends only on the input voltage and load impedance, not on the coupling capacitance, matching network parameters, or switching frequency. Therefore, even if the coupling capacitance fluctuates due to misalignments, the transferred power remains constant as long as the resonant operation is maintained, such as by dynamically adjusting the system frequency. The resonant operation ensures that the maximum accessible power is transferred through the capacitive wireless medium. Additionally, as soft switching can be implemented in resonant converters, the parasitic resistance of high-frequency inductors in the matching network is responsible for the majority of overall power losses. By reducing the inductor current and eliminating the reactive power component, the system operates with optimized efficiency.

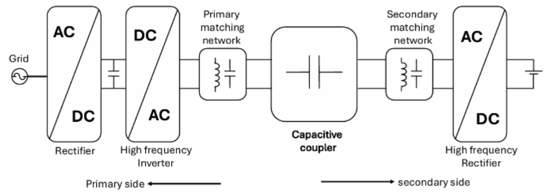

Fig. 1 Layout of capacitive wireless power transfer system

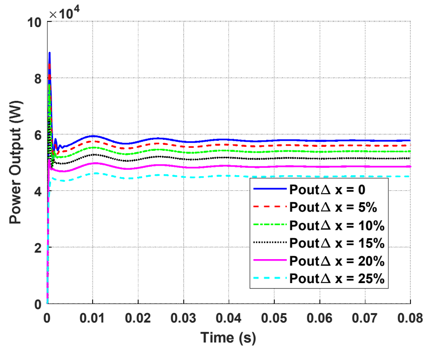

Fig. 2 Output power drop in an LCLC network under misalignment

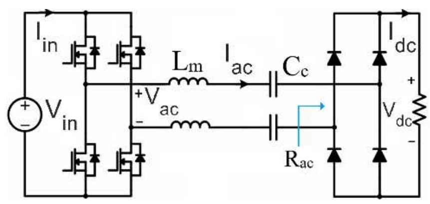

Fig. 3 CWPT system employing an L-type matching network

III. DYNAMIC MODELLING AND ANALYSIS

Fig. 3 illustrates the CWPT charger employing an L-type matching network. In contrast to the LC-type, which maintains a relatively flat impedance profile around the resonant frequency, the equivalent impedance of the series LC branch in the L-type topology exhibits a pronounced frequency dependence. This results in a highly sensitive power transfer characteristic, where even slight variations in the coupling capacitance can lead to significant power transfer losses. The simulation results, discussed in later sections, demonstrate that a 10% decrease in the coupling capacitance can lead to a significant transferred power reduction of nearly zero. In contrast, as illustrated in Fig. 2, the LCLC-type matching network shows a much more robust response. For L-type matching networks, implementing an additional control strategy is essential. This sensitivity to coupling capacitance is particularly problematic in harsh environments, such as maritime. Due to continuous vibrations induced by sea waves and wind, the coupling capacitance in these applications can fluctuate over a wide range. It should be noted that under such extreme conditions, even LCLC-type networks will fail to sustain effective wireless power transfer. To address this challenge, this study assumes that the capacitive coupler and switching frequency are sufficiently high, allowing for the selection of a reasonable series inductance to establish a series-resonant circuit. For higher frequency requirements, in addition to employing wide-bandgap transistors, it is also possible to leverage harmonic components of the square AC waveform (V_{ac}) rather than relying solely on the fundamental frequency for resonance. Such kind of approach enables the wireless power transfer frequency to be several times higher than the inverter switching frequency. Regardless of the nature of the DC load, the equivalent input resistance of the DC-AC rectifier in Fig. 3 is denoted as R_{ac}. The high-frequency AC voltage at the output of the DC-AC inverter is $V_{ac}(t) = V_m \sin(\omega t)$, the simplified dynamic model of the system can be represented as a sinusoidal voltage source driving a series RLC circuit. During steady-state operation under resonance, the voltage V_{ac} is applied across R_{ac}, and the complex power ($S_{steady-State}$) transferred through the capacitive coupler is defined as $S_{steady-State} = P_{SS} + Q_{SS}$, where:

$$P_{SS} = \frac{0.5{V_m}^2}{R_{ac}},\ Q_{SS} = 0 \tag{1}$$

This indicates that if the coupling capacitance is an uncertain parameter, the frequency of $V_{ac}(t) = V_m \sin(\omega t)$ must be dynamically adjusted to ensure that the inductance of the matching network (L_m) remains in resonance with the coupling capacitor, despite variations in C_c. Considering the inductor's current $i_L(t)$ and capacitor voltage $v_C(t)$ in Fig. 3 as the system's state variables, the state-space model of the circuit can be formulated as:

$$\frac{d(i_L(t))}{dt} = \frac{1}{L_m}(V_{ac}(t) - R_{ac} i_L(t) - v_C(t)) \tag{2}$$

$$\frac{d(v_C(t))}{dt} = \frac{1}{C_c} i_L(t) \tag{3}$$

Assuming that the circuit dynamics are radically faster than the controller's response, the state variables can be approximated during frequency changes by:

$$i_L(t) = I_m \sin(\omega t + \varphi) \tag{4}$$

$$v_C(t) = V_{C,m} \sin(\omega t + \varphi - 90^\circ) \tag{5}$$

During the steady state operation, it is expected to achieve $\varphi = 0$ under resonant operation. If $I_m = \frac{V_m}{|Z|}$ and $Q = 0.5 V_m I_m \sin(\varphi)$, where $Z = R_{ac} + j(\omega L_m - \frac{1}{\omega C_c})$ and $\sin(\varphi) = \frac{\omega L_m - \frac{1}{\omega C_c}}{|Z|}$, the transferred reactive power can be:

$$Q = \frac{{V_m}^2}{2} \frac{\omega L_m - \frac{1}{\omega C_c}}{{R_{ac}}^2 + \left(\omega L_m - \frac{1}{\omega C_c}\right)^2} \tag{6}$$

From Equation (6), it is evident that under resonant operation, where $\omega L_m = \frac{1}{\omega C_c}$, the reactive power reduces to zero, confirming that resonance is achieved.

IV. SMC Design for Dynamic Frequency Tuning

To maintain resonance despite variations in Cc, a frequency-tuning controller is required. Given the sensitivity of L-type matching networks to uncertainties and coupling capacitance fluctuations, such control is crucial for sustaining power transfer, especially in scenarios like offshore electrified vessel charging. It should be noted that a conventional PI controller struggles with real-time stabilization, leading to performance degradation. In contrast, the SMC ensures fast, robust frequency adaptation despite C_c variations. To achieve resonance, the SMC regulates reactive power to $Q_{ref} = 0$, ensuring maximum power transfer by eliminating reactive losses. Thus, reactive power serves as a feedback signal in the proposed controller. The SMC is designed following the step-by-step procedure detailed below.

A. Sliding Surface Definition

The sliding surface is defined based on the system error. The integral term ensures the elimination of steady-state error, while the proportional term enables fast convergence.

$$S = \left(Q_{ref} - Q\right) + \lambda \int \left(Q_{ref} - Q\right) dt \tag{7}$$

where $\lambda > 0$ is a tuning parameter. Considering the $Q_{ref} = 0$, the sliding surface simplifies to:

$$S = -\mathrm{Q} - \lambda \int (Q)\, dt \tag{8}$$

B. Equivalent Controller Design

The equivalent controller is derived by setting the time derivative of the sliding surface to zero. Ensuring that the system remains on the sliding surface once it reaches it.

$$\dot{S} = -\frac{dQ}{dt} - \lambda Q \tag{9}$$

Given that the frequency (ω) is chosen as the control input, the time derivative of the reactive power and sliding surface can be expressed using Equation (6) as follows:

$$\frac{dQ}{dt} = \frac{dQ}{d\omega} \times \frac{d\omega}{dt} \Rightarrow \dot{S} = -\beta(w)\frac{d\omega}{dt} - \lambda Q \tag{10}$$

$$\beta(w) = \frac{dQ}{d\omega} = \frac{{V_m}^2}{2}\left[\frac{\left(L_m + \frac{1}{\omega^2 C_c}\right)\left({R_{ac}}^2 + \left(\omega L_m - \frac{1}{\omega C_c}\right)^2\right)}{\left({R_{ac}}^2 + \left(\omega L_m - \frac{1}{\omega C_c}\right)^2\right)^2} - \frac{2\left(\omega L_m - \frac{1}{\omega C_c}\right)\left(L_m - \frac{1}{\omega^2 C_c}\right)}{\left({R_{ac}}^2 + \left(\omega L_m - \frac{1}{\omega C_c}\right)^2\right)^2}\right] \tag{11}$$

Considering $\dot{S} = 0$, the equivalent sliding mode controller (SMC) can be derived using Equation (10):

$$\left(\frac{d\omega}{dt}\right)_{eq} = -\frac{\lambda Q}{\beta(w)} \tag{12}$$

C. Reaching Condition

To ensure finite-time convergence to the sliding surface, the equivalent controller in (12) must be modified according to the reaching law ($\dot{S} = -\eta sgn(S)$) as follows:

$$\frac{d\omega}{dt} = \frac{\eta sgn(S) - \lambda Q}{\beta(w)} \tag{13}$$

It is recommended to replace sgn with a saturation function, which provides smoother transitions near $S = 0$. Hence, the final control law becomes:

$$\frac{d\omega}{dt} = \frac{\eta \frac{S}{|S| + \varepsilon} - \lambda Q}{\beta(w)} \tag{14}$$

where $\varepsilon > 0$ is a small constant.

D. Stability Analysis Using Barbalat's Lemma

To evaluate the stability of the proposed controller, the system Lyapunov function and its time derivative are selected:

$$V = 0.5 S^2 \Rightarrow \dot{V} = S\dot{S} \tag{15}$$

Substituting $\dot{S}$ from (10) and control law from (14):

$$\dot{V} = S\left(-\beta(w)\frac{d\omega}{dt} - \lambda Q\right) = S\left[-\beta(w)\frac{\eta\frac{S}{|S|+\varepsilon} - \lambda Q}{\beta(w)} - \lambda Q\right] \quad (16)$$

Therefore, the time derivative of the Lyapunov function can be simplified in this manner:

$$\dot{V} = -\eta\frac{S^2}{|S|+\varepsilon} \quad (17)$$

Since both η and ε are positive constants, $\dot{V} \leq 0$. This ensures that $S \to 0$ as $t \to \infty$, proving stability. Based on Equation (15), it is observed that $\dot{V}$ is uniformly continuous because S is a continuously differentiable function. Hence, based on the Barbalat's Lemma, $\lim_{t\to\infty} \dot{V} = 0$, which implies that $S \to 0$.

V. Simulation Results and Discussions

To verify the accuracy and effectiveness of the proposed SMC for frequency control in a CWPT system operating under harsh conditions, the control law derived in Equation (14) is simulated and evaluated using MATLAB/Simulink. This modelling specifically focuses on offshore charging of electrified vessels, where continuous variations in coupling capacitance can significantly affect the charger's performance. The proposed controller aims to eliminate reactive power, ensuring that the matching network inductance resonates with the coupler despite uncertainties. In addition to evaluating the steady-state response, the controller's dynamic performance is assessed to confirm its ability to optimize operation under continuously changing conditions. The nominal system parameters, as shown in Fig. 3, are provided in Table I. The 35 kW load demonstrates feasibility, but power level considerations and modular inverter-rectifier design complexities are beyond this study's scope.

TABLE I. Nominal System Parameters

Variable	*Value*	*Unit*
Input DC voltage (V_{in})	400	V
L-type matching network (L_m)	101.32	μH
Nominal coupling capacitance	1000	pF
Switching frequency	0.5	MHz
DC load	4.57	Ω
Smoothing gain (ε)	0.05	--
Control Gain (η)	1.5	--
Control gain (λ)	2.5	--

A. Test 1: Open-Loop Response

In the first test, the open-loop response of the system is evaluated at a fixed operating frequency. The coupler capacitance is assumed to be at its nominal value and the applied frequency is determined based on $\omega L_m = \frac{1}{\omega C_c}$. The controller is not activated in this test, allowing for an assessment of the system's natural response without frequency adjustment when there are no uncertainties. The results demonstrate that, in the absence of misalignment, the nominal frequency in an open-loop setup provides a satisfactory operation. However, due to parasitic capacitances introduced by power electronic switches and the relatively small coupling capacitance, a significant amount of reactive power is observed in the charger. This finding highlights that even under ideal conditions, the open-loop configuration fails to optimize the charger's performance due to reactive power losses. Fig. 5 explains the impact of a 10% reduction in coupling capacitance, causing transferred power to drop drastically from 35 kW to below 1 kW. The inverter output current becomes predominantly reactive, leading to significant power losses, highlighting the L-type compensator's sensitivity to parameter variations.

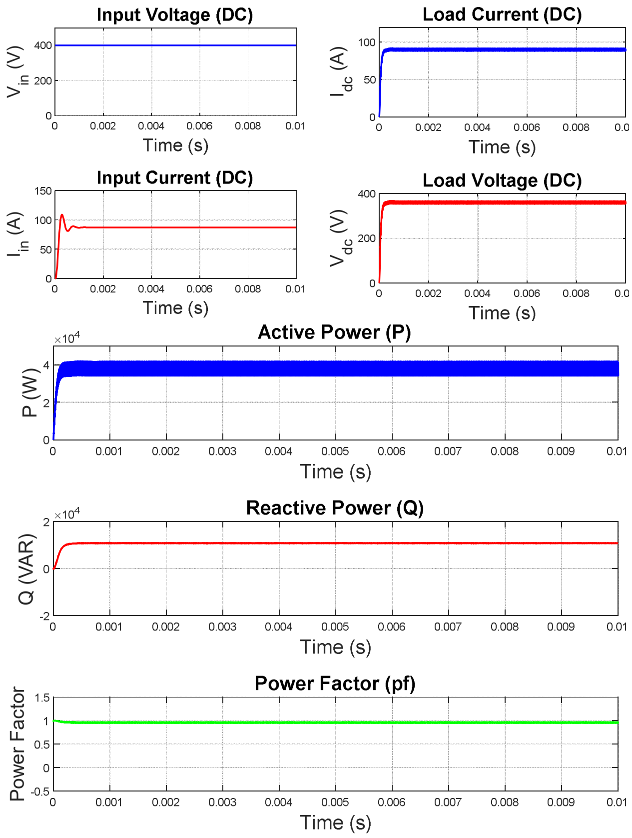

Fig. 4 Input and load voltage/current and transferred power at a fixed operating frequency (without the controller) under no misalignment

B. Test 2: Dynamic and Steady-State Response of Proposed SMC for the Promising CWPT System

In this test, the proposed SMC compensates for a 10% reduction in coupling capacitance (C_c=900 pF). As shown in Fig. 6, the controller eliminates reactive power and ensures maximum power transfer by maintaining resonance, even with parameter uncertainties. The settling time of approximately 0.01 seconds, observed in Fig. 6, highlights the fast dynamic response of the controller, making it ideal for applications with continuously varying coupling capacitance.

C. Test 3: Performance Under Wide Variations:

This test evaluates the controller's performance across a range of coupling capacitance variations. Fig. 7 shows the system's responses for C_c =750 pF and C_c =500pF, respectively. In both cases, the transferred active power stays near 35 kW, demonstrating the controller's ability to maintain maximum power transfer.

VI. Conclusion

This paper presents an innovative sliding mode control (SMC) strategy utilizing dynamic frequency tuning for innovative capacitive wireless power transfer (CWPT) chargers. This method guarantees maximum power transfer and efficiency optimization, even under continuous misalignments. The simulation results confirm that the proposed sliding mode control (SMC) effectively mitigates the sensitivity of L-type compensators to coupling capacitance variations. The controller adjusts the system frequency in real time to maintain resonance, eliminating reactive power and ensuring maximum power transfer, even under significant misalignment. The system exhibits excellent dynamic performance, quickly tracking the optimal operating frequency despite rapid capacitance changes, making it ideal for harsh environments, such as dynamic wireless charging for ground EVs and offshore vessels.

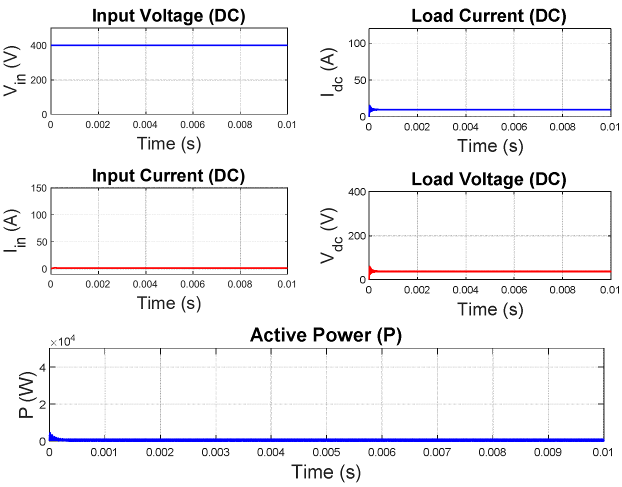

Fig. 5 Response of the fixed-frequency L-type matching network to 10% variation in the coupling capacitance

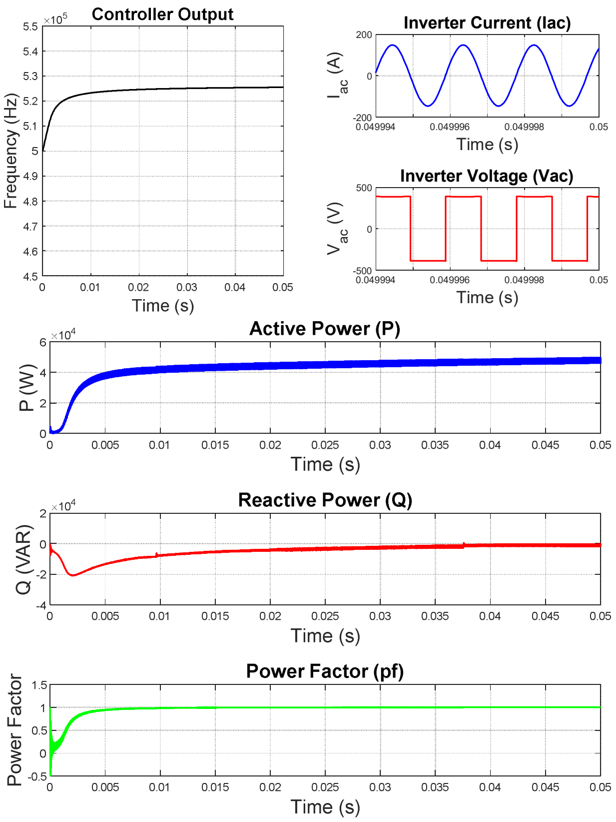

Fig. 6 Dynamic and steady state response of the proposed SMC to 10% variation in the coupling capacitor value.

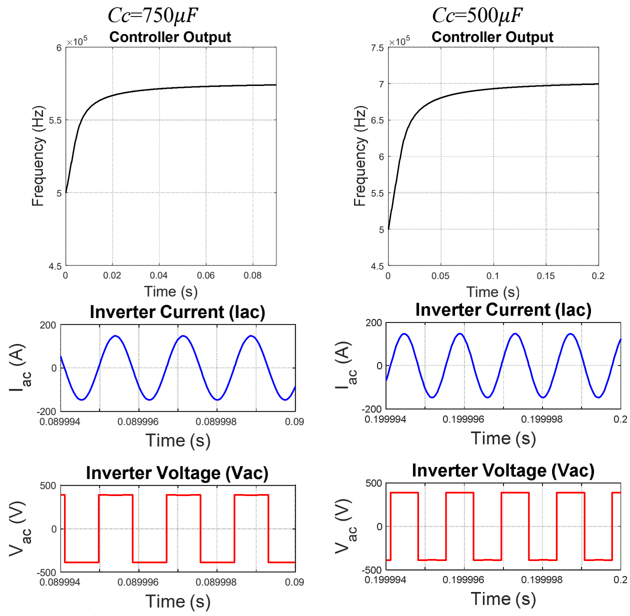

Fig. 7 Performance analysis under wide variations

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the University of Greenwich for their support through an internal grant, which played a crucial role in facilitating this research.

REFERENCES

[1] M. Safayatullah, M. T. Elrais, S. Ghosh, R. Rezaii and I. Batarseh, "A Comprehensive Review of Power Converter Topologies and Control Methods for Electric Vehicle Fast Charging Applications," in IEEE Access, vol. 10, pp. 40753-40793, 2022

[2] R. Makhdoom, S. Maji, S. Sinha, D. Etta and K. Afridi, "Multi-MHz In-Motion Capacitive Wireless Power Transfer System for Mobile Robots," *2022 Wireless Power Week (WPW)*, Bordeaux, France, 2022

[3] E. Rong, P. Sun, K. Qiao, X. Zhang, G. Yang and X. Wu, "Six-Plate and Hybrid-Dielectric Capacitive Coupler for Underwater Wireless Power Transfer," in IEEE Transactions on Power Electronics, vol. 39, no. 2, pp. 2867-2881, Feb. 2024

[4] S. Sinha, A. Kumar, B. Regensburger and K. K. Afridi, "Design of High-Efficiency Matching Networks for Capacitive Wireless Power Transfer Systems," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 10, no. 1, pp. 104-127, Feb. 2022

[5] Lu, Fei, Hua Zhang, and Chris Mi. "A Review on the Recent Development of Capacitive Wireless Power Transfer Technology" Energies vol. 10, no. 11, 2017

[6] F. Wang, Q. Yang, X. Zhang, T. Chen and G. Li, "Enhancing Misalignment Tolerance in Hybrid Wireless Power Transfer System With Integrated Coupler via Frequency Tuning," in IEEE Transactions on Power Electronics, vol. 39, no. 9, pp. 11885-11899, Sept. 2024

[7] J. Lian and X. Qu, "An LCLC-LC-Compensated Capacitive Power Transferred Battery Charger With Near-Unity Power Factor and Configurable Charging Profile," in *IEEE Transactions on Industry Applications*, vol. 58, no. 1, pp. 1053-1060, Jan.-Feb. 2022

[8] F. Lu, H. Zhang, H. Hofmann and C. Mi, "A Double-Sided LCLC-Compensated Capacitive Power Transfer System for Electric Vehicle Charging," in *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6011-6014, Nov. 2015