International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 16, No. 1, March 2025, pp. 225~234
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v16.i1.pp225-234

Enhancing efficiency and stability in CPT systems: a state feedback controller approach

Ahmed Al-Hattami[1], Shakir Saat[1], Yusmarnita Yusop[1], Md Rabiul Awal[2], A. H. M. Shapri[3], Huzaimah Husin[1]
[1]Faculty of Electronics and Computer Technology and Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[2]Department of Electrical Engineering, Universiti Malaysia Terengganu, Terengganu, Malaysia
[3]Faculty of Electronic Engineering and Technology, Universiti Malaysia Perlis, Perlis, Malaysia

Article Info

Article history:

Received Mar 11, 2024
Revised Oct 9, 2024
Accepted Oct 23, 2024

Keywords:

Comparative analysis
CPT
Lyapunov
PID controller
State feedback control

ABSTRACT

This work aims to present an innovative design and simulation of an auto-tuning capacitive power transfer (CPT) system. The system utilizes a Class-E converter, renowned for its exceptional efficiency. Challenges arise when trying to regulate the output voltage of a Class-E converter in the presence of load fluctuations, leading to an escalation in switching losses. By employing first harmonic approximation (FHA) and generalized state space averaging (GSSA), a state-space model of the system is constructed to effectively address this problem. The output voltage is regulated by a state feedback controller developed using the Lyapunov approach. This paper presents a comparative analysis of a traditional PID controller and a recently suggested state feedback controller, with a primary emphasis on system stabilization. The study examines the similarities and differences between the two controllers. The efficacy of the proposed controller design is demonstrated through the utilization of simulation data. Furthermore, these results confirm the validity of the comparative study, making it a substantial contribution to the field of CPT systems.

Corresponding Author:

Shakir Saat
Faculty of Electronics and Computer Technology and Engineering, Universiti Teknikal Malaysia Melaka
Melaka, 76100, Durian Tunggal, Melaka, Malaysia
Email: shakir@utem.edu.my

1. INTRODUCTION

Wireless power transfer (WPT) is attractive since it provides electricity without the need for connections. Inductive power transfer (IPT) is frequently employed for WPT, but its limitations result in decreased system efficiency. IPT systems are impacted by eddy current losses [1], which to exist despite attempts to decrease their occurrence [2]. On the other hand, capacitive power transfer (CPT) systems utilize electric fields rather than magnetic fields to deliver power. CPT systems exhibit cost-effectiveness, reduced weight, and superior performance in handling misalignment compared to IPT systems [3]. CPT systems effectively decrease electromagnetic interference (EMI) by confining electric fields mostly within electrically conductive surfaces [4].

However, CPT system has a high level of sensitivity to variations in both load and the separation distance between the plates [5], [6]. To deal with this sensitivity, researchers have suggested using compensation networks that can improve the efficiency of the system by converting the input impedance into a single resistive point even when there are changes in coupling [7], [8]. Several compensation topologies, including inductor, inductor-capacitor, inductor-capacitor-inductor or L, LC, and LCL, have been investigated to enhance CPT performance [9]. Nevertheless, these networks also pose difficulties, such as heightened intricacy and potential decline in performance under different circumstances, highlighting the necessity for alternate methods to uphold system stability and effectiveness. In ongoing CPT research, researchers are researching compensation topologies to boost power and efficiency [10], [11]. CPT can now be used in high-power electric vehicle charging systems and low-power biomedical implants [12], [13]. However, compensation networks can increase losses, reducing system efficiency [14].

The variability of circuit characteristics, such as mutual inductance or coupling capacitance, presents substantial hurdles in practical WPT applications. Differences in characteristics can cause the resonance frequency to deviate, resulting in a reduction in the ability to transfer power and overall efficiency. In IPT systems, these challenges have been resolved by using optimized compensation networks, such as LCL and CLC topologies [15], [16] and employing advanced control methods, such as resilient H∞ controllers [17], [18]. Although IPT and CPT systems share commonalities in their modeling, CPT systems face more significant difficulties because of their intrinsically low coupling capacitance [19]. Therefore, it is necessary to have controllers that improve resilience. However, most current CPT controllers only concentrate on achieving impedance-matching [20], [21].

Motivated by the above concerns and drawbacks, this article aims to design a reliable controller that improves CPT system stability in the face of load variation. This article uses generalized state-space averaging (GSSA) and frequency-harmonic analysis (FHA) to model the system. A linear state space model is generated by linearizing the nonlinear system by its steady-state operating point. The main contribution of this paper can be summarized as:

- Novel approach: This paper presents a new method for voltage regulation in Class-E converters of CPT systems using a Lyapunov-based controller, offering a fresh perspective on CPT system efficiency and stability.
- Empirical validation: The paper provides simulation results that confirm the effectiveness of the Lyapunov controller, serving as a valuable reference for future studies.
- Practical impact: The research potentially enhances CPT system efficiency and stability, impacting WPT applications significantly.

The remainder of the paper is arranged as section 2 analysis of Class-E CPT is done. Section 3 presents the modeling procedure that was used to obtain the system's state space model. The Lyapunov approach-based state feedback control design is shown in section 4. Section 5 presents an illustration of the simulation outcome, while section 6 presents the conclusion.

2. ANALYSIS AND MODELLING OF CLASS E CPT

In this section, we begin by constructing the initial harmonic model of the CPT system using Class-E topology, utilizing FHA. After that, a linearization procedure is performed at the system's operating point, which leads to the creation of a linear state-space model for the CPT system based on Class-E. Figure 1(a) shows the schematic diagram of the Class-E-based CPT system, while Figure 1(b) depicts the system's equivalent circuit.

The resonant capacitor, C_s, represents the equivalent capacitance formed by the series combination of capacitors , C_{s1} and C_{s2}, while the resistance R_t accounts for the total resistance of the loaded full-wave rectifier, as detailed in [22]. The equations related to C_s and R_t are shown in (1). The calculations provided here were comprehensively detailed in references [23], [24].

$$C_s = \frac{C_{s1} * C_{s2}}{C_{s1} + C_{s2}}, R_t = \frac{8 * R_l}{\pi^2} \tag{1}$$

The assumptions for the CPT system are consistent with the assumptions outlined in [25], while depending on [26], the calculations used to determine the values of the components in Figure 1 are as follow: the output power of the system, P_o is calculated using the (2).

$$P_o = \frac{8V_{cc}}{(\pi^2+4)R_t} \tag{2}$$

the resonant inductance, L_t, was separated into two components, L_{ext} and L_{res}, which were computed using the (3).

$$L_t = \frac{1.153\, R_t}{w} + \frac{QR_t}{w} \tag{3}$$

where, Q is the quality factor, and the w is the switching frequency. C_p, and C_s are the shunt capacitance and the resonant capacitance respectively, both can be obtained as in (4).

$$C_p = \frac{P_O}{\pi w {V_{cc}}^2}, C_s = \frac{1}{wQR_t} \tag{4}$$

The chock inductor's minimum value is calculated as in (5).

$$L_{c\_min} = 2\left(\frac{\pi^2}{4} + 1\right)\frac{R_t}{f} \tag{5}$$

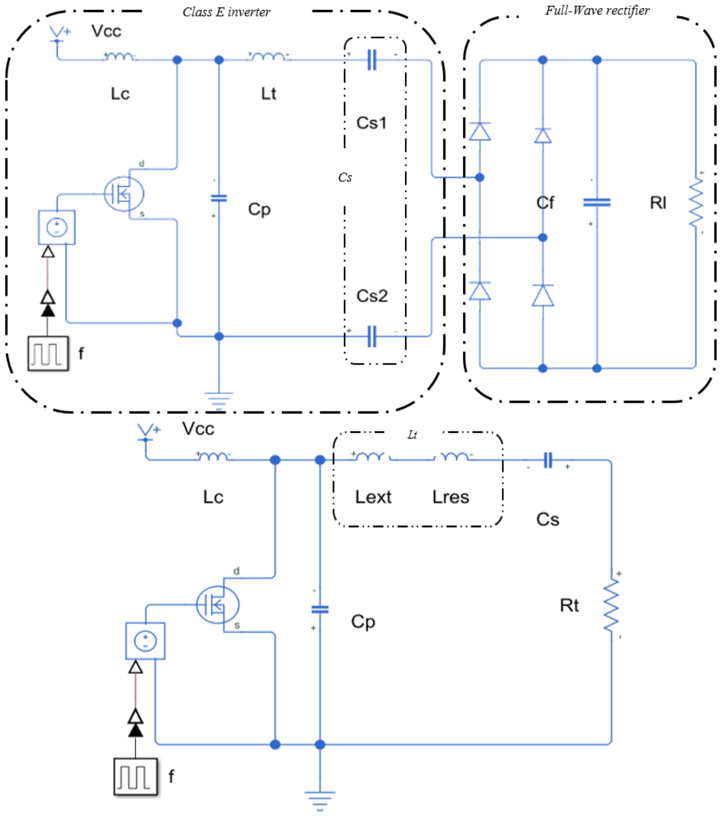

Figure 1. Class-E-based CPT system of (a) schematic diagram and (b) equivalent circuit

3. DYNAMIC MODELLING OF CLASS-E CPT SYSTEM

In this section, the state space representation of the Class-E CPT is obtained, followed by performing linearization to derive the linearized state matrix, input matrix, and output matrix of the system. The modelling procedure employs the FHA, assuming that only the fundamental harmonic contributes to the power transfer. Through the utilization of Fourier series expansion, the first harmonic of the series current (denoted as i) passing through Lt and Cs, as well as the voltage Vcs applied to capacitor Cs, can be expressed in accordance with the FHA. Where i_s, i_c, v_s, and v_c are the Fourier coefficients for representing i and V_{cs} respectively. By differentiating both side of (6), we obtained (7).

$$\begin{cases} i = i_s \sin wt + i_c \cos wt \\ v_{cs} = v_s \sin wt + v_c \cos wt \end{cases} \tag{6}$$

$$\begin{cases} \frac{di}{dt} = \left(\frac{di_s}{dt} - wi_c\right) sin(wt) + \left(\frac{di_c}{dt} + wi_s\right) cos(wt) \\ \frac{di_{vc}}{dt} = \left(\frac{dv_s}{dt} - wv_c\right) sin(wt) + \left(\frac{dv_c}{dt} + wv_s\right) cos(wt) \end{cases} \tag{7}$$

By analyzing the equivalent circuit in Figure 1(b) using KVL, and KCL, the (8) are obtained.

$$\begin{cases} V_{AB} = L_t \frac{di}{dt} + V_{cs} + sgn\,(i)\,V_f \\ i = C_s \frac{dv_{cs}}{dt} \\ |i| = C_f \frac{dv_f}{dt} + \frac{v_f}{R_l} \end{cases} \tag{8}$$

In (8), V_{AB} represents the voltage across the shunt capacitor C_p, while C_f, denotes the system's output voltage. The function $sgn\,(x)$, denotes the signum function and it is given in (9).

$$sgn\,(x) = \begin{cases} 1\; x < 0 \\ 0\; x = 0 \\ -1\; x > 0 \end{cases} \tag{9}$$

According to Wang *et al.* [27], the symbol, $sgn\,(x)$ is approximate as in (10).

$$\begin{cases} sgn\,(i) = \frac{4\,i_s}{\pi i_p} sin(wt) + \frac{4\,i_c}{\pi i_p} cos(wt) \\ |i| \approx \frac{2}{\pi} i_p \\ i_p = \sqrt{{i_s}^2 + {i_c}^2} \end{cases} \tag{10}$$

The voltage across MOSFET, V_{AB}, is expressed as in (11).

$$V_{ab} = \begin{cases} \frac{I_o}{wC_p} [wt - \frac{3\pi}{2} - \frac{\pi}{2} cos(wt) - sin(wt)\; \pi < wt < 2\pi \\ 0\; 0 < wt < \pi \end{cases} \tag{11}$$

The Fourier series expansion of the voltage V_{AB} is simplified as in (12),

$$V_{AB} = a_1\, sin(wt) + b_1\, cos(wt) \tag{12}$$

where a_1 and b_1 are formulated as in (13).

$$\begin{cases} a_1 = \frac{1}{\pi} \int_{\pi}^{2\pi} v_{AB}\, sin(wt)\, d(wt) = -\frac{\pi V_{cc}}{2} \\ b_1 = \frac{1}{\pi} \int_{\pi}^{2\pi} v_{AB}\, cos(wt)\, d(wt) = \frac{(8-\pi^2) V_{cc}}{4} \end{cases} \tag{13}$$

By substituting (6), (7), (10), (12), and (13) into (8), and then setting the coefficients of the DC, sine, and cosine terms equal to each other, the state-space equation can be derived as in (14).

$$\begin{cases} L_t \frac{di_s}{dt} = L_t w i_c - v_s - \frac{4 i_s}{\pi i_p} v_f - \frac{\pi V_{cc}}{2} \\ L_t \frac{di_c}{dt} = -L_t w i_s - v_c - \frac{4 i_c}{\pi i_p} v_f + \frac{(8-\pi^2) V_{cc}}{4} \\ C_s \frac{dv_s}{dt} = i_s + C_s w v_c \\ C_s \frac{dv_c}{dt} = i_c - C_s w v_s \\ C_f \frac{dv_f}{dt} = \frac{2}{\pi} i_p - \frac{v_f}{R_l} \end{cases} \tag{14}$$

In steady state, $\frac{2}{\pi} I_p - \frac{v_f}{R_l} = 0$, where I_p and V_f are the steady state value of i_p and v_f. Hence, (14) can be expressed as follows:

$$A_{ss} = \begin{bmatrix} -\frac{8R_l}{\pi^2 L_t} & w & -\frac{1}{L_t} & 0 \\ -w & -\frac{8R_l}{\pi^2 L_t} & 0 & -\frac{1}{L_t} \\ \frac{1}{C_s} & 0 & 0 & w \\ 0 & \frac{1}{C_s} & -w & 0 \end{bmatrix} \qquad B_{ss} = \begin{bmatrix} -\frac{\pi V_{cc}}{2L_t} \\ \frac{(8-\pi^2) V_{cc}}{4L_t} \\ 0 \\ 0 \end{bmatrix}$$

The equilibrium point is determined when $\dot{x} = 0$,which yields $x_0 = -A^{-1}BV_{CC}$. Performing linearization of (14) around this equilibrium point provides the linearized state matrix, input matrix, and output matrix of the system, we arrive at (15).

$$A = \begin{bmatrix} -\frac{4I_c{}^2V_f}{\pi L_t I_p{}^3} & w_0 + \frac{4I_cI_sV_f}{\pi L_t I_p{}^3} & -\frac{1}{L} & 0 & -\frac{4I_s}{\pi L_t I_p} \\ \frac{4I_cI_sV_f}{\pi L_t I_p{}^3} - w_0 & -\frac{4I_c{}^2V_f}{\pi L_t I_p{}^3} & 0 & -\frac{1}{L} & -\frac{4I_c}{\pi L_t I_p} \\ \frac{1}{C_s} & 0 & 0 & w_0 & 0 \\ 0 & \frac{1}{C_s} & -w_0 & 0 & 0 \\ \frac{2I_s}{\pi C_p I_p} & \frac{2I_c}{\pi C_p I_p} & 0 & 0 & \frac{1}{R_l C_f} \end{bmatrix}, B = \begin{bmatrix} I_c \\ -I_s \\ V_c \\ -V_c \\ 0 \end{bmatrix}, C = \begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \\ 1 \end{bmatrix}^T \quad (15)$$

4. STATE FEEDBACK CONTROL DESIGN

The main part of the control design is a state feedback (SF) controller based on the Lyapunov approach. The SF controller adjusts the switching frequency of the Class-E converter according to the state variables of the CPT system, so the output voltage is regulated, and the system stability is ensured. To ensure zero steady state error, the system is enhanced by incorporating an integrator state. The overall controller design based on the Lyapunov approach is depicted in Figure 2, where C_g is the controller gain. Consider the following system as in (16).

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \quad (16)$$

The state of integrator is introduced as in (17).

$$\begin{cases} \dot{x} = Ax + C_gB\alpha \\ \dot{\alpha} = u \end{cases} \quad (17)$$

Hence, the system state equation with the integrator's state becomes as in (18).

$$\begin{cases} \begin{bmatrix} \dot{x} \\ \dot{\alpha} \end{bmatrix} = \begin{bmatrix} A & C_gB \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ \alpha \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u \\ y = \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} x \\ \alpha \end{bmatrix} \end{cases} \quad (18)$$

So, the linearized system now becomes the (19).

$$A_l = \begin{bmatrix} A & C_gB \\ 0 & 0 \end{bmatrix}, B_l = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}, C_l = \begin{bmatrix} C & 0 \end{bmatrix} \quad (19)$$

A Lyapunov is introduced as in (20)

$$V = x^T P x \quad (20)$$

where P is the Lyapunov matrix that will satisfy the following condition as in (21) and (22).

$$V(x) > 0 \quad (21)$$

$$\frac{dv}{dx} \leq 0 \quad (22)$$

The controller is selected to be on the form of (23),

$$u = -Kx \quad (23)$$

where the K is the gain value of the controller.

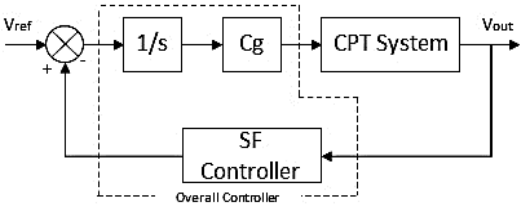

Figure 2. Block diagram of the controller design

- Theorem1

By formulating the Lyapunov equation and employing calculus theory to simplify it along with its associated conditions, we have derived the following linear matrix inequality (LMI) equation. Moreover, it is worth noting that the system can be stabilized through state feedback if and only if $\begin{bmatrix} X \\ \dot{X} \end{bmatrix}^T \begin{bmatrix} A & B \\ B^T & C \end{bmatrix} \begin{bmatrix} X \\ \dot{X} \end{bmatrix} \leq 0$ is met.

- Proof of the Theorem 1

According to (22), the differentiation of V should be less than zero and as known from the Lyapunov in (20).

$$V = x^T P x$$

$$\frac{d(x^T P x)}{dx} = \dot{X}^T P X + X^T P \dot{X} \leq 0$$

$$\frac{d(x^T P x)}{dx} = X^T (A^T P + AP - K^T B^T P - PBK) X \leq 0$$

From this, you can infer that A, and B value are as follow:

$$A = (A^T P + PA)$$

$$B = -(PBK + K^T B^T P)$$

Converting Lyapunov function to matrix form using Schur complement, one arrives at:

$$\begin{bmatrix} X \\ \dot{X} \end{bmatrix}^T \begin{bmatrix} A^T P + PA & -(PBK + K^T B^T P) \\ -(PBK + K^T B^T P)^T & 0 \end{bmatrix} \begin{bmatrix} X \\ \dot{X} \end{bmatrix} \leq 0$$

The proof is completed.

5. SIMULATION RESULT

This section discusses the effectiveness of the proposed method. The simulation work is done using the following specifications:

$$V_{cc} = 24V, R_l = 40\ \Omega, f = 2MHz, Q = 20, C_f = 20\ \mu F, V_o = 14.4V, C_{s1}, C_{s2} = 245.38\ pF,$$

$$C_p = 453\ pF, L_t = 54.55\ \mu H, L_{c\_min} = 138.7\ \mu F$$

A complete CPT system, employing the Class-E converter and incorporating an automatic frequency tuning mechanism, has been realized within the MATLAB environment, utilizing the sim electronics package within Simulink. The schematic representation of the system is delineated in Figure 3.

For this design, it is necessary to keep the system output voltage steady at 14.4 V. Following the design procedure of our Lyapunov controller present in section 4, the Lyapunov matrix and control gain is calculated by employing YALMIP tools in MATLAB and obtained as follow:

$$\text{Lyapunov matrix}, P = \begin{bmatrix} 0.9001 & -0.1646 & -0.0002 & -0.0002 & -0.0275 \\ -0.1646 & 0.7340 & 0.0000 & 0.0003 & -0.0009 \\ -0.0002 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ -0.0002 & 0.0003 & 0.0000 & 0.0000 & 0.0000 \\ -0.0275 & -0.0009 & 0.0000 & 0.0000 & 0.1974 \end{bmatrix}$$

$$\text{control gain}, K = [2.804 \quad -1.768 \quad -0.002644 \quad -0.00406 \quad 68.0083]$$

For this simulation, the open-loop signal is impacted when altering the load by +30% at 4 ms and -30% at 10 ms. The proposed controller is then compared with PID controller. The comparison is shown in Figure 4 between the proposed one and with open loop and PID. The performance of the proposed controller when compared with PID controller is shown in Table 1.

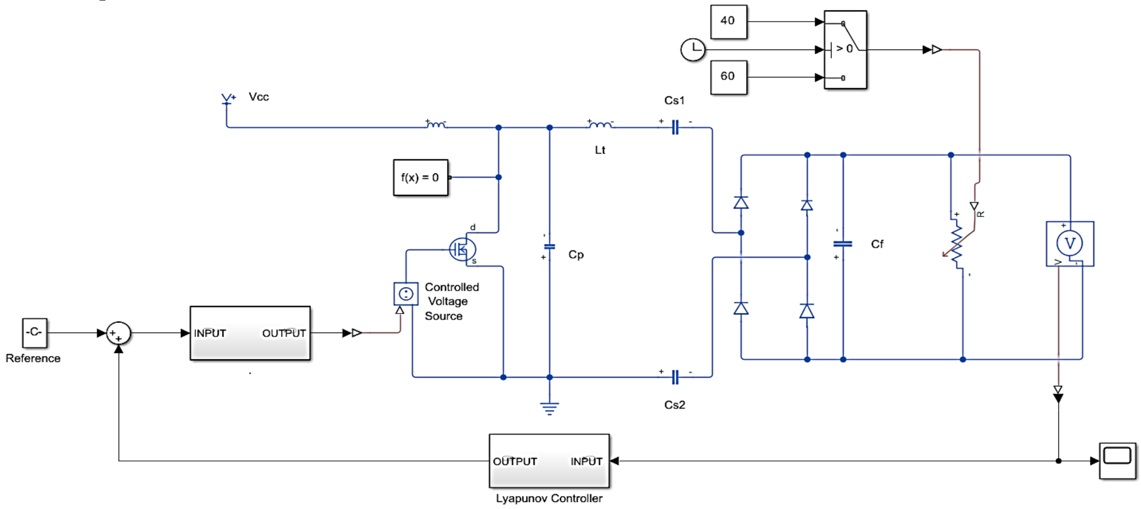

Figure 3. Auto frequency tuning Class-E CPT system

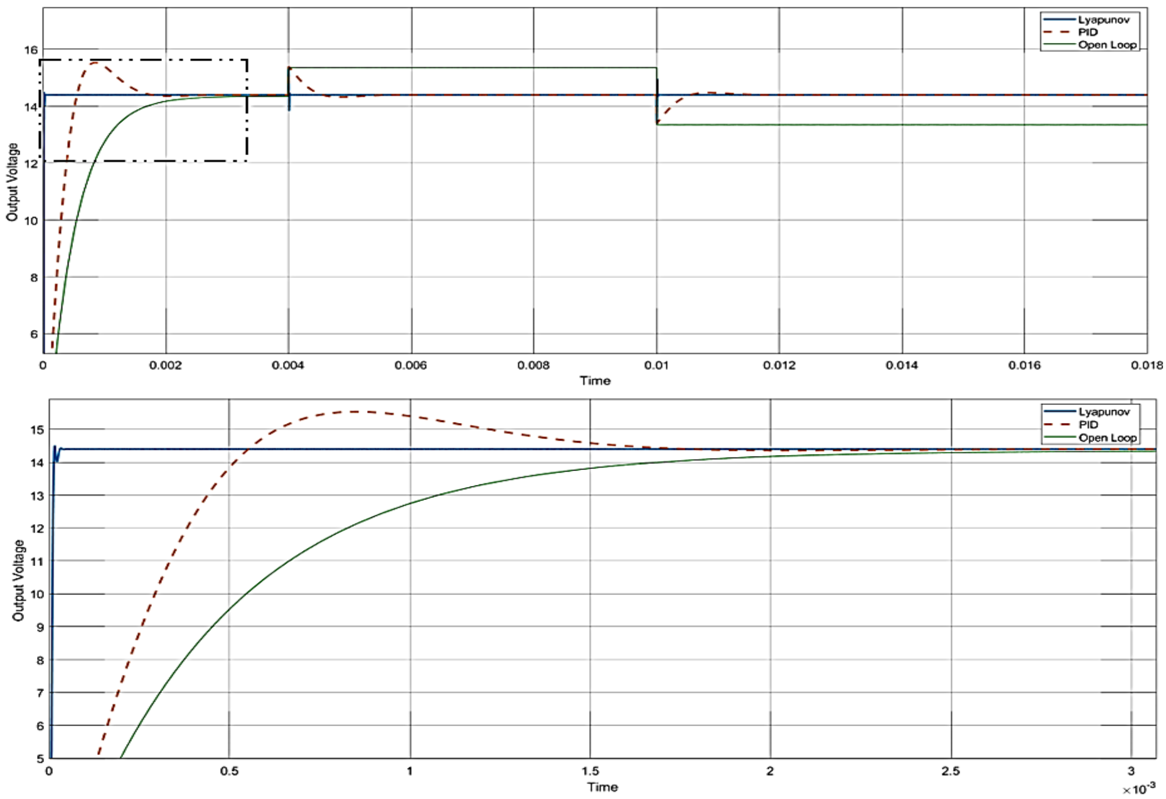

Figure 4. Open loop vs PID and Lyapunov

Table 1. The performance of Lyapunov vs PID

Term	Lyapunov	PID
Settling time (ms)	0.05	2.7
Overshoot	0.4	1.437
Steady-state error	0.3	0.3

6. CONCLUSION

This study presents a comprehensive analysis of CPT systems, with a particular emphasis on the integration of SF into the design of Class E inverters. Utilizing the GSSA method and MATLAB simulations, a thorough evaluation of CPT system performance is conducted. Drawing inspiration from successful Lyapunov-based SF controllers in similar CPT configurations, the investigation is extended to incorporate widely used PID controllers. The Lyapunov-based SF controllers exhibit remarkable robustness against load variations, thereby ensuring stable output voltages. These controllers, developed through principled Lyapunov techniques, demonstrate resilience in the face of diverse disturbances, affirming their effectiveness in maintaining system stability. In conclusion, this paper contributes to the field by providing insights into the efficacy of Lyapunov-based SF controllers in CPT systems. The findings offer valuable considerations for engineers and researchers seeking optimal control strategies in similar energy transfer systems. As progress is made towards more efficient and reliable CPT systems, the findings presented serve as a stepping stone for future advancements in controller design and application.

ACKNOWLEDGEMENTS

This study is funded by Ministry of Higher Education (MOHE) of Malaysia through the Fundamental Research Grant Scheme (FRGS), no. FRGS/1/2022/TK07/UTEM/02/46. The Authors also would also like to thank Universiti Teknikal Malaysia Melaka (UTeM) for all the supports.

REFERENCES

[1] O. Imoru, A. Jassal, H. Polinder, E. Nieuwkoop, J. Tsado, and A. A. Jimoh, “An inductive power transfer through metal object,” *1st International Future Energy Electronics Conference, IFEEC 2013*, pp. 246–251, 2013, doi: 10.1109/ifeec.2013.6687511.

[2] D. Kim, A. Abu-Siada, and A. Sutinjo, “State-of-the-art literature review of WPT: Current limitations and solutions on IPT,” *Electric Power Systems Research*, vol. 154, pp. 493–502, 2018, doi: 10.1016/j.epsr.2017.09.018.

[3] L. Huang, A. P. Hu, A. Swain, S. Kim, and Y. Ren, “An overview of capacitively coupled power transfer - A new contactless power transfer solution,” *Proceedings of the 2013 IEEE 8th Conference on Industrial Electronics and Applications, ICIEA 2013*, pp. 461–465, 2013, doi: 10.1109/ICIEA.2013.6566413.

[4] T. Komaru and H. Akita, “Positional characteristics of capacitive power transfer as a resonance coupling system,” *2013 IEEE Wireless Power Transfer, WPT 2013*, pp. 218–221, 2013, doi: 10.1109/WPT.2013.6556922.

[5] T. M. Mostafa, D. Bui, A. Muharam, R. Hattori, and A. P. Hu, “Capacitive power transfer system with reduced voltage stress and sensitivity,” *Applied Sciences (Switzerland)*, vol. 8, no. 7, 2018, doi: 10.3390/app8071131.

[6] Z. Wang, Y. Zhang, X. He, B. Luo, and R. Mai, “Research and Application of Capacitive Power Transfer System: A Review,” *Electronics (Switzerland)*, vol. 11, no. 7, 2022, doi: 10.3390/electronics11071158.

[7] H. Sun, X. Zhang, and L. Huang, “A Compact Capacitive Power Transfer System Based on Planar Inductors BT - The proceedings of the 16th Annual Conference of China Electrotechnical Society,” 2022, pp. 570–577.

[8] S. Choi, G. C. Lim, J. S. Hong, E. Chung, G. Y. Choe, and J. I. Ha, “Compensation Network Design Method for Capacitive Power Transfer System Considering Coupling Variation,” *2022 IEEE Energy Conversion Congress and Exposition, ECCE 2022*, pp. 1–6, 2022, doi: 10.1109/ECCE50734.2022.9947582.

[9] J. Xia *et al.*, “A General Parameter Optimization Method for a Capacitive Power Transfer System with an Asymmetrical Structure,” *Electronics (Switzerland)*, vol. 11, no. 6, 2022, doi: 10.3390/electronics11060922.

[10] C. Lecluyse, B. Minnaert, and M. Kleemann, “A review of the current state of technology of capacitive wireless power transfer,” *Energies*, vol. 14, no. 18, pp. 1–22, 2021, doi: 10.3390/en14185862.

[11] N. I. Siddique, S. M. Abdullah, Q. Nafees, and U. Islam, “A Comprehensive Overview on the Development of Compensation Topologies for Capacitive Power Transfer System,” *Electrical and Electronic Engineering*, vol. 9, no. 1, pp. 9–16, 2019, doi: 10.5923/j.eee.20190901.02.

[12] F. Lu, H. Zhang, H. Hofmann, and C. Mi, “A Double-Sided LCLC-Compensated Capacitive Power Transfer System for Electric Vehicle Charging,” *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6011–6014, 2015, doi: 10.1109/TPEL.2015.2446891.

[13] R. Jegadeesan, K. Agarwal, Y. X. Guo, S. C. Yen, and N. V. Thakor, “Wireless Power Delivery to Flexible Subcutaneous Implants Using Capacitive Coupling,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 1, pp. 280–292, 2017, doi: 10.1109/TMTT.2016.2615623.

[14] F. Gao, Z. Wang, J. Deng, S. Wang, and Y. Wang, “A Comparison Study of Compensation Topologies for Capacitive Power Transfer,” *IEEE International Symposium on Industrial Electronics*, vol. 2019-June, pp. 691–696, 2019, doi: 10.1109/ISIE.2019.8781437.

[15] R. Mai, Y. Chen, Y. Li, Y. Zhang, G. Cao, and Z. He, “Inductive Power Transfer for Massive Electric Bicycles Charging Based on Hybrid Topology Switching With a Single Inverter,” *IEEE Transactions on Power Electronics*, vol. 32, no. 8, pp. 5897–5906, 2017, doi: 10.1109/TPEL.2017.2654360.

[16] Y. Wang, Y. Yao, X. Liu, and Di. Xu, “S/CLC compensation topology analysis and circular coil design for wireless power transfer,” *IEEE Transactions on Transportation Electrification*, vol. 3, no. 2, pp. 496–507, 2017, doi: 10.1109/TTE.2017.2651067.

[17] C. Xia, W. Wang, G. Chen, X. Wu, S. Zhou, and Y. Sun, "Robust Control for the Relay ICPT System under External Disturbance and Parametric Uncertainty," *IEEE Transactions on Control Systems Technology*, vol. 25, no. 6, pp. 2168–2175, 2017, doi: 10.1109/TCST.2016.2634502.
[18] C. Xia, Q. Sun, X. Li, and A. P. Hu, "Robust μ-Synthesis Control of Dual LCL Type IPT System Considering Load and Mutual Inductance Uncertainty," *IEEE Access*, vol. 7, no. c, pp. 72770–72782, 2019, doi: 10.1109/ACCESS.2019.2920411.
[19] F. Lu, H. Zhang, and C. Mi, "A review on the recent development of capacitive wireless power transfer technology," *Energies*, vol. 10, no. 11, 2017, doi: 10.3390/en10111752.
[20] D. Bui, T. M. Mostafa, A. P. Hu, and R. Hattori, "DC-DC Converter Based Impedance Matching for Maximum Power Transfer of CPT System with High Efficiency," *2018 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer, Wow 2018*, pp. 1–5, 2018, doi: 10.1109/WoW.2018.8450929.
[21] S. Sinha, A. Kumar, B. Regensburger, and K. K. Afridi, "Active Variable Reactance Rectifier-A New Approach to Compensating for Coupling Variations in Wireless Power Transfer Systems," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 3, pp. 2022–2040, 2020, doi: 10.1109/JESTPE.2019.2958894.
[22] T. M. Mostafa, D. Bui, A. Muharam, R. Hattori, and A. P. Hu, "A Capacitive Power Transfer System with a CL Network for Improved System Performance," *2018 IEEE Wireless Power Transfer Conference, WPTC 2018*, pp. 1–4, 2019, doi: 10.1109/WPT.2018.8639497.
[23] S. Aldhaher, D. C. Yates, and P. D. Mitcheson, "Modeling and Analysis of Class EF and Class E/F Inverters with Series-Tuned Resonant Networks," *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3415–3430, 2016, doi: 10.1109/TPEL.2015.2460997.
[24] M. Yousefi, Z. D. Koozehkanani, J. Sobhi, H. Jangi, and N. Nasirezadeh, "Efficiency analysis of low power class-E power amplifier," *Modern Applied Science*, vol. 8, no. 5, pp. 19–29, 2014, doi: 10.5539/mas.v8n5p19.
[25] N. O. Sokal and A. D. Sokal, "Class of High-Efficiency Tuned Switching Power Amplifiers," *IEEE J. Solid-State Circuits*, vol. 10, pp. 168–76, 1975.
[26] T. Suetsugu and M. K. Kazimierczuk, "Analysis and design of class E amplifier with shunt capacitance composed of nonlinear and linear capacitances," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 51, no. 7, pp. 1261–1268, 2004, doi: 10.1109/TCSI.2004.830695.
[27] P. Wang, C. Liu, and L. Guo, "Modeling and simulation of full-bridge series resonant converter based on generalized state space averaging," *Applied Mechanics and Materials*, vol. 347–350, pp. 1828–1832, 2013, doi: 10.4028/www.scientific.net/AMM.347-350.1828.

BIOGRAPHIES OF AUTHORS

Ahmed Al-Hattami was born in Sana'a, Yemen in 1998. He obtained his B.Eng. in Electrical Engineering from Universiti Teknikal Malaysia Melaka. Currently, he is pursuing his master's degree in electronic engineering. His master project is a combination of electronic and control systems. His research interest is on linear and nonlinear systems control theory and wireless power transfer technologies. He can be contacted at email: ahmed.alhattami@outlook.com.

Shakir Saat was born in Kedah, Malaysia in 1981. He obtained his bachelor's degree in electrical engineering from Universiti Teknologi Malaysia and master's in electrical engineering from the same university in 2002 and 2006, respectively. Furthermore, he obtained his Ph.D. in Electrical Engineering from The University of Auckland in the field of nonlinear control theory in 2013. He started his carrier as a lecturer at Universiti Teknikal Malaysia Melaka in 2004 and he is now an associate professor of the same university. His research interest is on nonlinear systems control theory and wireless power transfer technologies. He has published one book (published by Springer Verlag) on polynomial control systems and more than 50 journals and mostly published in the high-quality journal such as The Journal of the Franklin Institute, International Journal of Robust and Nonlinear Control, and IET Control. More than 30 conference papers have also been published and most of them are in the framework of nonlinear control theory and wireless power transfer technologies. He is also appointed as a reviewer for IEEE Transaction journals, The Journal of System Science, The Journal of the Franklin Institute, International Journal of Robust and Nonlinear Control, Circuit, Systems, and Signal Processing and many more. He can be contacted at email: shakir@utem.edu.my.

Yusmarnita Yusop was born in Melaka, Malaysia in 1979. She received the B. Eng in Electrical Engineering (Mechatronic) from Universiti Teknologi Malaysia, in 2001, the M. Eng degree in Electrical Engineering from Kolej Universiti Tun Hussein Onn, Malaysia, in 2004 and Ph.D. degree in Electrical Engineering (capacitive power transfer) from Universiti Teknikal Malaysia Melaka in 2018. Her career as academician begins in 2005 as a teaching engineer at Department of Industrial Electronic, Technical University Malaysia Malacca and now she is a senior lecturer at the same university. Her area of research interests includes electronic system design, wireless power transfer and power electronics. She can be contacted at email: yusmarnita@utem.edu.my.

Md Rabiul Awal is currently working with School of Ocean Engineering, Universiti Malaysia Terengganu (UMT) as a lecturer. He has received his Ph.D. in Communication Engineering from Universiti Malaysia Perlis (UniMAP), Malaysia, in 2018. He was awarded master's in computer science from International Islamic University Malaysia (IIUM), Malaysia and the B.Sc. in Electrical & Electronics Engineering from International Islamic University Chittagong (IIUC), Bangladesh and in 2015 and 2011 respectively. From 2011 to 2012, he worked as a RF engineer in 3S Network (BD) Ltd. and from 2013 to 2015 he worked as research assistant in IIUM and UniMAP. His research interests include underwater communications, wireless power transfer and energy harvesting. He can be contacted at email: rabiulawal1@gmail.com.

A. H. M. Shapri graduated from Universiti Teknologi Malaysia (UTM) with a B.Eng. (Hons) degree in Computer Engineering in 2003 before joining MIMOS Berhad as an integrated circuit design engineer. He received his M.Sc. degree in Computer Science from Universiti Putra Malaysia (UPM) in 2007 and his Ph.D. in imaging from Universiti Sains Malaysia (USM) in 2019. Since August 2008, he has been a lecturer with Universiti Malaysia Perlis (UniMAP). In addition, he is a graduate engineer of the Board of Engineer Malaysia (BEM). His research interests include imaging, machine learning, and electronic system design. He has published many research articles in international journals and conference proceedings. Presently, he is the program chairperson of the Electronic Engineering Programme at the Faculty of Electronic Engineering and Technology, Universiti Malaysia Perlis. He can be contacted at email: ahmadhusni@unimap.edu.my.

Huzaimah Husin received the B.Eng. in 2000 from Multimedia University, M. Eng in 2005 from Kolej Universiti Tun Hussein Onn, Malaysia respectively. She was first appointed as engineering instructor in 2001 at Kolej Universiti Teknikal Malaysia Melaka and promoted as lecturer in 2005 and senior lecturer in 2008 in the Department of Industrial Electronics, Faculty of Electronic and Computer Engineering at Universiti Teknikal Malaysia Melaka. Since September 2014, she is pursuing Ph.D. in Advanced Control Technology that focused on acoustics energy transfer. She can be contacted at email: Huzaimah@utem.edu.my.