Continuous Control Set Model Predictive Control for Inductive Power Transfer system with Constant Voltage Load

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***Abstract*—This paper presents a continuous control set model predictive control (CCS-MPC) method for reducing oscillations in an inductive power transfer (IPT) charging system with constant voltage load (CVL). The proposed power control method inherently reduced the output fluctuations by minimizing the error between the actual power and the reference power, which is expressed as a cost function. Then, by solving this optimization problem, the optimal pulse density can be obtained for pulse density modulation (PDM) techniques in order to adjust the average sending voltage. This optimal pulse density is applied to enhanced/pulse density modulation (E/PDM) based on delta-sigma modulator (DSM) approach. The proposed CCS-MPC based on EPDM regulates power transfer control to ensure high efficiency by maintaining the low current/power ripple, fast dynamic response and achieving zero voltage switching (ZVS) in a full operation range. To verify the performance and effectiveness of the proposed control method, a comparison between the proposed CCS-MPC and PI control methods based on different modulators has been tested in MATLAB/Simulink.**

***Index Terms*—Constant voltage load, continuous-control-set model predictive control, inductive power transfer.**

I. Introduction

Inductive Power Transfer (IPT) technology is becoming increasingly important in the electric vehicle (EV) industry, as it facilitates a convenient and efficient way to charge EVs without requiring cables and connectors. Moreover, IPT charging systems have several advantages over traditional charging methods, including high reliability, more flexibility, and safer power conversion technology [1]. However, this technology can result in higher costs and lower efficiency, particularly when misalignment and/or output power fluctuations occur. In high-power transport applications, the IPT systems often operate under highly variable conditions such as a wide range of coupling and output power. Therefore, advanced control strategies focused on high efficiency are necessary to address variations in power transfer and/or coupling conditions.

To apply model-based control and optimization methods in the IPT systems, an accurate dynamic model must be created, which includes a proper representation of the load side. There is a conventional approach based on studying an equivalent constant resistance load (CRL), but this is only applicable to steady-state conditions and is not suitable for analyzing dynamic characteristics. This issue can be addressed by using a constant voltage load (CVL) or slowly varying load voltage, which is the most common receiver interface for battery charging in practical applications [2].

Conventional modulator-based control methods such as PI-based phase shift modulation (PSM) and pulse density modulation (PDM) are the most commonly used techniques to regulate voltage and control power transfer in IPT charging systems [3], and [4]. However, the PSM method typically causes hard switching in such systems at low output voltages. Furthermore, the IPT systems with large variations in power transfer and/or coupling conditions, a fast dynamic response to the power transfer process and different coupling coefficients is required. While PI-based strategies do not provide a significant response to fast dynamic changes in a poorly damped oscillation mode of IPT systems with CVL. Additionally, pulse-skipping modulations, such as PDM, generate high current/power ripples on this type of load. To address this problem, an EPDM method combined with active damping is presented in [5]. This method reduces the output oscillations caused by skipped pulses, however; it introduces a PSM for a small number of cycles, which leads to hard switching and increased loss.

In this paper, a continuous control set model predictive control (CCS-MPC) approach is presented for further investigation of the performance of pulse skipping modulator techniques in IPT systems with CVLs, as well as to address the above mentioned challenges. The objective of this method is to enhance the dynamic performance of the IPT system with CVL in order to maintain maximum power transfer while providing a fast dynamic response with low output fluctuations and a wide range of soft switching operations. In the proposed CCS-MPC control method, a nonlinear dynamic model is used to predict the behavior of the IPT system with CVL, which has been neglected in previous MPC methods [6]–[8]. It has been mentioned above that this type of load can cause significant output fluctuations by applying pulse-skipping modulations that cannot be predicted by CRL-based models. Therefore, in

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this study a dq synchronous reference frame model of a SS-compensated IPT system is provided to predict the optimal control degree of freedom (i.e., phase shift angle, duty cycle, etc). It is worth noting that the analysis is focused on the ability to avoid large oscillations caused by CVL characteristics. The proposed control strategy optimizes power transfer and ensures high efficiency while maintaining low current/power ripples. Toward this end, the output voltage of the full-bridge inverter on the primary side is controlled by solving an optimization problem which minimizes the error between real power and reference power. To evaluate the performance effectiveness of the proposed CCS-MPC method with E/PDM based on DSM, a comparative study is presented in this paper. First, in order to regulate power flow, the proposed CCS-MPC strategy is used to determine one control of freedom α (the optimal phase shift angle (PSA)). However, the CCS-MPC based on PSM cannot achieve soft switching at low voltages, which leads to increased power losses and consequently reduces the system efficiency. Therefore, to solve this issue, the proposed CCS-MPC method is designed to obtain the optimal pulse density for E/PDM based on DSM technique.

As compared with the previous pulse skipping methods [4] and [5], the proposed CCS-MPC method based on PDM-DSM can limit current/power fluctuations while ensuring a fast dynamic response. However, although in the proposed method is expected to reduce the power ripple by minimizing the error between the predicted power value and the reference power value, skipping a full period using the PDM pattern causes a large fluctuation. In a steady-state situation, this fluctuation would disrupt the system's operation and negatively impact its efficiency. Therefore, it is preferable to implement methods that involve skipping single pulses/half-periods (i.e. EPDM). In contrast to the conventional EPDM method in [5], the proposed CCS-MPC control method based on EPDM can suppress output fluctuations in any case without adding active damping, while maintaining ZVS. Moreover, unlike ON-OFF modulation [9], the proposed control method does not require a low-pass filter in the feedback control loop to avoid large output ripples. Indeed, the proposed CCS-MPC using EPDM can reduce output fluctuations by minimizing the error between the actual power and the reference power. The performance and effectiveness of the proposed CCS-MPC based on PSM and PDM/EPDM method compared to PI-based PDM/EPDM are validated by MATLAB/Simulink results.

II. System Modeling

IPT systems as a dynamic charging system for EVs must be able to handle variations in power transfer rates and/or coupling coefficients. Therefore, to achieve a high control performance, an accurate dynamic model of the system is essential. In this regard the state-space model in dq synchronously rotating reference frame is suitable for the IPT system as a multi-input multi-output (MIMO) system [2], [10]. Moreover, SS- compensated IPT system is often the most appropriate for studying the system behavior in high power applications. Indeed, the SS- compensated IPT system with

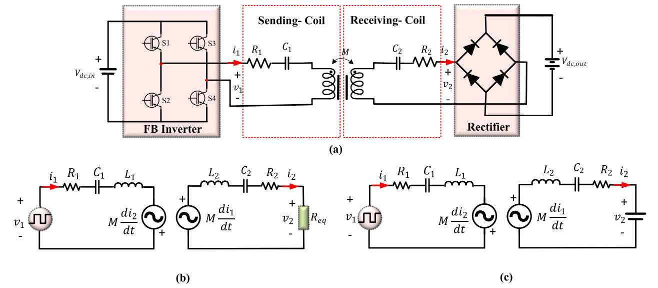

Fig. 1. SS- compensated IPT system: (a) topology with constant voltage load, and (b) equivalent of the IPT system with CRL, and (c) equivalent of the IPT system with CVL.

a diode-rectifier on the receiving side offers the minimum number of components and reduce the costs and losses in such systems [11]. Furthermore, the proposed model must include an accurate model of the load side interface for a battery charging. As the CRL model is only applicable to steady-state conditions and it is not suitable for analyzing dynamic characteristics, CVL or slow-varying voltage load is mostly used in practical applications [2]. As shown in Fig. 1(a), this type of load is considered in this paper. The equivalent circuit for the SS- compensated IPT charging system with CRL and CVL is illustrated in Fig. 1(b) and (c), which consists of a high-frequency full bridge inverter with a constant DC voltage source as input voltage $V_{dc,in}$ on the primary side. R_1, R_2, C_1, C_2, L_1, and L_2 are the series equivalent resistance, capacitance and inductance of primary and secondary coils, respectively, and M is the mutual inductance between two coils. Furthermore, the sending/receiving currents and voltages are expressed by I_1, I_2, V_1 and V_2, respectively. The nonlinear state-space model of IPT system with CVL in dq model with first harmonic approximation can be represented as follows [2]:

$$
\begin{aligned}
\frac{di_{1,d}}{dt} &= -\frac{R_1}{L_{\alpha1}}i_{1,d} + \omega i_{1,q} - \frac{MR_2}{L_{\alpha1}L_2}i_{2,d} - \frac{1}{L_{\alpha1}}v_{c1,d} \\
&\quad - \frac{M}{L_{\alpha1}L_2}v_{c2,d} + \frac{1}{L_{\alpha1}}v_{1,d} - \frac{M}{L_{\alpha1}L_2}v_{2,d} \\
\frac{di_{1,q}}{dt} &= -\omega i_{1,d} - \frac{R_1}{L_{\alpha1}}i_{1,q} - \frac{MR_2}{L_{\alpha1}L_2}i_{2,q} - \frac{1}{L_{\alpha1}}v_{c1,q} \\
&\quad - \frac{M}{L_{\alpha1}L_2}xv_{c2,q} + \frac{1}{L_{\alpha1}}v_{1,q} - \frac{M}{L_{\alpha1}L_2}v_{2,q} \\
\frac{di_{2,d}}{dt} &= -\frac{MR_1}{L_{\alpha2}L_1}i_{1,d} + \frac{R_2}{L_{\alpha2}}i_{2,d} + \omega i_{2,q} + \frac{M}{L_{\alpha2}L_1}v_{c1,d} \\
&\quad + \frac{1}{L_{\alpha2}}v_{c2,d} - \frac{M}{L_{\alpha2}L_1}v_{1,d} + \frac{1}{L_{\alpha2}}v_{2,d} \\
\frac{di_{2,q}}{dt} &= -\frac{MR_1}{L_{\alpha2}L_1}i_{1,q} - \omega i_{2,d} + \frac{R_2}{L_{\alpha2}}i_{2,q} + \frac{M}{L_{\alpha2}L_1}v_{c1,q} \\
&\quad + \frac{1}{L_{\alpha2}}v_{c2,q} - \frac{M}{L_{\alpha2}L_1}v_{1,q} + \frac{1}{L_{\alpha2}}v_{2,q} \\
\frac{dv_{c1,d}}{dt} &= \frac{1}{C_1}i_{1,d} + \omega v_{c1,q}, \qquad \frac{dv_{c1,q}}{dt} = \frac{1}{C_1}i_{1,q} - \omega v_{c1,d} \\
\frac{dv_{c2,d}}{dt} &= \frac{1}{C_2}i_{2,d} + \omega v_{c2,q}, \qquad \frac{dv_{c2,q}}{dt} = \frac{1}{C_2}i_{2,q} - \omega v_{c2,d}
\end{aligned}
\tag{1}
$$

In general the nonlinear state-space model of the system can be rewritten as:

$$\begin{cases} \dot{x} = f(x, u) \\ y = g(x, u) \end{cases} \tag{2}$$

where $x = [i_{1,d}\ i_{1,q}\ i_{2,d}\ i_{2,q}\ v_{c1,d}\ v_{c1,q}\ v_{c2,d}\ v_{c2,q}]^T$ is state variable, $u = [v_{1,d}\ \ v_{1,q}]^T$ is input control signal, which is output voltage of the full-bridge (FB) inverter on the primary-side. By aligning the voltage vector to the d axis, the output voltage of the q channel $v_{1,q} = 0$, therefore; the input control signal is simplified as $u = v_{1,d}$. $L_{\alpha 1} = L_1 - M^2/L_2$ and $L_{\alpha 2} = L_2 - M^2/L_1$ are leakage inductance, $\omega = 2\pi f_0$ (f_0 is resonant frequency). Furthermore, in order to minimize losses in all operations while satisfying the ZVS requirements, the secondary side's resonant frequency may be slightly higher than the primary side. Therefore, compensation capacitors can be designed accordingly as (3), with a detuning factor x_c that is slightly larger than 1 [12].

$$C_1 = x_c \cdot C_2 \cdot \frac{L_2}{L_1} \tag{3}$$

As shown in Fig. 2, the sending current waveform of IPT system with CVL and CRL has been generated by implementing the proposed CCS-MPC based on PDM under the step power change at $10ms$, from $6kW$ to $4kW$. The IPT system parameters are listed in Table I. This figure confirms that the IPT system with CVL has a completely different behaviour compared to CRL mode and it has large output oscillation. Therefore, the receiving side voltage of IPT system is different for the CRL and CVL models [5], which is defined as dq-components (i.e. $v_{2,d}$ and $v_{2,q}$) in dq-axis reference frame. Indeed, CVL model represents the nonlinear term of IPT system with CVL, which is defined as:

$$v_{2,dq} = \begin{cases} \frac{4}{\pi}.V_{dc,out}.\frac{i_{2,dq}}{\sqrt{i_{2,d}^2 + i_{2,q}^2}} & CVL \\ R_{eq}.i_{2,dq} & CRL \end{cases} \tag{4}$$

where, $R_{eq} = \omega_0.k_c.L_2$ [11], in which k_c is coupling coefficient and it is expressed as $k_c = \frac{M}{\sqrt{L_1 L_2}}$. Furthermore, in (2) $y = P_{in}$, the input power which is represented as:

$$P_{in} = v_{1,d} \cdot i_{1,d} \tag{5}$$

TABLE I
GENERAL PARAMETERS OF THE IPT SYSTEM.

Parameter	Symbol	Value
Nominal Power	P_{nom}	6.5kW
Nominal Sending Voltage	$V_{1,nom}$	380 V
Output DC voltage	$V_{dc,out}$	184 V
Nominal Coupling Coefficient	k_c	0.2
Resonance Frequency	f_0	85 kHz
Primary/Secondary self inductances	L_1/L_2	176/41 μH
Primary/Secondary capacitances	C_1/C_2	20/85 nF
Primary/Secondary Resistances	R_1/R_2	0.3303/0.8111 Ω
Detuning factor	x_c	1.03

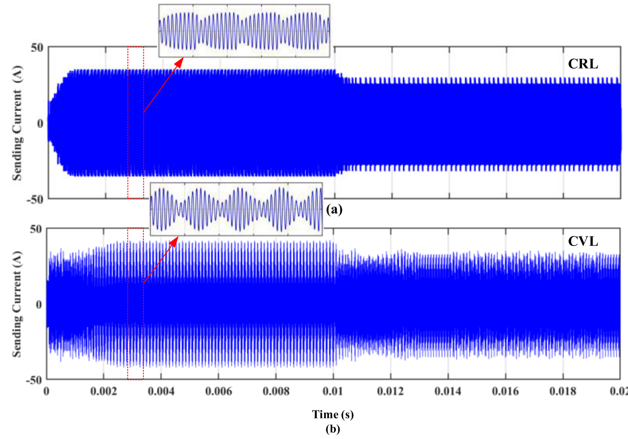

Fig. 2. Sending current waveform of IPT system using the proposed CCS-MPC based on PDM: (a) with CRL mode, and (b) with CVL mode.

III. CCS-MPC CONTROL DESIGN

In this section, the implementation of the proposed CCS-MPC is presented. The use of model predictive control (MPC) has recently gained recognition as a powerful tool for controlling high-power converters [13]. As a result of its inherent characteristics, this strategy is well suited for regulating power electronic systems, including a fast transient response, high bandwidth control, and an ability to accommodate nonlinearities and system constraints [14]. An MPC can be used to control power flows between different parts of a system and ensure that the system operates within certain parameters and objectives. Using the proposed control method for the studied IPT system, the system power can be predicted at each sampling time. Then, the sending voltage is adjusted by minimizing the error between the predicted power and the power reference value. It is worth noting that the input power is considered in the cost function to avoid the need for two-way communication and to avoid the appearance of output/current delay in the feedback signals. The schematic diagram of the proposed CCS-MPC control method for the IPT system with CVL is shown in Fig. 3.

The design of an MPC algorithm for power systems involves several steps. First, a mathematical model should be derived to predict the future behavior of the system. It includes the dynamics of the power flow and the constraints on the system variables. The next step is to define an objective function

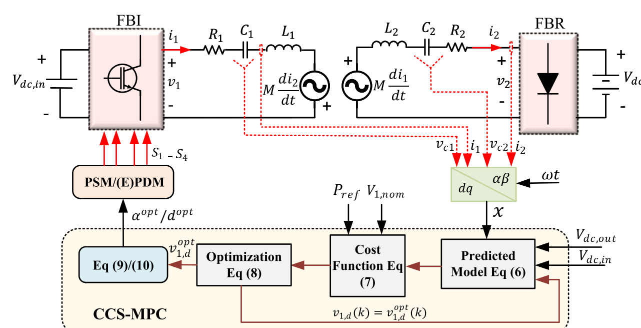

Fig. 3. Schematic diagram of the proposed CCS-MPC for SS- compensated IPT system with CVL.

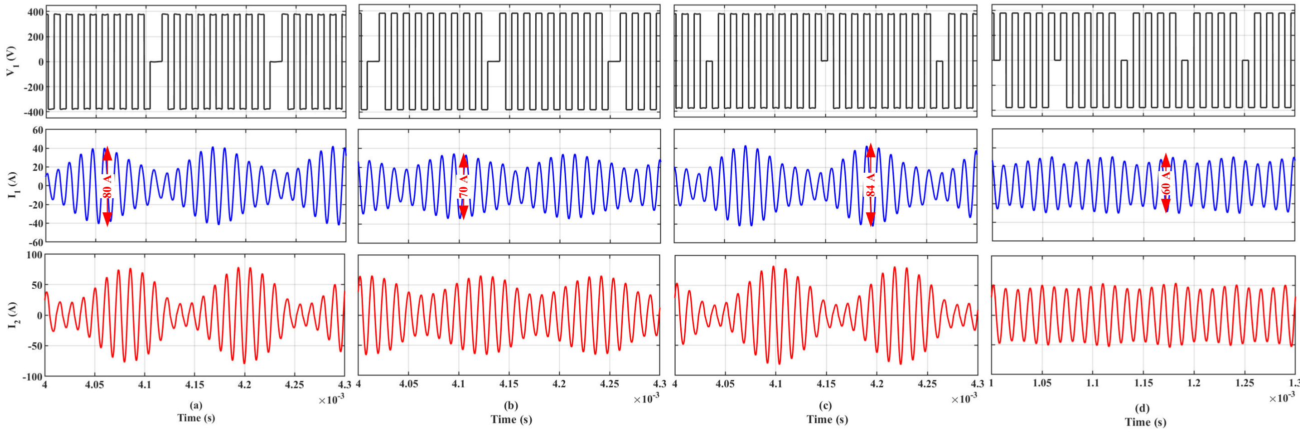

Fig. 4. Steady-state performance of the IPT system with CVL, when $D_{opt} = 0.9$: (a) PI-based PDM, (b) CCS-MPC-based PDM, (c) PI-based EPDM and (d) CCS-MPC-based EPDM .

that specifies the performance criteria in which the controller should be designed to optimize over a given time horizon. Finally, the MPC problem must be solved using an optimization algorithm in order to generate the control action that will be applied to the system. According to this explanation the nonlinear model of the system by considering CVL as (1) is considered for control design. Then, to operate in a predictable and computationally efficient manner the discretized model of the system based on the forward's Euler method can be utilized, which is given by:

$$x(k+1) = x(k) + T_s f(x(k), u(k)) \tag{6}$$

where, $T_s = 12e^{-6}$ is the sampling time of the MPC controller. In the next step, an objective function is defined, which can include minimizing the deviation of the system variables from their set points, minimizing the use of control inputs, or minimizing the cost of energy production. Based on the main objective of this paper, which is power control flow by adjusting the sending voltage in order to maintain a low power/current ripple, the cost function can be calculated as follows:

$$J(k) = \frac{1}{N} \sum_{k=1}^{N} \left(P_{in}(k+1) - P_{ref}\right)^2 + \lambda \left(V_{1,d}(k) - V_{1,nom}\right)^2 \tag{7}$$

where, $N = 4$ is considered as the prediction horizon, λ is used as a weighting factor for the manipulated variables to avoid deviation from the target. The weighting factor for the manipulated variable is selected to be small so that the main focus is on output, which is set here to 0.4. $P_{in}(k+1)$ and P_{ref} are the predicted input power and the power reference, respectively. $P_{in}(k+1) = v_{1,d}(k) \cdot i_{1,d}(k+1)$, in which $v_{1,d}(k)$ is adjusted by optimization problem at each sampling time as optimal value of sending voltage (i.e,. $v_{1,d}^{opt}$), $i_{1,d}(k+1)$ is the predicted value of the sending current, and $V_{1,nom}$ is the nominal value of the sending voltage. Then, to solve the MPC problem and generate the control action that will be applied to the system, an optimization algorithm is considered. This involves solving a quadratic programming (QP) problem or a nonlinear programming (NLP) problem, depending on the complexity of the system model and constraints. In this paper, the optimization problem is carried out by the optimization toolbox using the sequential quadratic programming (SQP) algorithm as nonlinear optimization problem for finding the optimal control value of sending voltage by minimizing the cost function as (8) [15]. Finally, the control action is applied to the system and repeat the MPC algorithm at the next time step.

$$U^*(k) = \arg\min J(k) = \{v_{1,d}^{opt}(k), v_{1,d}^{opt}(k+1), ...\} \tag{8}$$

$$\text{subject to} \quad Eq(1) - (6), \text{ and } \quad 0 \leq v_{1,d} \leq \frac{4}{\pi} V_{dc,in}$$

By considering the optimal value of sending voltage in dq model, which is the control action of the proposed control method, the optimal phase shift angle or pulse density can be calculated as (9) and (10) for using the different modulator. Then, these optimal value based on required modulator is applied to the modulator for adjusting the switching sequence of full-bridge inverter on the primary side.

$$\alpha^{opt}(k) = \arcsin\left(\frac{\pi}{4} \frac{v_{1,d}^{opt}(k)}{V_{dc,in}}\right) \tag{9}$$

$$d^{opt}(k) = \frac{\pi}{4} \frac{v_{1,d}^{opt}(k)}{V_{dc,in}} \tag{10}$$

IV. Simulation Results

To confirm the effectiveness of the proposed CCS-MPC based on EPDM technique, a comparison of the studied IPT system performance using the PI and the proposed CCS-MPC based on different modulator techniques is presented in several scenarios.

A. Scenario 1: Steady-State Operation

Fig. 4. shows the steady-state waveform of the sending voltage and current as well as receiving current at the worst density under different methods. By considering the power reference equal to $P_{ref} = 6.1kW$ in PI-PDM and tuning the

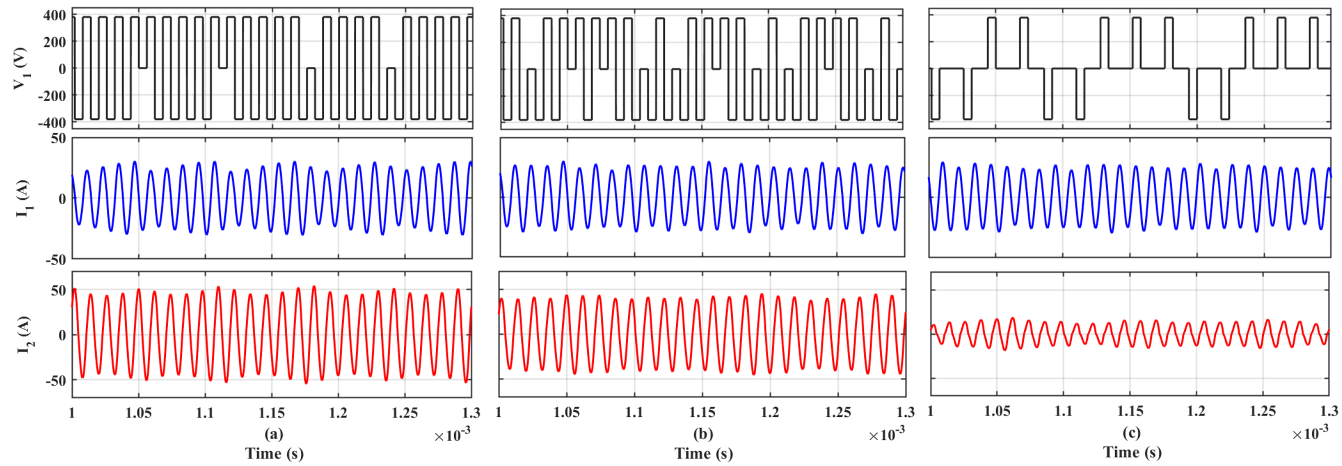

Fig. 5. Steady-state performance of the IPT system with CVL using the proposed CCS-MPC under different optimal pulse densities: (a) $D_{opt} = 0.9$, (b) $D_{opt} = 0.785$, and (c) $D_{opt} = 0.285$.

PI control parameters to $k_p = 0.009$ and $k_I = 100$, the pulse density can be adjusted to $d = 0.9$. This is the worst density of PDM, as the skipping pulse frequency is the same as the system's natural frequency, where the IPT system with CVL has a large oscillation in skipping pulses [8]. As shown in Fig. 4 (b), although the proposed CCS-MPC based on PDM can reduce the current/power ripple by 12.5% compared with PI-based PDM, significant undesired oscillations still appear. Thus, to suppress the current/power fluctuation at any pulse density the performance of the IPT system using the proposed CCS-MPC based on EPDM is conducted. Verification can be performed by analyzing the peak-to-peak transmitting current, which has been reduced to $70A$ and $60A$ through the proposed CCS-MPC based on PDM and EPDM methods, compared to $80A$ and $84A$ with PI-PDM and PI-EPDM, respectively. Moreover, the results of the IPT system at a variety of densities are shown in Fig. 5. It can be seen that the IPT system with the proposed control method based on EPDM has always obtained ZVS, while ensuring that the current/power ripple can be reduced regardless of density.

Furthermore, the soft switching performance of the IPT system with CVL is compared using the proposed CCS-MPC based on PSM and PDM. In this regard, the closed-loop system is tested under different power variations to verify the ZVS performance of the proposed control method. Fig. 6 shows the soft switching analysis of the IPT system using the CCS-MPC based on PSM. The result demonstrates that although this method has the potential to reach the power flow, it has a hard switching operation at any density, which results in increased power losses, thereby reducing the efficiency of the system. Fig. 7 provides a clearer understanding of the hard switching operation by using the proposed control method based on PSM. It can be found that in turn-on/off switching operations sufferers from hard switching. As addressed, in Fig. 8 can be seen that the CCS-MPC based on PDM always achieves ZVS operation, which leads to reduced power loss and increased system efficiency.

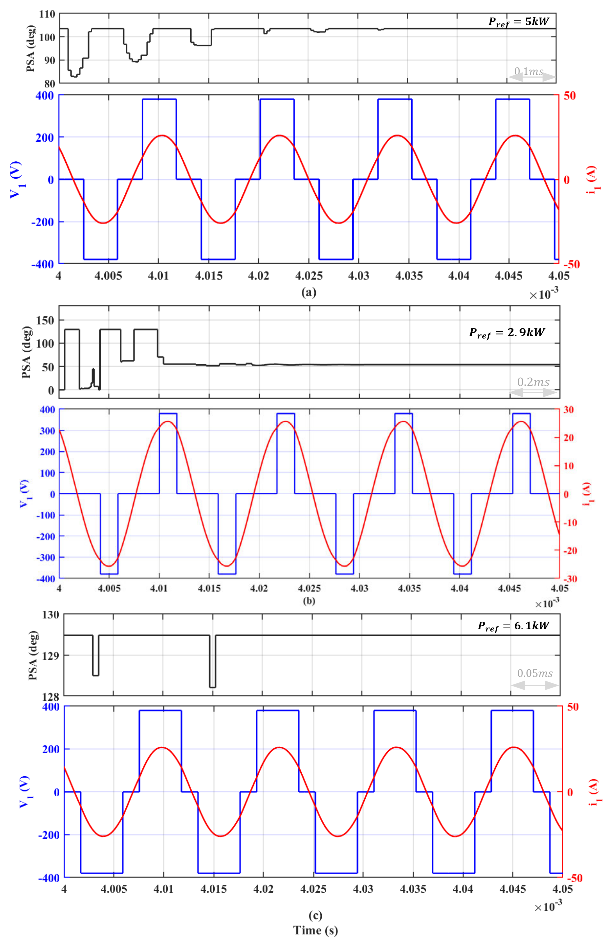

Fig. 6. Performance of the IPT system using the proposed CCS-MPC based on PSM under different power: (a) $P_{ref} = 5kW$, (b) $P_{ref} = 2.9kW$ and (c) $P_{ref} = 6.1kW$

B. Scenario 2: Power change Operation

In this scenario, the dynamic performance of the proposed CCS-MPC control method based on PDM and EPDM is investigated under reference power change in comparison with

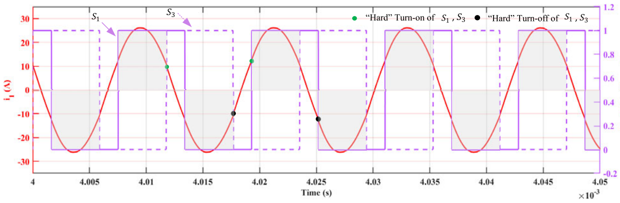

Fig. 7. Performance of sending current in the IPT system using the proposed CCS-MPC based on PSM against the switching output wave forms for switches S_1 and S_3.

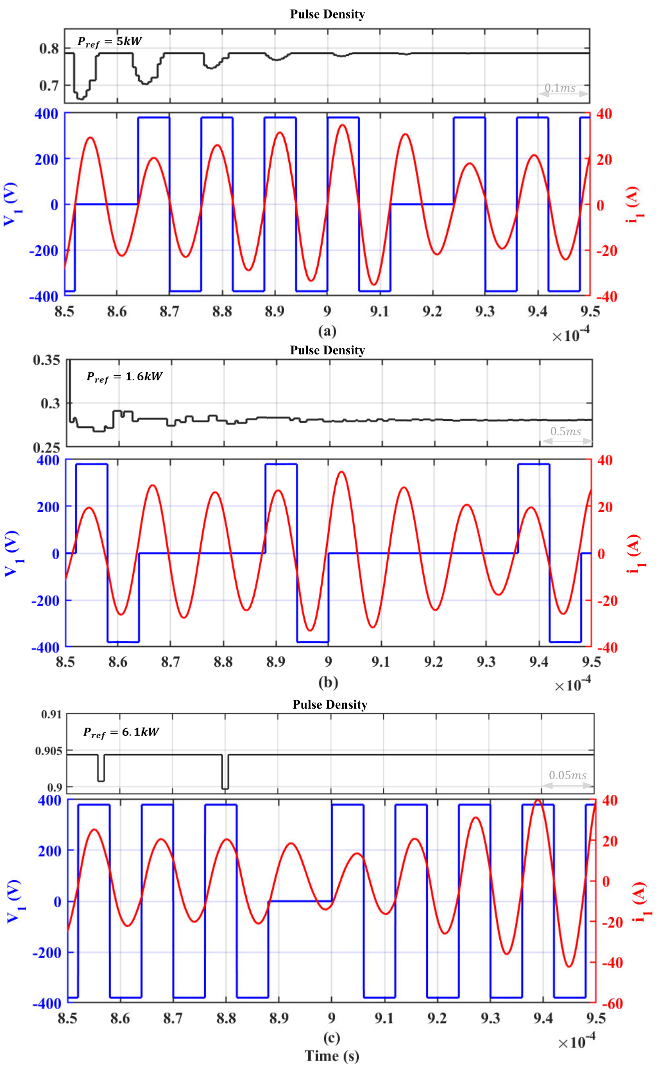

Fig. 8. Soft switching analysis of the IPT system using the proposed CCS-MPC based on PDM under different power: (a) $P_{ref} = 5kW$, (b) $P_{ref} = 1.6kW$ and (c) $P_{ref} = 6.1kW$

the PI-PSM/PDM. It is assumed that the reference power is changed of $P_{ref} = 5kW$ to $P_{ref} = 4kW$ at $t = 0.01s$. Fig. 9 shows a comparison of the dynamic response of the input power and output power using the proposed CCS-MPS and the PI-based PSM and PDM. It is observed that the IPT system with the PI control method reaches a new steady-state condition more slowly (about $2ms$); in addition, PI-based PDM has large current/power oscillations. In contrast, it can be seen that the IPT system with the proposed CCS-MPC control method under the same conditions can reach the new

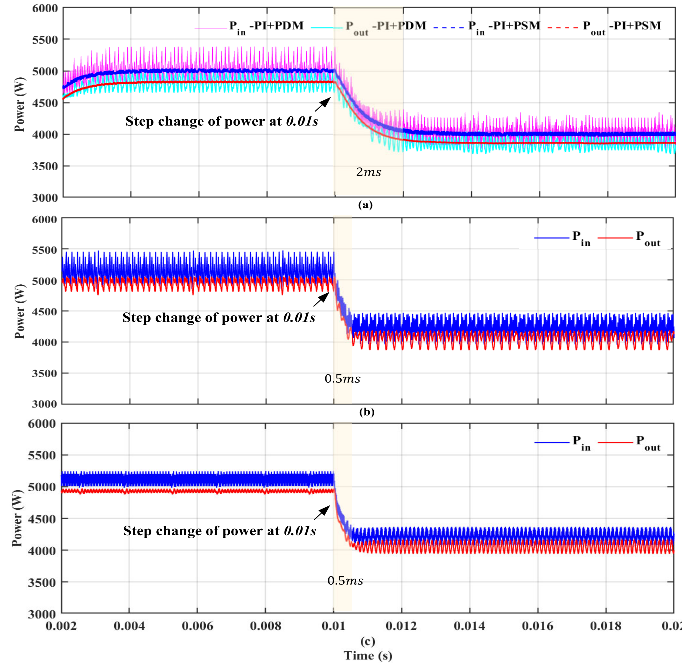

Fig. 9. Comparison of input/output power performance using: (a) PI-PSM and PDM, (b) CCS-MPS based on PDM, and (c) CCS-MPS based on EPDM.

steady-state very quickly only after $0.5ms$. Moreover, there are small current/power oscillations in the dynamic process, as well as the current/power ripples of the system with the proposed control method based on EPDM in steady-state are also slightly smaller than the system with PI and MPC based on PDM.

Furthermore, the dynamic response of the proposed IPT system in the synchronously rotating dq reference frame is evaluated under this step power change. Fig. 10 demonstrates the comparison between the performance of the IPT system using the proposed CCS-MPC based on PDM and EPDM. It is observed that the sending/pickup currents and output power reach the new steady-state very quickly (about $0.5ms$) in both methods. However, the results in this scenario verify that the proposed CCS-MPC based on EPDM strategy provides superior performance compared to other methods with a small current/power ripple.

C. Scenario 3: Coil Efficiency

In this scenario, a comparison of the proposed CCS-MPC performance under different modulators has been conducted to determine the coil-to-coil efficiency of the IPT system [16]. Fig. 11 shows the efficiency of the IPT system against different output power. It can be seen that the efficiency of the IPT system with EPSM is significantly higher than that of the IPT system with PSM. Meanwhile, this method can improve the efficiency of the system compared to PDM due to the lower current ripple that reduces the conduction loss of the system. As can be observed, the system efficiency with PSM and PDM, respectively, is $4\% - 8\%$ and $2\% - 6\%$ lower than that of the IPT efficiency using EPDM. Furthermore, the simulation results show that the system achieves higher

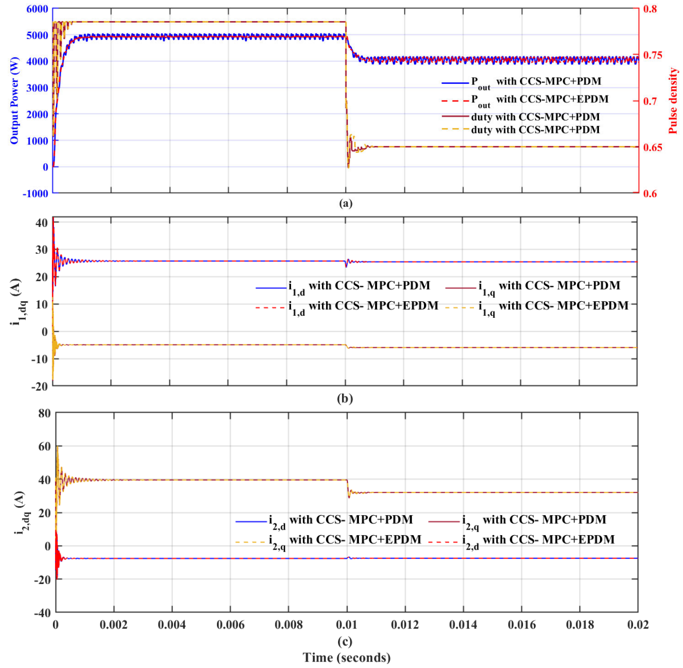

Fig. 10. Performance of the IPT system using the proposed CCS-MPC based on E/PDM under power change: (a) output power and optimal pulse density, (b) sending current in dq frame, and (c) receiving current in dq frame.

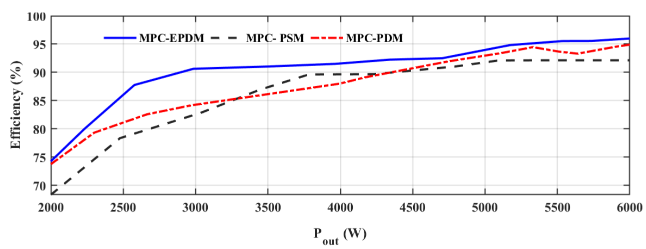

Fig. 11. Comparison of overall system efficiency against output power under the proposed control method based on PSM, PDM and EPDM.

efficiency at higher output power, with a maximum efficiency of 96%, 95% and 92% at the output power of 6kW for EPDM, PDM and PSM, respectively.

V. Conclusion

In this paper, a CCS-MPC control method for the IPT system with CVL is evaluated and compared with a conventional PI-based modulator control method. The proposed control method adjusts the output voltage of the full bridge inverter on the primary side by minimizing the proposed cost function. Thus, it is capable of obtaining the optimal PSA or pulse density for using the required modulators (e.g., PSM or PDM/EPDM). In contrast to the commonly used PSM method, PDM can always achieve the soft switching operation, resulting in decreased power losses and increased system efficiency. However, the proposed CCS-MPC based on PDM makes a large current/power ripple, even though it is lower than the PI-based PDM and EPDM methods. Therefore, the proposed CCS-MPC based on skipping single pulses/half-periods modulation such as EPDM is applied to achieve the smallest possible perturbation. This method maintains the performance of the IPT system with low current/power fluctuation while providing a fast dynamic response and a full-range of soft switching operation. Furthermore, the proposed CCS-MPC based on EPDM improves the system efficiency of the studied IPT system significantly compared to PDM and PSM under different output power conditions. Simulation results validate the effectiveness of the proposed CCS-MPC control method for an SS-compensated IPT system with CVL.

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