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An Efficiency Optimization Scheme for Bidirectional Inductive Power Transfer Systems

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Abstract – Unidirectional inductive power transfer (UIPT) systems allow loads to consume power while bidirectional IPT (BIPT) systems are more suitable for loads requiring two way power flow such as vehicle to grid (V2G) applications with electric vehicles (EVs). Many attempts have been made to improve the performance of BIPT systems. In a typical BIPT system, the output power is control using the pickup converter phase shift angle (PSA) while the primary converter regulates the input current. This paper proposes an optimized phase shift modulation strategy to minimize the coil losses of a series – series (SS) compensated BIPT system. In addition, a comprehensive study on the impact of power converters on the overall efficiency of the system is also presented. A closed loop controller is proposed to optimize the overall efficiency of the BIPT system. Theoretical results are presented in comparison to both simulations and measurements of a 0.5 kW prototype to show the benefits of the proposed concept. Results convincingly demonstrate the applicability of the proposed system offering high efficiency over a wide range of output power.

Index Terms – Bidirectional inductive power transfer (BIPT), efficiency optimization, and electric vehicles.

I. INTRODUCTION

Inductive power transfer (IPT) is a well-established technology that allows power transfer from one system to another without any physical contacts. It offers numerous advantages such as convenience, safety, isolation, flexibility and free maintenance. Applications of IPT range from low power systems such as biomedical implant, mobile device charging to medium and high power systems such as home appliances, material handling systems, street lighting systems, and charging of electric vehicles (EVs) [1]-[7]. A typical Unidirectional IPT (UIPT) system, as shown in Fig. 1, transfers power only from one side to the other. This system is beneficial in terms of simplicity in designing and controlling. However, the disadvantage of this system is the dependency of efficiency on the load as discussed in detail in the paper. This system is not suitable for applications with regenerative energy capability or active loads. Bidirectional IPT (BIPT) systems are considered to be the best choice to solve this issue. A typical BIPT system is shown in Fig. 3. Several studies carried out recently demonstrated the benefits of BIPT system, especially for EV charging systems [8]-[12]. In literature, the developments of BIPT system mostly focus on analyzing the characterization of this system. A generalized steady state model of BIPT system is developed in [10] with LCL compensation circuit. Synchronization of

Fig. 1. Circuit diagram of a typical UIPT system.

the primary and pickup converters is proposed in [12] and a closed loop controller is implemented in [14]. These systems demonstrate the applicability of BIPT system. However, one of the most important aspects of BIPT system, efficiency, has not been considered carefully in the literature.

The overall efficiency of an IPT system largely depends on the losses that incur in converters and coupling coils. In case of the former, many studies have been reported in relation to the development of converter topologies which are applicable for IPT systems [13]-[22]. In case of the latter, studies focus on the optimization of the proper magnetic circuit and coil winding designs [23]-[24]. This paper proposes a phase shift modulation to minimize the coil losses by selecting a proper phase shift angle (PSA) of the primary and secondary side converters of the BIPT topology. In addition, the converter power losses are also analyzed to obtain the overall efficiency of BIPT system. From these analyses, a solution for designing an efficient BIPT system is considered. The analysis is based on the series – series (SS) compensation circuit for the primary and pickup sides which is the most established compensation circuit model. A hardware laboratory prototype of 0.5-kW power rating BIPT system is implemented to investigate the behavior of the proposed concept. The experimental results show the efficacy of the proposed system.

II. TYPICAL IPT SYSTEM

A. Typical Unidirectional IPT system

A typical UIPT system is shown in Fig. 1. An H-Bridge converter is employed in the primary side while a full-bridge diode rectifier is used to convert high frequency current from the secondary resonant circuit to DC which is fed to a resistive load. Inductive coil resistances of the primary and secondary windings are R_1 and R_2 respectively. The efficiency of the resonant circuit of UIPT SS compensated circuit topology is as follows [19],

Fig. 2. The dependency of resonant circuit efficiency on the load resistance.

$$\eta = \frac{|i_L|^2 R_{Leq}}{|i_L|^2 R_{Leq} + |i_p|^2 R_1 + |i_s|^2 R_2} = \frac{1}{1 + \frac{R_2}{R_{Leq}} + \frac{R_1}{R_{Leq}} \left(\frac{R_2 + R_{Leq}}{\omega_T M} \right)^2} = f(R_{Leq}) \quad (1)$$

The equivalent load resistance R_{Leq} can be expressed in terms of DC load resistance as follows,

$$R_{Leq} = \frac{8}{\pi^2} R_L \quad (2)$$

As η is a function of R_{Leq} it can be maximized by tuning the load resistance.

Therefore,

$$\frac{d\eta}{dR_{Leq}} = 0 \quad (3)$$

The maximum efficiency can be determined as follows,

$$\eta_{\max} = \frac{1}{1 + \frac{2R_1 R_2}{(\omega_T M)^2} + \frac{2R_1}{(\omega_T M)^2} \sqrt{R_2^2 + \frac{R_2}{R_1} (\omega_T M)^2}} \quad (4)$$

And

$$R_{Leq} \Big|_{\eta=\eta_{\max}} = \sqrt{R_2^2 + \frac{R_2}{R_1} (\omega_T M)^2} \quad (5)$$

Fig. 2 shows the dependency of efficiency on the load resistance with the x – axis representing the normalized load resistance ($R_L/\omega M$) when the primary and secondary side coupling coil resistances are identical ($R_1 = R_2$). The simulation parameters are identical to the BIPT system

simulation parameters which are given in Table I. It is obvious that the efficiency of UIPT system significantly decreases with the change in load. This is the disadvantage of UIPT systems which can be improved by BIPT systems as shown in the next section.

B. Typical Bidirectional IPT system

A typical BIPT system shown in Fig. 3 (a) employs an H-bridge converter in the primary side to generate high frequency current to the primary coupling coil/track from DC power supply. H-Bridge converters are widely used in most IPT systems due to their simplicity and effectiveness. Another H-bridge converter employed in the secondary side can be connected to active loads such as Electric Vehicles which are able to consume or regenerate power.

High frequency current is transferred wirelessly through the air-gap to the secondary winding which is coupled to the primary winding via loose electro-magnetic coupling. The primary and the secondary circuits are identical with tuned series – series capacitive compensation circuits in order to operate the system at resonant frequency.

The amount of power transmission is controlled by the PSA of each converter (ϕ_1, ϕ_2) while the power direction is adjusted by the relative PSA between the primary and secondary side converters (θ) as shown in Fig. 3 (b).

In recent literature [10], [12], the PSA of the primary side converter in a BIPT system is adjusted to control the limit of input current while the output power is controlled by adjusting the PSA of the pickup side converter. This study presents a novel algorithm in obtaining the PSA in order to minimize coil losses.

With the phase shift modulation strategy as shown in Fig. 3 (b), the fundamental components of the input and output side voltages can be given as follows,

$$v_p(t) = \frac{4}{\pi} V_{DC1} \sin\left(\frac{\phi_1}{2}\right) \cos(\omega_T t) \quad (6)$$

$$v_s(t) = \frac{4}{\pi} V_{DC2} \sin\left(\frac{\phi_2}{2}\right) \cos(\omega_T t + \theta) \quad (7)$$

where ϕ_1, ϕ_2 are the PSAs between the two legs of primary and secondary converters respectively, and θ is the PSA between primary and secondary converters.

The voltages, V_{pi} and V_{si} that are induced in the primary and pickup coils respectively, are given by,

$$V_{pi} = j\omega M I_2 \quad (8)$$

$$V_{si} = j\omega M I_1 \quad (9)$$

Fig. 3. Circuit diagram of a typical BIPT system: (a) Topology; (b) Phase modulated voltages generated by the converters.

where M is the mutual inductance between the primary and secondary coils. The mutual inductance M is a function of the coupling coefficient between the two coils as follows,

$$M = k \sqrt{L_1 L_2} \quad (10)$$

where k is the coupling coefficient between primary and secondary windings.

From Fig. 3(a), the input and output currents are,

$$I_1 = \frac{V_p - V_{pi}}{R_1 + j\omega L_1 + \frac{1}{j\omega C_1}} \quad (11)$$

$$I_2 = \frac{V_s - V_{si}}{R_2 + j\omega L_2 + \frac{1}{j\omega C_2}} \quad (12)$$

The fundamental components of V_p and V_s given in (6) and (7) can be represented in phasor form as follows,

$$V_p = V_{pm} \angle 0^\circ \text{ and } V_s = V_{sm} \angle \theta \quad (13)$$

IPT operates at the resonance angular frequency of ω_r which is given by $\omega_r^2 = 1/L_1 C_1 = 1/L_2 C_2$. Substituting (8), (9) and (13) into (11), and (12), the input and output currents are given respectively as follows,

$$I_1 = \frac{R_2 V_{pm} - j\omega M V_{sm} \angle \theta}{\omega^2 M^2 + R_1 R_2} \quad (14)$$

$$I_2 = \frac{-j\omega M V_{pm} + R_1 V_{sm} \angle \theta}{\omega^2 M^2 + R_1 R_2} \quad (15)$$

The primary and secondary active and reactive powers can be calculated by,

$$P_1 = \frac{1}{2} \text{Re} \{V_p \cdot I_1^*\} = \frac{1}{2} \frac{V_{pm} (R_2 V_{pm} + \omega M V_{sm} \sin \theta)}{\omega^2 M^2 + R_1 R_2} \quad (16)$$

$$Q_1 = \frac{1}{2} \text{Im} \{V_p \cdot I_1^*\} = \frac{1}{2} \frac{\omega M V_{pm} V_{sm} \cos \theta}{\omega^2 M^2 + R_1 R_2} \quad (17)$$

$$P_2 = \frac{1}{2} \text{Re} \{V_s \cdot I_2^*\} = \frac{1}{2} \frac{V_{sm} (R_1 V_{sm} - \omega M V_{pm} \sin \theta)}{\omega^2 M^2 + R_1 R_2} \quad (18)$$

$$Q_2 = \frac{1}{2} \text{Im} \{V_s \cdot I_2^*\} = -\frac{1}{2} \frac{\omega M V_{pm} V_{sm} \cos \theta}{\omega^2 M^2 + R_1 R_2} \quad (19)$$

The reactive power components at both sides of the system can be minimized by keeping the PSA between the primary and the secondary side converters to be either $+90^\circ$ or -90° . When $\theta = +90^\circ$, power will be transferred from the primary side to the secondary side, while power flow is reversed when $\theta = -90^\circ$.

III. PROPOSED OPTIMIZED PHASE SHIFT MODULATION STRATEGY FOR BIPT SYSTEMS

In this section, a phase shift modulation strategy will be introduced to minimize the inductive coil losses. To simplify the analyses, the power percentage transferred via the air-gap is defined as the resonant circuit efficiency (in both forward and reverse directions).

With the descriptions of BIPT system in the previous section, when $\theta = +90^\circ$, power is delivered from primary to secondary side, and the forward direction efficiency is given as follows,

$$\eta_{for} = \frac{|P_2|}{P_1} = \frac{V_{sm} (\omega M V_{pm} - R_1 V_{sm})}{V_{pm} (\omega M V_{sm} + R_2 V_{pm})} = \frac{\xi (\omega M - R_1 \xi)}{\omega M \xi + R_2} \quad (20)$$

where $\xi = V_{sm}/V_{pm}$ is the ratio of secondary and primary output voltages of the converters.

Fig. 4. The dependency of the resonant circuit efficiency on the converter AC voltage ratio (when $R_1 = R_2$)

Fig. 5. A schematic of the closed loop controller for the proposed BIPT system.

Similarly, when $\theta = -90^\circ$, power is delivered from secondary to primary side and the efficiency in the reverse direction is as follows,

$$\eta_{rev} = \frac{|P_1|}{P_2} = \frac{V_{pm}(\omega M V_{sm} - R_2 V_{pm})}{V_{sm}(\omega M V_{pm} + R_1 V_{sm})} = \frac{\omega M \xi - R_2}{\xi(\omega M + R_1 \xi)} \quad (21)$$

It is obvious from (20) and (21) that resonant circuit efficiency of BIPT system is a function of the converter output AC voltage ratio. By differentiating the efficiency as a function of AC voltage ratio,

$$\frac{d\eta}{d\xi} = 0 \quad (22)$$

From (20) and (22), the optimum AC voltage ratio to obtain the maximum efficiency in the forward direction is given as follows,

$$R_1 \omega M \xi_{for_opt}^2 + 2R_1 R_2 \xi_{for_opt} - R_2 \omega M = 0 \quad (23)$$

$$\Leftrightarrow \xi_{for_opt} = \frac{-R_1 R_2 + \sqrt{R_1^2 R_2^2 + R_1 R_2 \omega^2 M^2}}{R_1 \omega M} \quad (24)$$

From (20) and (23), the maximum efficiency in the forward direction can be achieved as follows,

$$\begin{aligned} (23) &\Leftrightarrow R_1 \xi_{for_opt} (\omega M \xi_{for_opt} + R_2) = R_2 (\omega M - R_1 \xi_{for_opt}) \\ &\Leftrightarrow \frac{\omega M - R_1 \xi_{for_opt}}{\omega M \xi_{for_opt} + R_2} = \frac{R_1}{R_2} \xi_{for_opt} \\ &\rightarrow \eta_{for_opt} = \frac{\xi_{for_opt} (\omega M - R_1 \xi_{for_opt})}{\omega M \xi_{for_opt} + R_2} = \frac{R_1}{R_2} \xi_{for_opt}^2 \\ &= 1 - \frac{2R_1 R_2}{R_1 R_2 + \sqrt{R_1^2 R_2^2 + R_1 R_2 \omega^2 M^2}} \end{aligned} \quad (25)$$

Similarly, the optimum AC voltage ratio and maximum efficiency in the reverse direction are as follows,

$$\xi_{rev_opt} = \frac{R_1 R_2 + \sqrt{R_1^2 R_2^2 + R_1 R_2 \omega^2 M^2}}{R_1 \omega M} \quad (26)$$

$$\begin{aligned} \eta_{rev_opt} &= 1 - \frac{1}{1 + \frac{\omega^2 M^2}{2(R_1 R_2 + \sqrt{R_1^2 R_2^2 + R_1 R_2 \omega^2 M^2})}} \\ &= \eta_{for_opt} \end{aligned} \quad (27)$$

Assuming $(R_1, R_2) \ll \omega M$, which is satisfied in most situations, from (24) and (26), it is seen that ξ_{for_opt} and ξ_{rev_opt} can be approximated to be $\sqrt{R_2/R_1}$ which becomes unity if both inductive coils are identical.

Fig. 4 shows the dependence of efficiency on the AC voltage ratio. It is obvious that the efficiency decreases with the change in AC voltage ratio. This property is similar to the UIPT system which is described in the previous section. However, the efficiency of BIPT system can be maximized by adjusting the AC voltage ratio as shown in (24) or (26) and it is independent on the load.

From (6) and (7), the calculations of the PSA used in the primary side and the pickup side converters are as follows,

$$\sin\left(\frac{\phi_1}{2}\right) = \frac{\pi}{4} \frac{V_{pm,ref}}{V_{DC1}} \quad (28)$$

$$\sin\left(\frac{\phi_2}{2}\right) = \frac{\pi}{4} \frac{V_{sm,ref}}{V_{DC2}} = \frac{\pi}{4} \frac{\xi V_{pm,ref}}{V_{DC2}} \quad (29)$$

where $V_{pm,ref}$ and $V_{sm,ref}$ are the desired output voltage amplitude of the primary and secondary H-bridge converters.

A closed loop controller can be applied for the given system to minimize coil losses by choosing an appropriate AC voltage ratio between the primary side and secondary side converters.

From (28) and (29), it is obvious that the following condition should be satisfied to ensure that the PSAs of the

Fig. 6. Output voltages and currents of converters.

Fig. 7. Power response of the PI controller.

Fig. 8. Resonant circuit efficiency of the proposed system.

Fig. 9. The variation of efficiency with the AC voltage ratio and output power range.

Fig. 10. Primary side full bridge converter and output waveforms.

TABLE I: SIMULATION AND EXPERIMENTAL PARAMETERS

Parameter	Simulation	Experiment
Coils inductance $L_1 = L_2$ (μH)	183	183.3
Equivalent AC resistance $R_1 = R_2$ (Ω)	0.1	0.14
Compensation capacitance $C_1 = C_2$ (μF)	0.06	0.06
Switching frequency f_T (kHz)	48	48
Coupling coefficient k	0.38	0.38
Power rating (kW)	6	0.5
Air gap (mm)		60

primary and secondary side converters are feasible,

$$V_{pm,ref} \leq \min\left(\frac{4V_{DC1}}{\pi}, \frac{4V_{DC2}}{\pi\xi_{opt}}\right) \quad (30)$$

where ξ_{opt} is calculated from either (24) or (26).

Fig. 5 presents a PI controller with the phase shift generator block using the set of equations (28), (29) and either (24) or (26) to calculate the PSA of both converters. Communication block is added to transfer the data between the primary and secondary – side converter controllers.

The BIPT system in Fig. 3 is simulated using the controller in Fig. 5 with the parameters in Table I. Fig. 6 shows the simulation results of input and output voltages and currents of the given system during the control process. Fig. 7 shows the power response of the controller with zero steady state error and no over shoot. The efficiencies of resonant circuit are maintained at around 99% for almost full range of the output power as shown in Fig. 8 in 2-dimensional and Fig. 9 in 3-dimensional graphs.

V. OVERALL EFFICIENCY OPTIMIZATION ANALYSIS

In the previous section, the analyses of the coil loss minimization have been presented. The phase shift modulation has been investigated to optimize the efficiency in the resonant sides. However, the overall power losses of BIPT system are not only coil losses but also power converter losses which comprises of switching losses and conduction losses. Therefore, an analysis of overall BIPT system efficiency is presented in this section.

In order to simplify the analyses, assuming that the power is transferred from the primary side to the secondary side and the relative PSA θ is kept at $+90^\circ$ to minimize the reactive power.

From (6) and (7), the amplitudes of primary and secondary converter output voltages are given as follows,

$$V_{pm} = \frac{4}{\pi} V_{DC1} \sin\left(\frac{\varphi_1}{2}\right) \quad \text{and} \quad V_{sm} = \frac{4}{\pi} V_{DC2} \sin\left(\frac{\varphi_2}{2}\right) \quad (31)$$

With the definition of ξ in the previous section, from (31) we have,

$$V_{sm} = \frac{4}{\pi} V_{DC2} \sin\left(\frac{\varphi_2}{2}\right) = \xi V_{pm} = \frac{4\xi}{\pi} V_{DC1} \sin\left(\frac{\varphi_1}{2}\right) \quad (32)$$

From (32), the relationship between the PSA of primary and secondary side converters can be derived as follows,

$$\varphi_2 = 2 \arcsin\left(\frac{\xi V_{DC1} \sin\left(\frac{\varphi_1}{2}\right)}{V_{DC2}}\right) \quad (33)$$

From (16), (18), (31) and (32), the primary and secondary active powers can be rewritten as follows,

$$P_1 = \frac{8}{\pi^2} V_{DC1}^2 \sin^2 \frac{\varphi_1}{2} \frac{R_2 + \omega M \xi}{\omega^2 M^2 + R_1 R_2} \quad (34)$$

$$|P_2| = \frac{8\xi}{\pi^2} V_{DC1}^2 \sin^2 \frac{\varphi_1}{2} \frac{\omega M - R_1 \xi}{\omega^2 M^2 + R_1 R_2} \quad (35)$$

With above assumptions ($\theta = +90^\circ$), it is obvious from (14) and (15) that the output voltages and currents of the primary converters (v_p, i_l) are in phase while those of the secondary converter (v_s, i_2) are anti-phase. Suppose the effect of higher order harmonics is negligible then the output currents of converters are found to be sinusoidal as shown in Fig. 10.

For the given assumption ($\theta = +90^\circ$), from (14) and (15), the RMS value of input and output converter currents are respectively given as follows,

$$I_1 = \frac{1}{\sqrt{2}} V_{pm} \frac{R_2 + \omega M \xi}{\omega^2 M^2 + R_1 R_2} \quad (36)$$

$$\begin{aligned} &= \frac{2\sqrt{2}}{\pi} V_{DC1} \sin \frac{\varphi_1}{2} \frac{R_2 + \omega M \xi}{\omega^2 M^2 + R_1 R_2} \\ I_2 &= \frac{1}{\sqrt{2}} V_{pm} \frac{\omega M - \xi R_1}{\omega^2 M^2 + R_1 R_2} \\ &= \frac{2\sqrt{2}}{\pi} V_{DC1} \sin \frac{\varphi_1}{2} \frac{\omega M - \xi R_1}{\omega^2 M^2 + R_1 R_2} \end{aligned} \quad (37)$$

To evaluate the overall efficiency of the system, let's calculate the power losses of the converters. The power losses of a converter consist of conduction losses and switching losses of diodes and switching devices such as MOSFETs and IGBTs. The power losses of full-bridge converter for IPT system have been reported in one of our previous works [19] as follows.

• Conduction loss of diode

$$P_{cond_D} = \frac{2\sqrt{2}}{\pi} V_f I_0 \left[1 - \sin\left(\frac{\varphi}{2}\right) \right] + \frac{1}{\pi} r_D I_0^2 (\pi - \varphi - \sin \varphi) \quad (38)$$

where V_f and r_D are the threshold voltage and equivalent on-state resistance of diodes respectively; φ and I_0 are the PSA and the output RMS current of converters respectively.

• Conduction loss of MOSFET

$$P_{cond_MOS} = \frac{1}{\pi} r_{DS} I_0^2 (\pi + \varphi + \sin \varphi) \quad (39)$$

where r_{DS} is the equivalent on-state resistance of MOSFETs.

• Switching loss of full-Bridge converter

$$P_{SW} = 2V_{DC} I_0 \sqrt{2} \cos\left(\frac{\varphi}{2}\right) f_T \left(\frac{e_{SW_ON} + e_{SW_OFF}}{V_R I_R} + \frac{Q_{RR}}{I_{R_D}} \right) \quad (40)$$

where e_{SW_ON} and e_{SW_OFF} are the turn-on and turn-off energy losses of MOSFET; V_R and I_R are the reference drain-source voltage and source current of MOSFET; Q_{RR} and I_{R_D} are the reverse recovery charge and the reference current of the diode, respectively, which are provided by the manufacturer.

Therefore, the total power losses of primary - side and secondary - side converters are respectively given as follows,

$$\begin{aligned} P_{loss_p} &= \frac{2\sqrt{2}}{\pi} V_f I_1 \left[1 - \sin\left(\frac{\varphi_1}{2}\right) \right] + \frac{1}{\pi} r_D I_1^2 (\pi - \varphi_1 - \sin \varphi_1) \\ &\quad + \frac{1}{\pi} r_{DS} I_1^2 (\pi + \varphi_1 + \sin \varphi_1) \\ &\quad + 2V_{DC1} I_1 \sqrt{2} \cos\left(\frac{\varphi_1}{2}\right) f_T \left(\frac{e_{SW_ON} + e_{SW_OFF}}{V_R I_R} + \frac{Q_{RR}}{I_{R_D}} \right) \end{aligned} \quad (41)$$

And

$$\begin{aligned} P_{loss_s} &= \frac{2\sqrt{2}}{\pi} V_f I_2 \left[1 - \sin\left(\frac{\varphi_2}{2}\right) \right] + \frac{1}{\pi} r_D I_2^2 (\pi - \varphi_2 - \sin \varphi_2) \\ &\quad + \frac{1}{\pi} r_{DS} I_2^2 (\pi + \varphi_2 + \sin \varphi_2) \\ &\quad + 2V_{DC2} I_2 \sqrt{2} \cos\left(\frac{\varphi_2}{2}\right) f_T \left(\frac{e_{SW_ON} + e_{SW_OFF}}{V_R I_R} + \frac{Q_{RR}}{I_{R_D}} \right) \end{aligned} \quad (42)$$

The input power supply and output power can be calculated as follows,

$$P_{in} = P_1 + P_{loss_p} \quad (43)$$

$$P_{out} = |P_2| - P_{loss_s} \quad (44)$$

Fig. 11. Overall efficiency of BIPT system versus AC voltage ratio and output power for different DC voltage ratios.

Fig. 12. Overall efficiency of BIPT system versus AC voltage ratio for different output power surfaces $P_1 < P_2 < P_3$ and DC voltage ratios.

Fig. 13. Converter and coil loss percentage versus AC voltage ratio for different output power surfaces $P_1 < P_2 < P_3$ and DC voltage ratios.

Fig. 14. Optimal overall efficiency versus output power for different DC voltage ratios.

Fig. 15. Variation of optimal overall efficiency with the DC voltage ratio.

The overall efficiency of the system is given as follows,

$$\eta_{\text{overall}} = \frac{P_{\text{out}}}{P_{\text{in}}} = f(V_{\text{DC1}}, V_{\text{DC2}}, \phi_1, \xi) \quad (45)$$

It is obvious that the overall efficiency is a function of input and output DC voltages (V_{DC1} , V_{DC2}), AC voltage ratio (ξ) and primary and secondary converter PSAs (ϕ_1 , ϕ_2) where secondary PSA is also a function of primary PSA and AC voltage ratio as shown in (33).

Fig. 11 shows the overall efficiency in 3-dimensional graphs as a function of AC voltage ratio and output power with different DC voltage ratios. Fig. 12 shows the overall efficiency variation with each power surface clearly. Fig. 13 shows the inductive coil loss percentage and converter loss percentage as a function of AC voltage ratio with different power levels and DC voltage ratios. It is obvious from Fig. 13 that the converter losses are much higher than the coil losses. The coil losses are independent of output power level and DC voltage ratio (confirmed with (25) and (27)) while converter losses are largely dependent on the output power level and DC voltage ratios.

For all aforementioned analyses and simulation results, optimization routines and operating modes can be given as follows.

Firstly, an optimized AC voltage ratio must be determined based on the minimization of inductive coil losses and converter losses. The inductive coil losses are minimized if the AC voltage ratio is maintained as in (24) and (26) (approximate to be $\sqrt{R_2/R_1}$) while the converter losses are minimized if the AC voltage ratio is equal to DC voltage ratio as shown in Fig. 13. Therefore, maximum overall efficiency takes place if and only if $\xi_{\text{opt}} = V_{\text{DC2}}/V_{\text{DC1}} = \sqrt{R_2/R_1}$. In IPT systems, the inductive coils are designed before applying the DC power supply to the system. Therefore, to minimize the overall power losses, the DC voltage ratio must be maintained to be equal to $\sqrt{R_2/R_1}$.

Fig. 14 presents the optimal overall efficiency as a function of output power with different DC voltage ratios where AC voltage ratio is kept identical to DC voltage ratio to minimize the converter losses. In this simulation, the input DC voltage is kept at 400V while output DC voltage is varied from 200V to 800V (DC voltage ratio is varied from 0.5 to 2). Fig. 15 presents the maximum overall efficiency boundary (maximum output power) as a function of DC voltage ratio. It is obvious from Fig. 15 that the maximum overall efficiency of the given system takes place when $\xi_{\text{opt}} = V_{\text{DC2}}/V_{\text{DC1}} = \sqrt{R_2/R_1} = 1$ ($\sim 97.55\%$). When the DC voltage ratio changes from 0.5 to 2, the overall efficiency decreases by an amount of 0.6%.

In the situation the above conditions are not satisfied ($V_{\text{DC2}}/V_{\text{DC1}} \neq \sqrt{R_2/R_1}$), the AC voltage ratio will be chosen as follows,

1. If $V_{\text{DC2}}/V_{\text{DC1}}$ is not far away from $\sqrt{R_2/R_1}$ (for example, $0.2 < \frac{V_{\text{DC2}}}{V_{\text{DC1}}} < 2$), since the converter losses are much higher than coil losses, the AC voltage ratio is chosen to be equal to DC voltage ratio, as shown in Fig. 11 – Fig. 13 (b) and (c).
2. If $V_{\text{DC2}}/V_{\text{DC1}}$ is much smaller or much larger than $\sqrt{R_2/R_1}$, AC voltage ratio is chosen to be between $\sqrt{R_2/R_1}$ and $V_{\text{DC2}}/V_{\text{DC1}}$ (for example, if $\sqrt{R_2/R_1} = 1$ and $V_{\text{DC2}}/V_{\text{DC1}} = 5$ then $1 < \xi_{\text{opt}} < 5$). In this case, the set of Fig. 11 – Fig. 13 will be used to determine the optimal AC voltage ratio.

After the optimal AC voltage ratio is chosen, the primary and secondary side PSA will be calculated using (28) and (29). A closed loop power controller with optimized efficiency will be employed as shown in Fig. 5.

Fig. 16. Hardware prototype of the proposed BIPT system.

(a) delivering 450 W with 92% efficiency

(b) delivering 300 W with 90% efficiency

Fig. 17. Experimental results – Voltage and current waveforms.

Fig. 18. Experiment results – Efficiency versus input power.

Fig. 19. Experiment results – Efficiency versus AC voltage ratio.

TABLE II. SWITCHING DEVICE PARAMETERS (SiC MOSFETS AND DIODES)

	Parameter	Symbol	Value	Unit
C2M0080120D	Drain-Source On-State Resistance	R_{DS}	0.08	Ω
	Turn-On Switching Loss	$e_{SW\ ON}$	290	μJ
	Turn-Off Switching Loss	$e_{SW\ OFF}$	130	μJ
	Reference Drain-Source Voltage	V_R	800	V
CPW5-0650-Z030B	Reference Source Current	I_R	20	A
	Anode-Cathode On-State Resistance	R_D	0.02	Ω
	Forward Threshold Voltage	V_f	1.37	V
	Reverse Recovery Charge	Q_{RR}	0	nC
	Reference Anode-Cathode current	I_{R_D}	30	A

VI. EXPERIMENTAL VERIFICATION

In order to verify the efficacy of the proposed optimized phase shift modulation strategy, an experiment system has been implemented using FPGA Spartan 3E card for controlling and modulating high switching speed SiC MOSFETs (C2M0080120D) and SiC diodes (CPW5-0650-Z030B) as shown in Fig. 16. Table II shows the parameters of power losses in the previous section. Compared to the traditional Silicon (Si) devices, Silicon Carbide (SiC) devices provide several advantages such as high switching speed, low power loss for high voltage and high current operation capabilities. Moreover, SiC semiconductors work better at higher temperatures compared to Si devices [25-26]. The resonance circuit parameters as well as switching frequency are given in Table I.

Fig. 17 shows the voltage and current waveforms of the proposed BIPT system in the situation where both converter PSAs as well as both converter DC voltages are maintained equal to obtain the maximum efficiency. It is obvious that the voltages and currents in the primary converter are in phase and those in the secondary converter are anti-phase. The current waveforms are almost sinusoidal as in the assumption in Fig. 10. Due to the effect of conduction losses in

connecting wires, filter losses and the delay in the driver circuit, the experimental overall efficiency of the proposed BIPT system is lower than that in the simulation results. Fig. 18 and Fig. 19 show the variation of the overall efficiency with the desired power and AC voltage ratio. These experimental results confirm the conclusions drawn in the previous section.

VII. CONCLUSIONS

In this paper, an optimized phase shift modulation to minimize coil losses for BIPT systems has been theoretically analyzed and modelled using Matlab. Moreover, a comprehensive study on the impact of system parameters on the overall efficiency has been carried out. The analyses and simulation results provide the conditions for obtaining the maximum overall efficiency which is the most important factor in an IPT system. A closed loop controller has been proposed to operate the system at the optimized efficiency. Experimental results demonstrate the feasibility of the proposed concept.

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