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Efficiency Optimization for Bidirectional IPT system

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Abstract — Compared with unidirectional inductive power transfer (UIPT) systems which are suitable for passive loads, bidirectional IPT (BIPT) systems can be used for active loads with power regenerative capability. There are numerous BIPT systems that have been proposed previously to achieve improved performance. However, typical BIPT systems are controlled through modulation of phase-shift of each converter while keeping the relative phase angle between voltages produced by two converters at ± 90 degrees. This paper presents theoretical analysis to show that there is a unique phase shift for each converter at which the inductive coils losses of the system is minimized for a given load. Simulated results of a BIPT system, compensated by CLCL resonant networks, are presented to demonstrate the applicability of the proposed concept and the validity of the mathematical model.

Keywords: efficiency optimization, bidirectional inductive power transfer (BIPT), CLCL.

I. INTRODUCTION

The impending depletion of fossil fuels has caused a significant paradigm shift in power sector where the electrification of many applications, which are usually powered by fossil fuel, has been happening in rapid manner. This is clearly visible in transport applications where the use of Electric Vehicles (EVs) has seen an upward trend. Consequently, charging and discharging of EVs become an important issue. Inductive power transfer (IPT) systems offer numerous advantages over conventional wired power systems in terms of convenience, safety, isolation, operation in hostile conditions and flexibility [1] – [2]. A typical unidirectional IPT (UIPT) system includes a converter at the input side to convert DC or low frequency AC voltage into high-frequency AC voltage, which in turns excites the primary side resonant tank [3]-[5], as shown on Fig. 1. Power is transferred wirelessly to the secondary side coil due to the electromagnetic induction. In the secondary or receiving side, a rectifier is employed to convert high frequency AC voltage to a DC voltage and optimal power transmission is achieved at the resonance frequency. This system is simple and easy to

Fig. 1. A typical UIPT system.

control since there is no need for communications between the primary and secondary side converters. However, UIPT systems are not suitable for loads that require regenerative power capabilities such as EVs or vehicle-to-grid (V2G) systems. Bidirectional IPT (BIPT) systems are ideal for such applications.

A typical BIPT system is shown in Fig. 2(a). A H – bridge converter is employed for the pickup side. The direction and the amount of power transfer are regulated by the relative phase shift angle between the primary and the secondary side converters and by the voltages produced by the two converters. According to literature [6]-[8], the primary converter regulates the magnitude of input current while the secondary converter controls the output power.

In an IPT system, the overall efficiency is the most important consideration. Therefore, the development of efficient IPT systems has been receiving increased attention. 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 conducted for the development of appropriate converter topologies which can be readily used for IPT systems [9]-[13]. In case of the latter, the studies have focused on optimizing the magnetic circuit and coil winding designs. This paper proposes a phase shift modulation method to minimize the coil losses by selecting a proper phase shift angle of the primary and secondary side converters of the BIPT topology. The analysis is based on

Fig. 2. A typical BIPT system with LCL compensated circuit.

CLCL compensation circuit which is suitable for high power applications [6]–[7]. The analysis is the premise for designing an optimal controller for BIPT system with variable output power. A closed loop PI controller is also employed to get the desired output power. The simulation results show high efficiency for a wide range of desired output power, zero steady state error and fast response in the control process, all of which demonstrate the feasibility of the proposed method.

II. BIDIRECTIONAL IPT SYSTEM

A BIPT system with the CLCL compensated configuration is shown in Fig. 2(a). Both converters are operated at the resonant frequency of the CLCL circuit as follows,

$$f_r = \frac{\omega_r}{2\pi} = \frac{1}{2\pi\sqrt{(L_i - 1/\omega_r^2 C_i)C_1}} = \frac{1}{2\pi\sqrt{L_1 C_1}} \quad (1)$$

$$= \frac{1}{2\pi\sqrt{L_2 C_2}} = \frac{1}{2\pi\sqrt{(L_o - 1/\omega_r^2 C_o)C_2}}$$

The mutual inductance $M = k\sqrt{L_1 L_2}$, where k is the coupling coefficient between the two windings or inductances. The primary and pickup converters are controlled by phase shift modulation method shown in Fig. 2(b). The output voltages produced by converters are given as follows,

$$v_p(t) = \frac{4V_{DC1}}{\pi} \sum_{k=1,3,5,\dots}^{\infty} \left[\frac{1}{k} \cos(k\omega_r t) \sin\left(\frac{k\phi_1}{2}\right) \right] \quad (2)$$

$$v_s(t) = \frac{4V_{DC2}}{\pi} \sum_{k=1,3,5,\dots}^{\infty} \left[\frac{1}{k} \cos(k\omega_r t + k\theta) \sin\left(\frac{k\phi_2}{2}\right) \right] \quad (3)$$

where ϕ_1, ϕ_2 are the phase shift angles of primary and pickup converters respectively, and θ is the relative phase shift angle between the primary and the pickup converters.

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

$$v_{pi} = -j\omega M i_2 \quad (4)$$

$$v_{si} = j\omega M i_1 \quad (5)$$

By applying Thevenin's theorem into the circuit as shown in Fig. 2(a), we get,

$$v_p = (R_i + j\omega L_i - \frac{j}{\omega C_i})i_i + (R_1 + j\omega L_1)i_1 + v_{pi} \quad (6)$$

$$v_{pi} = -(R_1 + j\omega L_1)i_1 + \frac{1}{j\omega C_1}(i_i - i_1) \quad (7)$$

$$v_s = -(R_2 + j\omega L_2)i_2 - (R_0 + j\omega L_0 - \frac{j}{\omega C_0})i_0 + v_{si} \quad (8)$$

$$v_{si} = (R_2 + j\omega L_2)i_2 + \frac{1}{j\omega C_2}(i_2 - i_0) \quad (9)$$

Assume that the high order harmonics of v_{pi} and v_{si} have no significant effect on the system. From the set of equations (4) – (9), the input and output currents of the system can be derived as,

$$i_i = \Gamma v_p + j\Phi v_s \quad (10)$$

$$i_0 = -j\Phi v_p - \Psi v_s \quad (11)$$

where

$$\Gamma = \frac{C_1 [R_1(L_2 + R_0 R_2 C_2) + \omega^2 M^2 R_0 C_2]}{(L_1 + R_1 R_1 C_1)(L_2 + R_0 R_2 C_2) + R_1 R_0 C_1 C_2 \omega^2 M^2}$$

$$\Phi = \frac{M}{\omega \left[(L_1 + R_1 R_1 C_1)(L_2 + R_0 R_2 C_2) + R_1 R_0 C_1 C_2 \omega^2 M^2 \right]}$$

$$\Psi = \frac{R_2 C_2}{L_2 + R_0 R_2 C_2}$$

$$+ \frac{\omega^2 M^2 R_1 C_1 C_2 L_2}{(L_2 + R_0 R_2 C_2) \left[\left(L_1 - \frac{1}{\omega^2 C_1} + R_1 R_1 C_1 \right) (L_2 + R_0 R_2 C_2) + R_1 R_0 C_1 C_2 \omega^2 M^2 \right]}$$

Assuming that $R_p, R_l, R_2, R_0 \ll \omega M$ and $k^2 \ll 1$ where k is the coupling coefficient of the inductance coils, Γ, Φ, Ψ can be approximated as follows,

$$\Gamma \approx \frac{R_1 C_1}{L_1}; \quad \Phi \approx k \sqrt{\frac{C_1}{L_2}} \quad \text{and} \quad \Psi \approx \frac{R_2 C_2}{L_2} \quad (12)$$

III. EFFICIENCY OPTIMIZATION STRATEGY

The fundamental components of v_p and v_s given in (2) and (3) can be represented in phasor form as follows,

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

The input and output active powers are given in equations (14) and (16) while input and output reactive powers are given in equations (15) and (17) respectively as follows,

$$P_{in} = \frac{1}{2} \text{Re}\{v_p \cdot (i_i)^*\} = \frac{1}{2} (\Gamma V_{pm}^2 - \Phi V_{pm} V_{sm} \sin \theta) \quad (14)$$

$$Q_{in} = \frac{1}{2} \text{Im}\{v_p \cdot (i_i)^*\} = -\frac{1}{2} \cdot \Phi V_{pm} V_{sm} \cos \theta \quad (15)$$

$$P_{out} = \frac{1}{2} \text{Re}\{v_s \cdot (-i_o)^*\} = \frac{1}{2} (\Psi V_{sm}^2 + \Phi V_{pm} V_{sm} \sin \theta) \quad (16)$$

$$Q_{out} = \frac{1}{2} \text{Im}\{v_s \cdot (-i_o)^*\} = \frac{1}{2} \cdot \Phi V_{pm} V_{sm} \cos \theta \quad (17)$$

The reactive power component in both side of the system can be negated by maintaining the phase shift angle between the primary and the secondary side converters to be either $+90^\circ$ or -90° . When $\theta = -90^\circ$, the power will be transferred from the primary side to the secondary side, while the direction of power transmission is reversed in case of $\theta = +90^\circ$.

When $\theta = -90^\circ$, the efficiency is given as follows,

$$\eta_{for} = \left| \frac{P_{out}}{P_{in}} \right| = \left| \frac{\Psi V_{sm}^2 - \Phi V_{pm} V_{sm}}{\Gamma V_{pm}^2 + \Phi V_{pm} V_{sm}} \right| = \left| \frac{\Psi \xi^2 - \Phi \xi}{\Gamma + \Phi \xi} \right| \quad (18)$$

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

Fig. 3. The dependency of the efficiency on the converter output voltages.

When $\theta = +90^\circ$, we get the efficiency in the reverse direction as follows,

$$\eta_{rev} = \left| \frac{P_{in}}{P_{out}} \right| = \left| \frac{\Gamma V_{pm}^2 - \Phi V_{pm} V_{sm}}{\Psi V_{sm}^2 + \Phi V_{pm} V_{sm}} \right| = \left| \frac{\Gamma - \Phi \xi}{\Psi \xi^2 + \Phi \xi} \right| \quad (19)$$

It is obvious from (18) and (19) that the efficiency of the resonant sides of IPT system depends on the ratio of converter output voltages. Fig. 3 shows the dependency of efficiency on the voltage ratio. It is obvious that the efficiency can reach a maximum value at an appropriate converter voltage ratio. The forward and reverse efficiencies become maximal when the following conditions are respectively satisfied,

$$\xi_{opt,for} = \frac{-\Gamma\Psi + \sqrt{\Gamma^2\Psi^2 + \Gamma\Phi^2\Psi}}{\Phi\Psi} \quad (20)$$

$$\xi_{opt,rev} = \frac{\Gamma\Psi + \sqrt{\Gamma^2\Psi^2 + \Gamma\Phi^2\Psi}}{\Phi\Psi} \quad (21)$$

From (12), an approximate of $\xi_{opt,for}$ and $\xi_{opt,rev}$ can be obtained as follows,

$$\xi_{opt,for} \approx \xi_{opt,rev} \approx \frac{L_2}{L_1} \sqrt{\frac{R_1}{R_2}} \quad (22)$$

Let's define $V_{pm,ref}$ as the desired primary amplitude voltage which is calculated from a closed loop controller. From (2) and (3), we get

$$\sin\left(\frac{\varphi_1}{2}\right) = \frac{\pi}{4} \frac{V_{pm,ref}}{V_{DC1}} \quad (23)$$

$$\sin\left(\frac{\varphi_2}{2}\right) = \frac{\pi}{4} \frac{V_{sm,ref}}{V_{DC2}} = \frac{\pi}{4} \frac{\xi_{opt} V_{pm,ref}}{V_{DC2}} \quad (24)$$

From (20) - (24), it can be seen that a properly tuned closed loop controller can be used for the given system to

Fig. 4. A PID controller for the proposed IPT system.

minimize coil losses by determining an appropriate voltage ratio (ξ_{opt}) between the primary side and secondary side converters. To ensure that a feasible value for the phase shift angle of the primary and secondary side converters is obtained, a saturation block is added after the controller. In that case, $V_{pm,ref}$ must satisfy the following condition,

$$V_{pm,ref} \leq \min\left(\frac{4V_{DC1}}{\pi}, \frac{4V_{DC2}}{\pi\xi_{opt}}\right) \quad (25)$$

Fig. 4 presents a PI controller with the phase shift generator block using the set of equations (22), (23) and (24) to calculate the phase shift angle of both converters.

IV. RESULTS

The IPT system in Fig. 2 is simulated using the controller in Fig. 4 with the parameters given in Table I.

Fig. 5 shows the input and output voltages and currents of the given system during the control process.

Fig. 6 shows the instantaneous voltages and currents of the primary side and secondary side converters. It is obvious that the voltages and currents of both converters: (v_p, i_i) and (v_s, i_o) are in phase while the induced currents i_l and i_2 are 90° lagging and leading the voltages v_p and v_s respectively. The phase shift angle θ between primary converter and secondary converter is maintained to be -90° when the power is transferred from the primary to the secondary side. The input and output currents are not sinusoidal due to the effect of high order harmonic in the converter voltages.

Fig. 7 shows power response of the controller. As evident from Fig. 7, the power response is fast with settling time less than 0.1 s. The steady state error and over shoot are zero. A maximum power of 4 kW has been transferred from the primary to the pickup side with an efficiency of 96% which is maintained over a wide range of output power as shown in Fig. 7 and Fig. 8. When the desired output power is 500 W, the efficiency of the system is a little less than that in case of higher desired output power. This is the effect of the presence of high order harmonics in input and output currents due to low phase shift angle.

By setting the phase shift angle $\theta = +90^\circ$, the power can be delivered in the inverse direction.

Fig. 5. The voltage and current waveforms of converters.

Fig. 6. Instantaneous voltages and currents of converters.

TABLE I
SIMULATION PARAMETERS

Parameter	Symbol	Value	Unit
DC input voltage	V_{DC1}	500	V
DC output voltage	V_{DC2}	400	V
Inductive coils	$L_l = L_2$	33.8	μH
Compensated coils	$L_i = L_o$	67.6	μH
Equivalent AC resistance	$R_i = R_l = R_2 = R_o$	0.05	Ω
Compensator capacitance	$C_i = C_l = C_2 = C_o$	0.3	μF
Switching frequency	f_T	50	kHz
Coupling coefficient	k	0.38

Fig. 7. Power response of the PI controller.

Fig. 8. Efficiency of the proposed system.

V. CONCLUSIONS

An efficiency optimization control algorithm for BIPT system with CLCL compensated circuit has been proposed in this paper. A mathematical analysis together with simulation results has been presented to show that the proposed algorithm is feasible and efficient. A PI controller is proposed to regulate the output power with fast response and zero steady state error.

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