A Bidirectional Inductive Power Interface for Electric Vehicles in V2G Systems

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***Abstract*—Demand for supplying contactless or wireless power for various applications, ranging from low-power biomedical implants to high-power battery charging systems, is on the rise. Inductive power transfer (IPT) is a well recognized technique through which power can be transferred from one system to another with no physical contacts. This paper presents a novel bidirectional IPT system, which is particularly suitable for applications such as plug-in electric vehicles (EVs) and vehicle-to-grid (V2G) systems, where two-way power transfer is advantageous. The proposed IPT system facilitates simultaneous and controlled charging or discharging of multiple EVs through loose magnetic coupling and without any physical connections. A mathematical model is presented to show that both the amount and direction of power flow between EVs or multiple systems can be controlled through either phase or/and magnitude modulation of voltages generated by converters of each system. The validity of the concept is verified by theoretical analysis, simulations, and experimental results of a 1.5-kW prototype bidirectional IPT system with a 4-cm air gap. Results indicate that the proposed system is an ideal power interface for efficient and contactless integration of multiple hybrid or EVs into typical power networks.**

***Index Terms*—Distributed power generation, electric vehicles (EVs), inductive power transmission.**

I. Introduction

DEPLETION of fossil fuel reserves and current practice in generation, transmission, distribution, and utilization of energy are major worldwide concerns, for which distributed generation (DG) and harnessing of renewable energy are considered to be partial and acceptable solutions [1]–[9]. However, the quality of power delivered by DG systems, particularly those based on wind energy and solar energy, is largely affected by the stochastic nature of their energy production [10]. Consequently, in order to improve the power quality while meeting the demand in the most economical and efficient way, energy suppliers relied on energy storage systems, particularly for DG systems of medium power levels. Among various storage solutions such as flywheels, batteries, supercapacitors, etc., the vehicle-to-grid (V2G) concept, which uses hybrid vehicles or pure electric vehicles (EVs) to store and supply energy back to the grid, is gaining more and more popularity as hybrid and EVs are considered to be an indispensable component in both "living and mobility" and sustainable living in near future [11].

Irrespective of whether the EV or a fleet of EVs is used solely for medium-scale energy storage or microscale residential use as in the case of "living and mobility" [12], there lies the challenge of charging and retrieval (discharging) of energy. Consequently, techniques for charging and discharging of EVs, with emphasis on simplicity, low cost, convenience, high efficiency, and flexibility, have become the main focus of current research in both industrial and academic communities, whose fields of interests are in V2G and sustainable living. Contactless or wireless charging techniques are emerging as a viable choice as they meet most of the aforementioned attributes [13]–[15].

Inductive power transfer (IPT) is a technology that has gained global acceptance and popularity as a technique, which is suitable for supplying power to variety of applications with no physical contacts. IPT technology transfers power from one system to another through weak or loose magnetic coupling and offers the advantages of high efficiency, typically about 85%–90%, robustness, and high reliability in hostile environments being unaffected by dust or chemicals, which, in fact, are the key to its popularity. According to the literature, many IPT systems, with various circuit topologies or compensation strategies and levels of sophistication in control, have been proposed and successfully implemented to cater for a wide range of applications, which range from very low-power biomedical implants to high-power battery charging systems [16]–[26]. The focus of all but two of these reported systems has solely been to make improvements to the contactless power flow in unidirectional applications. Consequently, they have specifically been designed for unidirectional power flow and, thus, are not suitable for applications, such as EVs, V2G systems, regenerative equipment, etc., which require bidirectional power flow. A bidirectional IPT system can be realized by employing two identical unidirectional IPT systems. Obviously, such a system cannot be justifiable due to high-component count and cost, large size, and reduced reliability. Of the two bidirectional IPT systems reported in the past, one has been developed for aircraft applications [26], [27]. It employed a tightly coupled magnetic circuit, where the leakage inductance of a transformer forms a resonant circuit with a series capacitor to facilitate the bidirectional power transfer between two systems while operating as a voltage source. Such a system would not be appropriate for applications such as V2G, where a fleet of EVs is to be simultaneously powered. In contrast, the second system used a loosely coupled magnetic circuit with series

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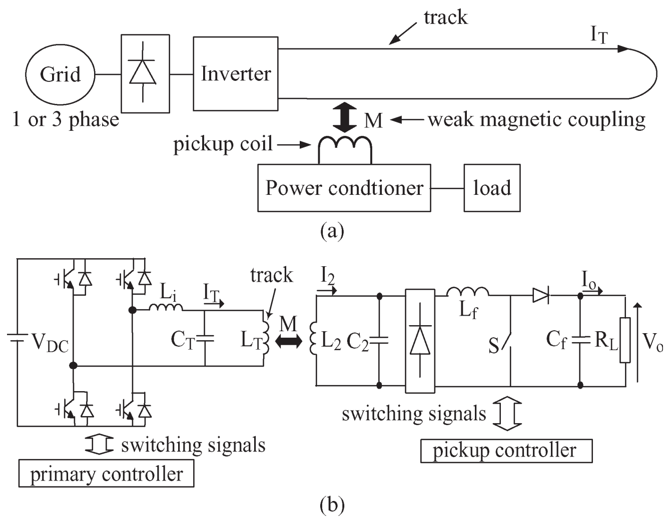

Fig. 1. (a) Conceptual IPT schematic. (b) Unidirectional IPT system.

compensation or series resonant circuits on both sides of the air gap to realize the bidirectional power flow, which has, again, been used for power transfer between two systems and operated as a voltage source.

This paper proposes a novel current-sourced bidirectional IPT power interface, which is suitable for simultaneous contactless charging/discharging of multiple EVs or equipment. In contrast to the systems reported in [26] and [27], the proposed IPT interface is simple in design, implementation, and control, and it allows for modular operation to cater for high-power applications. A converter or reversible rectifier, together with an inductor–capacitor–inductor (LCL) parallel resonant circuit, is employed in each EV or equipment to facilitate the controlled and bidirectional power flow between EVs or equipment and the grid. A mathematical model, which describes the behavior of the proposed IPT interface, is derived to show that both amount and direction of power flow between EVs or equipment and the grid can be controlled through either relative phase or/and magnitude modulation of voltages generated by each converter. The validity of the mathematical model is verified by simulations and experimental results of a 1.5-kW bidirectional IPT system. Theoretical analysis is in good agreement with both simulated and experimental results and indicates that the proposed system, through which multiple electric or hybrid vehicles can easily be integrated into the grid, is an ideal contactless power interface for the V2G concept and sustainable living.

II. IPT TECHNOLOGY

An IPT system, as shown conceptually in Fig. 1(a), has two sides, called primary and pickup, which are separated by an air gap and magnetically coupled to each other. Power is transferred from the primary to the pickup through weak or loose magnetic coupling. Generally, a controller is employed on each side to regulate the power transfer from one side to the other.

The primary side power is usually derived either from a three-phase or single-phase utility supply, depending on the power requirement. A typical unidirectional IPT system, shown in Fig. 1(b), employs an inverter to produce a constant ac current in the primary winding, which is referred to as the track being a single and long wire. The primary controller maintains the constant track current at a desired frequency, which ranges from 10–40 kHz in typical IPT systems, while compensating for any variations in input supply and reflected pickup load. A resonant circuit, such as $L_i - C_{\mathrm{T}} - L_{\mathrm{T}}$ in Fig. 1(b), is preferably used to minimize the var requirement on the primary side. The track inductance L_{T} is magnetically coupled through M to a pickup coil L_2. For IPT systems with multiple pickups, a constant track current is essential, but a varying track current may also be employed for systems with a single pickup. A resonant circuit, comprising L_2 and C_2, and tuned to the same track frequency, is also employed in the pickup system to provide the var compensation and maximize the amount of power delivery. As shown in Fig. 1(b), the pickup-side controller uses switch S to operate the pickup-side circuit as a boost converter and regulates the amount of power extracted from the track through magnetic coupling to meet the load demand. In this control arrangement, the pickup behaves as a constant current source feeding the load. The amount of current fed to the load is controlled by the duty cycle of the switch S, which essentially decouples the load from the track when turned "on" and is operated at a moderate frequency to lower switching losses.

Thus, the maximum possible power takes place when the duty cycle of S is zero and can be given by

$$P_{o,\max} = \frac{\pi}{2\sqrt{2}} I_{\mathrm{sc}} V_o \tag{1}$$

where I_{sc} is the short-circuit current of the pickup coil defined by $I_{\mathrm{sc}} = (M\ I_{\mathrm{T}}/L_2)$. Simplification of (1) yields

$$P_{o,\max} = \omega \frac{M^2}{L_2} I_{\mathrm{T}}^2 Q_2 \tag{2}$$

where Q_2 is the quality factor. According to (2), the maximum possible pickup power can be increased by the best possible pickup design, which ensures that M^2/L_2 ratio is optimum within any given design constrains [28]. Frequency of operation can also be increased to improve the power output, but it is limited by switching losses and ratings of high-power semiconductor switches. The operation at high values of Q will increase the power output, but it is usually considered to be undesirable due to practical reasons such as high var circulation and instability and susceptibility to component tolerances. Further information

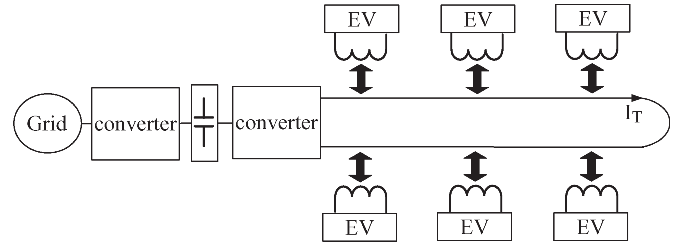

Fig. 2. Schematic of the proposed bidirectional IPT system.

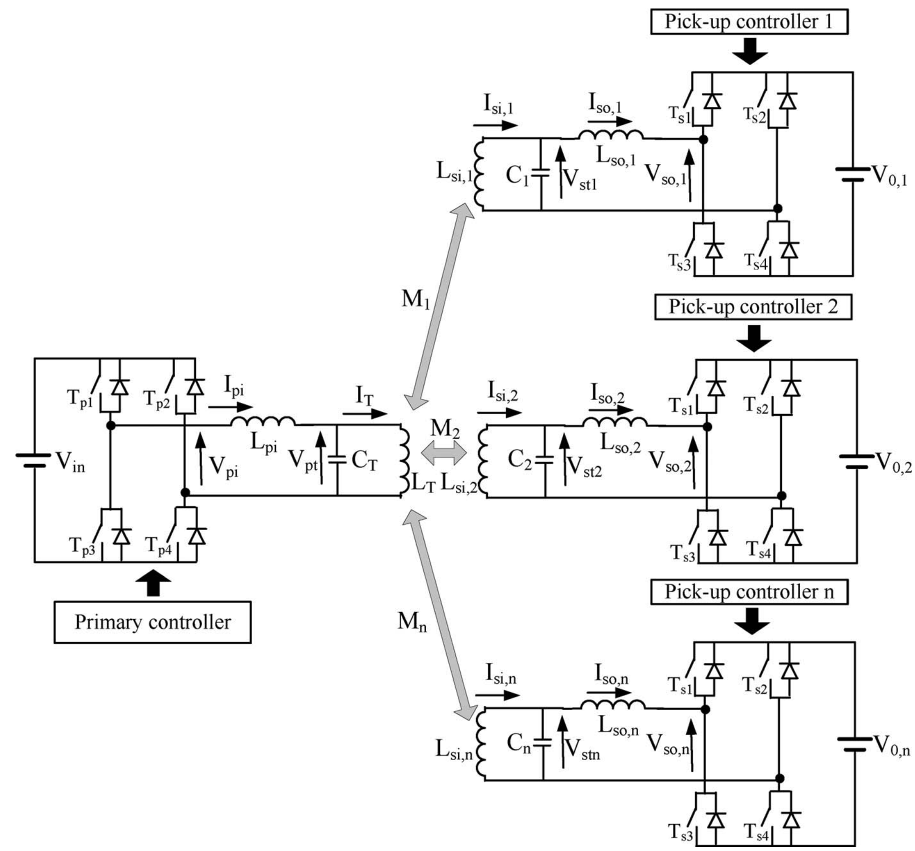

Fig. 3. Simplified circuit of the proposed bidirectional IPT system.

with regard to detailed design aspects of IPT systems can be found in [28]–[33].

III. Proposed Bidirectional IPT System

The proposed contactless IPT system, which facilitates the integration of multiple hybrid or EVs with bidirectional power flow, is schematically shown in Fig. 2. The bidirectional IPT system is equally applicable to "living and mobility" systems with a single EV or stand-alone systems, for which an energy storage is used to store energy from renewable energy sources. A simplified circuit, omitting the grid side converter and representing the EVs as dc sources, is shown in Fig. 3.

As in the case of typical IPT systems, the primary side converter, derived from the grid and fed by dc link voltage $V_{\rm in}$, generates a constant current $I_{\rm T}$ in a track $L_{\rm T}$, which is magnetically coupled to pickup coils. Outputs of all pickup circuits are considered to be connected to EVs and represented by individual dc sources to either absorb or deliver power. The primary and pickup circuits are implemented with virtually identical electronics, which include a converter (reversible rectifier) and a tuned (resonant) LCL circuit, to facilitate bidirectional power flow between the track (grid) and EVs (pickups). Each LCL circuit is tuned to the frequency of the track current, generated by the primary supply, and each reversible rectifier is operated either in the inverting or rectifying mode, depending on the direction of the power flow. Both magnitudes and relative phase angles of reversible rectifiers will determine the amount and direction of power flow between the grid and EVs, as described hereinafter.

A. Operation

Consider the IPT system with "n" pickups (EVs) in Fig. 2. The primary side converter (reversible rectifier) produces a sinusoidal voltage $V_{\rm pi}\angle 0$ at an angular frequency ω which is assumed to be the reference voltage. The current $I_{\rm T}$ in the track or inductor $L_{\rm T}$ is essentially held constant by the primary side controller.

At steady state, the induced voltage $V_{{\rm si},n}$ of the "nth" pickup coil $L_{{\rm si},n}$, due to track current $I_{\rm T}$, can be given by

$$V_{{\rm si},n} = j\omega M_n I_{\rm T} \tag{3}$$

where M_n represents the magnetic coupling or mutual inductance between the track inductance $L_{\rm T}$ and pickup coil inductance $L_{{\rm si},n}$.

Any pickup can be operated either as a source or a sink through the appropriate control of its own reversible rectifier. Despite the mode of operation, the voltage $V_{\rm rn}$ reflected into the track due to "nth" pickup can be expressed by

$$V_{\rm rn} = -j\omega M_n I_{{\rm si},n} \tag{4}$$

where $I_{{\rm si},n}$ is the current in pickup coil inductance $L_{{\rm si},n}$. The nth pickup of the system at steady state can thus be represented by the model in Fig. 4(a).

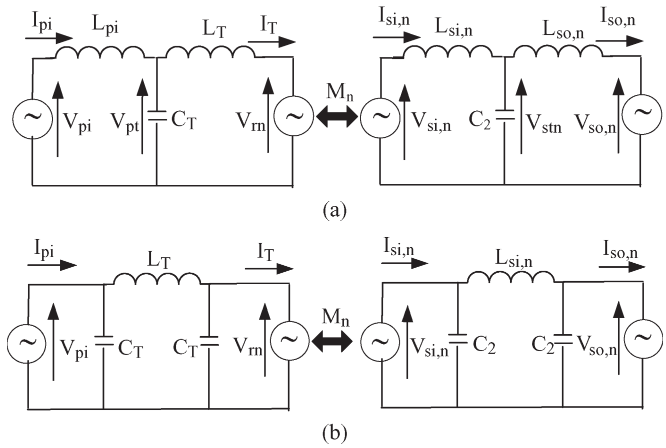

Fig. 4. Model for the nth pickup. (a) T-equivalent. (b) π-equivalent.

If the LCL circuits on both primary and pickup sides are tuned to the frequency of ω, and $L_{\mathrm{pi}} = L_{\mathrm{T}}$, $L_{\mathrm{si},1} = L_{\mathrm{so},1}, \ldots, L_{\mathrm{si},n} = L_{\mathrm{so},n}$, then

$$\omega^2 = \frac{1}{L_{\mathrm{T}} C_{\mathrm{T}}} = \frac{1}{L_{\mathrm{si},1} C_{\mathrm{T}}} = \cdots = \frac{1}{L_{\mathrm{si},n} C_n} = \cdots = \frac{1}{L_{\mathrm{so},n} C_n}. \tag{5}$$

Under the condition in (5), the "T" equivalent model in Fig. 4(a) can be represented by its π equivalent model as shown in Fig. 4(b).

Using Fig. 4, the primary current I_{pi} and track current I_{T}, for "n" pickups, can now be expressed by

$$I_{\mathrm{pi}} = V_{\mathrm{pi}} \cdot j\omega C_{\mathrm{T}} + \frac{\left(V_{\mathrm{pi}} - \sum_{k=1}^{n} V_{\mathrm{rk}}\right)}{j\omega L_{\mathrm{T}}} \tag{6}$$

$$I_{\mathrm{T}} = \frac{\left(V_{\mathrm{pi}} - \sum_{k=1}^{n} V_{\mathrm{rk}}\right)}{j\omega L_{\mathrm{T}}} - j\omega C_{\mathrm{T}} \sum_{k=1}^{n} V_{\mathrm{rk}}. \tag{7}$$

Simplification of (6) and (7) yields

$$I_{\mathrm{pi}} = j \frac{\sum_{k=1}^{n} V_{\mathrm{rk}}}{\omega L_{\mathrm{T}}} \tag{8}$$

$$I_{\mathrm{T}} = -j \frac{V_{\mathrm{pi}}}{\omega L_{\mathrm{T}}}. \tag{9}$$

Similarly, the input and output current of the "nth" pickup circuit can be derived and given by

$$I_{\mathrm{si},n} = j \frac{V_{\mathrm{so},n}}{\omega L_{\mathrm{si},n}} \tag{10}$$

$$I_{\mathrm{so},n} = -j \frac{V_{\mathrm{si},n}}{\omega L_{\mathrm{so},n}}. \tag{11}$$

Substitution of (3) and (8) in (11) yields

$$I_{\mathrm{so},n} = -j \frac{j\omega M_n I_{\mathrm{T}}}{\omega L_{\mathrm{so},n}} = -j \frac{M_n}{L_{\mathrm{so},n}} \frac{V_{\mathrm{pi}}}{\omega L_{\mathrm{T}}}. \tag{12}$$

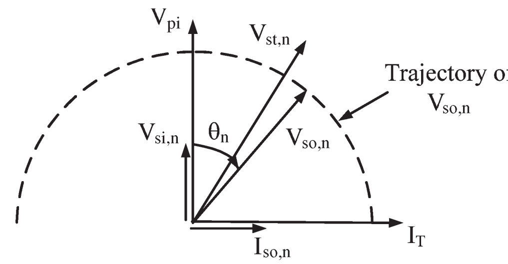

Fig. 5. Phasor diagram of nth pickup for relative phase angle control.

If the equivalent ac voltage of the output or the input voltage of the reversible rectifier of the nth pickup system is given by $V_{\mathrm{so},n}\angle - \theta_n$, then the real power output P_{on} of the nth pickup can be given by

$$P_{\mathrm{on}} = \mathrm{Re} : \{V_{\mathrm{so},n}(-I_{\mathrm{so},n})^*\}. \tag{13}$$

Substituting (12) in (13)

$$P_{\mathrm{on}} = -\frac{M_n}{L_{\mathrm{si},n}} \frac{V_{\mathrm{pi}}}{\omega L_{\mathrm{T}}} |V_{\mathrm{so},n}| \sin(\theta_n). \tag{14}$$

From (14), it is evident that the power output of any pickup system for a given design depends on both the magnitude and the relative phase angle between the voltages of the primary and pickup systems. Thus, the power output can be regulated by controlling the voltage magnitudes and/or the phase angles with respect to the primary side voltage. For any given voltages, the maximum power transfer takes place when the phase angle of the pickup system is $\pm 90^\circ$ with respect to the primary voltage. A leading phase angle constitutes power transfer from the pickup to the track or primary, while a lagging phase angle enables power transfer from the track to the pickup. Thus, for any given primary and pickup voltages, both the amount and direction of power flow between the track and the pickup can be regulated by controlling the relative phase angle between voltages generated by primary and pickup reversible rectifiers. A diagram, depicting the phasor relationship between the circuit variables of the primary and the nth pickup, is given in Fig. 5.

With magnitude control of voltage, the relative phase angle is essentially maintained constant at $\pm 90^\circ$, and therefore, the pickup operates at unity power factor. The power output of an IPT system with a single pickup can be regulated by varying the track current using a unidirectional controller in Fig. 1. In multipickup IPT systems, however, pickups are essentially designed for a particular track current to allow for all pickup to receive power simultaneously at varying power levels. Multipickup IPT systems, therefore, invariably have a constant track current, which is usually dictated by the voltage of the primary converter for a given track inductance. In this proposed bidirectional multipickup IPT system, the track current is essentially held constant too, and thus, the primary side voltage control cannot be used to regulate the pickup output power. The only option is, therefore, to control the magnitude of voltage of the pickup-side converter to regulate the output power of the pickup at unity power factor, and the phasor diagram in this situation is shown in Fig. 6.

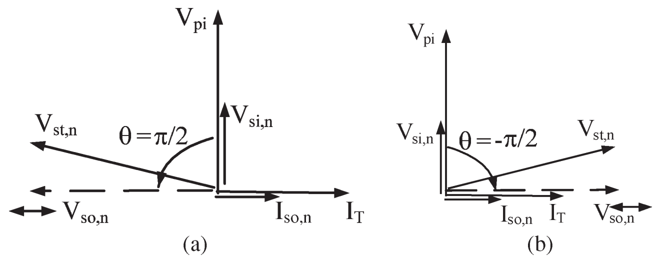

Fig. 6. Phasor diagram of nth pickup for voltage magnitude control. (a) Pickup receives power. (b) Pickup delivers power.

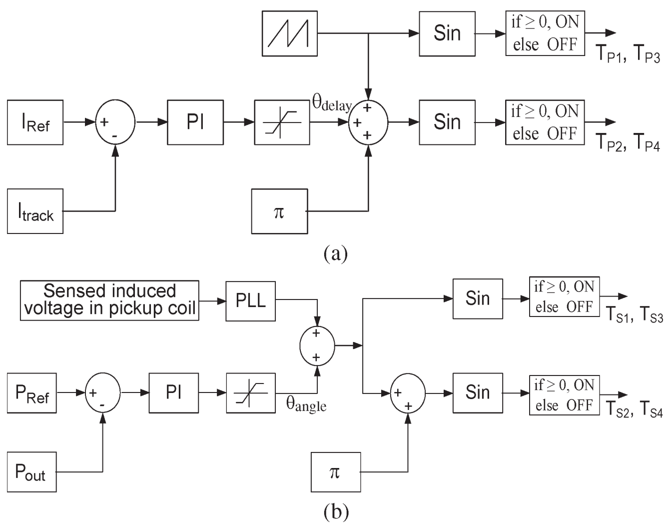

Fig. 7. Control block diagrams. (a) Primary controller. (b) Pickup controller.

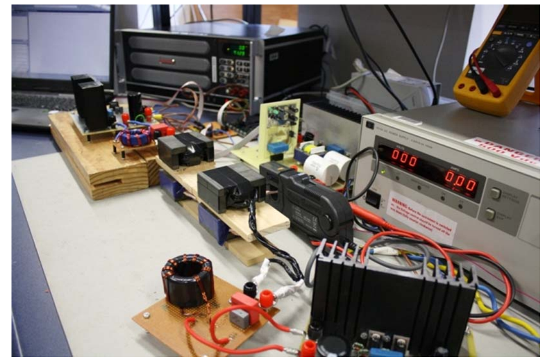

Fig. 8. 1.5-kW prototype bidirectional IPT system.

TABLE I
PARAMETER OF THE PROTOTYPE IPT SYSTEM

Parameter	Value
V_{in}	190-200 V
$V_{o,1}$	50 V
$V_{o,2}$	50 V
L_{pi} and L_T	30 μH
$L_{si,1}$ and $L_{so,1}$	27.3 & 28 μH
$L_{si,2}$ and $L_{so,2}$	13.7 & 14 μH
C_T	2.2 μF
C_1	2.43 μF
C_2	4.7 μF
M_1	6.75 μH
M_2	2.85 μH

B. Control

The primary-side full-bridge converter (reversible rectifier) can be driven by the primary controller in Fig. 7(a). It has a triangle wave generator and a proportional–integral (PI) controller, to produce a phase-modulated square wave voltage $(V_{\rm pi})$ to regulate the track current at the desired value. Pulsewidth modulation control of the converter is not generally used to keep the switching losses low. The frequency of the track current is dictated by the triangle wave generator, and the regulation is achieved by comparing the current that is flowing in the track inductor $(L_{\rm T})$ with a reference value, corresponding to the required track current. The error between the reference value and the actual track current is fed into a PI controller to generate a phase delay $\theta_{\rm delay}$ and subsequent control signals for the reversible rectifier in such a manner to produce a variable voltage and maintain a constant track current regardless of the load.

Although the pickup controllers are similar to the primary side controller, the output power of the pickups in this case is regulated as required to charge or discharge the batteries of EVs. The error between the reference and the actual power is fed through a PI controller to generate a phase angle $\theta_{\rm angle}$ in such a manner that the error is reduced when the pickup-side reversible rectifier is operated to produce a voltage at this phase angle with respect to the induced voltage in the pickup. The controller in Fig. 7(b) drives the pickup-side reversible rectifier in such a way that the voltage $V_{{\rm so},n}$ leads or lags the induced voltage $(V_{{\rm si},n})$ by a phase angle $\theta_{\rm angle}$, where $-\pi/2 < \theta_n < \pi/2$. A phase angle between zero and $\pi/2$ results in the pickup-side converter operating as a rectifier to deliver power to the EV or pickup-side source. When the pickup-side converter is operated in the inverter mode, the phase angle varies between $-\pi/2$ and zero, and the EV or pickup-side source supplies power to the track, which is taken by the sources of the primary side and other pickups. Alternatively, a controller similar to the one shown in Fig. 7(a) can be implemented to control the pickup output power by regulating the magnitude of voltage of the pickup-side converter at unity power factor. However, a phase controller is implemented for the experimental verification of the proposed concept.

IV. RESULTS

In order to verify the viability of the proposed bidirectional and contactless power interface, a prototype 1.5-kW IPT system shown in Fig. 8, consisting of two pickups and a primary, was built, and its performance was compared with simulations using Simulink. The design parameters of the prototype, which has an efficiency of ∼85%, and the simulated system are given in Table I. The primary converter of the system, fed by a 200-V source, was controlled to maintain a constant track current of 50 A at 20 kHz, while the converters (reversible rectifiers) of two pickups were connected to 50-V battery sources. For simplicity, the track inductor was wound on a C89 ferrite E core, representing the inductance of a long track, and no attempt has been made to optimize the magnetic circuit design, which requires finite element analysis. The two pickups were

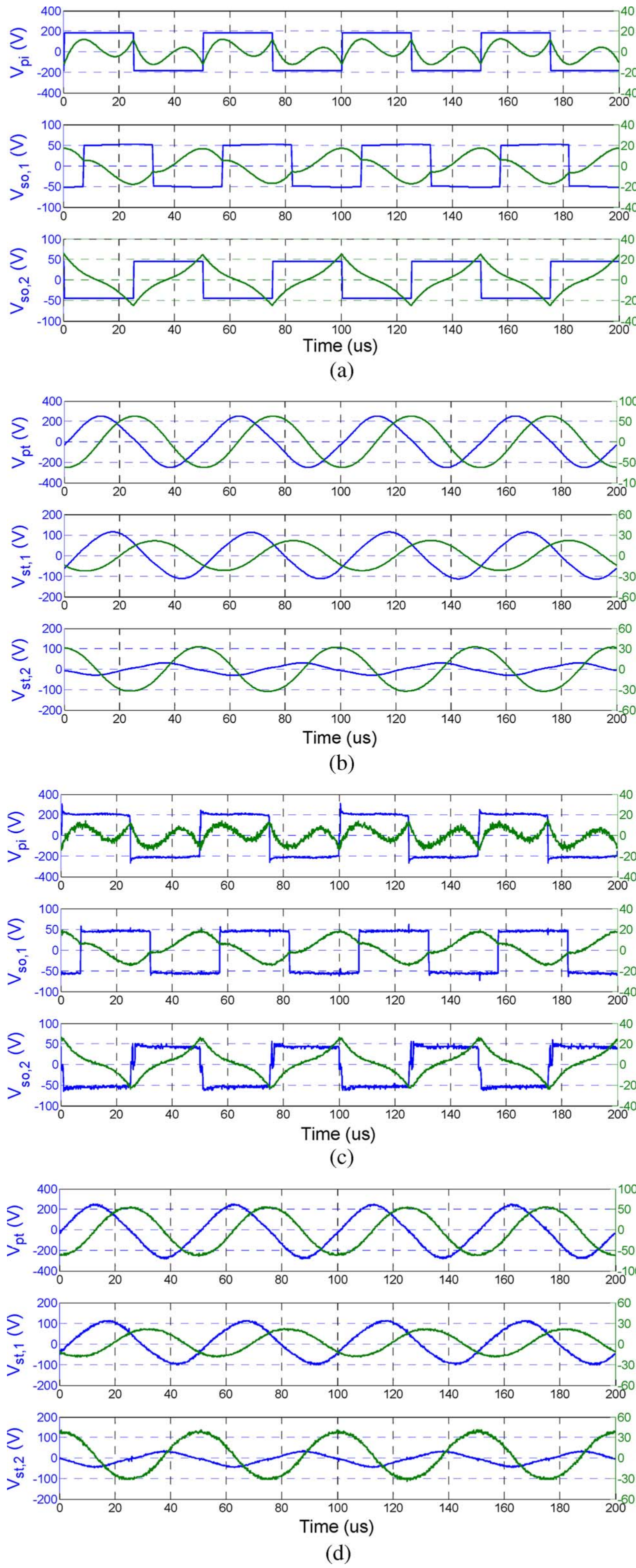

Fig. 9. Pickup 1 receives 600 W from the primary while pickup 2 idles. (a) and (b) Simulated waveforms. (c) and (d) Experimental waveforms.

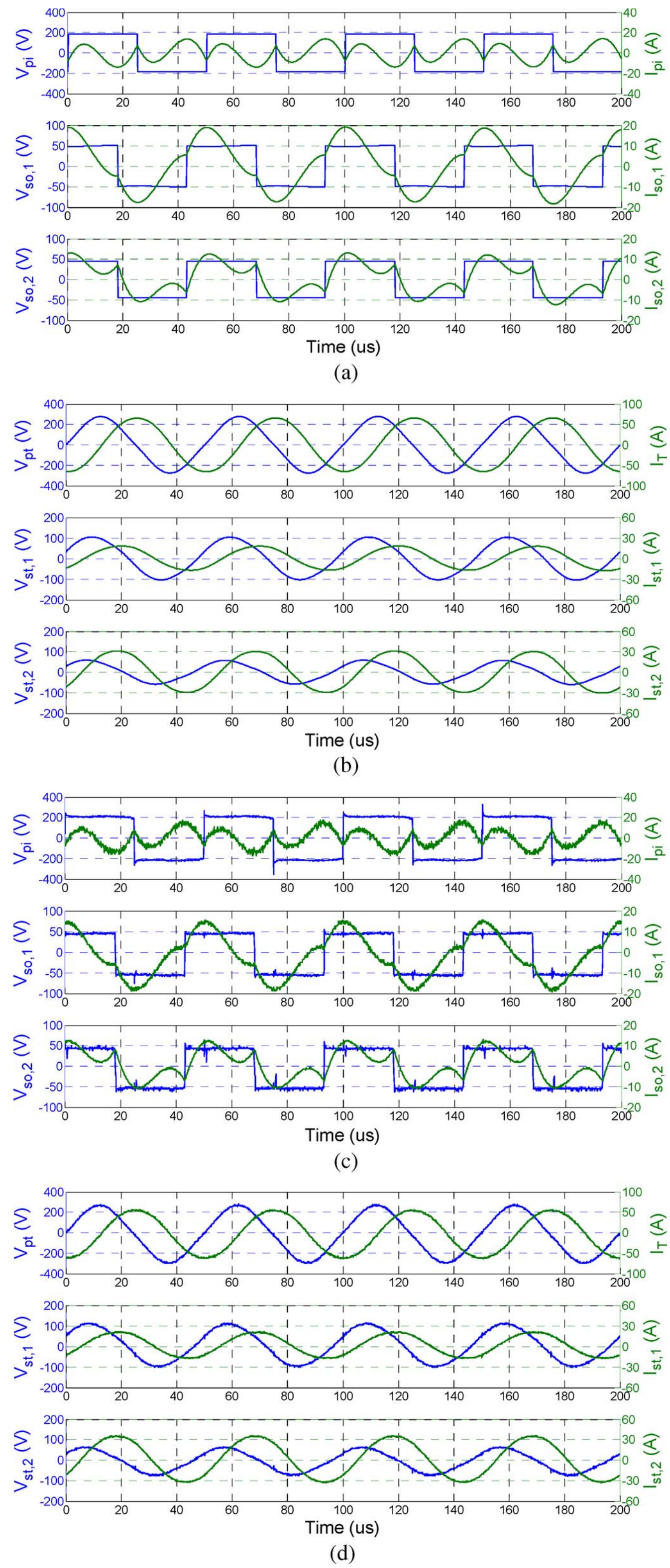

Fig. 10. Pickups 1 and 2 deliver 600 W to the primary. (a) and (b) Simulated waveforms. (c) and (d) Experimental waveforms.

magnetically coupled, using C89 ferrite E cores, to the track to either extract power from the track or deliver power back to the track, and a phase controller in Fig. 7(b) was implemented using Atmel Meg32 microprocessor to regulate the power flow in both directions.

Fig. 9 shows the comparison between the simulated and measured waveforms in a situation where the primary delivers approximately 600 W to pickup 1 while pickup 2 idles.

The top two plots in Fig. 9 are the simulated results, and the bottom two plots show the measured waveforms under the same

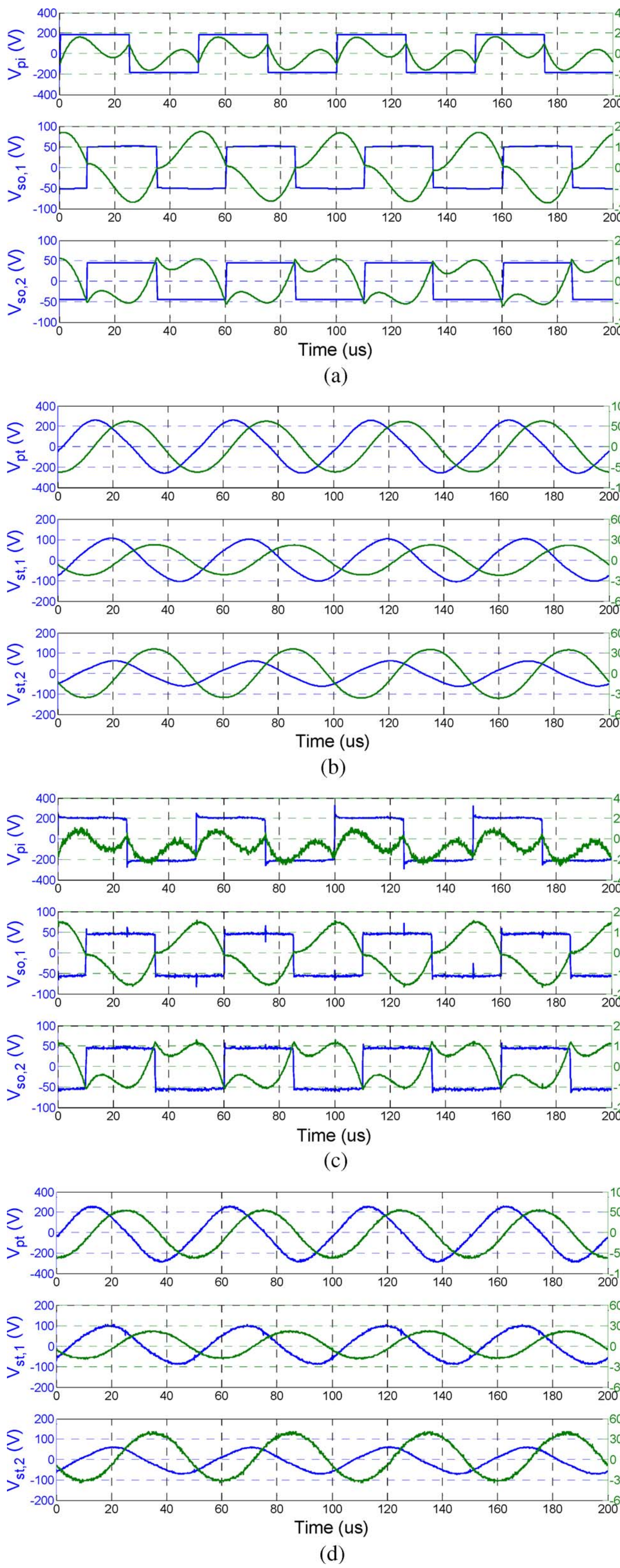

Fig. 11. Pickups 1 and 2 receive 900 W from the primary. (a) and (b) Simulated waveforms. (c) and (d) Experimental waveforms.

conditions. As can be seen from plots 1 and 2, voltages generated by the converter in pickup 1 and pickup 2 are lagging and out of phase, respectively, with respect to the primary voltage. Therefore, as expected, the pickup 1 receives power from the primary, while the pickup 2 neither receives nor delivers power.

The good agreement between simulated and measured results confirms the validity of the proposed bidirectional concept and its control philosophy. As evident from the second and fourth plots in Fig. 9, the voltage and current waveforms in the track and the pickup coils are smooth and sinusoidal despite the fact that converters were operated in a square-wave mode, and this can be attributed to the filtering action of the LCL circuit.

Fig. 10 shows the waveforms of the system during the reverse power flow. In this situation, both pickups supply approximately 600 W to the primary. The voltages generated by both pickup-side converters are clearly leading the voltage that is produced by the primary side converter, and hence, the power flow is from the pickup side to the primary. Despite the change in the direction of power flow, the primary side controller maintains a constant track current at 50 A.

Waveforms that correspond to a forward power flow of 900 W are shown in Fig. 11. As expected, both voltages generated by pickup systems are lagging, and thus, the pickups receive power from the primary. An increase in phase lag, in contrast to Fig. 10, is noticeable and reflects the increase in power from 600 to 900 W.

V. Conclusion

A novel contactless power interface, which is based on IPT technology and ideal for bidirectional power transfer between a common dc bus and multiple electric or hybrid vehicles, has been described. A mathematical model has been presented to show that both direction and amount of power flow could be controlled in the proposed system through the control of either the magnitude or/and relative phase of voltages produced by converters. Theoretical analysis, simulations, and experimental measurements of a 1.5-kW prototype IPT system under various operating conditions indicate that the proposed bidirectional contactless power transfer concept is viable and can be used in applications such as V2G systems to charge and discharge electric or hybrid vehicles, which are connected to the power grid.

References

[1] M. H. Nehrir, C. Wang, and S. R. Guda, "Alternative energy distributed generation: Need for multi-source operation," in *Proc. North Amer. Power Symp.*, 2006, pp. 547–551.

[2] Y. Xue, L. Chang, S. B. Kjær, J. Bordonau, and T. Shimizu, "Topologies of single-phase inverters for small distributed power generators: An overview," *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1305–1314, Sep. 2004.

[3] R. B. Godoy, H. Z. Maia, F. Jacques, T Filho, L. Galotto, J. Onofre, P. Pinto, and G. S. Tatibana, "Design and implementation of a utility interactive converter for small distributed generation," in *Proc. IEEE Ind. Appl. Conf.*, 2006, pp. 1032–1038.

[4] M. N. Marwali and A. Keyhani, "Control of distributed generation systems-Part I: Voltages and currents control," *IEEE Trans. Power Electron.*, vol. 19, no. 6, pp. 1541–1550, Nov. 2004.

[5] J. Balakrishnan, "Renewable energy and distributed generation in rural villages," in *Proc. IEEE Ind. Inf. Syst. Conf.*, 2006, pp. 190–195.

[6] D. N. Gaonkar and R. N. Patel, "Modeling and simulation of microturbine based distributed generation system," in *Proc. IEEE Power India Conf.*, Apr. 2006, pp. 5–10.

[7] T. J. Hammons, "Integrating renewable energy sources into European grids," in *Proc. Univ. Power Eng. Conf.*, 2006, pp. 142–151.

[8] Q. Mei, W. Wu, and Z. Xu, "A multi-directional power converter for a hybrid renewable energy distributed generation system with battery storage," in *Proc. IEEE Power Electron. Motion Control Conf.*, 2006, pp. 1–5.

[9] R. Ramakumar and P. Chiradeja, "Distributed generation and renewable energy systems," in *Proc. IEEE Energy Convers. Eng. Conf.*, 2002, pp. 716–724.

[10] J. G. Slootweg and W. L. Kling, "Impacts of distributed generation on power system transient stability," in *Proc. IEEE Power Eng. Soc. Summer Meet.*, 2002, pp. 862–867.

[11] B. Kramer, S. Chakraborty, and B. Kroposki, "A review of plug in vehicles and vehicle to grid capability," in *Proc. IEEE Ind. Electron. Conf.*, 2008, pp. 2278–2283.

[12] U. K. Madawala and H. Vincenz, "Living and mobility—A novel multipurpose in-house grid interface with plug-in hybrid blueangle," in *Proc. IEEE* , 2008, pp. 531–536.

[13] M. G. Eagen, D. L. O'Sullivan, J. G. Hayes, M. J. Willers, and C. P. Henze, "Power factor corrected single stage inductive charger for electric vehicle batteries," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 1217–1226, Apr. 2007.

[14] G. A. Covic, J. T. Boys, M. L. G. Kissin, and H. G. Lu, "A three-phase inductive power transfer system for roadway-powered vehicles," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3370–3378, Dec. 2007.

[15] U. K. Madawala, D. J. Thrimawithana *et al.*, "A two-way inductive power interface for single loads," in *Proc. IEEE Ind. Technol. Conf.*, 2010, pp. 673–678.

[16] U. K. Madawala and D. J. Thrimawithana, "A ring inductive power transfer system," in *Proc. IEEE Ind. Technol. Conf.*, 2010, pp. 667–672.

[17] D. J. Thrimawithana and U. K. Madawala, "A novel matrix converter based bi-directional IPT power interface for V2G applications," presented at the IEEE International Energy Conference and Exhibition, Manama, Bahrain, 2010. ISBN 9789990171105.

[18] K. D. Papastergiou and D. E. Macpherson, "An airborne radar power supply with contactless transfer of energy—Part II: Converter design," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2885–2893, Oct. 2007.

[19] M. H. Ryu, H. Cha, Y. H. Park, and J. W. Back, "Analysis of the contactless power transfer system using modeling and analysis of the former," *Proc. IEEE Ind. Electron. Soc.*, pp. 1036–1042, 2005.

[20] P. Sergeant and A. Van den Bossche, "Inductive coupler for contactless power transmission," *IET Trans. Elect. Power Appl.*, vol. 2, no. 1, pp. 1–7, Jan. 2008.

[21] C. G. Kim, D. H. Seo, J. S. You, J. H. Park, and B. H. Cho, "Design of a contactless battery charger for cellular phone," *IEEE Trans. Ind. Electron.*, vol. 48, no. 6, pp. 1238–1247, Dec. 2001.

[22] U. K. Madawala and D. J. Thrimawithana, "A single controller for inductive power transfer systems," in *Proc. IEEE Ind. Electron. Conf.*, 2009, pp. 109–113.

[23] U. K. Madawala, D. J. Thrimawithana, and N. Kularatna, "An ICPT-supercapacitor based hybrid system for surge free power transfer," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3287–3297, Dec. 2007.

[24] H. Chang-Yu, G. A. Covic, and J. T. Boys, "Detection of the tuned point of a fixed-frequency LCL resonant power supply," *IEEE Trans. Power Electron.*, vol. 24, no. 4, pp. 1140–1143, Apr. 2009.

[25] D. J. Thrimawithana and U. K. Madawala, "A multi-source green energy system with a novel grid interface," in *Proc. IEEE Sustainable Energy Technol. Conf.*, 2010, pp. 1–6.

[26] J. Jang and M. Jovanovic, "Contactless electrical energy transmission systems," U.S. Patent 6 301 128 B1, Oct. 2001.

[27] J. G. Meins and J. D. Sinsley, "Method and apparatus for supplying contactless power," U.S. Patent 6 515 878 B1, Feb. 2003.

[28] A. W. Green and J. T. Boys, "10 kHz Inductively coupled power transfer-concept and control," *Proc. IEE Power Electron. Variable Speed Drives*, pp. 694–699, 1999.

[29] C. Wang, O. H. Steilau, and G. A. Covic, "Design considerations for a contactless electric vehicle battery charger," *IEEE Trans. Ind. Electron.*, vol. 52, no. 5, pp. 1308–1314, Oct. 2005.

[30] D. J. Thrimawithana and U. K. Madawala, "A contactless bi-directional power interface for plug-in hybrid vehicles," in *Proc. IEEE Veh. Power Propulsion Conf.*, 2009, pp. 396–401.

[31] M. L. G. Kissin, J. T. Boys, and G. A. Covic, "Interphase mutual inductance in polyphase inductive power transfer systems," *IEEE Trans. Ind. Electron.*, vol. 56, no. 7, pp. 2393–2400, July 2009.

[32] D. J. Thrimawithana, U. K. Madawala, and Y. Shi, "Design of a bidirectional inverter for a wireless V2G system," in *Proc. IEEE Sustainable Energy Technol. Conf.*, 2010, pp. 1–5.

[33] N. A. Keeling, J. T. Boys, and G. A. Covic, "A unity-power-factor IPT pickup for high-power applications," *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 744–751, Feb. 2010.

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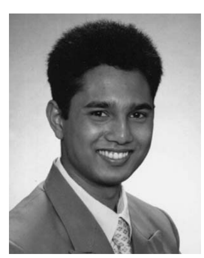

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