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A BIDIRECTIONAL INDUCTIVE POWER INTERFACE FOR ELECTRIC VEHICLES

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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. 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. 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, super capacitors, 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. Irrespective of whether the EV or a fleet of EVs is used solely for medium-scale energy storage or micro scale residential use as in the case of “living and mobility”, 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. 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. 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. 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 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 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.

2. IPT TECHNOLOGY

An IPT system, as shown conceptually in 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 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 Li − CT − LT in preferably used to minimize the vary requirement on the primary side. The track inductance LT is magnetically coupled through M to a pickup coil L2.

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 L2 and C2, and tuned to the same track frequency, is also employed in the pickup system to provide the vat compensation and maximize the amount of power delivery. As shown in 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

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

WhereIscis the short-circuit current of the pickup coil defined by Isc= (M IT/L2). Simplification of (1) yields

$$P_{o,\max} = \omega \frac{M^2}{L_2} I_T^2 Q_2$$

WhereQ2 is the quality factor. According to, the maximum possible pickup power can be increased by the best possible pickup design, which ensures that M2/L2 ratio is optimum within any given design, constrains. 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 with regard to detailed design aspects of IPT systems can be found in.

3. 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 the bidirectional IPT system is equally applicable to “living and mobility” systems with a single EV or stand-alone systems, for which 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 as in the case of typical IPT systems, the primary side converter, derived from the grid and fed by dc link voltage Vin, generates a constant current IT in a track LT, which is magnetically coupled to pick up 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 the primary side converter (reversible rectifier) produces a sinusoidal voltage Vpi∠0 at an angular frequency ω which is assumed to be the reference voltage. The current IT in the track or inductor LT is essentially held constant by the primary side controller. At steady state, the induced voltage Vsi,nof the “nth” pickup coil Lsi,n, due to track current IT, can be given by

$$V_{\mathrm{si},n} = j\omega M_n I_{\mathrm{T}}$$

WhereMnrepresents the magnetic coupling or mutual inductance between the track inductance LT and pickup coil inductance Limn. 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 Vrnreflected into the track due to “nth” pickup can be expressed by

$$V_{\mathrm{rn}} = -j\omega M_n I_{\mathrm{si},n}$$

Whereisin is the current in pickup coil inductance Limn. The nth pickup of the system at steady state can thus be represented by the model in Fig. 4(a).

B. Control

The primary-side full-bridge converter (reversible rectifier) can be driven by the primary controller in it has a triangle wave generator and a proportional–integral (PI) controller, to produce a phase-modulated square wave voltage (Vpi) to regulate the track current at the desired value. Pulse width 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 (LT) 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 delayand 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 anglein 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 $V_{so,n}$leads or lags the induced voltage ($V_{si,n}$) by a phase angle θangle, where $-\pi/2 < \theta n < \pi/2$. A phase angle between zero and $\pi/2$ results in the pick upside 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 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.

Fig. 1. 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

4. 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 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 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 was implemented using Atmel Meg32 microprocessor to regulate the power flow in both directions.

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. 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.

5. 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.

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