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ilmiy elektron jurnali

Vebsayt: http://2ndsun.uz/index.php/yt

THE NORMATIVE MAGNITUDE

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INFO:

Accepted: 26.03.2022
Reviewed: 26.03.2022
Published: 31.03.2022

Keywords: *switch-mode, power electronic circuitry*

ABSTRACT

The aim of an inductively coupled wireless power transfer (ICWPT) system is to provide power to a movable object across a gapped magnetic structure. Its theoretical development relies on both magnetic and power electronics together as an integrated system. In the case of magnetic structure, designing a magnetic coupling structure with a small air gap would result in high magnetic coupling coefficient and increased power transfer capability. Modeling and representing the magnetic circuit and associate its geometrical characteristics with its electrical behavior are very important as: to enable predicting the circuit performance and to provide the insight needed to achieve an optimized design.

Furthermore, the magnetic structure of an ICWPT system combines the magnetic properties of both an ideal transformer and an inductor. There are more room for theoretical improvements in magnetization, mutual inductance, leakage inductance, and their connection with the structure geometry and AC losses that are critical in power electronic designs. In ICWPT systems, in order to reduce the skin and proximity effects associated with the coils, multi-strands-woven Litz wire is often used. Modeling and developing functional analysis of such a phenomenon associated with Litz wire are of high importance for the development of an efficient ICWPT system.

Power electronics, on the other hand, covers a large area including electronics, control, and communications. Analysis and modeling of switch-mode non-linear circuits are the main concerns. Like most other power electronic applications, the further development of ICWPT systems depends largely on some fundamental advances in switch-mode non-linear theories. Moreover, the loose magnetic coupling between the primary and the secondary coils of an ICWPT power supply is more difficult to analyze than a traditional closely coupled transformer. This further increases the circuit complexity so that proper compensation and control have to be taken into consideration in the design [2].

Because of the air gap, designing an ICWPT system poses some unusual design constraints compared to the traditional compactly coupled design. The relatively large gap in the magnetic circuit results in a low mutual inductance and high leakage inductances. Eddy currents caused by fringing flux can be formed in the magnetic material near the air gap and cause power losses and EMI. Operating at high frequencies presents unique design problems due to the increased core losses, leakage inductance, and winding capacitance. This is because physical orientation and spacing of the windings determine the leakage inductance and winding capacitance which are distributed throughout the windings in the magnetic structure. Experienced SMPS (switch-mode power supply) designers know that SMPS success or failure heavily depends on the proper design and implementation of the magnetic components. Inherent parasitic elements in high-frequency inductive power transfer applications cause a variety of circuit problems including: high power losses, high-voltage spikes necessitating snubbers or clamps, poor cross regulation between multiple outputs, noise coupling to input or output, restricted duty cycle range, etc.

Some major constrains associated with the design and practical implementations are:

It is often difficult to deliver the required power to a load via ICWPT system due to limited space on the receiver side and specific power flow regulations.

Operating at a higher frequency can help reduce the size of an ICWPT system. However, the switching speed of the switches is one of the major constraints. The most suitable switching devices for ICWPT applications seem to be insulated gate bipolar transistors (IGBTs) with commercial products up to the power level of 3kV/2kA, and a switching frequency up to 80 kHz. Power metal oxide silicon field effect transistors (MOSFETs) can switch at a speed up to MHz levels, but their voltage levels are too low for high-power ICWPT applications.

Due to various copper and ferrite losses, achieving high system power efficiency is a challenging task.

This is an important factor to keep the system operating in an acceptable range of temperature, especially when the system is used in a specified temperature environment.

The size and weight are limiting factors in designing an ICWPT system. The conversion process in power electronics requires the use of magnetic components that are usually the heaviest and bulkiest items of the circuit. The design of such components has an important influence on the overall system size/weight, power conversion efficiency, and cost.

It is always important to have a stable system under full range of load and magnetic coupling variations in practical applications. Variable frequency controlled ICWPT power supplies can become unstable if not designed properly.

Cost effectiveness. Existing ICWPT systems are costlier than traditional wired counterparts due to the complicated power electronic circuitry and magnetic coupling design. It is a challenging task to improve the system design to bring the cost down for practical applications.

Compliance. Final practical products of ICWPT systems need to pass electromagnetic compatibility (EMC) and safety standards, which can be a challenging engineering design task.

The above mentioned challenges may interact with each other, making the system optimisation very difficult. Trade-offs often need to be made depending on practical constraints and requirements.

The fundamental theory of ICWPT systems is governed by Faraday and Ampere's laws as shown in Figure 1. Based on Ampere's law, current I generates a magnetic field H. Some of this magnetic field links the secondary power pickup coil and according to Faraday's law causes a voltage V to be induced.

$$\oint \vec{H} \,.\, \vec{dl} = I \qquad E_1$$

Ampere's law can be mathematically expressed as:

This equation states that the line integral of the magnetic field intensity around a closed loop is equal to the current flowing through it.

Faraday's law, on the other hand, is expressed by:

$$V = -N_2 \frac{d\phi}{dt} \qquad E_2$$

where N2 is the number of turns of the secondary coil.

The negative sign in (6) is described by Lenz's law, which states that the current flow in the secondary coil (when a load is connected) will be such that it creates a magnetic field that opposes the primary magnetic field.

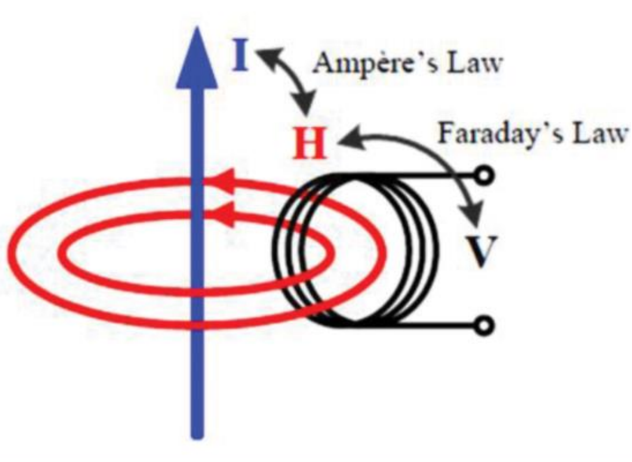

Figure 1.

Fundamental theory of an ICWPT system.

A typical ICWPT system is normally constructed by winding the primary and secondary coils into separate halves of ferrite cores parted by an air gap as shown in Figure 2. Since direct physical contacts are eliminated in such a system, magnetic link is used to provide a reliable and efficient power transfer across an air gap. As it can be seen, the magnetic flux φm couples from one half of the core to the other half and provides a mutual inductance M that couples energy from the primary to the secondary side. The mutual inductance M is a function of geometry and can be found by simulation, measurement, or modelling the physical structure [7, 8].

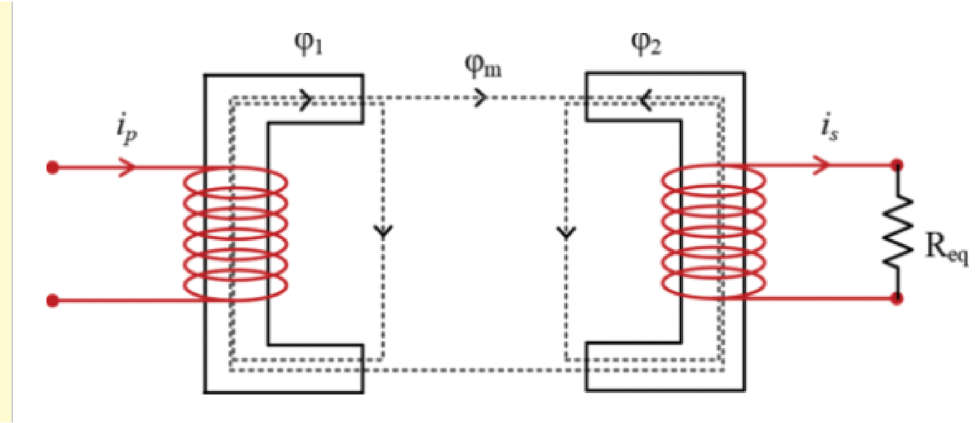

Figure 2.

Typical flux linkage in an ICWPT system.

In such a loosely coupled power transfer system, the leakage fluxes can be very large and cannot be ignored. The proportion of the primary coils flux that links with the secondary coil is known as the primary coupling coefficient expressed by:

$$k_1 = \frac{\emptyset_M}{\emptyset_1} \qquad \text{E3}$$

Likewise, the secondary coupling coefficient is given by:

$$k_2 = \frac{\emptyset_M}{\emptyset_2} \qquad \text{E4}$$

These two values are typically combined to give the overall system coupling coefficient as:

$$k = \sqrt{k_1 k_2} \qquad \text{E5}$$

The mutual inductance between the primary and the secondary coils then is given by:

$$M = k\sqrt{L_pL_s} \qquad \text{E6}$$

where Lp and Ls are the self-inductances of the primary and the secondary coils.

An ICWPT system can then be considered as a loosely coupled power transfer system using modern power conversion, control, and magnetic coupling techniques to achieve wireless power transfer as shown in Figure 3. It consists of a primary side AC/DC/AC resonant converter which converts the rectified AC power into high frequency AC power. The high-frequency AC power then is fed to the primary coil which is magnetically coupled to the secondary coil, while physically separated. The secondary side then can be movable (linearly or/and rotating), giving flexibility, mobility, and safeness for supplied loads. In the secondary side, the induced high-frequency power is converted and controlled by a secondary converter to meet the requirements specified by the load parameters. In fact, the time-varying magnetic field generated by the primary coil induces an electromotive force in the secondary coil which forms the voltage source of the secondary power supply. Since the magnetic coupling of an ICWPT system is normally very loose compared to normal transformers, the induced voltage source is usually unsuitable to be used to drive the load directly. Thus, a power conditioner with proper circuit tuning and conversion is required to control the output power according to the load requirements.

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