Maximum Energy Efficiency Operation of Series-Series Resonant Wireless Power Transfer Systems Using On-Off Keying Modulation

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***Abstract*—Maximum energy efficiency in wireless power transfer (WPT) systems can be achieved through the use of magnetic resonance technique at a certain load resistance value. However, practical load resistance is not constant. Previously, a switched mode dc-dc converter was used in the receiver circuit to emulate an equivalent load resistance for maximum energy efficiency. In this paper, a new approach based on the On-Off Keying is proposed to achieve the high energy efficiency operation over a wide range of load power without using an impedance-matching dc-dc power converter. This simple and effective method has reduced average switching frequency and switching losses. It can be applied to any series-series resonant WPT system designed to operate at a constant output voltage. Practical measurements have confirmed the validity of the proposal.**

***Index Terms*— Wireless power transfer, on-off keying, magnetic resonance**

I. INTRODUCTION

MAGNETIC resonance developed by early pioneers of wireless power transfer (WPT) since late 1800s has been a cornerstone technology for efficient WPT applications. Early pioneers of WPT improved the energy transfer performance by maximizing the *kQ* product of the transmitter and receiver coils, where *k* is the mutual coupling coefficient and *Q* is the quality factor of the coil [1]. With the availability of fast power electronics devices for providing high-frequency power sources and Litz wire for reducing ac winding resistance, WPT has re-emerged as a hot research topic for a wide range of applications since 1980s. The progress of wireless power transfer (WPT) technology over the last three decades has enabled WPT to reach commercialized stage in mobile robots [2], consumer electronics [3] and medical implants [4]. Active research and development activities are being devoted to extend WPT to Electric Vehicle charging applications [5].

The power electronics community has been using magnetic coupling and resonant circuits for efficient WPT for several decades. Various combinations of series and parallel inductor-capacitor (LC) resonant circuits have been compared in [6] [7]. Recently, high-order resonant circuits such as LCC are also investigated [8] [9] particularly for dynamic charging of electric vehicles.

While high energy efficiency can be achieved at resonant operation of a WPT system, it should be noted that the maximum energy efficiency point only occurs at a certain load resistance. This implies that the load resistance should be transformed to the optimum value in order to achieve high energy efficiency.

Typical approaches for impedance transformation are to use:

- transformers or magnetically coupled coils [10] ;
- impedance transformation networks (like those used for impedance matching);
- DC-DC power converters [11]-[13].

Since the load resistance of a practical system varies with time in practice, therefore the first two methods are not suitable to transform the load resistance to the optimum value for all possible load resistances. In [10], the primary coil is split into two to transfer the current stress from the primary circuit to the intermediate coil. One can transform the rated load resistance (to the minimum load resistance for a constant output voltage) to the optimum value of the system. Then as the load resistance changes to a larger value, a Boost Converter could be used to adjust the equivalent load resistance to the optimum value [11]-[13].

Among various combinations of resonant circuits for WPT, the series-series resonant system is probably the widely adopted. This point is certainly correct for most of the wireless charging products for portable consumer electronics in the market [3]. In this paper, a simple and yet highly effective method of maximizing energy efficiency over a wide load range without using impedance-matching dc-dc power converter in the receiver circuit is presented. Unlike previous maximum energy efficiency tracking concept [11] [12], this new approach firstly determines the optimal input voltage of the series-series resonant WPT system that is designed to operate at a certain output voltage. Then it ensures that the WPT system operates at the optimal efficiency condition whenever the system is energized. This method is based on an underlying principle that, “for any series-series resonant WPT system with a constant output voltage, there will be an optimum input voltage for the system at which a maximum efficiency can be achieved regardless of load changes”. This principle

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implies that high energy efficiency can be achieved for a wide load range (including light load conditions). It will be practically demonstrated that the proposal method can be achieved through the use of On-Off Keying (OOK) modulation. In this paper, the condition of the optimal load resistance at which maximum energy efficiency occurs is firstly re-iterated. Then the implementation of the OOK method is explained. A hardware prototype of a series-series resonant WPT system has been constructed to evaluate the proposed method. Practical measurements are included to confirm the validity of the proposal.

II. IMPORTANCE OF OPTIMUM LOAD RESISTANCE

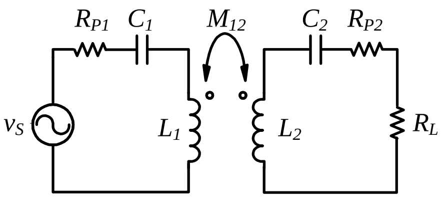


Fig. 1. Circuit model of a 2-coil series-series resonant WPT system.

Fig. 1 shows the circuit model for a 2-coil series-series resonant WPT system. It is assumed that the operating frequency should equal to the resonant frequency of these two *L-C* resonators, i.e. $f = \frac{1}{2\pi\sqrt{L_1C_1}} = \frac{1}{2\pi\sqrt{L_2C_2}}$, where L_1 and L_2 are the self-inductance values and C_1 and C_2 are the resonant capacitance of the transmitter and receiver circuits, respectively. Thus the system can be expressed with (1) and (2).

$$R_{P1}\mathbf{I_1} + j\omega M_{12}\mathbf{I_2} = V_S \tag{1}$$

$$j\omega M_{12}\mathbf{I_1} + \left(R_{P2} + R_L\right)\mathbf{I_2} = \mathbf{0} \tag{2}$$

where V_S is the RMS value of the input sinusoidal voltage and M_{12} is the mutual inductance between the transmitter and receiver coils. If the input voltage has a rectangular waveform (e.g. generated by a full-bridge inverter), V_S should equal to the RMS value of the fundamental component of the rectangular waveform. $\mathbf{I_1}$, $\mathbf{I_2}$ are the phasors of primary current i_1 and secondary current i_2, respectively. R_{P1} and R_{P2} are the a.c. winding resistance of the transmitter and receiver coil resonators as shown in Fig. 1. The load resistance is labelled as R_L.

It has been pointed out that the load resistance is a crucial factor for reaching a high efficiency for a WPT system [3]. The reason is that there is an optimum load resistance for a given WPT system. When the actual load resistance does not equal to the optimum value, the efficiency of the system will be degraded. The optimum load resistance for a WPT system based on Series-Series resonant compensation circuits in a 2-coil system can be expressed as [14]

$$R_{L\_OPT\_\eta} = R_{P2}\left(\sqrt{1 + \frac{\omega^2 M_{12}^2}{R_{P1}R_{P2}}}\right) \tag{3}$$

Equation (3) indicates that the optimal load resistance depends on the system parameters of the transmitter and receiver coils and the operating frequency only. This value does not necessarily match the actual load resistance which is usually not a constant.

Generally speaking, in the design stage of a series-series resonant WPT system with a constant output voltage, the optimum load resistance of the system will be preferably designed to equal to the minimum load resistance (i.e. the equivalent load resistance value at the rated or maximum power). When the actual load power is less than the rated power, the equivalent load resistance will increase because it is assumed here that the WPT system has a constant output voltage. Therefore, only the situation that the load resistance larger than the optimum load (i.e. lowest equivalent load resistance in the design) is needed to deal with.

High system energy efficiency should be maintained not only at the optimal load resistance value, but also under light load conditions. A case study is used here to illustrate the engineering principle of using optimal load resistance value for a wide range of operation within which high efficiency can be achieved. The parameters of the 25 W example are listed in TABLE I.

The system energy efficiency curve is plotted in Fig. 2. The optimum load is 4 Ω in this case and the achievable maximum efficiency is 80%. Therefor the minimum load resistance of the system is set at 4 Ω. When the load power is 1/10 of the rated power, i.e. 2.5 W, the load resistance becomes 40 Ω and the efficiency is 46.2%. Now suppose that there is a method for transforming the load resistance to the optimum value. The energy efficiency of the system can be maintained at a value near 80%. Therefore, the efficiency improvement for 1/10 rated power situation is 33.8%.

TABLE I PARAMETERS OF A WPT SYSTEM

Resonant frequency f_0	100 kHz
Self-inductance L_1, L_2	91.5 μH
Coupling coefficient	0.0689
Output voltage	10 V
Quality factor of the coils $(Q_i = \frac{\omega L_i}{R_{Pi}}, i = 1, 2)$	130

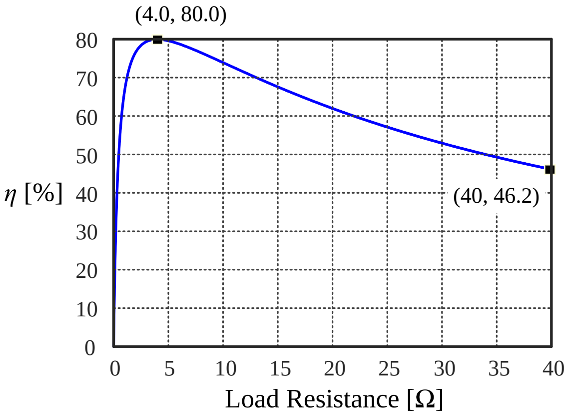


Fig. 2. Energy efficiency as a function of the load resistance in the WPT system.

Consider a simple 2-coil wireless power transfer (WPT) system with its equivalent circuit shown in Fig.1. Assuming that the power losses in the ferrite plates that shield the transmitter and receiver coils are negligible, the coupled circuit equations for the system are

$$(R_{P1}+jX_1)\mathbf{I_1}+j\omega M_{12}\mathbf{I_2}=\mathbf{V}_{in} \tag{1}$$

$$j\omega M_{12}\mathbf{I_1}+(R_{P2}+R_L+jX_2)\mathbf{I_2}=\mathbf{0} \tag{2}$$

where ω is the angular frequency of the operation; X_i (i=1,2) is the reactance ωL_i-1/(ωC_i) of Resonator-i; $\mathbf{I_1}$ and $\mathbf{I_2}$ are the current vectors of the Resonator-1 and Resonant-2 respectively; R_{P1} and R_{P2} are the winding resistance of Resonant-1 and Resonant-2, respectively; C_1 and C_2 are the resonant capacitors of Resonant-1 and Resonant-2, respectively; R_L is the load resistance.

A. Optimum Load for Maximum Energy Efficiency Operation

Assuming the core losses in the magnetic ferrite plates and the power inverter losses are negligible, the energy efficiency (η) of a 2-coil wireless power transfer system can then be expressed as:

$$\eta=\frac{I_2^2R_L}{I_1^2R_{P1}+I_2^2(R_{P2}+R_L)}=\frac{R_L}{(\frac{I_1}{I_2})^2R_{P1}+R_{P2}+R_L} \tag{3}$$

The ratio of the root-mean-square currents I_1/I_2 can be obtained by solving (2) without using (1). In other words, the compensating condition in Resonator-1 (or the value of X_1) will not affect the efficiency of the system. With (2), the energy efficiency can be further determined as

$$\eta=\frac{\omega^2M_{12}^2R_L}{[(R_{P2}+R_L)^2+X_2^2]R_{P1}+\omega^2M_{12}^2(R_{P2}+R_L)} \tag{4}$$

If the operating frequency f ($\omega=2\pi f$) is chosen, the maximum energy efficiency (MEE) conditions can be determined by the following procedure. Firstly, by differentiating η with respect to X_2 and equating the differential function to zero,

$$\frac{\partial\eta}{\partial X_2}=0 \tag{5}$$

the optimum value of X_2 for maximum efficiency can be obtained as

$$X_{2\_OPT\_\eta}=0 \tag{6}$$

Then by differentiating η with respect to R_L and equating the differential function to zero,

$$\frac{\partial\eta}{\partial R_L}=0 \tag{7}$$

the optimum value of R_L for maximum efficiency can be obtained as

$$R_{L\_OPT\_\eta}=\sqrt{R_{P2}^2+X_2^2+\omega^2M_{12}^2R_{P2}/R_{P1}} \tag{8}$$

If $X_2=X_{2\_OPT\_\eta}=0$, then the optimal load for maximum energy efficiency is [20]:

$$R_{L\_OPT\_\eta}=R_{P2}\left(\sqrt{1+\frac{\omega^2M_{12}^2}{R_{P1}R_{P2}}}\right) \tag{9}$$

B. Optimum Load for Maximum Power Operation

The output power of the system is

$$P_O=I_2^2R_L$$

$$=\frac{\omega^2M_{12}^2V_{in}^2R_L}{(\omega^2M_{12}^2+R_{P1}R_{P2}+R_{P1}R_L-X_1X_2)^2+(R_{P1}X_2+R_{P2}X_1+R_LX_1)^2} \tag{10}$$

By solving

$$\frac{\partial P_O}{\partial R_L}=0 \tag{11}$$

the optimal load for maximum power transfer can be determined as:

$$R_{L\_OPT\_Po}=\sqrt{\frac{(\omega^2M_{12}^2+R_{P1}R_{P2}-X_1X_2)^2+(R_{P1}X_2+R_{P2}X_1)^2}{R_{P1}^2+X_1^2}} \tag{12}$$

When the system is operated at the resonant frequency of the receiver resonator ($X_2=0$) so that the maximum efficiency of the system can be achieved, equation (12) can be rewritten as

$$P_O=\frac{\omega^2M_{12}^2V_{in}^2R_L}{(\omega^2M_{12}^2+R_{P1}R_{P2}+R_{P1}R_L)^2+(R_{P2}X_1+R_LX_1)^2} \tag{13}$$

therefore

$$X_{1\_OPT\_Po}=0 \tag{14}$$

and the expression in (12) can now be simplified as:

$$R_{L\_OPT\_Po} = R_{P2}\left(1+\frac{\omega^2 M_{12}^2}{R_{P1}R_{P2}}\right) \tag{15}$$

C. Comparison of optimal load conditions

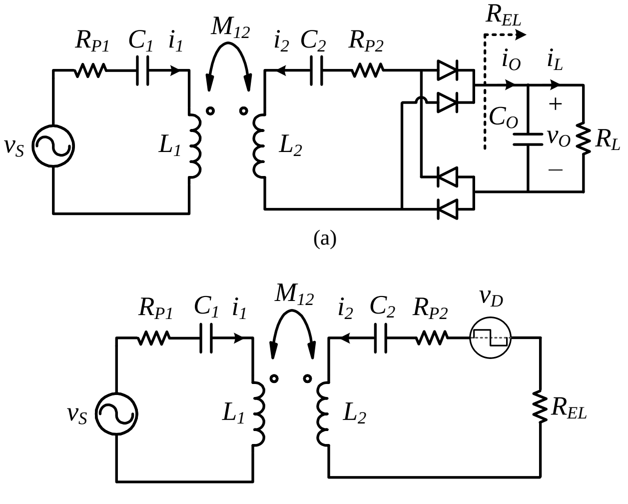
From (9) and (15), it can be seen that the optimal load conditions for maximum energy efficiency operation and maximum power transfer operation are different. The bracketed term in (9) is $\sqrt{1+\frac{\omega^2 M_{12}^2}{R_{P1}R_{P2}}}$. The bracketed term in (15) is $\left(1+\frac{\omega^2 M_{12}^2}{R_{P1}R_{P2}}\right)$. In addition, since the bracket term in (15) is greater than 1, comparing (9) and (15) leads to the following inequality:

$$R_{L\_OPT\_\eta} < R_{L\_OPT\_Po} \tag{16}$$

In the proposed MEET method for, it is the optimal load resistance $R_{L\_OPT\_\eta}$ in (9) that is adopted.

III. DERIVATION OF CONSTANT INPUT VOLTAGE PRINCIPLE

A. Theoretical Analysis on WPT Systems with Output Rectification



(a)

(b)

Fig. 3.(a) A series-series resonant WPT system with output rectification; (b) Simplified model of the system.

Fig. 3(a) shows a typical series-series resonant WPT system with a given v_S and output rectification. The output voltage v_o depends on the input voltage. A simplified model, as shown in Fig. 3(b), is built on the following assumptions.

- The voltage drop of the diode rectifier is constant;
- Only the fundamental components of v_D and v_O are considered.
- The current i_O is continuous and sinusoidal.

Therefore,

$$R_{EL} = \frac{8}{\pi^2} R_L \tag{4}$$

The circuit equations of the system in Fig. 3 (b) are:

$$R_{P1}\mathbf{I_1} + j\omega M_{12} I_2 = \mathbf{V_S} \tag{5}$$

$$j\omega M_{12}\mathbf{I_1} + \left(R_{P2}+R_{EL}\right)I_2 + V_{D1} = \mathbf{0} \tag{6}$$

where V_{D1} is the RMS value of the fundamental component of v_D. Here V_{D1} and I_2, which are in phase, are assumed to have zero phase angle.

Then by rearranging (6),

$$\mathbf{I_1} = j\frac{\left(R_{P2}+R_{EL}\right)I_2 + V_{D1}}{\omega M_{12}} \tag{7}$$

$$\begin{aligned}\mathbf{V_S} &= R_{P1}\mathbf{I_1} + j\omega M_{12} I_2 \\ &= j\left(\frac{\left(R_{P2}+R_{EL}\right)I_2 + V_{D1}}{\omega M_{12}} R_{P1} + \omega M_{12} I_2\right)\end{aligned} \tag{8}$$

Therefore, **Vs** has a 90º phase angle and thus it can be expressed as

$$\mathbf{V_S} = jV_S \tag{9}$$

By substituting (9) into (5) and solving (5) and (6),

$$\mathbf{I_1} = j\frac{V_S(R_{P2}+R_{EL}) + \omega M_{12}V_{D1}}{\omega^2 M_{12}^2 + R_{P1}(R_{P2}+R_{EL})} \tag{10}$$

$$I_2 = \frac{\omega M_{12}V_S - R_{P1}V_{D1}}{\omega^2 M_{12}^2 + R_{P1}(R_{P2}+R_{EL})} \tag{11}$$

The efficiency of the system with switching losses neglected can be expressed as

$$\eta = \frac{I_2^2 R_{EL}}{I_1^2 R_{P1} + I_2^2(R_{P2}+R_{EL}) + V_{D1}I_2} \tag{12}$$

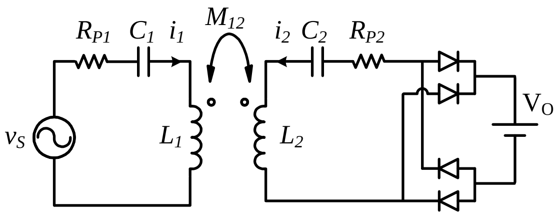
Substituting (10) (11) into (12) and putting $\frac{\partial \eta}{\partial R_{EL}} = 0$, the optimum load resistance can be obtained as:

$$R_{EL\_OPT} = \frac{1}{V_S}\sqrt{\frac{\Lambda}{R_{P1}}} \tag{13}$$

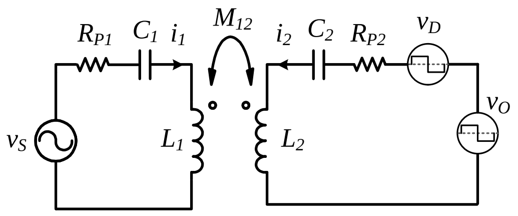
where $\Lambda = R_{P1}\left(\omega M_{12}V_D + R_{P2}V_S\right)^2 + R_{P2}\left(\omega M_{12}V_S - R_{P1}V_D\right)^2 + \frac{2\sqrt{2}}{\pi}V_D\left(\omega M_{12}V_S - R_{P1}V_D\right)\left(\omega^2 M_{12}^2 + R_{P1}R_{P2}\right).$

According to (13), the optimum load resistance can be obtained. Therefore, the optimum load resistance will be dependent of the input voltage when the voltage drop of the diodes is included.

B. Theoretical Analysis on WPT Systems with Constant Output Voltage



(a) Schematic of a series-series resonant WPT system with constant output voltage.



(b) Simplified mode of a series-series resonant WPT system with constant output voltage.

Fig. 4. Modeling of a series-series resonant WPT system with constant output voltage.

Batteries are common loads in WPT applications. The common output of a series-series resonant WPT system is a constant voltage source and there will be a rectification stage before the output stage. Therefore, the schematic of the system is redrawn in Fig. 4(a). Similar assumptions are made to simplify the analysis and the simplified model is shown in Fig. 3(b). The mathematical expressions of the system in Fig. 4(b) are shown below.

$$R_{P1}\mathbf{I_1} + j\omega M_{12} I_2 = \mathbf{V_S} \tag{14}$$

$$j\omega M_{12}\mathbf{I_1} + R_{P2} I_2 + V_{D1} + V_{O1} = \mathbf{0} \tag{15}$$

where V_{D1} and V_{O1} are the RMS values of the fundamental components of v_D and v_O, respectively. Here V_{D1}, V_{O1} and I_2, which are in phase, are assumed to have zero phase angle. It should be noted that the simplifications will bring some errors, which will be observed in the experimental results. Nevertheless, the simplified model provides the insights into the performance of the system.

Similarly, $\mathbf{V_S}$ has a 90° phase angle and can be represented with (9). By solving (14) and (15),

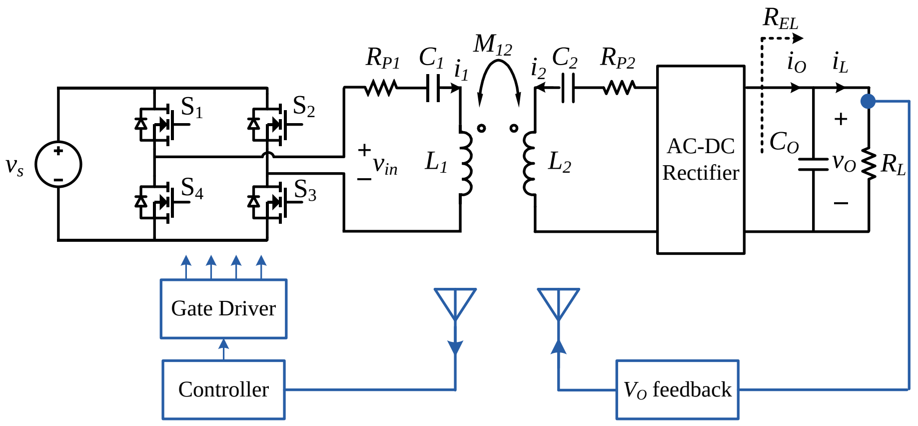
$$\mathbf{I_1} = j\frac{V_S R_{P2} + \omega M_{12}\left(V_{D1} + V_{O1}\right)}{\omega^2 M_{12}^2 + R_{P1} R_{P2}} \tag{16}$$

$$I_2 = \frac{\omega M_{12} V_S - R_{P1}\left(V_{D1} + V_{O1}\right)}{\omega^2 M_{12}^2 + R_{P1} R_{P2}} \tag{17}$$

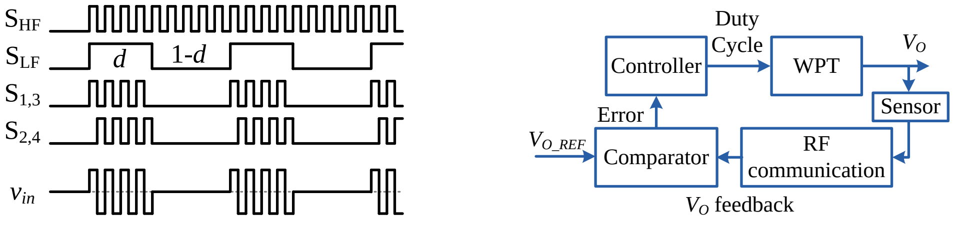
The efficiency of the system with switching losses neglected can be expressed as

$$\eta = \frac{V_{O1} I_2}{I_1^2 R_{P1} + I_2^2 R_{P2} + \left(V_{D1} + V_{O1}\right) I_2} \tag{18}$$

Substituting (16), (17) into (18) and putting $\frac{\partial \eta}{\partial V_S} = 0$, the



(a) Schematic of the proposed WPT system



(b) Switching signals for the inverter

(c) Control loop of the system

Fig. 5. The proposed OOK modulated series-series resonant WPT system.

optimum input voltage equation is:

$$V_{S\_OPT} = \frac{-b + \sqrt{b^2 - 4ac}}{2a} \tag{19}$$

where

$a = \omega M_{12} R_{P1} R_{P2}^2 + \omega^3 M_{12}^3 R_{P2}$;

$b = -2 R_{P1} R_{P2} \left(\omega^2 M_{12}^2 + R_{P1} R_{P2}\right)\left(V_{D1} + V_{O1}\right)$;

$c = -\omega M_{12} R_{P1} \left(\omega^2 M_{12}^2 + R_{P1} R_{P2}\right)\left(V_{D1} + V_{O1}\right)^2$.

From the analysis, the following important points about achieving maximum energy efficiency in a series-series resonant WPT system can be made:

- The optimum input voltage of a series-series resonant WPT system can be expressed without considering the load resistance if the output dc voltage is well regulated at a constant level.
- For a given output voltage, the optimum input voltage can be determined.

IV. AN OOK MODULATED WPT SYSTEM

In order to maintain the output voltage while still maintaining optimal energy efficiency over a wide load operation (i.e. from light load to rated load power), the On-Off Keying (OOK) control is proposed. Fig. 5(a) shows the schematic of a 2-coil series-series resonant WPT system based on the On-Off Keying (OOK) modulation. Two frequencies are involved in the switching control of the power inverter. The high-frequency signal S_{HF} and a low-frequency signal S_{LF} are shown in Fig. 5(b). The switching actions of the primary inverter are modulated with a lower frequency. S_{HF} is the original high frequency switching signal for the inverter and S_{LF} is the low frequency OOK modulation signal. When S_{LF} is logic high, the inverter operates normally and when S_{LF} is logic low, the switching action of the inverter is effectively disabled. In this way, the output power of the system can be regulated through the on/off control of the low-frequency signal S_{LF}.\

There are two major differences between the OOK method with other traditional control method such as phase-shift control and standard duty-cycle control.

Firstly, the transmitter inverter is only actively enabled for WPT with the receiver circuit when the low-frequency modulation signal S_{LF} is in its active state. The typical switching action of the transmitter circuit is shown as v_{in} in Fig. 5. The average switching frequency of the OOK method is therefore much lower than that of phase-shift control in which the transmitter circuit has to be switched continuously without and prolonged OFF periods.

Secondly, for light load conditions, the OOK method does not face narrow pulse width problem as the standard high-frequency duty-cycle control does. The ON and OFF control of the OOK method is of low frequency shown as S_{LF} in Fig. 5. Each ON period of the OOK method contains an integral number of high-frequency on-off switching pulses. The OFF period of the OOK is primarily responsible for keeping the power low in the light load situation.

A. Theoretical Analysis on the Effect of OOK

To simplify the analysis, it is assumed that the transient process only takes up a small part of the whole operating time and thus only steady state is considered. This assumption should be valid when S_{HF}/S_{LF} is large enough.

1) Power Aspect

For a given set of an optimal input voltage and a constant output voltage, the output current of the output rectifier i_O is controlled to a constant value whenever the WPT system is activated for power transferred to the load. This rectifier current is set for the maximum (rated) load conditions. That is, the rated output power of the rectifier is set as $P_o = v_o i_o$. Therefore, the output power of the output rectifier will be constant whenever the WPT system is activated. The actual load power may vary with time. To match the rectifier power output and the actual load power requirements, the average output power could be regulated by adjusting the duty cycle of the modulation signal as:

$$P_L = dP_O \tag{20}$$

where P_O is the output power of the output rectifier when the system is activated, and d is the duty cycle. The equivalent resistance R_{EL} will be constant, which can be expressed as

$$R_{EL} = \frac{V_{O1}}{I_O} \tag{21}$$

where V_{O1} is the rms value of v_o and I_o is the rms value of i_o.

By choosing the optimal input voltage using (19) and selecting R_{EL} to match the optimal equivalent load resistance using (13), the energy efficiency of the system will be maximized, because the energy efficiency of the system will equal to that of the system when it is activated (on-state).

2) Impedance Aspect

Now the duty cycle of S_{LF} is d ($0 < d < 1$). The current injected into the output capacitor and the load is i_O when S_{LF} is high and the load current is i_L as marked in Fig. 5. Therefore, the output energy of the rectifier should equal to the energy consumption of the load, i.e.

$$V_{O1} I_O dT = V_O I_L T \tag{22}$$

where T is the period of S_{LF}; V_O is DC output voltage and V_{O1} is the RMS value of the fundamental component of v_D as defined above. Therefore,

$$V_{O1} = \frac{2\sqrt{2}}{\pi} V_O \tag{23}$$

$$I_O = \frac{\pi \cdot I_L}{2\sqrt{2}d} \tag{24}$$

Equation (24) offers a solution for closed-loop control for determining the duty cycle. The optimal value of I_o is constant for a given WPT system. By monitoring the output load current I_L, the duty cycle can be adjusted so that the ratio on the right-hand side of (24) will be kept at I_o.

Define R_{EL} (see Fig. 5) as the resistance through which i_O will generate the same amount of power as that injected into the capacitor and the load, i.e. $V_{O1}I_O$. It should be noted that the energy efficiency of the system calculated with R_{EL} is not exactly equal to the practical value because R_{EL} is an equivalent value from the aspect of power. However, it is close enough for practical purpose.

$$I_O^2 R_{EL} = V_{O1} I_O \tag{25}$$

therefore,

$$R_{EL} = \frac{V_{O1}}{I_O} = d\,\frac{8}{\pi^2}\,\frac{V_O}{I_L} = d\,\frac{8}{\pi^2}\,R_L \tag{26}$$

Equation (26) shows that the equivalent load resistance R_{EL} can be adjusted by changing the duty cycle d of S_{LF}. In practice, the maximum rated output power corresponds to the minimum value of R_L ($R_{L\text{-}min}$), at which the duty cycle (d) should become 1.0. When the actual load resistance value is larger than $R_{L\text{-}min}$, the duty cycle will be smaller than 1.0. The control of the duty cycle is the basis of this OOK method. Whenever the WPT system is activated (i.e. ON time of the control), power transfer occurs at the optimal energy efficiency condition. This makes the control of the series-series resonant WPT system very simple and effective in achieving high energy efficiency over the load range.

B. Simulation Study

To illustrate the design process for such a control scheme, we use the parameters of practical coils (Fig. 6) for the following simulation study. The parameters are listed in TABLE II.

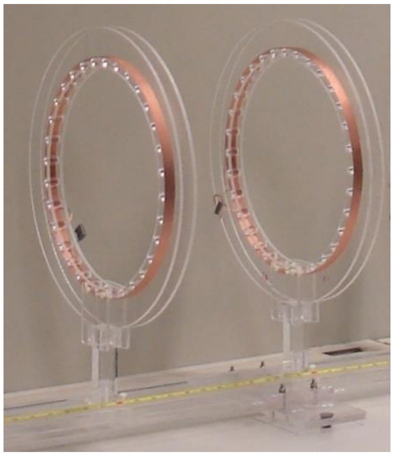


Fig. 6.Coil resonators used for simulation study and experiments.

According to (19), the optimum input voltage of the system is 11.2 V for an output voltage of 10 V. By using the mathematical model Fig. 4(b), the theoretical duty cycle of the OOK modulation signal can be expressed as a function of the load resistance. The variation of the duty cycle with the load resistance is shown in Fig. 7. The variation of the output power of the system with the duty cycle is shown in Fig. 8. So the maximum (or rated power) of the system is 23.2 W.

TABLE II PARAMETERS OF A WPT SYSTEM

Resonant frequency f_0	97.56 kHz
Radius of windings	155 mm
Number of turns	11
Layers of the wire	1
Structure of the wire	Ø0.12 mm×50 strands Outer Ø1.2 mm
L_1	91.24 μH
L_2	91.77 μH
Distance of the windings, d_{12}	200 mm (k = 0.0689)
R_{P1}	0.441 Ω (including the on-state resistance of the MOSFETs in the inverter)
R_{P2}	0.415 Ω
R_L	20 Ω
V_O	10 V
V_D	2 × 0.4 V

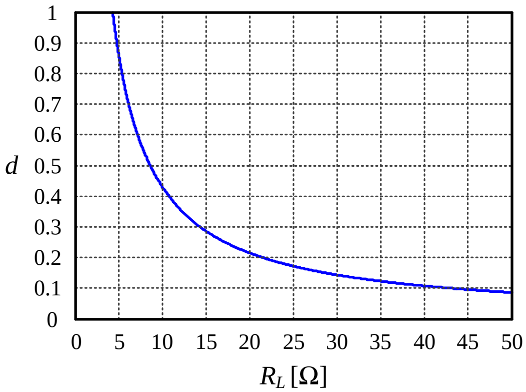


Fig. 7. Variation of the duty cycle of the OOK modulation signal with the load resistance.

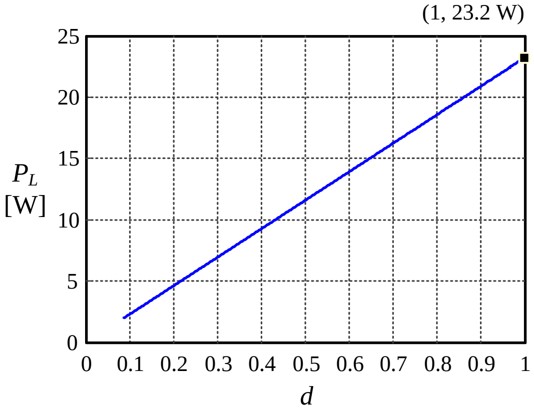


Fig. 8.Variation of the load power with the duty cycle of the OOK modulation signal.

V. EXPERIMENTAL VERIFICATIONS

Experiments have been carried out based on the 2-coil system shown in Fig. 6. Fig. 9 shows the inverter and the microprocessor in the primary side. MOSFET DMT6016LSS is used in the full-bridge inverter. The microprocessor is STM32F100RBT6B. Schottky diode PMEG3050EP is used in the full-bridge output rectifier. Practical measurement results are recorded in Fig. 10 to Fig. 12. Fig. 10 shows the low-frequency switching signal S_{LF} (upper trace), the input voltage of the primary resonator v_{in} (middle trace) and the output voltage of the system v_o (lower trace). The frequency of S_{LF} is 1 kHz. In this implementation, the inverted signal of S_{LF} $(\overline{S}_{LF})$ is used as the disable signal of the gate drive IC of the inverter. Fig. 11 is an enlarged view of Fig. 10. The high frequency switching signal in the middle trace is 97.56 kHz when the inverter is activated.

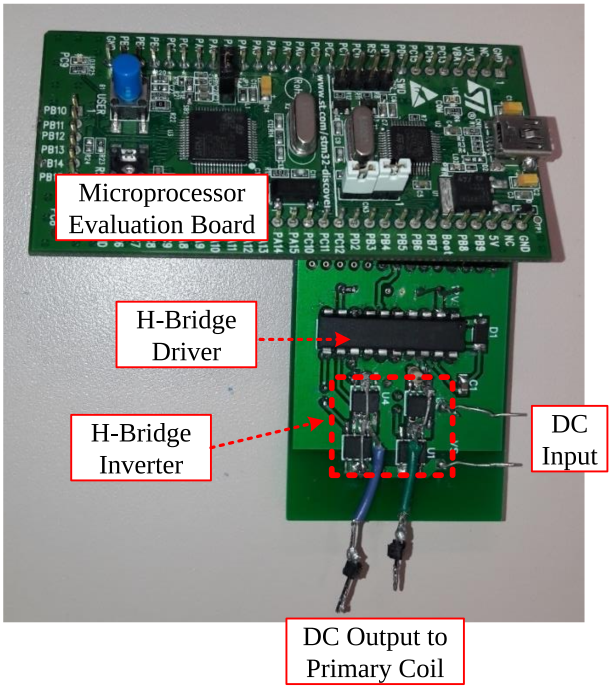


Fig. 9. Primary circuit.

A. Verification of Optimal Energy Efficiency at the Optimal Input Voltage

Fig. 12 shows the system efficiency variations as the input voltage changes under three loading conditions which are approximately

- 10 Ω load resistance and 10 W output power (43% rated load);
- 20 Ω load resistance and 5 W output power (22% rated load);
- 40 Ω load resistance and 2.5 W output power (11% rated load).

The observations from Fig. 12 and relevant discussions are listed below.

1) All three measured curves peak at the same input voltage range.

2) The system efficiencies are improved significantly by changing the input voltage for all three loads. Table III provide a comparison among several operation scenarios. The comments on the comparison are provided below.

- Theoretical System Efficiency without Transforming Load Resistance. Without transforming load resistance, the efficiencies are the lowest.
- Theoretical System Efficiency without Transforming Load Resistance and **NOT** Counting the loss of the rectification. For 20 Ω and 40 Ω cases, the efficiencies of the proposed system is higher than those in this scenario, which implies that the proposed system is capable to transform the load resistance to the optimum value.
- Theoretical System Efficiency with **Lossless** DC-DC Converter for Load Resistance Transformation. The efficiencies of the proposed system are higher than those in this scenario, which implies that the proposed system is superior over the systems using DC-DC converters for load resistance transformation. The reason is that the proposed system can also reduce the loss of the rectification stage.

3) When the input voltage is high, the errors between the measurements and the theoretical values become larger. There are two major reasons. Firstly, the three assumptions are made in the simplified model. Secondly, there is transient process when the OOK method engages the transmitter circuit for WPT with the receiver circuit as shown in Fig. 10. The extra power losses in these transients are neglected in the analysis. Therefore, when the input voltage is higher, the transient processes will be more obvious and affect the results more. Also because of these reasons, the practical optimum input voltage is not exactly the same as the theoretical one.

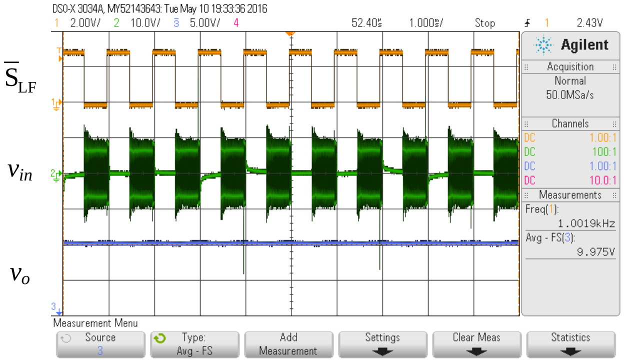


Fig. 10. Top waveform: Inverted signal of S_{LF} (2 V/div.); Middle waveform: voltage applied on the primary resonator v_{in} (10 V/div.); Bottom waveform: output voltage of the system v_o (5 V/div.). Time division is 1 ms/div.

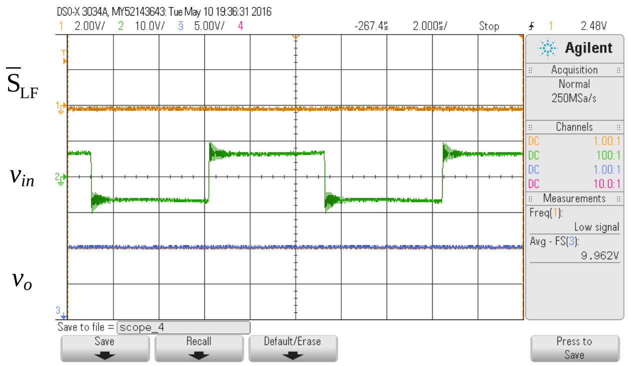


Fig. 11. Enlarged view of the waveforms in Fig. 10 when the inverter is activated. Top waveform: Inverted signal of S_{LF} (2 V/div.); Middle waveform: voltage applied on the primary resonator v_{in} (10 V/div.); Bottom waveform: output voltage of the system v_o (5 V/div.). Time division is 2 μs/div.

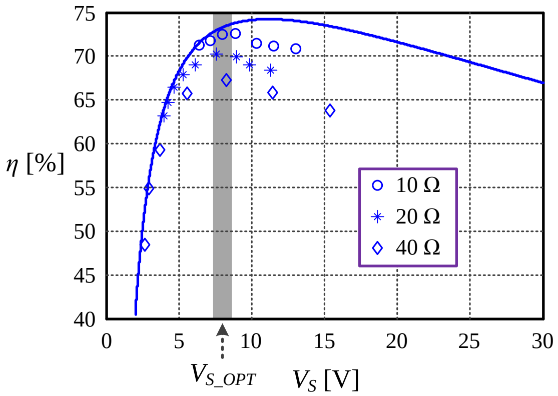


Fig. 12. Overall system efficiency variation as a function of the input voltage VS. Real line: theoretical calculations; Dots: practical measurements.

TABLE III COMPARISON AMONG SEVERAL OPERATION SCENARIOS

	10 Ω (43% P_{Lrated})	20 Ω (22% P_{Lrated})	40 Ω (11% P_{Lrated})
Theoretical System Efficiency without Transforming Load Resistance	69.58%	59.15%	44.73%
Theoretical System Efficiency without Transforming Load Resistance and **NOT** Counting	76.01%	65.4%	50.13%
Theoretical System Efficiency with **Lossless** DC-DC Converter for Load Resistance	71.90%	69.01%	65.32%
Measured Maximum System Efficiency (Apply OOK)	**72.60%**	**70.20%**	**67.27%**

B. Verification of High System Energy Efficiency Performance over Wide Load Range at the Optimum Input Voltage

According to the above results, the optimum input voltage of the system is in the range of 8 V-9 V. Therefore, the performance of the system is investigated under a constant input voltage of 8.5 V (near the optimum value). Fig. 13 and Fig. 14 record the measurement results. Fig. 13 shows the load power variation as the duty cycle of the OOK modulation signal changes. The measured maximum power at an input voltage of 8.5 V is 16.95 W (with a load resistance of 5.9 Ω). The solid line in Fig. 13 is the theoretic prediction for an input voltage of 8.5V. Fig. 14 shows the energy efficiency of the system as the load resistance increases from the minimum value, i.e. 5.9 Ω. The measured efficiencies (dotted points) of the system based on the proposed method are compared with the calculated efficiencies (solid line) "without using load resistance transformation". It is clear that the proposed method allows high energy efficiency to be maintained over a wide load range.

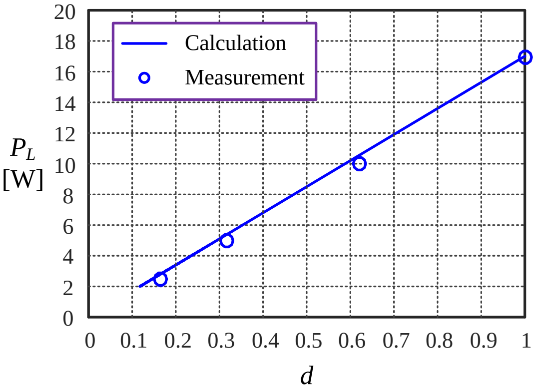


Fig. 13. Load power variation with respect to the duty cycle of the OOK modulation signal (VS = 8.5 V). Solid line: theoretical calculations; Dots: practical measurements.

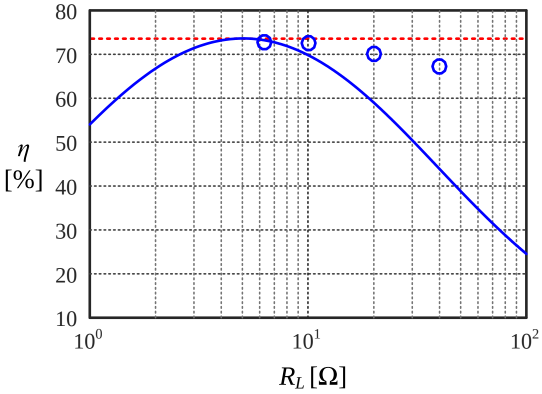


Fig. 14. Measured energy efficiency of the system with a constant input voltage of 8.5 V. [Real line: theoretical efficiency of the system without using load resistance transformation; Dots: practical measurements of the proposed system.]

VI. CONCLUSIONS

Series-series resonant WPT systems are often used to charge a dynamic electric load. In order to maintain high-efficiency operation over a wide load range, a simple and effective OOK method is presented. By determining the optimal input voltage for a given output voltage in a series-series resonant WPT system, optimal energy efficiency operation can theoretically be achieved independently of the electric load. This feature is different from previous maximum energy efficiency tracking because the system is designed to operate only at the optimal energy efficiency points in the energized state. Unlike traditional power control methods such as phase-shift control and standard duty-cycle control, the OOK method does not need the transmitter inverter to be switched continuously at high frequency. Thus, the OOK method has lower switching losses than many traditional methods. In addition, it does not suffer serious narrow duty-cycle problem as the standard duty-cycle control does under light load conditions, because it uses the OFF time of the modulation signal SLF to keep the power low. The OOK method has been analyzed and practically tested confirmed for a WPT system. The OOK modulation of the WPT can be achieved with simple duty cycle control. This simple method can therefore be implemented in series-series resonant WPT systems without complex electronics. The measurements have practically confirmed that system energy efficiency close to the theoretical maximum limit can be achieved over a wide load range.

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