Importance of High Power/ High Frequency CS-devices on Wireless Power Supply Using Direct Current Resonance System

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Abstract

In this paper, Direct Current Resonance is introduced as one of the major wireless power supply systems. This system comes from a new technical idea, which can make resonance from DC power and transfer the energy through space. Energy exchange of electricity and electromagnetic field has been done here using a kind of electromagnetic phenomena called Resonance Field. The performance and efficiency of this system is strongly dependent on those of the power devices. The big expectation is on compound semiconductor power devices due to their very high potential. In fact, the very high performance of 89.5% DC-RF-DC power efficiency (from DC power source to load) and 22.4W output power have been achieved in the system with 6.78MHz, using GaN-HEMTs.

1. INTRODUCTION

The wireless power transfer (WPT) system is now known as a revolutionary new technology, which can change our life style. Its application is widely spread from power station level to home apparatus, like smart phone, tablet, Electric Vehicle, etc. The applications are generally divided into three groups, i) electromagnetic induction type for short distance, several mm, such as a phone charge machine, ii) resonance system for longer distance, several dozen cm, useful for home electrics and iii) microwave system for longer distance up to satellite system though the size is a few km. Direct Current-Resonance (DC-R) system is one of the major wireless power transfer systems in category ii) [1]-[5]. This technology requires a combination of separate fields; power electronics, high frequency power device technology, and high frequency electronics. The DC-R system is so simple and effective that development of the super small module of the DC-R system is expected. In this paper, overall technology of DC-R is introduced. It is anticipated that Compound Semiconductor devices will play a key role in realizing compact and high efficiency systems.

2. COMPOUND SEMICONDUCTOR AND HIGH-FREQUENCY POWER ELECTRONICS

2.1 Expectation of new power compound semiconductors

"Power Electronics" is the technology to convert and control the electric power by using power semiconductor devices. The main parts are switching power supplies. Today, nearly all electronic systems use switching power supplies to deliver specific voltages and currents. The switching power supplies need to have small size, high efficiency and high reliability. The power semiconductor devices are the most important elements in the power conversion circuits of the switching power supplies. The wireless power supply systems that are included the switching power supplies can derive great benefits from compound semiconductor devices like GaN-HEMTs, which provide high output power at high frequency.

2.2 Power compound semiconductor operated in MHz band

On DC-R systems, application of switching technology and power electronics are being promoted. Operational frequency bands at 6.78MHz and 13.56MHz have been proposed to the ISM (Industry-Science-Medical), in order to minimize interference with communication devices. Operation at these high frequencies allows small system size, especially through size reductions in the electric transmitting or receiving coils, capacitors, and inductors. Unfortunately, higher operational frequency also tends to cause lower efficiency.

Typical general purpose switching power supplies operate at about 100kHz. When much higher frequencies are used (e.g., 6.78MHz and 13.56MHz), new revolutionary semiconductor devices and circuit technologies will be needed to maintain acceptable efficiencies. High performance power conversion circuits at these higher MHz frequencies have been achieved by using various new circuit topologies, control methods, and improved power semiconductor devices. At such higher frequencies, Si device performance begins to degrade, and newer wide bandgap materials like SiC, GaN and diamond are expected to efficiency advantages and improved system performance. When we use the new power semiconductor devices, it's important for the improvement of the power conversion circuit to deeply learn the properties of the devices in order to bring out the maximum potential of the new devices.

Therefore, communication and collaboration between semiconductor developers and those of power circuits is the key to success.

2.3 High-frequency power electronics

Technology of MHz frequency range for DC-R system needs both power electronics, treating static magnetic field and electric field, and high frequency wireless communication technology. So to say, it can be called new “high-frequency power electronics”, that gives us new value creation[3]. The concept of this new field is shown in Fig.1. There are three main fields, power electronics, radio frequency electronics and power devices. This is the new disciplinary field, where new technology development is expected by technology fusion and synergetic effect. The power electronics was firstly proposed by Dr. Newell in 1973. The radio frequency electronics is the technology to develop system and devices for communication by using electromagnetic wave engineering and semiconductor engineering. It can be said that power device technology is developing power electric parts using power semiconductor engineering and electric material engineering. The new technical revolution can be expected by using strong points of each technologies and fusion of them.

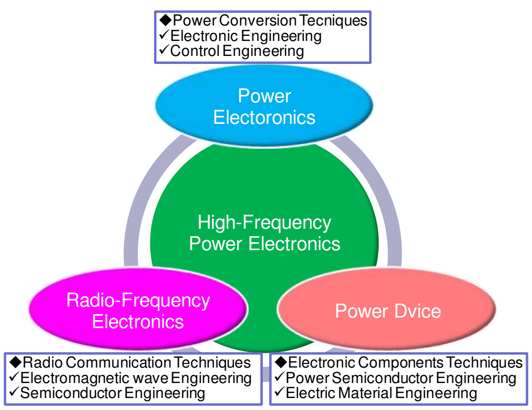
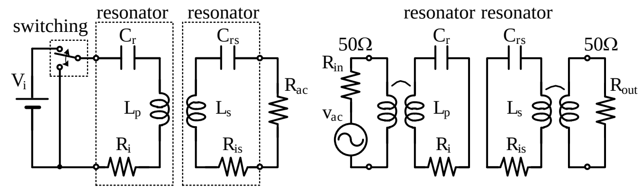


Fig. 1 High-frequency power electronics.

3. DC-R WIRELESS POWER SUPPLY SYSTEM

3.1 Basic composition of a DC-R system

We’ve developed DC-R system as a new wireless power supply system. Fig.2 shows the comparison between this new system and conventional one. Basic confirmation of DC-R system is shown in Fig.3. DC-R system is a new type energy conversion system, where electromagnetic resonance occurs and electric power is transformed in the air. DC power is intermittently supplied to resonance part to form RF (Radio Frequency) Electromagnetic Resonance Field. Another resonance part with some distance from the input part gets the magnetic or electric energy. This energy is integrally vibrated to have interaction for each. The downsizing of the system has been done by improving DC-RF-DC conversion efficiency from view point of overall system from transmitting to receiving.



(a) DC-R system (b) General system

Fig. 2 A novel direct current resonance system.

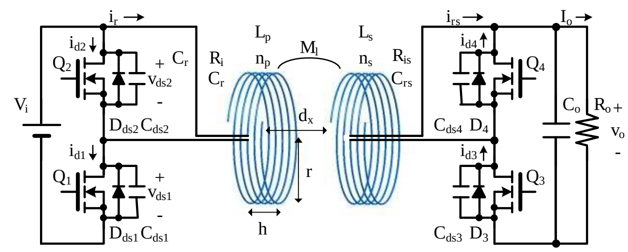


Fig. 3 Proposed DC-R WPT system.

3.2 Major features

(1) This is a wireless power transfer system from a direct current (DC) power source

• Most of the power that people use is DC. Even commercial alternating current (AC) is converted to DC, and nearly every electronic device runs on DC voltage. Therefore converting energy from a DC power source can enhance efficiency.

(2) The technology directly converts between electric energy and electromagnetic field energy

• The goal is to require only one direct power conversion when transmitting power wirelessly, as opposed to the four to six repetitions required up to now. This allows overwhelming energy savings and creates a big advantage in terms of compactness and lightness.

(3) The technology expands the resonance field to transmit power

• Innovations in transmitting and receiving devices and resonance devices can expand the resonance field and create new possibilities, such as supplying power to multiple loads. This should lead to technical applications and product development for various usage scenarios.

3.3 Comparison with existing methods

• Configuration is simpler, devices can be made smaller and lighter, and system power efficiency can be improved as compared to the magnetic resonance method

• There is a higher degree of freedom in the layout of power transition and receiving devices compared to the inductive coupling method, and no heavy magnetic material (iron) and coils (copper) are needed

• Compared to the electric field coupling method, the new technology is superior when a greater transfer distance is required. No physical contact is required

• A great amount of power is transmitted than with the radio wave method. This allows power transmitting and receiving devices to be smaller

3.4 Background of development

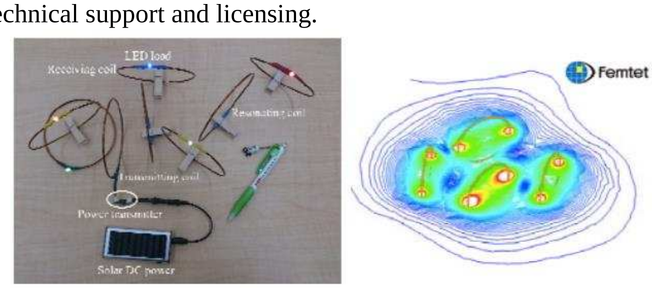
10MHz experiment[6] which the researcher of Massachusetts Institute of Technology presented in 2007 in research of wireless power transfer is famous. In the experiment of 2m distance, they attained the power efficiency of 15% using Colpitts oscillator.

We conducted pioneering research on the use of the “magnetic field resonance” method, which we presented a novel ZVS multi-resonant converter operated in 10 MHz range at an international academic conference in 1994[7]. We have attained the power efficiency of 77.7% in proximity distance[8]. Based on this, we began further research in 2009, using the newly discovered physical phenomenon of the “electromagnetic resonance field” to develop a DC-R method in wireless power transfer system.

3.5 An experiment and applications

Fig.4(a) depicts the proving experiments of the novel DC-resonance wireless power supply system. The example of analysis of the resonance field using product finite-element-method analysis made from Murata software soft Femtet® is shown in Fig. 4 (b). An electromagnetic resonance field is generated from DC power produced by a solar cell, lighting up multiple light-emitting diodes (LEDs). This demonstrates new innovative technologies, such as (1) DC/ DC power transfer, (2) power transfer to multiple loads, (3) amplification of the electromagnetic resonance field, and (4) power transfer to various directions. The new system is widely expected to be used for industrial applications.

Our objective is to get the technology into use in fields where a wireless arrangement is of high value. These are not limited to supplying power to such mobile devices as smart phones and tablets. They could also include small battery-operated electronic devices and communications cards. We will develop the technology primarily for applications requiring relatively small amounts of power. For applications requiring relatively large amounts of power, such as electric vehicle recharging, Murata will also consider the use of arrangements like open innovation as well as technical support and licensing.



(a) Experimental system (b) Analytical magnetic field

Fig.4 Analysis and experiment of electromagnetic resonance field.

4. 6.78MHz GaN-FET DC-R WIRELESS POWER SUPPLY

4.1 Figure of merit for power loss

A new performance index has been proposed that can evaluate the performance of switching devices on the design of power conversion circuit, because it is important to properly evaluate the influence of higher switching frequency on power loss and system efficiency. The loss mechanisms which determine operating efficiency of the power conversion circuit are switching loss P_{sw}, conduction loss P_{con}, driving loss P_{drv}. Performance index of power loss in case of hard switching and soft switching are fom1 and fom2, respectively. In the hard switching, current and voltage are overlapped (that causes loss) when the switching happened in the power conversion circuit. The operation with small overlap is called soft switching, with low loss. Anyway, fom1 and fom2 show lower values for better devices.

Current of the switching device to be evaluated and applied voltage are $I_{d\ max}/2$ and $V_{ds\ max}$, respectively. The switching loss P_{sw1} equivalent to active region movement during the transition is shown in equation (1).

$$P_{sw1} = \frac{1}{6}\frac{I_{d\,max}}{2}V_{ds\,max}(t_r + t_f)\,f_s \tag{1}$$

Electric charge at output capacity is consumed through short circuit when it turns-on, that causes Switching loss P_{sw2}, shown in equation (2).

$$P_{sw2} = \frac{1}{2}C_{oss}V_{ds\,max}{}^2\,f_s \tag{2}$$

From P_{sw1} and P_{sw2}, switching loss P_{sw} is;

$$P_{sw} = \frac{I_{d\,max}V_{ds\,max}(t_r + t_f)\,f_s}{12} + \frac{C_{oss}V_{ds\,max}{}^2\,f_s}{2} \tag{3}$$

Conduction loss P_{con} is shown by the (4)

$$P_{con} = \frac{R_{on}I_{d\,max}{}^2}{4} \tag{4}$$

Driving loss P_{drv} is shown using Gate total charge Q_g and Gate voltage V_{gs}

$$P_{drv} = Q_g V_{gs}\,f_s \tag{5}$$

From these equations, performance index of power loss at hard switching and soft switching, fom1, fom2 respectively, are;

$$\mathrm{fom1} = P_{sw} + P_{con} + P_{drv} \tag{6}$$

$$\mathrm{fom2} = P_{con} + P_{drv} \tag{7}$$

Table 1 shows fom1 and fom2 of GaN-FET produced by Efficient Power Conversion Corporation with breakdown voltage of 40V, and those of Si-FET by ROHM Corporation. GaN-FET has smaller on-resistance R_{on}, rise time/fall time, t_r and t_f, gate total charge Q_g, and the size are much smaller for the GaN-FET. These merits mainly come from lower Ron of GaN-FET, because Si-FET needs structure with higher Ron to keep high breakdown voltage.

Table 1 Characteristics of GaN-FET & Si-MOSFET

$V_{ds\,max}$= 40V	GaN-FET		Si-MOSFET	
(V_{gs} = 5V)	EPC2014	EPC8004	RQ3G100GN	RSD200N05
size [mm]	1.7×1.1	2.1×0.85	3.4×3.4	9.5×9.5
$I_{d\,max}$ [A]	10	4.4	10	20
R_{on} [mΩ]	16	125	18.3	35
C_{oss} [pF]	150	17	100	250
Q_g [nC]	2.5	0.36	4.3	12
t_r [ns]	1.0	0.21	4.2	20
t_f [ns]	2.6	0.54	3.2	50
fom1 [W]	2.13	0.78	2.82	23.3
fom2 [W]	0.48	0.62	0.60	3.91

Comparison of fom1, fom2 are also shown in Fig.5. GaN-FET shows smaller fom1 and fom2 than those of Si-FET, meaning GaN-FET has superior performance. Furthermore, EPC2014 (GaN-FET) has lower R_{on} and larger Q_g than those of EPC8004 (GaN-FET), whose feature is high speed. Low R_{on} type EPC2014 has lower performance on hard switching than that of high switching type EPC8004, but better on soft switching. That means, superiority of fom1 and fom2 depends on operation mode, hard or soft.

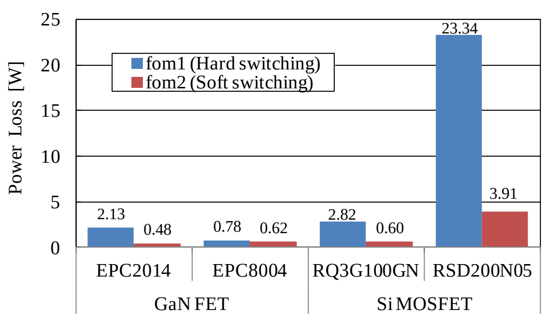


Fig.5 Figure of merit for high-frequency power electronics.

4.2 Power conversion operation in DC-R system

Typical circuit of DC-R wireless power transfer system using two single loop coils is shown in Fig.6. Fig.7 shows ZVS operation waveforms of this system, where transmitting and receiving coils, n_p, n_s respectively, consist of copper wire of 2mm diameter and radius = 50mm. The resonant current i_r with sinusoidal waveform is obtained by resonance phenomenon. Resonance frequency f_r of multi-resonance circuit including electromagnetic coupling is set up at little bit lower than switching frequency of 6.78MHz and reactance is to have enough small inducible.

The commutation can be done by charging and discharging of parasitic capacitance C_{ds} between the two FETs during the dead time t_d when both two FETs are off. On the ZVS operation system, the operation can be realized by turning of the FET during parasitic diode conduction time t_a after the commutation time t_c. The following relation is obtain in this operation.

$$t_c \cong t_r \cong t_f \leq t_d \leq t_c + t_a \quad (8)$$

Under the condition of term t_a = 0, switching loss can be minimized by both ZVS operation itself and optimized ZVS operation where the turn-off is done at the minimum current. In this operation mode, gradient of FET Q_1's voltage v_{ds1} becomes soft and FET Q_1 turns on when dv_{ds1}/dt = 0 and v_{ds1} = 0. FET Q_2 shows the same operation. The optimized ZVS operation has the smallest turn-on current under the condition the ZVS operation can be done.

4.3 Current-voltage characteristics of GaN-FET

DC I-V characteristics of EPC2014 (GaN-FET) is shown in Fig.8. The GaN-FET has no parasitic diode like Si-FET does, but it shows unique conduction at reverse side by different mechanism. Reverse bias voltage drop $-V_{ds}$ shown in the third quadrant is larger than that of parasitic diode in Si-FET. In case v_{gs}=0V, $-V_{ds}$ shows large value of around -1.8V even under the small current, that causes the conduction loss. In order to minimize this loss, following procedure is carried out; 1) keep the commutation time, 2) minimize the dead time, 3) lower the R_{on} by applying v_{gs} like a synchronous rectification operation and 4) set t_c = t_d in equation (8). The reverse voltage drop can be decreased by supplying v_{gs} to the same level of that in the first quadrant.

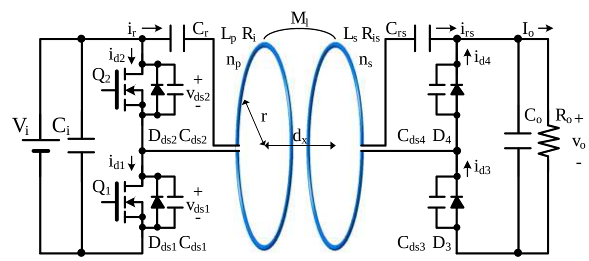


Fig.6 DC-R WPT system using two single loop coils.

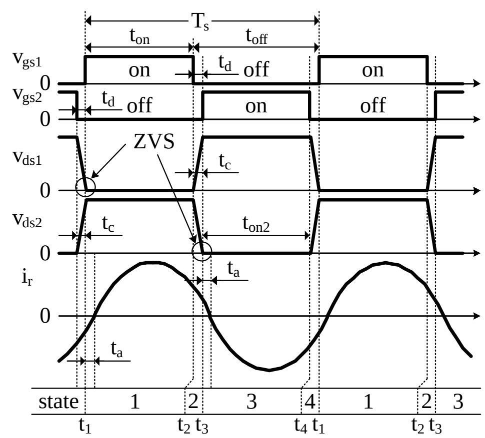


Fig.7 ZVS operation waveforms.

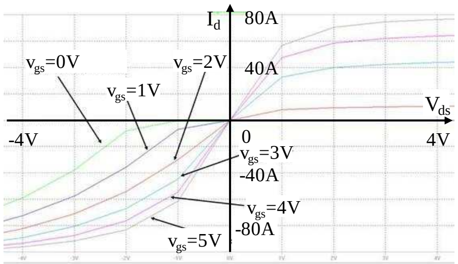


Fig.8 I_d - V_{ds} on GaN-FET.

4.4 6.78MHz Experimental operation

The experiment was done under the condition of switching frequency f_s = 6.78MHz, C_r = C_{rs} = 1.68nF, distance d_x = 3mm. By using GaN-FET (EPC2014), output voltage 61.8V and supply power 22.4W had achieved at V_i = 18V and load R_o = 170Ω.

Fig.9 shows DC-RF-DC power efficiency when dead time t_d was controlled to be 0 – 16ns, load R_o was changed from 90 to 150Ω. The commutation time was around 10ns. Very high efficiency of 89.5% had achieved at t_d = 10ns and load R_o = 110Ω.

Fig.10 showed the comparison of the efficiency of DC-RF-DC conversion in case input power V_i =15V and load R_o=20 – 160Ω. Maximum efficiency of GaN-FET had reached 89.5%, while that of Si-FET is 87.1%. More than that, the result also shows the Si-FET couldn't reach the high output operation over 10W because of its poor operation at high frequency, compared with GaN-FET.

In this system, the losses occurred in three times, that is, 1) DC-RF conversion, 2) RF-RF transfer (wireless part) and 3) RF-DC conversion. In case of conventional system, such as linear power amplifying circuit system, the loss is 50% even in the first step of DC-RF conversion. The DC-R system showed only around 10% after the all three steps. This is outstanding. Furthermore, the output power can go far over 10W keeping high efficiency by using GaN-FET.

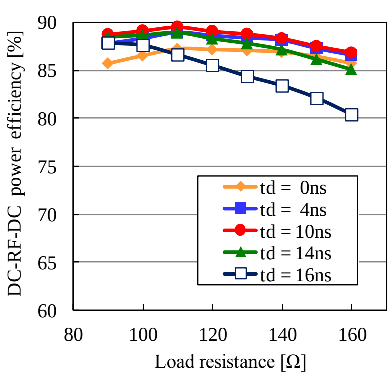


Fig.9 DC-RF-DC power efficiency.

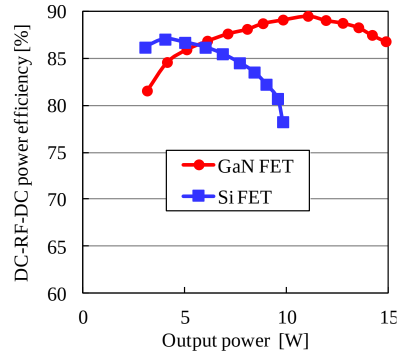


Fig.10 Output power characteristics with GaN-FET and Si-FET.

5. Conclusion

The new academic field, "high-frequency power electronics" is introduced. It expects a lot on the compound semiconductors. As a good example, 6.78MHz DC-R wireless power supply system using GaN-FETs was described. This achieved the outstanding results of power supply 22.4W, DC-RF-DC power efficiency 89.5%. These results indicate DC-R wireless system with GaN-FET have great possibility to realize excellent wireless power transfer system with high efficiency and high power.

We will keep on aiming the new value creation and the contribution to the society in this new field. We are also doing hard efforts to develop the excellent products to the market.

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