Research Inventy: International Journal Of Engineering And Science
Vol.3, Issue 11 (November 2013), PP 30-37
Issn(e): 2278-4721, Issn(p):2319-6483, Www.Researchinventy.Com

Design Of Contactless Power Supply(Cps) System

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ABSTRACT : *This paper describes a high power generating contactless power supply system for DC power with 300 V and 10 A. It is composed a primary power converter and a secondary power converter. The secondary power converter, pickup, is magnetized by the primary power converter. The primary power converter is an inverter system which is used to invert 50/60Hz power supply to 20kHz power supply. The secondary system is used to generate DC power supply by boosting circuit. The power is transferred from the primary to secondary through pickup. The simulation is implemented using Matlab simulink program. The simulation and experiment data show the effectiveness of the proposed power supply system.*

KEYWORDS: *Contactless power supply(CPS), Pickup, Boosting circuit, Full bridge IGBT.*

I. INTRODUCTION

The contactless power supply (CPS) is a technique of using an inductive magnetic coupling (pickup) by a LC resonance [1]. The pickup has been developed to supply power over relatively small air gaps to one or more moving objects. The CPS system is used as power supply of many kinds of movable vehiclespower supplying for a high speed train, an autonomous underwater vehicle, a power transmission system for harsh environments, and so on [2]-[4]. These have a merit that a movable vehicle operates with charging batteries. So it does not need time to charge the machine. In this paper, high voltage output CPS is developed using full digital control method. The desired output voltage of this CPS system is DC 300V. And output current is 10A. So experiments of in this paper bring focus into increasing the CPS output voltage by the LC resonant method.

The SCR controls source AC power. It can adjust variable output DC voltage. PIC 18F452 (micro controller) catches the zero crossing point of one phase AC. After frequency calculation, the PIC controls the three phase AC source power in full bridge SCR. Primary part consists of the two full bridge IGBT(SKM400GB128D)'s that have 1200V, 400A maximum ratings. The SKHI module controls the IGBT. It has error detecting and circuit auto-break down functions during in the over-current or over-voltage. Secondary part consists of the rectifier and the boosting circuit IGBT(SKM75GB063D). This IGBT has 600V, 100A maximum ratings. It is controlled by the micro processor PIC 18F452 with 70kHz. All control circuits are designed by OR-CAD version 9.2. Finally, experiment results are shown.

II. CPS SYSTEM

Fig. 1 shows description of CPS system developed in this paper. It is isolated between primary part and secondary part by the air gap. By changing the source rectified voltage, the pickup output can be changed. In Fig. 1, 'A' part is a primary part circuit, 'B' part is a primary resonant, 'C' part is a secondary resonant, and 'D' part is a secondary part circuit.

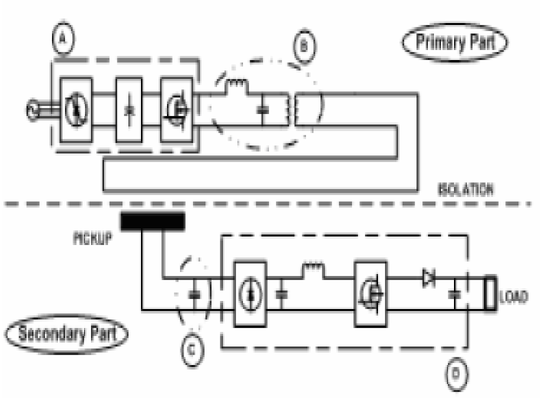

Fig.1 Schematic diagram of CPS System

2.1 Primary part of system

A simple IGBT driver, SKHI module, controls the IGBT gate signals. Both sides of this driver are isolated each other. And it can monitor the voltage error and current error in real time. If over-voltage or over-current flows into IGBT, the driver breaks down the operation immediately. So the IGBT is protected. And the PWM modulation circuit consists of TL494, damping circuit and buffer circuit with PI controller. Primary resonant frequency is 20kHz. In Fig. 1 primary LC resonant part 'B', the resonant frequency can be given as

$$f=\frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

From the equation (1), the capacitance is calculated with at fixed inductance and fixed resonant frequency. Capacitors are tuned by using serial connection or parallel connection given as the equation (2).

$$C_{parallel}=C_1+C_2+C_3+\cdots \qquad (2)$$

$$C_{serial}=\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}+\cdots$$

Fig. 2 shows simplified circuit of part 'B' in Fig.

1. R_1 and L_2 are resistance and inductance of transformer. R_2 and L_3 are resistance and inductance of load. And gain ratio of between input voltage *i V* and output voltage *o V* is expressed into equation (3). In equation (3), R_1 has very small value, so it can be ignored.

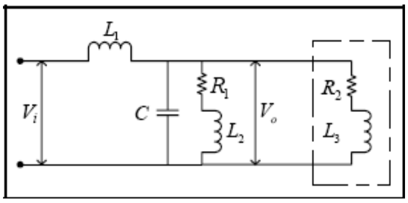

Fig. 2 Simplified circuit of part 'B'

$$\begin{aligned}\frac{V_0}{V_i}&=\frac{\dfrac{1/sC(sL_2+R_1)}{1/sC+sL_2+R_1}}{sL_1+\dfrac{1/sC(sL_2+R_1)}{1/sC+sL_2+R_1}}\\&=\frac{sL_2+R_1}{sL_1\left(1+s^2CL_2+R_1\right)+(sL_2+R_1)} \qquad (3)\\&=\frac{L_2}{s^2CL_1L_2+L_1+L_2}\end{aligned}$$

where s is laplace variable. And substituting $s=j\omega$ into equation (3) satisfies equation (4).

$$\frac{V_0}{V_i}=\frac{L_2}{L_1\left(1-\omega^2CL_2\right)+L_2} \qquad (4)$$

In equation (4), resonant frequency, ω is $2\pi f$.

If ω is $\dfrac{1}{\sqrt{L_2C}}$, $V_0=V_i$. In this station, the output voltage becomes input voltage as maximum value.

2.2 Secondary part of system

In Fig. 1, 'D' part is secondary part of system. The secondary part consists of the rectified diode, the 70kHz controlled boosting circuit and the LC resonant circuit. High frequency switching is used for high efficiency. The PWM modulation of secondary part is operated by function of PIC 18F452. And the A/D converter of PIC read the final output voltage feedback. The frequency of inductive voltage in pickup is 20kHz AC. Output voltage of pickup is resonated by using capacitors. And then, after the rectifier, the output voltage is increased by the boosting circuit. It is shown in equation (5).In this equation, D is duty ratio of IGBT control switch signal. It is always lower than one. So the output voltage V_0 is higher than the input voltage V_i.

$$V_0=\frac{1}{1-D}V_i \qquad (5)$$

III. PRIMARY INVERTER CONTROL

3.1 SCR Control

To control the source power, three full bridge SCR modules in Fig.3 are used. This module can use positive and negative AC power.

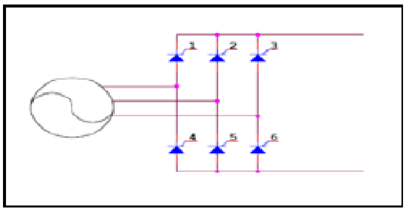

Fig. 3 Full bridge SCR

The three phase AC power has 120 degree phase difference. So it is required to get the zero crossing point. From one phase, other phases are calculated by PIC. The zero crossing circuit is shown in Fig. 4. The zero crossing time is obtained through this circuit making AC signal to TTL level signal. And the zero crossing time is taken by external interrupt of PIC.

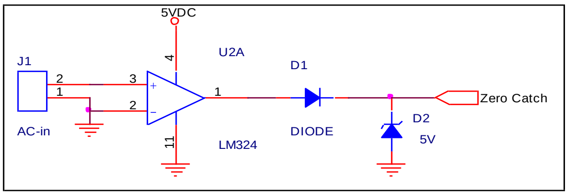

Fig. 4 Zero crossing circuit

Two module type SCR is used. So the six control signals are connected to SCR modules for each phase. The signals have 60 degree phase difference. A 10kHz single timer is used with the SCR turn-on signal. By this method, the SCR turn-on signal can be changed to high frequency. This high frequency signal turns on the SCR correctly. Fig. 5 shows SCR operating circuit with pulse transformer.

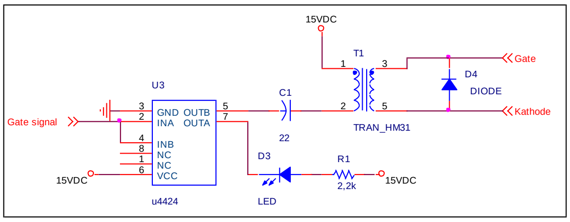

Fig. 5 SCR operating circuit

The SCR control signal is expressed into Fig. 6. This time table is example of 50% turn on. It is operated by timer function in PIC. SCR number in Fig. 3 is related with signal order number in Fig. 6. Each SCR gate input signal has 120Hz frequency. Between phases, control signal has 180Hz frequency. Based on this knowledge, the control signal output timing is calculated.

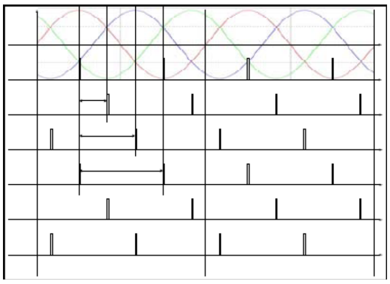

Fig. 6 SCR control time table

3.2 IGBT Control

Controlled source power is connected to IGBT. To control IGBT stably, SKHI module is used. This simple module operating circuit is designed in this section. One module can control halfbridge IGBT, so two modules are used to control full-bridge IGBT. These modules can be operated by TTL level signal. The voltage and current of source power are observed by realtime watching error function. Maximum value of errors in voltage and current are set by external circuit based on a kind of IGBT. The PI control circuit is designed for IGBT control with feedback current. The PI controller is operated by input setting value and feedback value. Fig. 7 shows relationship between control input voltage and output current obtained by experiment [7]. This is chosen as reference of output current.

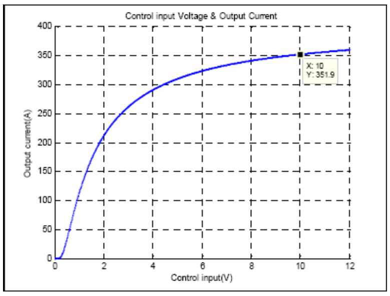

Fig. 7 Relationship between control input and current output

From Fig.7, equation (6) is obtained.

$$I_{out} = 400\,e^{(-1.28/U)} \qquad (6)$$

where U is control input voltage, and I_{out} is output current of IGBT. The equation (5) is used to design PI controller. In this controller, tracking error is defined as equation (7).

$$e = I_{ref} - I_{out} \qquad (7)$$

where *iref* and *iout* are reference value and output value of this system. And PI controller is expressed into equation (8).

$$U = K_p e + K_i \int_0^t e(\tau)\,d\tau \qquad (8)$$

where K_P and K_I are proportion gain and integral gain of controller, respectively. And it is expressed into equation (9) by discrete time transform.

$$U(i) = K_p e(i) + D(i) \qquad (9)$$

$$D(i) = D(i-1) + K_i \frac{e(i) + e(i-1)}{2} T_d \qquad (10)$$

where $U(i)$ and $e(i)$ are control input signal and tracking error of i^{th} sampling time, respectively.
And T_d is a sampling time of this controller. And PI controller configuration is shown in Fig. 8.

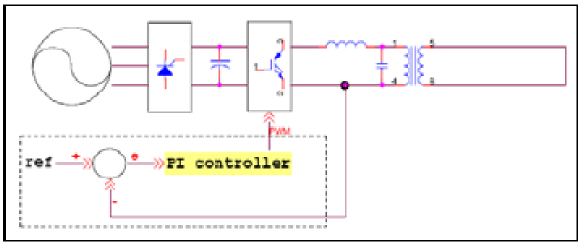

Fig. 8 Configuration of PI controller

IV. SECONDARY BOOSTING CONTROL

4.1 Pickup magnetic core

Fig. 9 shows external shape of pickup. In this paper, the ferrite type of pickup is experimented for inductive magnetic coupling. The winding wire of pickup has 15 turns. It operates like 3kW transformer with air gap. The turn times are important to produce high power output.

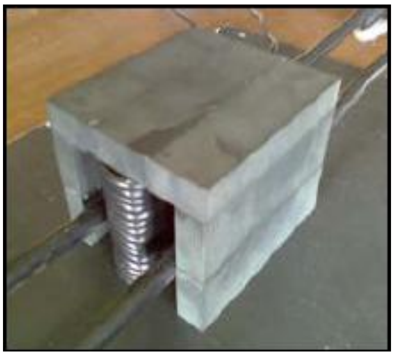

Fig.9 Shape of pickup

4.2 Boosting control

Boosting circuit is used for increasing output voltage. It consists of IGBT, diode and capacitor in Fig. 10. This IGBT is controlled by high frequency (70kHz) of PIC output. And the final output voltage is loaded to PIC A/D converter for feedback.

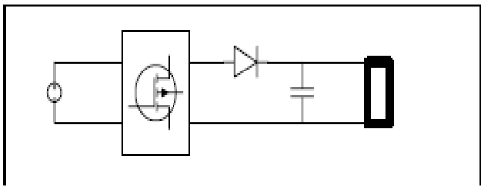

Fig. 10 Boosting circuit

Fig. 11 shows final DC output voltage feedback circuit. The maximum DC output voltage is 300V. So, in this circuit, feedback voltage is divided by small resistor. The feedback voltage is transformed to TTL level by OP Amp.

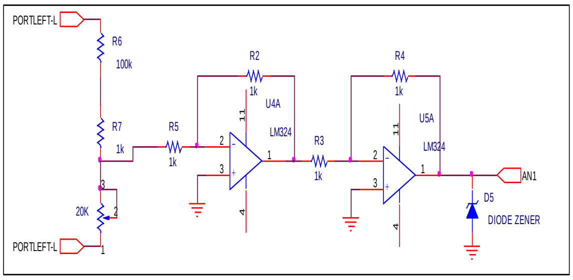

Fig. 11 Voltage feedback circuit

Fig. 12 shows IGBT gate turn on circuit. In Fig. 12, PWM is generated by the PIC.

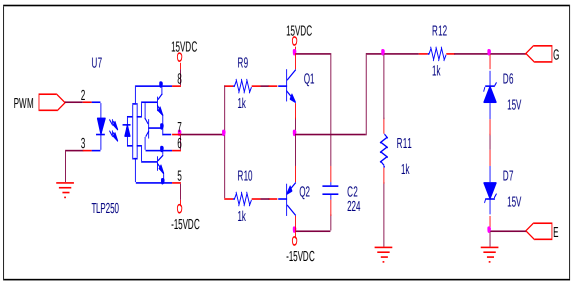

Fig. 12 IGBT gate circuit

V. HARDWARE COMPOSITION

5.1 Primary part hardware

Fig. 13 shows the developed PCB of the primary part in CPS system. This board can control IGBT/SCR. It is designed by OR-CAD.

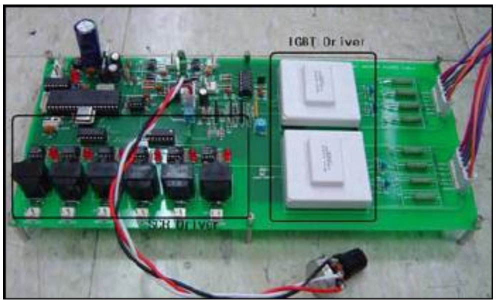

Fig. 13 PCB of primary part

5.2 Secondary part hardware

Fig. 14 shows the developed PCB of the secondary part in CPS system. It is boosting control board of IGBT. In this board, the PIC generates high frequency gate signal.

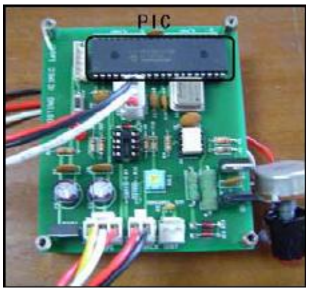

Fig. 14 PCB of secondary part

VI. SIMULATION AND EXPERIMENTAL RESULTS

6.1 Simulation results

In this section, the PI controller is simulated to compare the output of PI controller with the reference value. Fig. 7 shows reference value of this system. And Fig. 15 shows PI controlled signal in Matlab simulink program. It is simulated with step input signal of 10V. When the input voltage is 10 V, the reference output current is 351.9 A in Fig. 7. And PI controlled output current is 359.1 A. Without PI controller, the output current cannot follow the reference current of 351.9 A. This signal has a little time delay and steady state error of 48.2 V. Therefore, PI controlled output current and reference output current are same.

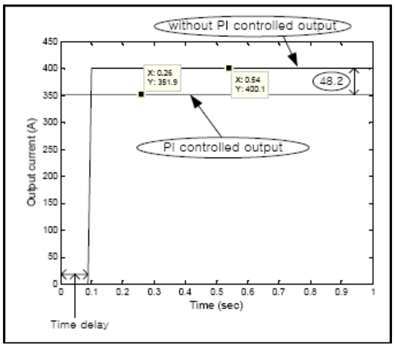

Fig. 15 PI controlled signal

6.2 Experimental results

Primary resonant frequency is 20kHz. In this experiment, the inductance is unknown value. And the length of wire is only 10m. This means the inductance value is very low. So tuning the capacitance is very difficult to get the maximum LC resonance. For the efficient resonance, some coil is used instead of long wire. And the isolation transformer (1:1) is used for protecting the IGBT. The source power of this experiment is three phase 220V. 33 Ω resister is used as a load to get the experimental current value.

6.2.1 Resonant of primary part

Fig. 16 shows the full bridge IGBT output signal used in this experiment. The frequency is about 20kHz. The maximum voltage is over 250V. And this is output signal of IGBT when control driver has 10% duty on-time.

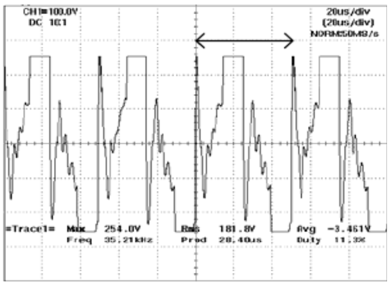

Fig. 16 Full bridge IGBT output signal

Fig. 17 shows primary resonant result with about 120A and about 130V. This signal looks like sine wave. This sine wave makes efficient inductive power deriver. Output of IGBT signal is resonated by capacitors and reactors.

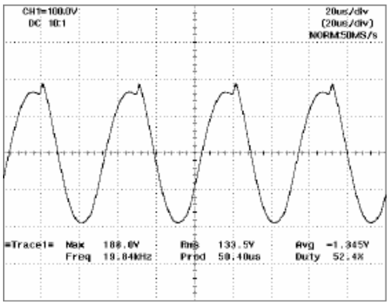

Fig. 17 Primary resonant

6.2.2 Resonant of secondary part

After pickup, inductive power signal frequency is same to primary resonant signal. Fig. 18 shows secondary resonant signal. The RMS of secondary power is about 50V.

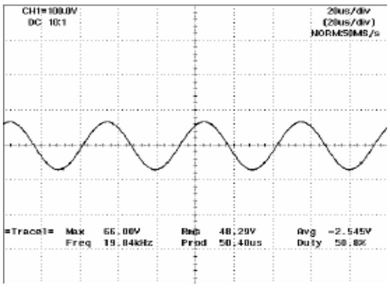

Fig. 18 Secondary resonant

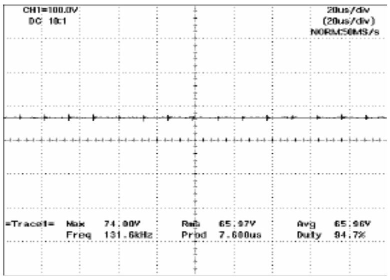

Fig. 19 shows rectified power signal of secondary inductive resonant AC signal in Fig. 18. It is about 65V DC.

6.2.3 Boosting generator

Fig. 20 shows voltage *CE V* of IGBT. Its frequency is about 77kHz. The RMS is about 100V and the maximum value is about 250V. In secondary part, the control frequency is increased for high efficient boosting. In spite of high frequency, the signal is so stable, because of digital control gate signal.

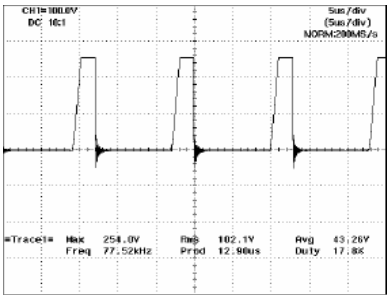

Fig. 20 voltage *CE V* of IGBT

After diode of boosting circuit, the IGBT output signal is rectified. PWM duty of IGBT gate is 80% for secondary controller. So the boosting power is five times as big as input voltage in equation (5). The result of this experiment is shown in Fig. 21. This signal is too high to be measured by oscilloscope. So using same two resisters serial connection, this signal is divided into two values. Voltage of one resister is measured about 150 V in Fig. 21. Therefore, the final DC output values are about 300V, 10A.

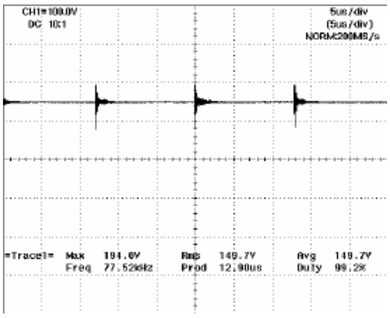

Fig. 21 Result of experiment

VII. CONCLUSION

In this paper, the developed results of CPS system are shown. In primary part of CPS system, PCB for SCR/IGBT control is developed. In this board, zero crossing circuit and SKHI module circuit are designed. And LC resonance is used for making sine wave. This sine wave makes the maximum output voltage. This output is controlled by PI controller. In secondary part of CPS system, boosting circuit PCB is developed. In this board, PIC is used for controller to make high frequency of 77kHz. Simulation result shows that PI controller can track the reference value. And in experimental results, reference values of linear 300 V DC and 10 A output are obtained. In future, this research will be implemented to increase output voltage and current of the secondary part. And by increasing the controlled frequency, power factor will be increased.

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