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Analysis and Design of an Air-Coupled DC Transformer with a Hybrid Modulation Control Method

Song Xu ^{1,2,†,‡} , Wei Jiang ^{2,*} and Seiji Hashimoto ^{1,2,‡}¹ Division of Electronic and Informatics, Gunma University, Kiryu 376-8515, Japan² Department of Electrical Engineering, Yangzhou University, N. 196 Huayang West Road, Yangzhou 225-000, China

* Correspondence: jiangwei@yzu.edu.cn; Tel.: +86-130-9207-6085

† Current address: Tenjin Cho 3-15-38, Kiryu, Gunma, Japan.

‡ These authors contributed equally to this work.

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Abstract: DC micro-grid is gaining increasing attention recently due to its highly efficient energy utilization and flexible energy exchange capabilities. In this paper, an air-coupled DC–DC transformer is proposed for the interconnection between the active load and the DC microgrid. The generic problems in an air-coupled power transfer system without ferromagnetic structure are discussed. A bidirectional half-bridge topology is also proposed to suit the characteristics of the stationary load and to realize the bidirectional power transfer between the active DC load and the DC grid. A Hybrid Modulation Method (HMM) is proposed; the small signal model is derived and linear control techniques are applied to the forward power transfer control, and phase model control is applied to the reverse power transfer model. The open-loop system is simulated by PSIM to get the characteristics of the forward and reverse transfer model, and the closed system is built in the MATLAB/SIMULINK to verify the effect of the forward frequency control method and the reverse phase control method. The prototype is built with a dsPIC controller, tests are performed to evaluate the characteristics of the transformer and the power flow control of the bidirectional power transfer.

Keywords: DC micro-grid; wireless power transfer; DC–DC transformer; Hybrid Modulation Method; bidirectional power transfer

1. Introduction

With the rapid development of new energy and distributed power generation technology, the DC micro-grid is gaining more and more attention due to its capability of island operation as well as power flow interaction with the utility grid. Protection and contingency management of a DC system has been troublesome and costly due to the non-cross-over feature of the DC system [1–5]. Wireless power transfer (WPT) technology provides a feasible way for isolated protection [6–12]. The idea behind this technology is to convert electric power into spatial magnetic power, which can be coupled to the load via different means [13–18]. The known three major means to implement WPT are the inductive power transfer, resonant power transfer and radiational power transfer [19–25].

As more loads and storages are integrated into the DC micro-grid, there are increasing demands for the enhanced plug-and-play and bi-directional power flow capability. Therefore, a power processing device that behaves like a DC transformer (DCX) is highly desirable [26–29].

Based on the aforementioned demand, this paper proposes an air-coupled DC transformer for the active load for the DC micro-grid using wireless power transfer technology. The dual half-bridge topology is proposed. The circuit operation and the small signal model for bidirectional

power transfer are analyzed in detail. The hybrid modulation method is proposed which suits the characteristics of each power transfer direction. The proposed DCX is finally verified experimentally with a dedicated prototype.

2. Proposed Air-Coupled DC Transformer

Different loads exist in the DC micro-grid system, the majority of which require smart operation as in the ac systems. Therefore, the point-of-load converters or dc plugs for a DC micro-grid require special attention since dc current does not have zero-cross points. Detaching the load from the ac-link is another option; in order to avoid undesired sparks, a detachable transformer is proposed by coupling two sets of the coil only through the air [30–32].

The system diagram and schematic diagram are shown in Figure 1; the proposed system mainly includes four parts: power input port, bidirectional power conversion unit, air coupling system and the power output port. The bidirectional power conversion unit includes the half-bridge switching pole both on the primary side and the secondary side; the output port is connected to the static or dynamic DC load.

Figure 1. The proposed DC transformer: (a) System structure (b) System schematic.

The P_1 port is the input of the system which is connected to the DC bus; P_2 is the output port connecting to the load. As per discussed in the previous section, the load served by this converter can be either static or active.

In this proposal, the air-coupled tank shown in Figure 1 is made by two air-coupled coils without magnetic core, and the series LC resonant technology is applied both in the primary side and secondary side to compensate for the high leakage and low coupling factor. The system working mode is decided by the load connected to the port P_2 : If the load is a power consuming load, the system will work in forward transfer mode to transfer the power from the DC grid to the power consuming load. Otherwise, if the load is a generator load, the system will work in the reverse transfer mode to transfer power from the generator load to the DC grid.

3. Power Stage Analysis

3.1. Resonant Analysis

In order to realize bidirectional power transfer, the symmetrical half-bridge resonant topology is chosen in this system, and a series resonant network in both the sending side and receiving side is used for the air-coupled power transfer. To facilitate the analysis, the system can be simplified to an LLC series resonant two-port network shown in Figure 2, by converting all the impedance to the sending side.

Figure 2. Simplified two-port network.

In the simplified series resonant network shown above, C_r is the series resonant capacitor (equivalent to the capacitance C_1 in schematic diagram), L_r is the leakage inductance of the air coupling transformer, L_m is the magnetizing inductance and Z_{ac} is the equivalent impedance of the transformer. The relationship between L_1 , L_r and L_m is shown as (1).

$$L_1 = L_r + L_m \quad (1)$$

This resonant network has two resonant frequencies, the first resonant frequency f_{r1} and the second resonant frequency f_{r2} .

$$f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}} \quad (2)$$

$$f_{r2} = \frac{1}{2\pi\sqrt{C_r(L_r + L_m)}} \quad (3)$$

In this design the ratio of the air-coupled transformer is set to 1, so the relationship between output voltage U_o and input voltage U_{in} can be obtained as (4).

$$\frac{U_o}{U_{in}} = \frac{\frac{j\omega Z_o}{j\omega L_m + Z_o}}{\frac{1}{j\omega C_r} + j\omega L_r + \frac{j\omega Z_o}{j\omega L_m + Z_o}} \quad (4)$$

where Z_o is the output characteristic impedance. We suppose $\lambda = L_r/L_m$ to be the ratio between leakage inductance L_r and magnetizing inductance L_m , and $f_n = f_s/f_{r1}$ is set to be the ratio between the switch frequency f_s and the first resonant frequency f_{r1} . Supposing that the system quality $Q = Z_o P_{out}/U_{out}^2$. The simplified function of the output voltage gain can be by introducing the impedance λ , f_n and Q into (4).

$$M(f_n, \lambda, Q) = \frac{1}{\sqrt{(1 + \lambda - \frac{\lambda}{f_n}) + Q^2(f_n - \frac{1}{f_n})}} \quad (5)$$

Hence, the characteristic of the output voltage ratio against the operation frequency ratio under the different value of Q can be easily concluded as Figure 3.

According to Figure 3, the system can be divided into three different working modes based on the operating frequency: inductive working mode ($f_s > f_{r1}$), load independent working mode ($f_s = f_{r1}$) and capacitive working mode ($f_{r2} < f_s < f_{r1}$). In this proposal, considering the safety of the system, the operating frequency is set to be bigger than f_{r1} .

Figure 3. Voltage gain vs. frequency ratio.

3.2. Forward Transfer Mode Analysis

To analyse the forward power transfer mode, considering that the system is working under very high switch frequency, it can be equivalent as the half-bridge LLC resonant converter shown in Figure 4; the output port P_2 is connected to the resistor to simulate the load, and the driver signal is only given to switch S_1 and S_2 in complementary mode, the half-bridge combined by S_3 and S_4 working as an uncontrolled rectifier, power flows from P_1 to P_2 .

Figure 4. Forward equivalent circuit.

To realize the linear control of the transfer power, the frequency of the driving signal on S_1 and S_2 should be higher than the first resonant frequency: $f_s > f_{r1}$. In this case, the system can be divided into six working modes in a switching cycle. The theoretical waveform is shown in Figure 5. Where v_{s1} and v_{s2} are the driving signal of the switch S_1 and S_2 , i_p is the current in the leakage inductance L_r , i_{s1} and i_{s2} are the currents flowing in the switches S_1 and S_2 , respectively; v_{C1} is the voltage on the resonant capacitor C_1 .

The following analysis is based on this case and the switch cycle time can be analyzed in six modes from t_a to t_g . Figure 6 shows the state diagram of the six working modes.

Model 1: Period between t_a and t_b , this period is the dead time of the driver signals, S_1 and S_2 are in the off state; in the primary side of the air coupled transformer, the current i_p is reverse, and it flows through the anti-parallel diode D_1 of S_1 , thus, the zero voltage switching (ZVS) of S_1 realized. In the second side, the resistor is powered by the output capacitor C_3 , and the coupled current flows through the inductance L_2 capacitor C_2 and D_4 , thus, the second side is divided into two loop cells.

Model 2: Period between t_b and t_c , in this mode switch S_1 on, S_2 off. The current i_p runs through the switch S_1 in forward direction and increasing, at the same time, the current i_m increases linearly,

the output power is supported by the coupled power. Assuming that the dead time is negligible, the current i_p is calculated as (6).

$$i_p(t) = i_p(t_b) \cos \omega_{r1}(t - t_b) + \frac{V_b}{Z_{r1}} \sin \omega_{r1}(t - t_b) \quad (6)$$

where $i(t_b)$ is the current value on L_r at time t_b , V_b is the voltage on L_r , ω_{r1} is the angular frequency of the system, V_{C1} is the voltage on the resonant capacitor C_1 , and V_{Df} is the voltage drop of the diode D_3 .

$$i_p(t_b) = (V_o + V_{Df}) L_m^{-1} (T_s/4 - \Delta/2) \quad (7)$$

$$V_b = V_{in} - V_{C1}(t_b) - (V_o + V_{Df}) \quad (8)$$

$$\Delta = t_d - t_c = t_g - t_f, \omega_{r1} = 2\pi f_{r1} \quad (9)$$

In this case, the current in magnetizing inductance L_m rises linearly in the forward direction, can be calculated as (10).

$$i_m(t) = i_m(t_b) + \frac{n(V_o + V_{Df})}{L_m} (t - t_b) = \frac{(V_o + V_{Df})}{L_m} (t - t_b - \frac{T_s}{4} + \frac{\Delta}{2}) \quad (10)$$

where $i_m(t_b) = i_p(t_b)$, T_s is the switching period, in this working state, the resonant network includes the series L_r and C_1 , and L_m is out of the resonance. The current i_p and i_m will become the same value at the end of this working state, and the current in the diode D_3 will become zero. If the switching frequency $f_s = f_{r1}$, then $\Delta = 0$.

Model 3: Period between t_c and t_d . At the end of Model 2, $i_p = i_m$, and the current in D_3 is zero. Thus, in this mode, L_2 , C_2 and D_4 form an independent loop that is isolated from the output load, the resistor is powered by the output capacitor C_3 . In this mode, L_m is involved in resonance, and the current i_p and i_m are equal. Therefore, we can calculate the current i_p as (11):

$$i_p(t) = i_p(t_c) Z_{r2} C_r \cos(\omega_{r2}(t - t_c)) + \frac{V_{Cr}(t_c)}{Z_{r2}} \sin \omega_{r2}(t - t_c) \quad (11)$$

Model 4 to Model 6 are working in the opposite state. In summary, it can be seen that the working mode of operation in Model 1 to Model 3 is symmetrical with respect to Model 4 to Model 6.

Figure 5. Theoretical waveform.

Figure 6. Forward working mode state diagrams.

3.3. Reverse Power Transfer Mode Analysis

In the reverse power transfer mode, the input port P_1 connects to a 48 V DC grid and output port P_2 is connected to the source load, a resistor in parallel with a controlled voltage source is used to simulate the generation load, the equivalent circuit is shown in Figure 7.

This way, the power flows from P_2 to P_1 . Due to the high-frequency working situation, the system is working under the phase control mode which can be seen as a dual active bridge, where L_{r1} is the leakage inductance of the primary side while L_{r2} is the leakage inductance of the second side, and L_m is the magnetizing inductance of the transformer. A phase control method is proposed to control the power flow by controlling the voltage of R_L .

Figure 7. Reverse equivalent circuit.

While the system is working, the switch S_1 to S_4 are driven at the same time, and the drive signals are complementary between S_1 and S_2 , S_3 and S_4 , a phase shift is between the signal of the S_1 and S_3 , S_2 and S_4 , thus, the system can be divided into eight states in a drive period, according to the state of the four switches and also including the direction of the current in L_{r1} and L_{r2} , take the direction from right to left as forward direction of the current in L_{r1} and L_{r2} , also as the voltage of the capacitor C_1 and C_2 . The diagram of the eight states is shown in Figure 8.

Figure 8. Reverse working mode state diagram.

The qualitative analysis of these working state are proposed as follows.

State 1: S_1 off S_2 on; S_3 on S_4 off, there are two connected loops in the secondary side: (I) the resistor R_L is powered by the controlled source; (II) the controlled source also powers the capacitor C_3 and the coupled net, and the current is decreasing in the forward direction. In the primary side only one loop is formed including L_{r1} , L_m , C_1 and S_2 . This way the source load transfer the power to the primary side.

State 2: S_1 off S_2 off; S_3 on S_4 off, the secondary side keeps the same as the State 1, with the current flows through S_3 instead of D_3 . In the primary side, the current flows through D_1 to transfer the power to DC grid, although in both sides the current continues to decrease in the forward direction. The power flow is transferred from the source load to the DC grid.

State 3: S_1 on S_2 off; S_3 on S_4 off. There are no changes on the secondary side loop. The primary side current change to flow through S_1 , and the loop changes to include S_1 instead of D_1 . In this state, the current of both sides first decreases to zero and then rises in the reverse direction. Thus, the simulate resistor is powered by both the DC grid and the source load.

State 4: S_1 on S_2 off; S_3 off S_4 off. The primary circuit state remains unchanged. in the second side, due to the shutdown of S_3 and the reverse direction of the current in L_{r2} , two independent circuits are formed: (1) Capacitor C_3 and resistor R_L are powered by source load; (2) Coupled current runs through L_m , L_{r2} , C_2 and D_4 , storing coupled power in the magnetizing inductance L_m , this state is called a coupled power storing state, and there is no power that is transferred to the DC grid.

The working mode of State 5 to State 8 is in the opposite direction of State 1 to State 4. From the above analysis, the working mode of the reverse transfer mode is also symmetrical.

4. Control System Design

The control strategies of the system are decided by the load condition, if the load is a power consuming load, the system will work in forward power transfer mode, this mode, the driving signals are given to S_1 and S_2 , S_3 and S_4 are off and using their anti-parallel diodes as an uncontrolled half-bridge to realize to highest transfer efficiency, and the frequency control method has been applied to control the output voltage, the controller is designed based on the built mathematical model of this transfer mode.

If the output voltage is over and out of control by using a frequency control method, that means the load has changed into a generator load; thus, the system will change to the reverse power transfer mode, the driving signals will also be given to S_3 and S_4 , and the control method will be changed into the phase control method; the power will be controlled through controlling the port voltage (voltage on R_L). Hence, the mathematical model of the reverse power transfer mode has not been built yet and the convention PI controller will be applied.

4.1. Small Signal Analysis

A frequency control method is proposed to control the output voltage of the forward power transfer. To realize the digital control of this system, a small signal model of the system is built, separating the output of the half-bridge inverter into a sine and a cosine voltage source, and the equivalent simplified circuit is shown in Figure 9.

Figure 9. Small signal equivalent circuit.

Where r_s represents the resistor of the coil, L_s is the primary resonant inductance (i.e., the leakage inductance of the air coupled transformer), C_s is the primary resonant capacitor (i.e., C_1 in Figure 4), r_c is the equivalent resistor of the output capacitor, C_f is the output capacitor (i.e., C_3 in Figure 4), and R is the output resistance.

The output voltage of the half-bridge can be divided into two parts, the sine voltage source v_{es} and the cosine voltage source v_{ec} , i_s is the current of the sine source and i_c is the current of the cosine source, v_{es} and v_{ec} can be obtained as (12) and (13), respectively.

$$v_{es} = L_s \left(\frac{di_s}{dt} + \omega_s i_c \right) + r_s i_s + v_s + v_{ps} = L_s \left(\frac{di_s}{dt} + \omega_s i_c \right) + r_s i_s + v_s + \frac{4n}{\pi} \frac{i_{ps}}{i_{pp}} v_{cf} \quad (12)$$

$$v_{ec} = L_s \left(\frac{di_s}{dt} + \omega_s i_s \right) + r_s i_c + v_c + v_{ps} = L_s \left(\frac{di_s}{dt} + \omega_s i_s \right) + r_s i_c + v_c + \frac{4n}{\pi} \frac{i_{pc}}{i_{pp}} v_{cf} \quad (13)$$

Introducing the small signal into the state equation of the system, the plant transfer function $G_p(s)$ between the output voltage and frequency is obtained as (14). The parameters already been considered.

$$G_p(s) = \frac{5.5895(1 + \frac{s}{3.314 \times 10^4}) \times (\frac{s}{8.262 \times 10^5} - 1)}{(\frac{s^2 + 973.6s}{8.949 \times 10^8} + 1) \times (\frac{s^2 + 2.76 \times 10^5 s}{1.227 \times 10^{12}} + 1)} \quad (14)$$

4.2. Forward Power Transfer Control Loop

For the forward power transfer, the voltage mode closed-loop control method is applied to control the power transmission. Considering the characteristics of the system, a frequency mode control method is proposed to control the output voltage. The control block diagram is shown in Figure 10. V_{ref} is the reference value, $Y(s)$ is the output of feedback loop, $G_p(s)$ is the transfer function of the plant, the function between output voltage and switching frequency, $G_c(s)$ is the controller.

Figure 10. Forward control loop diagram.

Considering the transfer function of the plant, the controller is designed as a two zeros and three poles controller. The testing and experimental method is applied to get the parameters of the controller, as is shown in (15).

$$G_c(s) = \frac{371249.6041 \times (s^2 + 973.6s + 8.949 \times 10^8)}{s \times (s + 3.314 \times 10^4) \times (s + 1.03 \times 10^6)} \quad (15)$$

The bode diagram can be easily obtained as shown in Figure 11, from which the crossing frequency of the system is 593 Hz, and the phase margin is 89.4 degrees, system stability requirement is satisfied and therefore the closed loop system can work stably.

Figure 11. Close loop system bode diagram.

4.3. Reverse Power Transfer Control Loop

For the reverse power transfer, the voltage of R_L is considered to control the transmission power. A phase control method is proposed for the reverse power flow control by controlling the voltage of R_L ; the closed loop control block diagram is shown in Figure 12, where V_{ref} is the set reference, $Y(s)$ is the output of feedback loop, $G(s)$ is the transfer function of the plant, the function between voltage on R_L and phase shift, $C(s)$ is the controller.

Figure 12. Reverse control loop diagram.

Since the model of $G(s)$ has not been built yet, a conventional PI controller is applied in this control system. The transfer function of the PI controller is as (16).

$$C(s) = K_P + \frac{K_I}{s} \quad (16)$$

The same method of the experimental method is used to obtain the parameters of the PI controller, as $K_P = 1$ and $K_I = 150$ satisfies the stability requirement of the system design.

4.4. System Working Strategy

In this proposal, the P_2 voltage is controlled by two main parameters, switching frequency f_s and phase angle between driving signals. For the forward power transfer mode, f_s is working under a specific range, when the load is getting lighter, the f_s control is applied to control the output voltage; this mode is called LLC mode. When the voltage is out of control, or the power flow tends to be reversed, the control strategy is changed to phase control under the optimal frequency point. The system switches to reverse transfer mode as Dual Active Bridge mode (DAB). The idea of the system working strategy is shown in Figure 13.

Figure 13. System working strategy.

5. PSIM/MATLAB System Simulation

5.1. Forward Open Loop System Simulation

In order to get the characteristics of the forward power transmission mode, an open-loop system model built in PSIM is proposed to sweep the switching frequency to obtain the system characteristics upon frequency. For the forward power transfer, only S_1 and S_2 are driven by the driven signal, S_3 and S_4 just in function as the half-bridge rectifier, output resistor $R_L = 8 \text{ Ohm}$, consider the parameters chosen, the first resonant frequency $f_{r1} = 225 \text{ kHz}$, and the second resonant frequency $f_{r2} = 80 \text{ kHz}$. Thus, sweeping the switching frequency between 0 Hz and 300 kHz, and the characteristic curve can be obtained as Figure 14.

Figure 14. Output voltage vs. frequency.

From the figure, it can be easily seen that when the switching frequency is over f_{r1} , the output voltage decreases as the switching frequency increases. Therefore, linear control of the output voltage can be realized in this interval.

5.2. Forward Closed Loop Simulation

In order to verify the correctness and accuracy of the controller, the closed loop system is built in MATLAB (R2017a, MathWorks, Inc, Natic, MA, USA). The reference output voltage 40 V, the output voltage and current waveform can be seen in Figure 15, and it can be concluded that the control system achieves the desired efficiency.

Figure 15. Output voltage and current waveform.

5.3. Reverse Open Loop System Simulation

In the reverse power transfer mode, the phase shift method is applied with S_3 and S_4 are driven together and ahead of the S_1 and S_2 drive signal. The open-loop simulation is built in PSIM to get the characteristic of the power transmission among phase shift. The parameter is the same as the forward simulation mode, and the load is changed to be the source load, 48 V DC load is connected to the output port. The simulation makes S_3 and S_4 drive signal lead ahead than the signal of S_1 and S_2 , scan the phase from 0 to 360 degrees, and the curve of the input and output power along with the phase is shown in Figure 16, and the curve of the voltage on R_L shown in Figure 17.

Figure 16. Input and output voltage vs. phase.

It can be easily concluded that reverse power transfer happens in the interval of 0–180 degrees of the leading phase, also in the range 0–90 degrees, the power transmission increases with the phase degree increase, while it decreases in the range 90–180 degrees. However, the voltage on R_L presents an opposite trend then the power transmission. Therefore, the interval of 0–90 degrees is chosen to be the limitation interval of the control system.

Figure 17. Voltage on R_L vs. phase.

5.4. Reverse Closed-Loop Simulation

As the PI controller is applied, to verify the efficiency of the control parameters, the closed-loop system model is built in the MATLAB (R2017a, MathWorks, Inc, Natic, MA, USA). Set the reference of the voltage on R_L be 45 V, the simulation waveform is shown in Figure 18. From the waveform, it can be shown that the control system achieves the desired efficiency.

Figure 18. Output waveform of voltage on R_L .

5.5. Full System Simulation

The whole system is carried out in MATLAB, using the idea switch to change the resistor load to the source load. In order to verify the power control strategy, set the origin transfer direction to forward, and control the output voltage 30 V, change the load to source load at 0.6 s and control the voltage of R_L 46 V; the simulation output waveform of the port voltage and the source load current is shown is Figure 19, from which the system function is verified.

Figure 19. Voltage waveform of full system.

6. Experiments and Analysis

An experimental platform was built as shown in Figure 20, concluding the DC voltage source, air-coupled transformer and the simulated load of DC grid, and the parameters of the hardware system as listed in Table 1.

The experiments including the open-loop sweep and closed-loop experiment on both forward and reverse power flow transfer was carried out on this platform.

Figure 20. Experiment platform of the system.

Table 1. System parameters.

Parameters	Quantity	Value
C_1, C_2	Resonant capacitor	$0.7 \mu\text{F}$
L_1, L_2	Coil self-inductance	$14.6 \mu\text{H}$
k	Coupling coefficient	0.865
L_m	Magnetizing inductance	$12.629 \mu\text{H}$
L_r	Leakage inductance	$1.971 \mu\text{H}$
R	Load resistor	8 Ohm
f_{r1}	First resonant frequency	225 kHz
f_{r2}	Second resonant frequency	83 kHz
V_{DC}	Supply voltage source	48 V DC
S_1, S_2, S_3, S_4	Power CMOS	RF540

6.1. Forward Transfer Open Loop And Closed Loop Experiments

Based on the simulation results of the forward power transfer mode, the experiment of the frequency sweep is carried out. Considering the system parameters, set the switching frequency at the range of 100–350 kHz, and the output voltage curve can be obtained in Figure 21. The diagram is similar to the simulation results and the system characteristics are verified.

Figure 21. Output voltage vs. frequency.

The closed-loop experiment is based on the open-loop sweep results, where the switching frequency setting is higher than the first resonant frequency. At the beginning, the initial frequency of the system is set to 244 kHz and the initial system waveform is shown in Figure 22, where the system frequency is 243.695 kHz.

Figure 22. Original waveform of forward transfer.

As can be seen, a reverse voltage is applied to turn off the switch. To verify the effectiveness of the control system, control the system output voltage at 25 V and 23 V, respectively; the waveforms are shown in Figures 23 and 24, respectively. From the waveforms, the output voltage is 25 V, the system switching frequency is 273.9 kHz, while the output voltage of 23 V and the frequency is 282.12 kHz. The results meet the open-loop sweep result. Therefore, the control system is efficient and verified.

Figure 24. Waveform of controlling output 23 V.

6.2. Reverse Transfer Open Loop and Closed Loop Experiments

This experiment is proposed to verify the bidirectional power transfer of the system; as in reverse power transfer mode, the switching frequency is higher than the first frequency. The drive signal of S_3 and S_4 leads the phase; sweep the phase from 30 degrees to 360 degrees under different switching frequency, the curve of the transfer power along with the phase can be obtained in Figure 25.

Figure 25. Output power vs. phase under different frequency.

It can be easily concluded that before 90 degrees, the transfer power increases when the phase increases, while after 90 degrees, the trend becomes the opposite. Also, the frequency affects the power transmission; the closer to the first resonant frequency, the higher power transferred.

Choose the frequency at 280 kHz, and the phase control in the range of 0–90 degrees, set the initial phase at 20 degrees, the initial waveform of the drive signal of S_1 and S_3 , the voltage on R_L and the current is shown in Figure 26.

To control the voltage of R_L , set the reference voltage as 43 V and the waveform can be obtained in Figure 27, where the voltage on R_L is 43.44 V, the phase is about 60 degrees, and the reverse transfer DC current is about 2.22 A, thus, the control system achieves the desired results.

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