A method of power regulation applied to the high frequency inverter for the IH home appliances

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Abstract

This paper describes a power regulation concept; CFPDM (Commercial Frequency Pulse Density Modulation) of the high frequency inverter for induction heating home appliances. CFPDM is a new type of PDM and it is easy to put CFPDM into practical use for any circuit topologies without any additional switches and passive components. Conventional PDM (Pulse Density Modulation) enables the high frequency inverter to control the output power over a broad range and to realize high power conversion efficiency at the same time. However, the resonant frequency of non-smoothing filter is close to the duty frequency of PDM, which may cause other harmonic current problems. In CFPDM, the duty frequency is set to lower than the line frequency unlike PLL. Therefore CFPDM surpass the advantages of PDM and also avoids generating harmonic current. This paper shows the sample of CFPDM controller and the operation principle by using simulated results. A prototype soft switching SEPP high frequency inverter controlled by CFPDM has been tested. Some experimental results of it are shown finally.

Power converter system for IH home appliances

The passive rectifier using the diode bridge can serve smoothed DC voltage by employing large capacitor. However it is well known the line current flowing into the diode bridge is distorted and the power factor becomes low. Therefore large numbers of power factor correction converters has been proposed and discussed. The home appliances take power from the single line and its rated power is several kW. In almost all IH appliances, changing the amplitude of the load voltage does not matter unlike other electric devices like DC-DC converter because the time constant of heat transfer in the IH load is big enough. Consequently the passive diode rectifier is served for high frequency inverter of IH home appliances by using small capacitor so that the output DC bus voltage is not smoothed (see Fig. 1) [1]. When the line frequency is 50Hz, the high frequency load voltage and current of the high frequency inverter have ripple at 100Hz as well as DC bus voltage. This circuit system has advantages that THD of the line current (i_{line}) is restrained and high input power factor can be achieved.

Power control method of the high frequency inverter for IH

Several output power control methods have been proposed for the high frequency inverters depending on various IH loads. PFM (Pulse Frequency Modulation) is widely used in the industrial IH applications for instance hardening, annealing, welding, and melting [2][3]. On the other hand, as it is well known, the high frequency inverter in the IH home appliances like multi-burner type IH cooking heater is required to have a power control function under constant frequency in order to prevent generating the beat sound. The power control methods under constant frequency which has been proposed are Asy-PWM (Asymmetric Pulse Width Modulation)[4], PS-PWM (Phase Shift Pulse

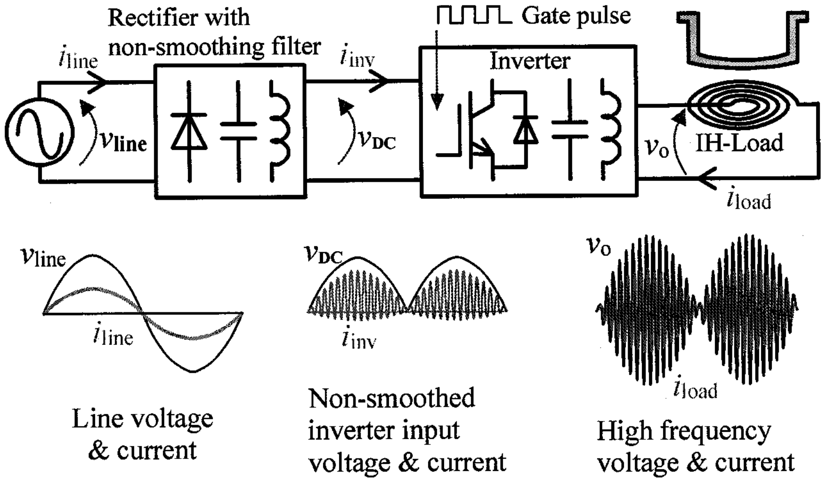


Fig. 1: General high frequency inverter system for IH home appliances

Width Modulation) [5], and PDM [6]. Some of these have been put into practical use. PWM type methods complete its operation for power control in one switching cycle of the high frequency inverter, which then realizes high speed response of the power control. But it is difficult for the high frequency inverter to operate under soft switching condition in whole power regulation range.

Advantages and disadvantages of PDM

PDM doesn't complete its power control in one switching cycle of the high frequency inverter but operates in 10 to 20 cycles called "duty cycle". Fig. 2 shows the principle of PDM. The power injection cycle is the term that gate pulses are given to the switches of an inverter. The inactive cycle is the term that gate pulses to switches are cut off. And the load power is defined as an average of electric energy which is supplied from the high frequency inverter during the duty cycle.

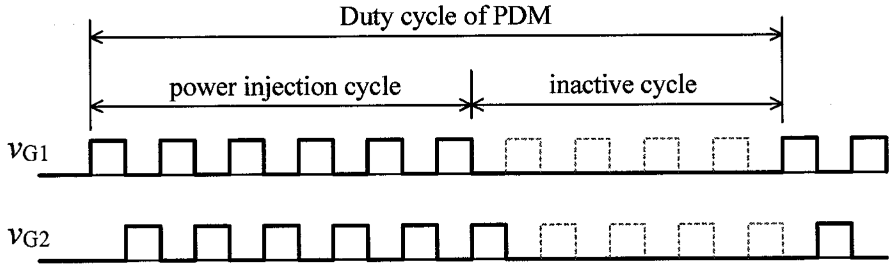


Fig. 2: Principle waveforms of PDM power control method

The duty of PDM (D_{PDM}) is defined as follows.

D_{PDM} = (power injection cycle) / (duty cycle)

When the D_{PDM} is high, the average power is increased. PDM is not adequate as the regulation method for DC-DC converters which are required to operate in high speed response because the duty frequency of PDM is lower than the switching frequency of the high frequency inverter considerably. However it is not necessary to regulate with fast response for loads using heat like IH appliances. Therefore the high frequency inverters for IH appliances has to have a high speed shut off function and does not need to have a high speed power regulation function. From these points, it is clear that the PDM power control method is adequate enough for the high frequency inverters of IH appliances.

Generally, the power conversion efficiency of any high frequency inverter is high when its power is large. But the efficiency tends to decrease when the power is low. It is thought that power loss on the switching devices is increased by increasing reactive power in the high frequency inverter. On the other hand, the PDM controlled high frequency inverter is able to maintain high power conversion efficiency at any power condition because it operates at rated power condition during the power injection cycle and no current flows while it is inactive.

On the down side, it has been reported that the PDM controlled high frequency inverter with non-smoothing filter causes the harmonic current [7]. Fig. 3 shows the line current i_{line}, the gate signals v_{G1} v_{G2}, the load current i_{load}, the voltages of switches v_{S1} v_{S1}, and the currents flowing through switching device i_{S1} i_{S2} calculated by a simulation. The simulated circuit is shown in Fig. 4. The simulation condition is the switching frequency; f_s=20kHz, D_{PDM}=0.6, the frequency of duty cycle; f_{PDM}=2kHz, L_{load}=40μH, R_{load}=2Ω, C_r=3.0μF, C_{sn}=0.05μF, L_f=1.15mH, C_f=4.5μF.

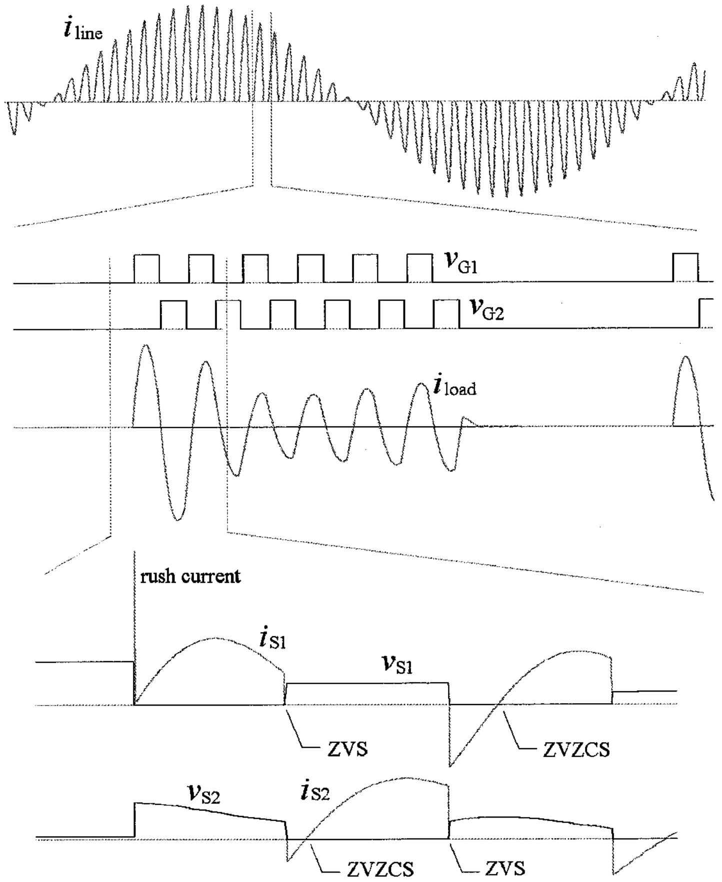


Fig. 3: Operation waveforms of the PDM controlled high frequency inverter with non-smoothing filter

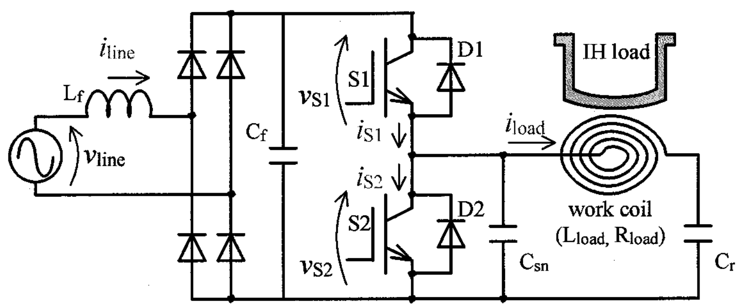


Fig. 4: SEPP high frequency inverter for IH appliances

Although the non-smoothing filter cut out the frequency derived from the switching operation of the high frequency inverter, however the frequency originated from the duty cycle of PDM is not filtered because it is close to the resonant frequency of the non-smoothing filter. To solve this problem, [7] proposed to optimize the design of non-smoothing filter. But the method is complicated and its effect is limited.

Many resonant inverters operate in the lagging phase for ZVZCS turn-on switching operation and achieve ZVS turn-off switching operation by employing C_{sn}. The PDM controlled high frequency inverter maintains soft switching operation in almost power injection cycle. Nevertheless it can not achieve soft switching operation at a first cycle in a power injection cycle because the rush current flows through the switches at turn-on transition (refer i_{S1} in Fig. 3). Hence it is difficult to expect the improvement of the power conversion efficiency by soft switching depending on the duty for power control.

Proposed CFPDM method

This paper describes the CFPDM (Commercial Frequency Pulse Density Modulation) method which solves the problems which PDM controlled inverters have. As mentioned before, the duty cycle of the conventional PDM is 10 to 20 times of inverter's switching cycle. On the contrary, the duty cycle of CFPDM is integral multiples of a commercial line cycle (20ms @50Hz).
The duty of CFPDM is also defined as follows like PDM.

D_{CFPDM} =(power injection cycle)/(duty cycle)

Fig. 5 illustrates a principle of this power control method by using a simulated data. The duty of CFPDM is 6/10 and the high frequency inverter operates for 6 cycles of commercial line. In this scheme, it is clear that the power regulation frequency of duty cycle of CFPDM is lower than the line commercial frequency. Basically CFPDM doesn't generate the harmonic current originated from the frequency of duty cycle of CFPDM. Therefore the line current achieves low THD while the high frequency inverter operates in the power injection cycle.

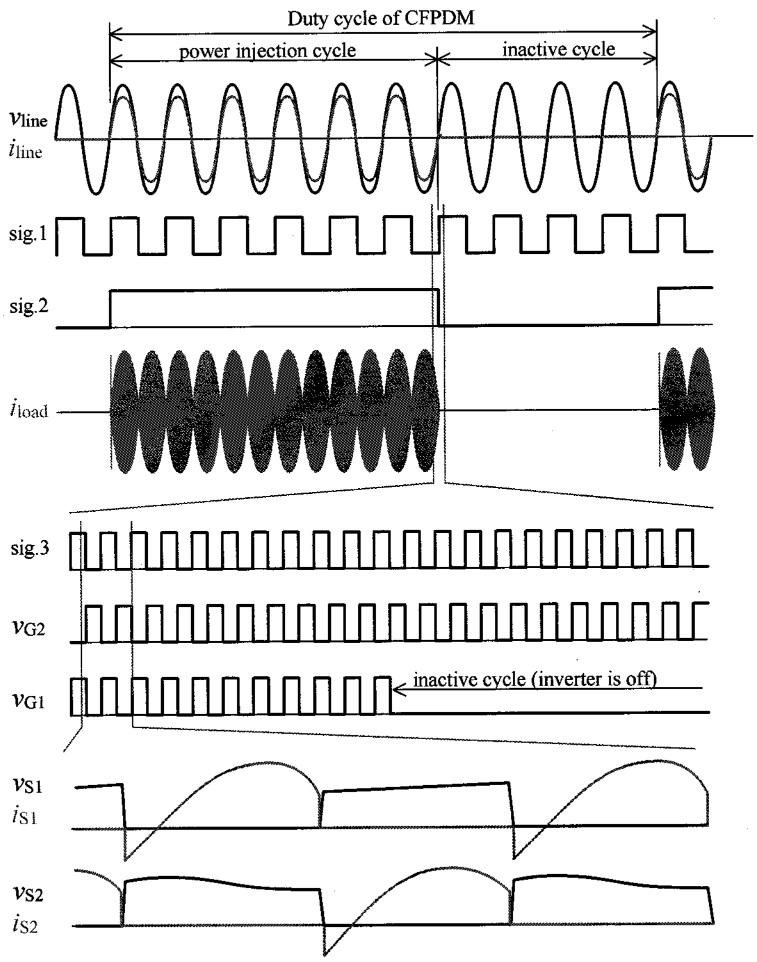


Fig. 5: Principle of CFPDM and operation waveforms

Fig. 6 illustrates the schematic diagram of the power control circuit for implementing the CFPDM method. The signal which is synchronized to the commercial line voltage is reformed to the PDM signal (sig.2) through the counter which is given a modulation command. The high frequency pulse is tuned in a little high than the resonant frequency of the resonant circuit including IH load, so that switches can achieve ZVS condition by a lagging phase. The conjunction of the PDM signal and the high frequency (switching frequency) pulse is delivered to the switches with a certain dead time. This proposed power control method can be implemented to any circuit topologies for instance SEPP (Single Ended Push Pull), HB (Half Bridge), and FB (Full Bridge).

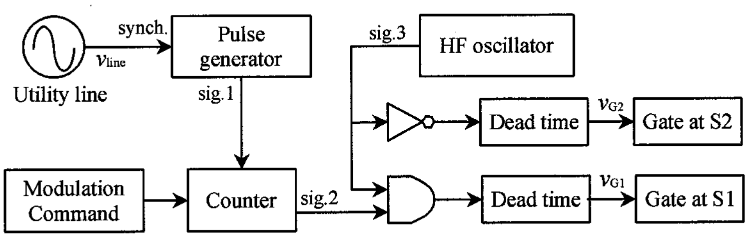


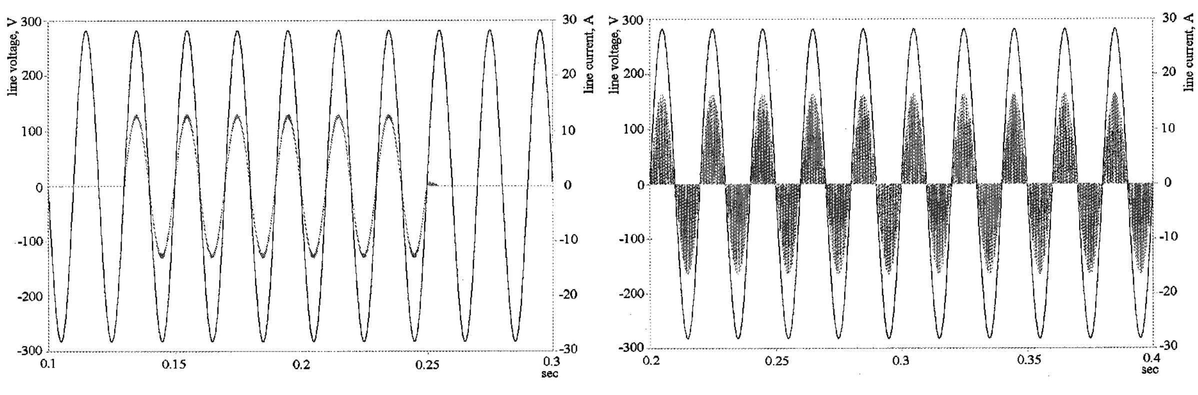
Fig. 6: Schematic diagram of CFPDM method

Advantages of CFPDM

As mentioned before, the PDM controlled high frequency inverter can not avoid the rush current if it has a loss-less snubber capacitor for ZVS turn-off operation, and it is inevitable to generate the power dissipation at a first cycle every duty cycle of PDM. CFPDM controlled inverter can also not avoid the rush current, and the rush current flows at first cycle every duty cycle of CFPDM as well as PDM. However, the frequency of duty cycle of PDM is considerably low compared to conventional PDM and the number of times which the rush current flows is decreased by CFPDM. As a result, the power dissipation by the rush current is decreased in the CFPDM controlled high frequency inverter compared to PDM one.

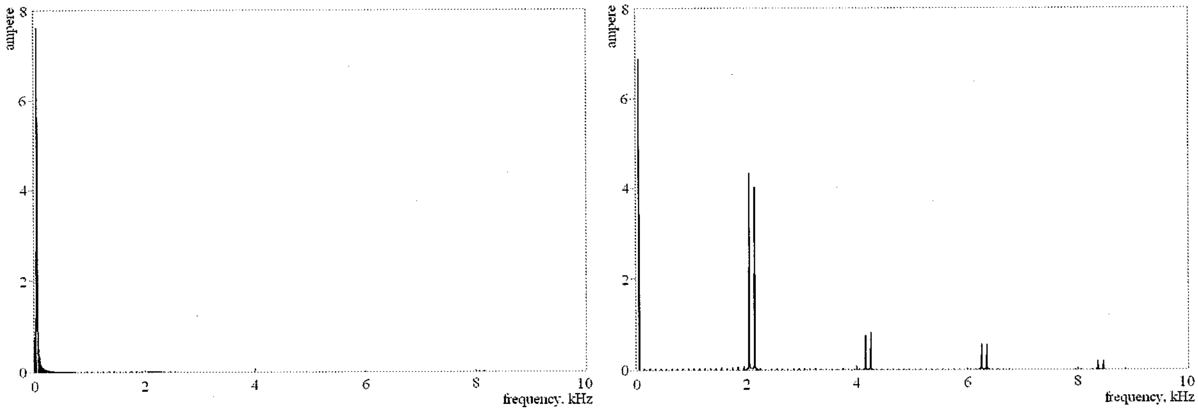
To compare the PDM and the CFPDM, the simulations were implemented. In the simulation, the switching frequency is f_s=21kHz, the duty of power regulation is D_{PDM}= D_{CFPDM}=6/10, L_{load}=40μH, R_{load}=2Ω, C_r=3.0μF, C_{sn}=0.05μF, L_f=1.15mH, C_f=4.5μF. Fig. 7 (a) shows the simulated line voltage and the line current in the SEPP high frequency inverter (refer Fig. 4) which is operated under CFPDM control. The line current waveform under PDM control, shown in Fig. 7 (b), is distorted. Fig. 8 shows the FFT results of simulated line current in duty=6/10. From Fig. 8 (b), it can be seen that the line current includes the harmonic current originated from the frequency of conventional PDM duty cycle (around 2kHz).

On the other hand, the line current under CFPDM control doesn't include higher harmonic current as shown in Fig. 8 (a).



(a) under CFPDM control (b) under PDM control

Fig. 7: Simulated line voltage and current in duty=6/10



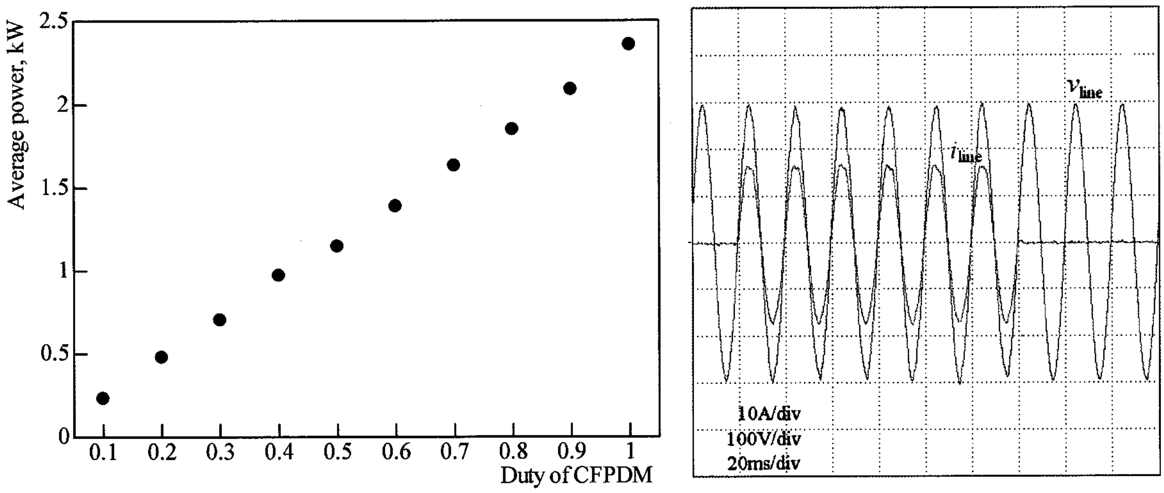
(a) under CFPDM control (b) under PDM control

Fig. 8: FFT results of simulated line current in duty=6/10

Experiment results and evaluations

A prototype was built to evaluate the proposed CFPDM method. The circuit topology is SEPP type high frequency inverter same as Fig. 4. In the prototype 2-in-1 module IGBT (2MBI100-060) is used for the switches, bridge diode (GBPC2502) is used for the rectifier. The duty cycle is set in 10 cycles, and the switching frequency is 22.5 kHz.

Fig. 9 (a) indicates the average power of the prototype circuit controlled by CFPDM method. The average power is controlled in proportion as the duty of CFPDM. Fig. 9 (b) shows observed waveforms of line voltage and current when the duty of CFPDM is 0.6. These waveforms correspond to the simulation results shown in Fig. 7. It can be confirmed the non-smoothing filter which consist of L_f and C_f works as it is expected and harmonic current derived from CFPDM duty cycle was not observed.



(a) measured average power under CFPDM method (b) observed line voltage and current

Fig. 9: Experimental results of prototype high frequency inverter controlled by CFPDM method

Conclusion

This paper described the conceptual power regulation method of the high frequency inverter for IH home appliances. The non-smoothing filter is utilized to eliminate the high frequency noise derived from the switching frequency, but it doesn't work effectively to prevent the flowing of the current from the PDM power regulation frequency. The basic idea of the proposed CFPDM method is that the frequency of duty cycle for power regulation is set lower than a commercial line frequency. As a result, the line current becomes free from the harmonic current. To implement the CFPDM method, no additional switches and no passive components are needed. Therefore the circuit topology of the high frequency inverter is simplified by adopting the CFPDM method and at the same time low THD is realized.

Although general power electronics has pushed for high frequency control method in order to achieve high speed and high quality performance, however proposed the CFPDM method has a lower speed and lower frequency than the conventional PDM method. Therefore the CFPDM method is not useful as the regulation method to a DC-DC converter which is required to operate in high speed response. On the other hand, it is not necessary to regulate with fast response for loads using heat like IH appliances, because the time constant of a heat transfer is big enough in IH loads and a function of precise temperature control is not expected. Therefore the high frequency inverters does not need to have high speed power regulation function, though they has to have a high speed shut off function.

From these points, the CFPDM method enables the high frequency inverter to control its output power under constant switching frequency, to restrain a higher harmonic current, to achieve soft switching condition for improving power conversion efficiency, and to simplify circuit topologies without additional circuit components. Hence it is clear that CFPDM power control method is adequate enough for the high frequency inverters of IH appliances.

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