A Novel Soft Switching Three-Phase Utility Frequency AC to High Frequency AC Direct Power Converter with PFC Function for Industrial IH Appliance

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Abstract—This paper presents performance characteristics of a novel soft switching three phase utility frequency AC (UFAC) to high frequency AC (HFAC) direct converter with PFC function for industrial induction heating and melting applications. The proposed “simple three phase system” consists of single phase UFAC to HFAC direct converter in each phase, three phase low pass filter and IH load. This power converter can regulate the output power under a condition of a constant frequency zero voltage soft switching (ZVS) commutation principle on the basis of unique asymmetrical PWM control scheme. In this paper, the input and output characteristics of proposed direct power converter on the basis of computer aided simulation are illustrated and discussed. Furthermore, Y-connected 3φ working coils for IH load with the balanced coupling coefficient in each phase is designed and evaluated from an experimental point of view.

Keywords-component: UFAC-HFAC direct power converter, power factor correction, soft switching, HF induction heating, coupling coefficient of IH load, asymmetrical PWM

I. INTRODUCTION

The technology using high frequency induction heating (IH) not only fill the key demands of high reliability, safety and cleanliness, but also has excellent advantages of very high thermal conversion efficiency, rapid heating, local spot heating, high power density, and low running cost. In recent years, high frequency power electronics becomes widely used for IH applications. IH technology has been also utilized for domestic applications such as cooking heater, rice cooker and hot water producer, and for industrial circuits such as metal working and super heated steamer.

Power converters changing utility frequency AC power source to high frequency AC like IH appliances cause harmonic currents to utility AC grid. Harmonic currents make utility AC source current non-sine wave and cause low power factor. Low power factor causes increasing of system values. In addition, harmonic currents cause harmonic pollutions in UFAC grid side equipments. To suppress these problem, the officially admitted regulations are provided about harmonic currents and harmonic contents [1], as well as effective power factor [2] in UFAC grid side.

Generally, the high frequency IH apparatuses based on the high frequency power conversion equipments have PFC rectifier stage or diode bridge rectifier stage as passive PFC converter (UFAC-DC) and high frequency resonant inverter stage for supplying high frequency AC power to various IH load structures (DC-HFAC). These IH products have high power factor and low utility AC current harmonics characteristics. However, the IH products are actually needed a lot of power semiconductor devices, passive resonant circuit components and bulky electrolytic voltage smoothing capacitor stack.

From these present backgrounds, this paper proposes soft switching three-phase utility frequency AC to high frequency AC direct converter with PFC function for industrial IH appliance, especially for hot water producers or super heated steamer. Proposed “simple three phase system” consists of single phase UFAC to HFAC direct power converter in each phase, three phase low pass LC filter and IH load using Y-connected working coils. This power converter can regulate its output power under a condition of a constant frequency zero voltage soft switching (ZVS) commutation principle on the basis of a unique asymmetrical PWM control scheme. This paper evaluates the input and output characteristics of proposed circuit on the basis of simulation. Furthermore, 3φ Y-connected working coils for IH load with the balanced coupling coefficient in each phase are evaluated from an experiment point of view.

II. PROPOSED CIRCUIT CONFIGURATION AND ITS CONTROL SCHEME

A. Proposed circuit configuration

Figure 1 illustrates proposed soft switching three phase UFAC-HFAC direct power converter. This frequency power converter consists of low pass filter $L_0$, $C_0$ with neutral point, three single phase UFAC-HFAC direct converters in each phase and “three winding input / single winding IH load”. The
single phase direct converter consists of active switching power devices $Q_1(S_1/D_1)$, $Q_2(S_2/D_2)$, diodes $D_3$, $D_4$, resonant capacitors $C_3$, $C_4$ and lossless snubbing capacitor $C_2$. 200Vrms utility frequency AC grid is connected via LC filer with neutral point. Any bulky DC smoothing capacitor is not necessary in this proposed direct frequency power converter. Single-phase UFAC-HFAC direct frequency converter in each phase can directly converts 60Hz power of UFAC grid into 24 kHz HFAC power and supplies high frequency AC to load working coil. This converter can operate with asymmetrical PWM (APWM) to regulate output high frequency AC power. Active switches $Q_1$ and $Q_2$ are operated under ZVS&ZCS turn on and ZVS turn off by loss-less snubbing capacitor $C_2$. 

The output IH load has three working coils at each phase and a heated object is set up in these working coils. The equivalent IH load circuit which includes the magnetically coupled components of working coil $R_1$, $L_1$, ($u$, $v$, $w$) can be described as shown in Fig.1. Three phase UFAC-HFAC direct power converter is composed of three units single phase ones at each phase intermediated neutral conductor. The circuit parameters and design specifications of proposed three-phase AC-HFAC direct converter are listed in Table I.

### B. Operating principle

As shown in Fig. 2, roles of the switches $Q_1$ & $Q_2$ in the bridge leg change under synchronizing with the polarity of the input AC phase voltage. In addition to this, roles of the resonant capacitors $C_1$ & $C_2$ exchange. In case of the input AC phase voltage $v_1(x; u, v, w) < 0$, $Q_1$ works as power regulating main switch and $C_1$ works as resonant and clamp capacitor, on the contrary, switch $Q_2$ works as main switch and $C_2$ works as resonant capacitor at $v_1(x; u, v, w) < 0$. The definition of the duty factor is expressed by eq.(1).

$$D = \frac{T_{on}}{T}$$

$T_{on}$ is gate injection time of the main switch; $T$ is one cycle of switching period. At the changing points of the polarity of the input AC phase voltage, roles of resonant capacitors $C_3$ & $C_4$

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**TABLE I. CIRCUIT PARAMETERS OF PROPOSED POWER CONVERTER**

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Source Voltage</td>
<td>$V_{ac}$</td>
<td>200[V]</td>
</tr>
<tr>
<td>AC Source Frequency</td>
<td>$f_{in}$</td>
<td>60[Hz]</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>$f_{SW}$</td>
<td>24[kHz]</td>
</tr>
<tr>
<td>Dead Time</td>
<td>$T_d$</td>
<td>1.0[μsec]</td>
</tr>
<tr>
<td>Inductance of Filter Inductor</td>
<td>$L_f$</td>
<td>1.3[mH]</td>
</tr>
<tr>
<td>Capacitance of Filter Capacitor</td>
<td>$C_1$</td>
<td>6.6[μF]</td>
</tr>
<tr>
<td>Capacitance of Lossless Snubber Capacitor</td>
<td>$C_2$</td>
<td>45.2[nF]</td>
</tr>
<tr>
<td>Capacitance of Resonant Capacitor</td>
<td>$C_3$</td>
<td>6.6[μF]</td>
</tr>
<tr>
<td>Capacitance of Resonant Capacitor</td>
<td>$C_4$</td>
<td>6.6[μF]</td>
</tr>
</tbody>
</table>

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**Fig. 2. Principle diagram of APWM control method**

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**Fig. 1. Proposed circuit configuration of three-phase AC-AC direct converter.**
exchange each other. At this time, residual electric charge remains at resonant capacitor. After phase voltage zero crossing point, residual charge is discharged by switching. This discharging currents cause harmonic currents and low power factor in input current. To avoid this problem, the gate signals in each phase are shifted $2\pi/3$ of switching frequency each other. These gate signals can be generated by the shifted triangular waves for the PWM operation. By this modulation method, remained voltage can be reduced and harmonic currents are suppressed [3].

III. OUTPUT AND INPUT CHARACTERISTICS

A. FFT analysis of input currents

Fig. 3 shows voltage and current waveforms of the switches $Q_1$ & $Q_2$ in case of duty factor $D=0.8$ at the positive peak point area in phase $u$. Observing this figure, all the switches can achieve soft switching operation, under ZVS&ZCS turn on and ZVS turn off condition.

Simulated input line voltage and current waveforms are illustrated in Fig. 4. Line current $i_n$ seems to be sinusoidal waveform. Line current phase lags about $\pi/2$ compared with line voltage $v_{vw}$. Fig. 5 illustrates FFT analysis of utility AC side line current for phase u. All harmonics are suppressed under regulation [1]. This shows excellent PFC performance of proposed circuit. Observing the simulated results, proposed direct converter can achieve under regulation in duty factor $D\leq0.9$.

B. Converter output characteristics

Fig. 6 illustrates three phase UFAC-HFAC direct converter output currents. This figure shows single phase converter operates in envelop curve of utility AC. Therefore, in single phase converter, eddy current in envelop curve of utility AC flows in heated object. However, this envelop curve has possibilities of delay heating responses. But, in three phase direct converter, triple eddy currents flow through heated object. The pulsation of eddy current in heated object can be reduced as compared with single phase converter. Proposed three phase UFAC-HFAC direct converter can achieve not only...
large capacity IH but also stable heating characteristics as compared with single phase direct converter.

Input power and power factor characteristics are illustrated in Fig. 7. As can be seen, proposed direct power conversion circuit can fill power factor regulation $\Delta D = \Delta 0.2$. Furthermore, proposed converter can operate under soft switching condition in $D \geq 0.3$. In $0.2 \leq D < 0.3$, direct UFAC-HFAC converter operates under a hard switching commutation, but it is possible to operate because of low input power. From input and output characteristics, a duty factor $D$ operated range of three phase UFAC-HFAC direct converter is defined as $0.2 \leq D < 0.9$.

IV. HIGH FREQUENCY INDUCTION HEATING BOILER FOR PIPE LINE INDUSTRIAL FLUID HEATING

A. Equivalent circuit of epoch making IH boiler

The schematic diagram of single phase IH boiler for fluid heating used in pipe line is shown in Fig. 8. This boiler consists of spiral type dual pack IH element, working coil and non-metal heating vessel. It is composed of the stainless steel spiral assembly and its outside edge point is connected to the inside edge point by the copper bar. In this assemble technique, it is possible to achieve rapid heating response of this induction fluid power heating appliance because of electromagnetic induction eddy current flows through this heat exchanger entirely. Fig. 9(a) represents transformer type equivalent model of IH boiler. This model is represented as the self-inductance $L_1$ and internal resistance $R_1$ of the working coil, self-inductance $L_2$ of eddy current heated element in electromagnetic induction transformer secondary side and mutual inductance $M$ between $L_1$ and $L_2$. $M$ is defined as

$$M = k_{12} \sqrt{L_1 L_2} \tag{2}$$

where $k_{12}$: electromagnetic coupled coefficient between $L_1$ and $L_2$. The circuit equations in transformer primary side and secondary side are as follows;

$$v_1 = j\omega (L_1-M)i_1 + j\omega M(i_1 + i_2) + R_1 i_1, \tag{3}$$

$$0 = j\omega (L_2-M)i_2 + j\omega M(i_1 + i_2) + R_2 i_2, \tag{4}$$

where $v_1$: the voltage of primary side, $i_1$ and $i_2$: the currents of primary and secondary side and $\omega$: the operating angular frequency of high frequency AC from direct power frequency converter. The voltage $v_1$ of primary side can be derived from (3) and (4);
IH model is defined as coefficient (9). The measurable parameter measured from working coil illustrated as simple equivalent inductive circuit model in Fig. 9(b). From eq.(5), the equivalent circuit model of IH load is derived with equivalent effective inductance components by mutual induction between phase (6). Mutual inductance and phase resistance by mutual induction are defined; 

\[ L_{uv} = k \frac{1}{\omega} \sqrt{L_u L_v} = k L_{uv} \]  

(10)

From eq.(5), the equivalent circuit model of IH load is illustrated as simple equivalent inductive circuit model in Fig. 9(b). The measurable parameter measured from working coil ports are used for simulation because it is impossible to measure self-inductance \( L_2 \) and skin-effect related resistance \( R_2 \) in secondary side.

B. IH boiler with three phase high frequency working coil

Three phase UFAC-HFAC direct converter has one unit IH load in each phase direct converter in Fig. 1. IH boiler with three phase working coil has triple separate working coils with one heated object. Mutual induction occurs between working coils in each phase. In this figure, the unit direct converters in each phase are simulated as current sources. Each circuit parameter in Fig. 11 is derived with equivalent effective inductance \( L_x, u, v, w \), equivalent effective resistance \( R_x(u, v, w) \) and coupled coefficient \( k \) among each working coil. Inductance \( L_u \) and resistance \( R_u \) by mutual induction are defined;

\[ R_u = R_{uw} + R_{uw} = R_{uw} + R_{uw} = R_{uw} + R_{uw} \]  

(8)

\[ L_u = L_{uw} + L_{uw} = L_{uw} + L_{uw} = L_{uw} + L_{uw} \]  

(9)

where \( R_{xy} \) and \( L_{xy} \) (x, y: u, v, w, x≠y): resistance and inductance components by mutual induction between phase x and phase y. Mutual inductance \( L_{xy} \) and \( L_{uv} \) is represented by:

\[ L_{uv} = L_{uv} = k \frac{1}{\sqrt{L_u L_v}} = k L_{uv} \]  

(10)

In the first condition (a), it is necessary for three phase type working coils have weak coupling. In the second condition (b), the coil currents tend to be unbalance, because mutual inductances are unbalance.

The prototype of working coils is shown in Fig. 11. This model has working coils in phase u and v between half of working coil in phase w and half of one. Self-inductance \( L \) in each phase is defined;

\[ L = \frac{K \mu_0 n^2 S}{l} \]  

(15)

where \( K \): nagaoka coefficient, \( \mu_0 \): space permeability, n: coil turns numbers and S: coil sectional area. Coupled coefficient \( k \) is shown by

\[ k = \frac{1}{2} \sqrt{1 + \frac{\omega^2 (L_x - L_{xy})^2}{L_x (L_u - L_{uv})}} \]  

(16)
where \( L_u \): self-inductance in phase u and \( L_{uv} \): inductance in phase u when terminals in phase v are shorted.

Coupling coefficient of working coil model is indicated in Table II. As can be seen, every coupling coefficient are balanced. Accordingly, the working coil model is suitable for three phase working coil type IH boiler.

VI. CONCLUSIONS

This paper evaluated the input and output characteristics of proposed three phase UFAC-HFAC direct power frequency conversion circuit on the basis of computer aided simulation. A novel soft switching three phase UFAC-HFAC direct converter with PFC function was discussed. Wide soft switching operation area and fine output power regulation characteristics are ascertained computer aided simulation. The input current harmonics and power factor in UFAC grid side were suppressed under limited value by asymmetrical PWM control. From the characteristics of proposed three phase UFAC-HFAC direct power converter, the duty factor \( D \) as a control variable was determined in \( 0.2 \leq D < 0.9 \).

Furthermore, new working coils design for IH load with the balanced coupling coefficient in each phase was evaluated from a theoretical point of view. The working coils are practically designed for the following specific conditions:

(a) phase coupled coefficient \( k \leq 0.25 \)

(b) phase coupled coefficient is symmetric between each phase.

In practical case, it has seemed every coupling coefficient of new working coil assembly was balanced. This working coil model is suitable for three phase working coil type IH boiler.

REFERENCES