A THREE PHASE INPUT UNITY POWER FACTOR QUASI-RESONANT INVERTER

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ABSTRACT

The proposed converter system has been designed to draw sinusoidal input current waveforms from the three-phase mains supply and can be divided into two relatively independent stages. The first stage consists of a Three-Phase Quasi-Resonant Push-Pull Buck Converter to transform the three-phase AC into DC. The second stage consists of a single ended resonant inverter which transforms the DC into AC. The converter circuit functions as a high power factor low harmonic rectifier based on the concept that the peak capacitor voltages are proportional to the line input currents. Hence the low frequency components of the capacitor voltages are also approximately proportional to the line input currents. The use of a single switch resonant inverter, which is operated with Discontinuous Conduction Mode (DCM), allows the switching device to turn off under zero current conditions, therefore switching losses are much reduced. A 1kW, three phase, unity input power factor induction heating system prototype, which achieves high quality sinusoidal input current waveforms, has been built and tested.

Keywords: Buck converter ,Power Factor Correction, Zero Current Switching, resonant inverter.

1. INTRODUCTION

In general, power conversion involves the process of either converting alternating current (AC) to direct current (DC) or converting DC of one voltage level to DC of another voltage level. The process of converting DC to a required AC of specified frequency is necessary for many applications(e.g., variable-speed AC motor drives, uninterruptible power supplies, induction heating). One of the major problems with present day converter system, is that the power drawn from the mains supply is often of low power factor and the current of high harmonic distortion (Nuns J., 1993). A standard three-phase bridge rectifier circuit feeding a single DC/DC converter is extensively used as a DC source in industrial applications up to 120 kW level. Unfortunately the conduction angle of each phase is limited to 120°(while the diode is forward biased) Consequently, resistive input currents can not be drawn from the supply using a very common rectifier system (Cavallini A., 1994). Similar results are achieved using a controlled three phase bridge with six thyristors. Operating a plant at low power factor results in additional voltage drops throughout the power supply system yielding a lower system voltage on the plant bus lines and increases plant operating cost (Andrews D., 1996).

In the past, however, a considerable amount of literature has been published dealing with methods of power factor improvement of the converters. Active power factor control methods include many alternatives, such as constant-frequency peak current control (Nalbant M.K., 1989), clamped-current control (Maximovic D., 1995), and operation at the boundary between the continuous and discontinuous conduction mode (Lai J.S., 1993). Although the requirement of a large number of switching devices and drivers leads to a very expensive system, three phase boost rectifiers are operated with unity power factor and sinusoidal ac input current (Bialoskrski P., 1993).

In order to achieve sinusoidal input currents from the three phase mains supply, a new type of three phase rectifier-converter topology concept has been identified. It is based on a three phase inductive/capacitive network, a high frequency full bridge rectifier, a DC/DC converter arrangement and a resonant inverter as seen in Figure 1. The system can be designed to achieve high quality sinusoidal input supply currents, when operated with discontinuous resonant capacitor voltages. A power circuit of the three phase input converter using quasi - resonant

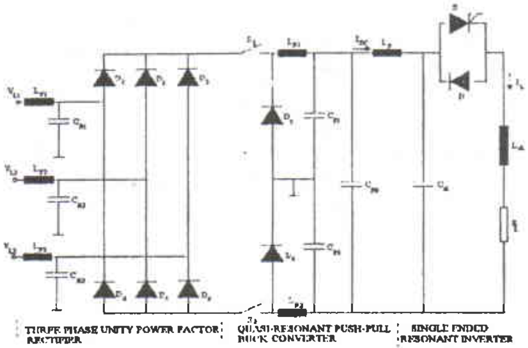

Figure 1 Circuit diagram of the proposed three phase unity input power factor converter system

technique has been developed to overcome the limitations of restricted power density and efficiency of PWM operation.

This topology is operated under the zero-current switching mode of the semiconductor devices(Sazak B.S(1), 1999). The use of a push-pull configuration with a pair of switches enables the use of high speed devices with a low voltage switching stress. Using quasi-resonant techniques the proposed topology is very suitable for practical application at high power level and it provides very low harmonic distortion of the input current.

2. GENERAL DESCRIPTION OF THE CONVERTER STAGE

The Three Phase Unity Power Factor Converter is operated with discontinuous resonant capacitor voltages. Discontinuous input capacitor voltages are obtained by employing an inductive/capacitive input network, L_{F1}, L_{F2}, L_{F3} and C_{R1}, C_{R2}, C_{R3} at the input of each phase. The output voltage of the QR Push-Pull Buck Converter is smoothed by using the filter capacitors C_{F1} and C_{F2}. The input currents I_1, I_2, I_3 are filtered through the input inductors L_{F1}, L_{F2}, L_{F3}.

A commonly used definition of the input power factor for sinusoidal line input voltages:

$$PF_{IN} = \frac{P_{IN}}{3V_{RMS} I_{RMS}} \qquad \text{Eq. 1}$$

where P_{IN} is the average input power, V_{RMS} is the RMS value of the sinusoidal input voltage and I_{RMS} is the RMS phase input current. The input power P_{IN} is presented as;

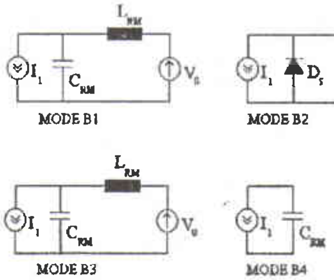

Figure 2 Equivalent modes of single phase converter model operation.

$$P_{IN} = \frac{1}{\pi}\int_0^{\pi} 3 v_L i_L d(\omega t) \qquad \text{Eq. 2}$$

In practice, typical AC current waveforms in single-phase and three-phase diode rectifier circuits are far from being sinusoidal. The power factor is also very poor because of the harmonic contents in the line current (Mohan N.,1989). For purpose of design and achieving the required high input power factor, it is important to outline operating conditions and restriction of the components used in the circuit. Each switching cycle of the proposed converter can be divided into four modes of operation as seen in Figure 2. During the Mode B1 of the unity power factor converter the three input capacitors C_{R1}, C_{R2}, C_{R3} are discharged. The rate of voltage decrease across each capacitor is dependent on the phase input currents I_1, I_2, I_3 and on the current stress of the active switches S_1, S_2. The average values of the capacitor voltages v_{CR1}, v_{CR2}, v_{CR3} during this Discharge Modes are therefore not linearly dependent on their phase input currents. In this case the line input current will become more dependent on the peak value and the length of the Discharge Modes. Since the area of the Mode B1 depends not only on the line input voltage but also on the output voltage more distortion will then appear in the phase input current.

The distortion during Mode B2 and B3 is very little and depends mainly on the value of the input filter inductors L_{F1}, L_{F2}, L_{F3}. The inductors can be designed so that they can provide approximately constant input current during a complete switching cycle.

During the Mode B4 all three capacitors are charged by the input currents I_1, I_2, I_3. As a result, the three capacitor voltages v_{CR1}, v_{CR2}, v_{CR3} begin simultaneously to increase at a rate proportional to their respective input currents. If discontinuous input capacitor voltage operation is assumed and initial voltages across each capacitor C_{R1}, C_{R2}, C_{R3} are zero, the peak voltage across each capacitor at the end of the Mode B4 is proportional to its respective phase input current. Since resonant capacitor voltages always begin at zero their average values during the Mode B4 are also linearly dependent on the phase input currents.

The output current also has influence on the power factor. If the load current I_0 increases the rate of the capacitor voltage discharge increases. The result is that average capacitor voltage is more dependent on its peak value and therefore is proportional to the phase input voltage. Hence the rectifier input characteristic becomes more linear.

There are several important conditions which provide the unity power factor property of the three phase rectifier stage. To draw sinusoidal input currents from the supply(automatic input power factor correction), the three-phase rectifier stage must draw input currents averaged over each converter switching cycle which is proportional to the phase voltages. Assuming steady state operation, the average phase input voltages over each switching cycle must be equal to the appropriate average input capacitor voltages C_{R1}, C_{R2}, C_{R3} during the switch OFF-time plus the average input capacitor voltages during the switch ON-time.

The average input capacitor voltages during the OFF-time have been shown to be proportional to the phase input currents (Pforr J., 1992). High quality, unity power factor input currents are achieved by keeping the discharging time of the capacitors short compared with the charging time. Therefore, the discharging currents of the input capacitors C_{R1}, C_{R2}, C_{R3} must be kept large in comparison to their charging currents. This increases the switch current crest factor and the rectifier should be optimized by this parameter.

The input filter inductors L_{F1}, L_{F2}, L_{F3} can be designed so that they can provide nearly constant input currents during a complete switching cycle. The filter capacitors C_{F1}, C_{F2} are chosen so that the output voltage is nearly constant during a whole mains cycle.

3. VOLTAGE CONVERSION RATIO CHARACTERISTIC OF THE CONVERTER

The equations describing each individual operation modes are combined by matching initial and boundary conditions for adjacent modes. The stored energy in the resonant capacitors is delivered to the load during mode 1, mode 2 and mode 3. There is no energy transfer from supply to the load during mode 4 where resonant capacitor is charged. The stored energy in the resonant capacitors during mode 4 is equal to transferred energy during the discharge mode. Delivered energy to the load during Mode B1 can be written as follows;

$$E_o(\theta_1)=V_o\left(-\frac{I_1}{\omega}\sin(\omega\theta_1)-\frac{i_{L_{RM}}(0)}{\omega^2}\cos(\omega\theta_1)+I_1\theta_1+\frac{i_{L_{RM}}(0)}{\omega^2}\right)$$

Eq. 3

At the end of this mode resonant capacitor is discharged and transfers its stored energy to the load. Energy delivered from supply to the load during Mode 2 is found from Eq. 4.25 as;

$$E_o(\theta_2)=V_o\left(-\frac{V_o}{2L_{RM}}\theta_2+i_{L_{RM}}(0)\theta_2\right)$$ Eq. 4

This mode ends when the freewheeling diode D_2 stops conducting. During Mode 3 switch current is equal to resonant inductor current and delivered energy to the load can be found as follows;

$$E_o(\theta_3)=V_o\left(\frac{i_{L_{RM}}(0)-I_1}{\omega}\sin(\omega\theta_3)-\frac{i_{L_{RM}}(0)}{\omega^2}\cos(\omega\theta_3)+I_1\theta_3+\frac{i_{L_{RM}}(0)}{\omega^2}\right)$$

Eq. 5

Resonant capacitor charging mode (Mode 4) follows on directly from Mode 3. Eq. 4.27 and Eq. 4.28 are obtained by equating input energy and energy delivered to the load and given as;

$$V_{IN}=\frac{F_S\{E_o(\theta_1)+E_o(\theta_2)+E_o(\theta_3)\}}{I_1}$$ Eq. 6

$$R_o=\frac{V_o^2}{F_S\{E_o(\theta_1)+E_o(\theta_2)+E_o(\theta_3)\}}$$ Eq. 7

where;

V_{IN} -Input voltage(V), I_1 -Input current (A).

R_o -Maximum load resistance(Ω).

V_o DC converter output voltage(V).

F_S -Switching frequency(Hz).

Switching frequency is depend on the time intervals of each modes and can be found as follows;

$$F_S=\frac{1}{\theta_1+\theta_2+\theta_3+\theta_4}$$ Eq. 8

Component value of the resonant capacitor is depend on the switching frequency F_S, required output power P_0, duty cycle D, and the converter input voltage V_{IN} (Pforr J., 1992);

$$C = \frac{P_0 T}{2 F_S V_{IN}^2} \qquad \text{Eq. 9}$$

The resulting equation system allows the calculation of switching frequency F_S, output voltage V_o and load resistance R_o as functions of the input voltage V_{IN} and the input current I_1. The equations, describing steady state converter operation, have been solved for a range of values of R_0 / Z_n and F_S / F_n (Sazak(2), 1997).

4. OPERATION OF THE SINGLE ENDED RESONANT INVERTER

The output voltage of the resonant inverters is controlled by changing the ratio of switching frequency to resonant frequency (F_S / F_n). In the Continuous Conduction Mode(CCM), the switch is controlled so that the resonant current i_r is continuous and the oscillation between the resonant capacitor and inductor is not interrupted (Ramanarayanan V., 1992). Another way to operate the resonant inverter is with the Discontinuous Conduction Mode(DCM). In this mode the resonating current is interrupted every cycle and during these interruptions the current has a value of zero. Output power control is obtained by varying the duration of the interruption.

The proposed single ended resonant inverter is operated under DCM by setting the switching frequency to half of the resonant frequency. The advantage of this topology is that the turn OFF of the switching action takes place at zero current, therefore, the switching losses are much reduced. An additional advantage of the proposed inverter topology is that it requires a small number of components and of lower in cost compared with the push-pull inverter and the bridge inverter.

The proposed Single Ended Resonant Inverter provides AC current through the coil. This AC current flowing in the turns of the coil creates an alternating electromagnetic field. The power device of the proposed inverter consists of a semiconductor switch S, an inductor L_{rL}, and a capacitor C_{rL}. The diode D, which is connected in antiparallel with switch S, implements bi-directional current flow through the load.

When the switch S is turned ON, the capacitor is discharged through the coil, transfers its stored energy to the load. During this mode a resonant pulse of current, which flows through the load, rises from zero to a maximum value and falls to zero and the switch is self comutated. However, the resonant oscillation continues through diode D in the reverse direction until the current falls again zero. During the OFF time of the switch S the resonance capacitor is charged by the DC supply voltage.

5. EXPERIMENTAL RESULTS

A prototype of the three phase unity input power factor converter system has been built and tested. The active switching devices employed in this prototype are 2xIGBTs (IRGPC40U), a thyristor (N105HR06) and a diode (RURU8060). The prototype is supplied by a three-phase 150V supply.

Figure 3 shows the voltage and current of one phase of the three-phase supply. As a result of the symmetrical converter structure and alternate mode of operation, it is clear that the quality of the phase input currents of phase two and phase three resembles that of phase one.

Practical output voltage and current waveforms of the converter, which is given in Figure 4 show that the delivered energy to the output is nearly constant during the whole switching cycle. Output voltage of the Quasi-Resonant Push-Pull Buck Converter stage is kept constant for a whole switching cycle by output filter components.The single switch resonant inverter converts this DC input to an AC of specific frequency. Discontinuous conduction mode of operation of the single switch resonant inverter is achieved by setting the switching frequency to half of the resonant frequency.

As seen in Figure 5 the proposed resonant inverter system produces nearly sinusoidal output current. As predicted the waveforms of the converter input currents are nearly sinusoidal with an input power factor approaching unity seen in Figure 6.

6. CONCLUSIONS

The proposed inverter system offers advantages including a relatively simple power circuit, high power capability, simple protection circuits and higher efficiency. Additionally, the use of resonant switching technique allows semiconductor devices to be operated at much higher frequencies and with reduced control requirements compared with conventional switch mode operation. Employing switching device with a higher current handling capability can increase the output power level of the proposed inverter.

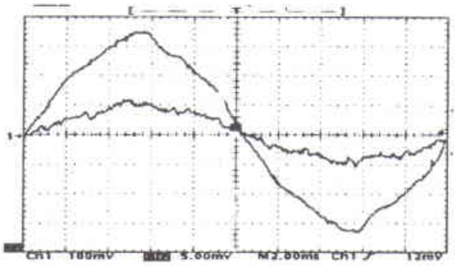

Figure 3 Supply voltage and current of one phase of the three-phase supply at maximum output power [CH1:40V, CH2:3A, T:2mS].

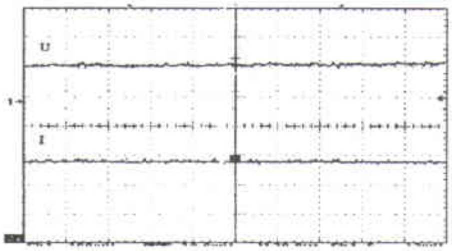

Figure 4 Output DC line voltage and current of the QRW Push-Pull Buck Converter [CH1:100V, CH2:1A, T:20µS].

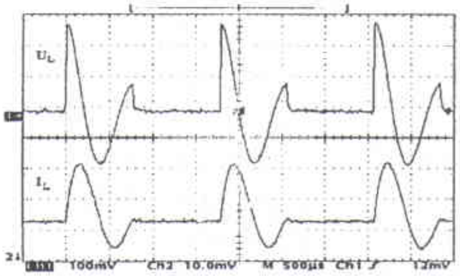

Figure 5 Measured load voltage v_L and load current i_L [CH1:100V, CH2:20A, T:0.5mS].

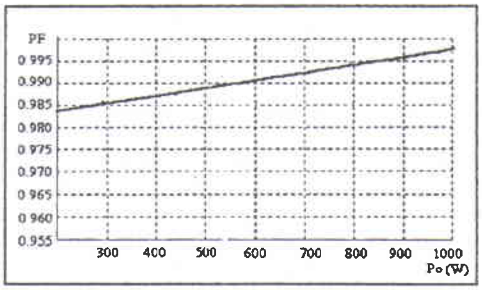

Figure 6 Variation of the input power factor with output power.

The proposed induction heating system offers advantages including a relatively simple power circuit, high power capability, simple protection circuits and higher efficiency. The system can be designed to achieve nearly sinusoidal supply input currents, when operated with discontinuous resonant capacitor voltages and provide output power control in a quasi-resonant mode. The converter also achieves unity power factor for the wide range of output power.

7. REFERENCES

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