PAMUKKALE ÜNİVERSİTESİ MÜHENDİSLİK FAKÜLTESİ
PAMUKKALE UNIVERSITY ENGINEERING COLLEGE
MÜHENDİSLİK BİLİMLERİ DERGİSİ
JOURNAL OF ENGINEERING SCIENCES
YIL : 1998
CİLT : 4
SAYI : 3
SAYFA : 725-731

A NOVEL THREE PHASE UNITY POWER FACTOR CONVERTER

Bekir Sami SAZAK
Pamukkale University, Technical Education Faculty, Department of Electric, Denizli

ABSTRACT

The proposed unity power factor converter system which is able to operate from a 150V three-phase supply whilst delivering the required 200V DC voltage has been built and tested. This 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 system can be designed to achieve nearly sinusoidal supply input currents, when operated with discontinuous resonant capacitor voltages Output power control is achieved by variations of the IGBTs switching frequency. The converter is therefore able to compensate for any changes in the load resistance. The proposed topology offers advantages, including: a relatively simple power, control and protection circuits, high power capability, and high converter efficiencies.

Key Words : Buck converter, Power factor correction, Zero current switching

YENİ BİR ÜÇ FAZLI YÜKSEK GÜÇ KATSAYILI GÜÇ DÖNÜŞTÜRÜCÜ

ÖZET

Sunulan 3 faz 150 V sistemden beslenen ve 200 V DC çıkışı olan yüksek güç katsayılı güç dönüştürücü sistem pratik olarak gerçekleştirildi ve test edildi. Devre yüksek güç katsayılı, düşük harmonik distorsiyonlu doğrultucu gibi çalışır ve temeli maksimum kondansatör gerilimlerinin kaynak giriş akımlarını izlemesidir. Bu nedenle kondansatör voltajının düşük frekanslı bileşenleri de kaynak giriş akımlarını izler. Sistem kesikli rezonans kondansatör voltajları ile çalıştığında hemen hemen sinüsoidal kaynak giriş akımları gerçekleştirilebilir. Çıkış gücü kapısı izole edilmiş Transistorlerin (IGBT) tetikleme frekansları değiştirilerek ayarlanabilir. Bu nedenle güç dönüştürücü yük direncinde oluşabilecek her türlü değişmeyi karşılayabilir. Sunulan metodun avantajlarından bazıları; Kendisine alternatif sistemlerle kıyaslandığında güç, kontrol ve koruma devrelerinin yapımının basitliği, yüksek çıkış gücü verme kapasitesi ve veriminin daha yüksek olmasıdır.

Anahtar Kelimeler : Düşürücü tip güç dönüştürücü, Güç katsayısı düzeltme, Sıfır akımla anahtarlama

1. INTRODUCTION

As a result of the increase in the use of power electronic converters, concern over low power factors, high harmonic currents and accurate control strategies for switching devices has increased considerably (Jayne and Luk, 1988). One of the major problems with present day converter systems, is that the power drawn from the mains supply is often of low power factor and the current of high harmonic distortion (Nuns et al., 1993). This is particularly important because of the present day regulation imposed by supply authorities Nationally and Internationally (Marshman, 1992). Operating a system at low power factor results in additional voltage drops throughout the power supply system yielding a lower system voltage on the plant bus lines. Low system voltage increases the overall plant operating cost. Low power factor (PF < 0.90) can also result in additional cost in the form of penalties from the electric-utility company.

Conventional switching power supplies operate by rectifying the input AC line voltage and filtering it with very large input electrolytic capacitors. This process involves both nonlinear and storage elements which have some very undesirable side effects such as the generation of distorted input current waveform with rich harmonic content that reduce the power factor.

During recent years, however, much research has been carried out to obtain a stabilized DC output voltage from an AC supply whilst drawing unity power factor input current (Pforr and Hobson, 1992), (Ghanem et al., 1996).

Active power factor control methods include many alternatives, such as constant-frequency peak current control (Nalbant and Klein, 1989), clamped-current control (Maximovic, 1995), and operation at the boundary between the continuous and discontinuous conduction mode (Lai and Chen, 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 and Koczara, 1993).

The proposed topology is operated in the Discontinuous Conduction Mode (DCM) When a converter is operated at fixed frequency and fixed duty ratio in the DCM, the low frequency component of the input current is approximately proportional to the input voltage, so that the power factor is automatically close to one (Hobson and Pforr, 1992).

One of the main feature of the proposed topology is its ability to provide high input power factor with a reduced number of components. In all three phases, the need to actively control of line currents is avoided by the use of a quasi-resonant switched mode circuit which naturally emulates a resistive input characteristic.

2. PRINCIPLES OF OPERATION

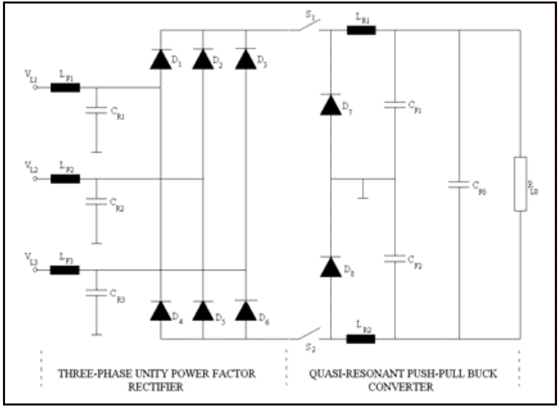

Figure 1. Principal circuit diagram of the overall three phase unity power factor converter and quasi-resonant DC converter

In order to achieve sinusoidal input currents from the three phase mains supply as required, 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 and a DC/DC converter arrangement. The system can be designed to achieve high quality sinusoidal input supply currents, when operated with discontinuous resonant capacitor voltages. As seen in Figure 1 the Three-Phase Unity Power Factor converter consists of two main stages: the passive input stage consisting of the three phase diode rectifier with the inductor/capacitor input filter L_{F1}, L_{F2}, L_{F3} and C_{R1}, C_{R2}, C_{R3} connected to the input of each phase; and the active output stage consisting of the Quasi-Resonant Push-Pull Buck Converter, including the active switches S_1, S_2, the diodes D_7, D_8, the resonant inductance L_{R1}, L_{R2} and the output filter capacitance C_{FO}, C_{F1} and C_{F2}. The active switching devices S_1, S_2 operate in quasi- resonant mode of operation and are switched alternately. Quasi-resonant mode of operation is obtained by allowing the switch current to resonate between the input capacitors C_{R1}, C_{R2}, C_{R3} and the resonant inductors L_{R1}, L_{R2}. Alternate operation of the switches S_1, S_2 has been chosen, because it does not change the overall converter operation in comparison to simultaneous switching, but it provides the advantage of reduced voltage stress across the three-phase rectifier diodes D_1-D_6. At switch turn ON, resonant capacitors are discharged by the resonating switch current and the discharging current of the input capacitors is therefore sinusoidally shaped. As soon as the capacitor voltages are reduced to zero, the diodes D_7, D_8 start conducting. The magnitude of the switch current falls rapidly down to a level equal to the sum of the phase input currents. The sum of the switch current plus the diode current linearly decreases with a slope determined by the inductances L_{R1}, L_{R2} and the output voltage. When the switch current is fully decreased to zero, the active switches are turned off and the input capacitors C_{R1}, C_{R2}, C_{R3} are charged linearly by their respective phase currents I_1, I_2, I_3 until the active switch is turned on again.

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, the three-phase rectifier stage must draw input currents averaged over each converter switching cycle which is proportional to the phase voltages (Sazak 1997). 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, 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.

3. DESIGN PROCEDURE

The design procedure of the QR Push-Pull Buck Converter with three phase input is carried out by using a single-phase model as shown in Figure 2.

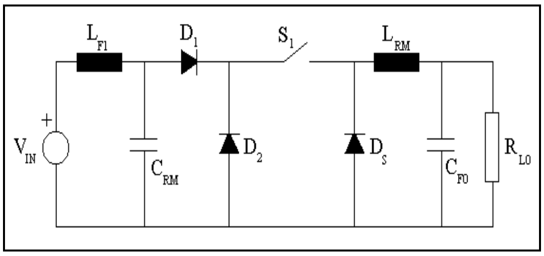

Figure 2. Single phase converter model of the three-phase QR push-pull buck converter

This model is obtained from the three phase converter by assuming that one phase voltage operates exactly at its cross over point. The supply voltage of one phase is therefore zero and the circuit is simplified. The model also assumes, that both active switches S_1, S_2 have been replaced by a single active switch. The design procedure of the converter has been carried out to achieve the converter specification given in Table 1.

Table 1. Design Target Specification of the Converter Based on the Three Phase Push-Pull Buck Rectifier Stage and the Quasi Resonant Buck Converter

Three Phase Unity Power Factor Converter	
Parameters	Prototype
Output Power P	500 W
Output Voltage V_0	200 V
Input Voltage-Three Phase Mains V_{LIN}	150 V
Supply Frequency	50 Hz
Maximum output resistance R_0	60 Ω
Minimum Input Power Factor PF	0.95
Converter Switching Frequency f_{sw}	20-40 kHz

Typical design procedure steps for the Three Phase Buck Rectifier Stage and Quasi-Resonant Push-Pull Buck Converter may be outlined as follows:

The design values of the resonant components of Three-Phase Quasi-Resonant Push-Pull Buck Converter could be obtained from the relationship of the single-phase model and the three-phase converter. It can be seen that the input capacitor values C_{R1}, C_{R2}, C_{R3} are twice as large and inductors L_{R1}, L_{R2} are twice as small as those calculated for the single phase model.

The required output voltage of the three-phase rectifier stage determines the Minimum Voltage Conversion Ratio V_B. A possible converter operating point, which provides the required output voltage could be obtained from the voltage conversion ratio characteristic shown in Figure 3.

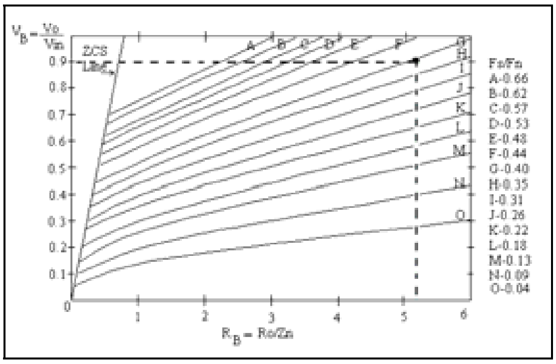

Figure 3. Voltage conversion ratio characteristic of the three-phase quasi-resonant push-pull buck converter (Sazak, 1997).

3. 1. Minimum Voltage Conversion Ratio V_B

In a Buck type converter average converter output voltage V_0, is less than the input voltage V_{IN}.

The voltage conversion ratio V_B, which is depending on the applied input voltage V_{IN} and the required output DC link value V_0, can be found as follows:

$$V_B = \frac{V_o}{V_{IN}} \tag{1}$$

Because the output voltage is always less then the input voltage, the voltage conversion ratio has a value between $0 < V_B < 1$. Voltage conversion ratio V_B for the proposed converter is found as follows;

From Eq.1

$V_0 = 200$ V.

$V_{L_{IN}} = 150$ V.

$$V_B = \frac{V_0}{V_{IN}} = \frac{V_0}{\sqrt{2}V_{L_{IN}}} = 0.9$$

where ;

V_0 - output DC link voltage.
$V_{L_{IN}}$ - three-phase AC mains supply voltage.

3. 2. Normalised Switching Frequency Ratio F_B

From Figure 4 it can be seen that a horizontal line of specified voltage conversion ratio will cross several curves which all provide the required voltage conversion ratio. The curves determine the normalized switching frequency ratio F_B of the converter. The normalized switching frequency ratio F_B, which depends on the switching frequency F_{SW} and the normalized resonance frequency F_N of the converter, is equal to;

$$F_B = \frac{F_{SW}}{F_N} \tag{2}$$

Switching frequency F_{SW} is obtained from Table 1 as 20 kHz < F_{SW} < 40 kHz. This is the switching frequency band of the proposed Three-Phase Buck Converter. Normalized resonance frequency F_N is determined by the resonant components of the converter.

3. 3. Normalized Load Resistance Ratio R_B

A vertical line of the selected normalized switching frequency ratio curve (G) estimates the normalized load resistance ratio R_B as seen in Figure 4. This vertical line determines the final converter design point. The normalized load resistance ratio R_B is given by;

$$R_B = \frac{R_O}{Z_N} \tag{3}$$

where;

Z_N -Normalized impedance.
R_0 -Output resistance of the converter

The normalized load resistance ratio R_B is determined from Figure 3 to be 5. 3.

3. 4. Resonant Components C_{RM} and L_{RM} of The Single Phase Model

Figure 3, 4 shows that several curves are available which all provide a voltage conversion ratio $V_B = 0.9$ (curves named A, B, C, D, F, G, and H). The curve G, which provides a normalized switching frequency ratio $F_B = 0.4$, is chosen because it leads to a design with smaller resonant components. The normalized switching frequency ratio F_B is used to determine the component values of the resonant inductor L_{RM} and resonant capacitor C_{RM}.

Normalized resonant frequency F_N and normalized impedance Z_N of the resonant circuit are given by (Pforr, 1992):

$$F_N = \frac{1}{2\pi\sqrt{L_{RM}C_{RM}}} \tag{4}$$

$$Z_N = \sqrt{\frac{L_{RM}}{C_{RM}}} \tag{5}$$

From the equations (Eq.4 and Eq.5) describing the normalized resonant frequency F_N and normalized impedance Z_N, the component values of the resonant capacitor C_{RM} and the resonant inductor L_{RM} are calculated. The calculation of the resonant capacitor is as follows :

Rearranging Eq. 4, which describes normalized resonant frequency F_N, gives:

$$C_{RM} = \frac{1}{(2\pi F_N)^2 L_{RM}} \tag{6}$$

Rearranging Eq. 5 gives;

$$L_{RM} = Z_N^2 C_{RM} \tag{7}$$

Combining equations Eq.6 and Eq.7 rearranging and collecting terms:

$$C_{RM} = \frac{1}{2\pi F_N Z_N} \tag{8}$$

The normalized resistance R_B and normalized switching frequency F_B found from Figure 3 are given by :

$$R_B = R_O / Z_N \quad = 5.3$$

$$F_B = F_{SW} / F_N \quad = 0.4$$

Combining Eq.2, Eq.3 and Eq.8 gives;

$$C_{RM} = \frac{1}{2\pi} \frac{F_B R_B}{F_{SW} R_O} \tag{9}$$

The solution of Eq.9 gives the component values of the resonant capacitor C_{RM} as follows;

$$C_{RM} = \frac{1}{2\pi} \frac{0.40 \times 5.3}{40 \times 10^3 \times 60}$$

$$=140 \text{ nF}$$

The equation, which determines the component values of the resonant inductor L_{RM}, is obtained by combining and rearranging Eq.3 and Eq.7 as follows:

$$L_{RM} = \left(\frac{R_O \sqrt{C_{RM}}}{R_B} \right)^2 \tag{10}$$

$= 17\ \mu\text{H}$ for the single phase model.

Component value of resonant capacitor for the single-phase model has been found from Eq.9 as C_{RM} = 140 nF. Capacitance value of the resonant capacitors for the three-phase converter can be found as follows ;

$$C_{R1} = C_{R2} = C_{R3} = 2C_{RM} = 280\text{nF}$$

Resonant inductor value for the single phase model has been obtained from Eq.10 as L_{RM} = 17μH. Consequently, the inductance value of the resonant inductors of the three-phase converter is;

$$L_{R1} = L_{R2} = \frac{L_{RM}}{2} = 8.5\mu\text{H}$$

4. EXPERIMENTAL RESULTS

To verify the simulated and theoretical results a 200 V, 500 W prototype converter has been built and tested. The active switching devices employed in this prototype are 2xIGBTs (IRGPC40U). The prototype is supplied by a three-phase 150 V supply.

The measured voltages across the three input resonant capacitors V_{CR1}, V_{CR2}, are shown in Figure 4. It can be noted that the initial voltages across each input resonant capacitor, V_{CR1} and V_{CR2} are zero at the beginning of the each switching cycle.

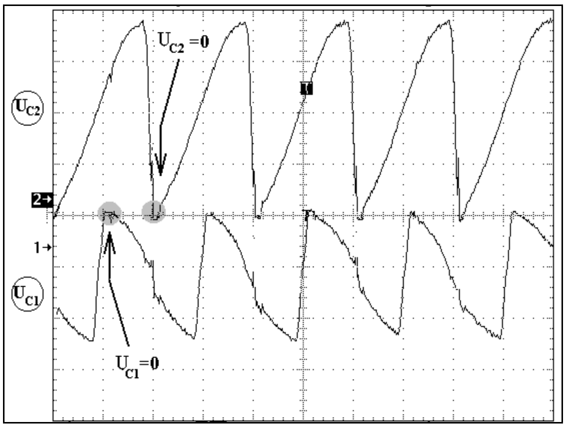

Figure 4. Measured voltage across the input resonant capacitors C_{R1}, C_{R2}, (CH1 : 50 V, CH2 : 50 V, T : 20 μS)

Figure 5 shows the voltage across and current through the IGBTs. It is seen that the turn-on and turn off of the switching device take place at zero current. The zero current switching technique allows the operation of IGBTs at a higher switching frequency and provides lower switching losses.

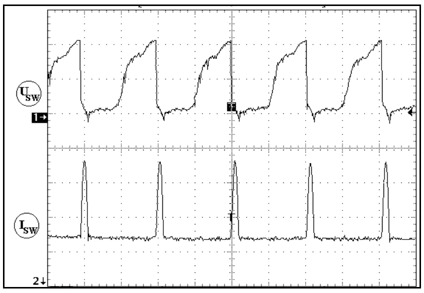

Figure 5. Measured switch voltage v_{S1} and switch current i_{S1} power [CH1 : 50 V, CH2 : 20 A, T : 20 μS]

Practical output voltage and current waveforms of the converter, which is given in Figure 6, 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.

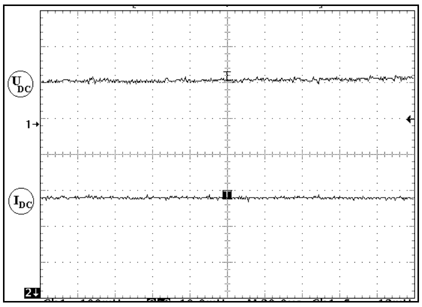

Figure 6. Output DC line voltage and current of the QRW Push-Pull Buck Converter [CH1 : 100 V, CH2 : 1A, T : 20 μS]

Figure 7 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.

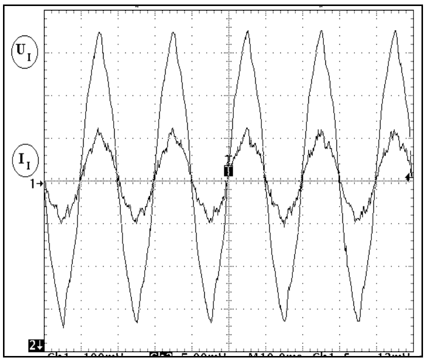

Figure 7. Supply voltage and current of one phase of the three-phase supply at maximum output power [CH1 : 40 V, CH2 : 3A, T : 10 mS]

As predicted the waveforms of the converter input currents are nearly sinusoidal with an input power factor approaching unity as seen in Figure 8.

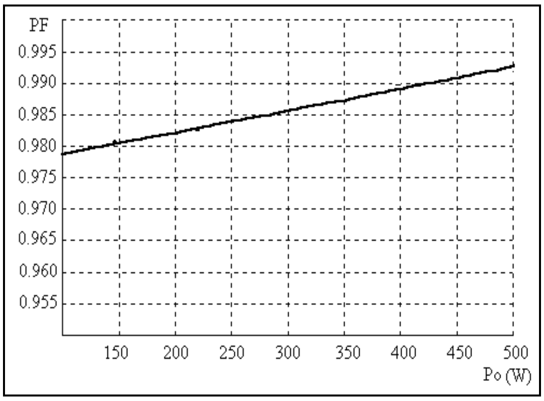

Figure 8. Variation of the input power factor with output power

Variation of the converter output voltage between $V_0 = 100V$ and $V_0 = 200V$ is achieved by varying the switching frequency within a bandwidth between $F_{SW} = 20$ kHz and $F_{SW} = 40$ kHz. The variation of the output voltage with input voltage at different switching frequencies is shown in Figure 9. It can be seen that the relationship between output voltage and input voltage is approximately linear, as expected, because the energy transferred to the output during each switching cycle is mainly determined by the energy stored in the three input capacitors C_{R1}, C_{R2}, C_{R3}.

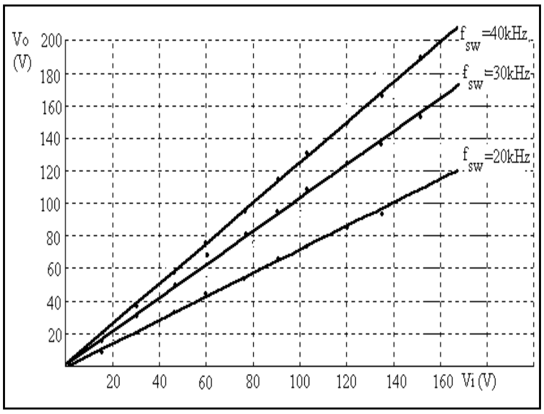

Figure 9. Variation of the output voltage of the Quasi-Resonant Push-Pull Buck Converter system with input voltage at different switching frequency levels

Figure 10 shows the converter output power versus the input voltage at different values of switch frequency. Variation of output power is achieved by changing the switching frequency, whilst the input voltage is maintained constant.

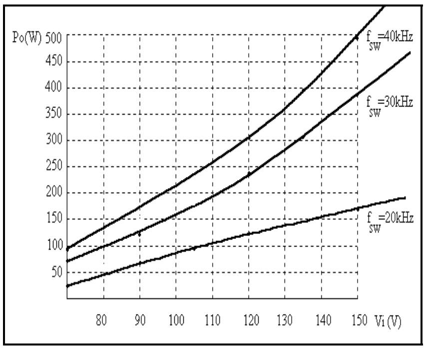

Figure 10. Output power of the induction heating system at different input voltage levels

5. CONCLUSIONS

The advantage of this topology is that it provides a high output power capability and requires a simple and cheap control system. 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.

The alternate switching operation mode of the IGBTs reduces voltage stress across the input rectifier diodes. The proposed system requires reduced number of components compared with the existing systems. The active switching device operate under zero current switching condition, resulting in higher efficiency and low EMI emission and reduces size and cost of snubber components. Additionally this technique allows semiconductor devices to be operated at much higher frequencies and with reduced control requirements compared with conventional switch mode operation.

6. REFERENCES

Bialoskrski P., Koczara, W. 1993. Unity Power Factor Three Phase Rectifier, PESC'93, 20-24 June., 669-674.

Ghanem, M. C., Haddad, K., Roy, G. 1996. A New Control Strategy to Achieve Sinusoidal Line Current in a Cascade Buck-Boost Converter, IEEE Tr. On Industrial Electronics, 43 (3), 441-449.

Hobson, L. Pforr, J. 1992. A Three-Phase Pre-Converter for Induction Heating MOSFET Bridge Inverter, Proc. of the PCIM'92, 464-477.

Jayne, M. G., Luk, C. P. 1988. The Use of Transputer for Pulse-Width Modulated (PWM) Inverter, UPEC'88, 81-84.

Lai, J. S., Chen, D. 1993. Design Consideration for Power Factor Correction Boost Converter Operating at the Boundary of Continuous and Discontinuous Conduction Mode, APEC'93, 267-273.

Marshman, C. 1992. The Guide To The EMC Directive 89/336/EEC, EPA Press.

Maximovic, D. 1995. Design of the Clamped-Current High-Power-Factor Boost Rectifier, IEEE Tr. On Industrial Applications, 31 (5), 986-992.

Nalbant, M. K., Klein, J. 1989. Design of a 1 KW Power Factor Correction Circuit, Proc. Power Conversion, Oct, 121-134.

Nuns, J. Foch, H., Metz M., Yang, X. 1993. Radiated and Conducted Interferences in Induction Heating Equipment: Characteristics and Remedies, The European Power Electronics Association, pp 194-199.

Pforr, J., Hobson, L. 1992. A Novel Power Factor Corrected Single Ended Resonant Converter with Three-Phase Supply, Proc PESC IEEE Toledo Spain, June, 1368-1375.

Sazak, B. S. 1997. A New Unity Power Factor Quasi-Resonant Induction Heater, Doktora Tezi, University of Glamorgan, U. K.