Practical Evaluation of a Novel High Frequency Power Supply for Induction Brazing

R. R. Sawant and N. K. Rana

***Abstract*-- The paper aims at design and Implementation of a high frequency power supply for induction brazing applications. A high frequency power MOSFET based, full bridge, series load-resonant inverter is designed for the present application. An advanced phase shifted PWM and PFM control strategy with zero voltage switching is discussed with its practical implementation. It eliminates the need of separate pre-regulator stage for power regulation. The designed parameters are verified with the Pspice computer simulation. The design is experimentally verified by building a 5kW, 50-100kHz induction heating industrial prototype and its successful testing for the desired specifications.**

Index Terms: **Brazing, Induction Heating, Resonant Inverter. MOSFETs, Pspice, ZVS etc.**

I. INTRODUCTION

THE Induction heating is proved the best technique in heating of metals by electrical means because of several advantages like energy-efficiency, cost-effectiveness, environment friendliness, compactness and ease in automation. In recent years, the high frequency and medium frequency power applications in the field of metal heat treatment have been providing an increasingly important place. With tremendous advancements of power semiconductor devices and electronic control circuits & systems, the voltage fed or current fed load resonant inverters using new power semiconductor devices such as MOSFETs, IGBTs, SITs etc. have been experimentally evaluated for Induction Heating power supplies in Industry.

The conventional implementation of an induction heating power supply consists of a load resonant inverter and a pre-regulator[3]. The pre-regulator regulates the output power during the heating cycle when the load is subjected to change in Q factor. During a heating cycle magnetic materials like iron and iron compounds exhibit large variations in Q and vice-versa for the non-magnetic materials like aluminium, silver, copper, brass etc. Attempts to eliminate the pre-regulator stage by using variable frequency controlled series resonant inverter have resulted in a wide operating frequency range for power control, poor inverter power factor, large circulating power and inefficient switch utilization. The Phase-Shift Controlled (PSC), Series Resonant Inverter (SRI) is practically evaluated for induction heating applications, which can operate over a narrow frequency range and does not require a pre-regulator. It uses the transformer leakage inductance and load inductance as the resonant inductor, resulting in a minimum amount of power components. It regulates the power transferred to the load by controlling the phase shift and ensuring switch turn on at zero voltage by controlling the inverter frequency [1].

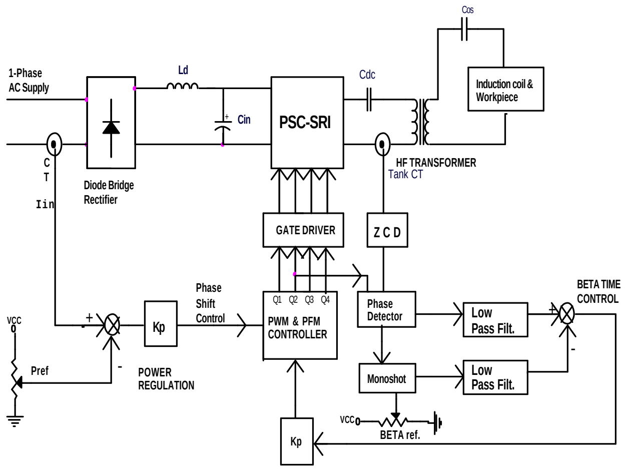

Fig. 1. Block Diagram of the PSC-SRI based Induction Heating System

The present paper describes the design and Implementation of a 5kW, 50-100kHz, PSC-SRI based Induction Heating System for Industrial Brazing applications. The section II describes the basic system block diagram and working of the phase-shift controlled series resonant inverter (PSC-SRI). The section III describes the detail design procedure for a phase-shift controlled series resonant inverter (PSC-SRI) with matching transformer considerations and loss evaluation. The design procedure is illustrated with a practical design example, which is used for practical implementation of the proto-type system. The theoretical design is also verified by Pspice computer simulation. The section IV describes the control strategy and its practical implementation with solid-state circuits. In section V., experimental results of an industrial prototype with different design parameters are presented.

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II. An Overview Of The Present Induction Heating System

2.1 Block Diagram of the present Induction Heating system

Fig.1 shows the block diagram of the present induction heating system. The input stage consists of a diode bridge rectifier with a L-C filter. The small value inductor L_d is sufficient to reduce the inrush current of the capacitor. The diodes are sufficiently rated to supply the initial surge and the rated current in full load condition. Each diode is protected with an appropriate R-C snubber circuit.

The input rectification and filtering stage is followed by a voltage fed MOSFET based, full bridge phase shift controlled series resonant inverter. The circuit diagram of the in3333verter stage is given in Fig. 2. The different inverter waveforms explaining the working and operating principle are depicted in Fig. 3 and 4. The quasi-square wave output of the inverter is fed to a high frequency water-cooled matching transformer. The DC blocking capacitor C_{dc} is connected in series with the transformer primary. The value of C_{dc} should be such that it should offer negligible impedance over the operating frequency range. It has two important functions namely: a) DC Blocking and b) Protecting the inverter during primary short circuit conditions. Its voltage rating should be slightly higher than the dc link voltage. The combined power factor of the induction coil and the load is compensated with the resonant capacitor C_{os} . It is formed using a bank of high frequency high current capacitors in parallel. The compensation of induction heating load on secondary side of the matching transformer is preferred since it reduces the required KVA rating of the transformer and the voltage rating of the compensating capacitors. The two control variables are the inverter frequency and the output power. The former is controlled by sensing the high frequency primary tank current and the latter by sensing the input line current.

2.2 Working of PSC-SRI

The power stage of a full bridge series resonant inverter is sown in figure 2. It consists of power MOSFETs as switches. The four transistors Q1-Q4 are operated with a 50% duty cycle. The switches in each leg of the bridge are on and off 180 degrees out of phase. When operating above the load current i_o lags the quasi-square wave voltage v_{AB}. The MOSFETs parasitic diodes conduct after the MOSFETs output capacitance is discharged. During the diode conduction period (β), the MOSFETs can be turned on at zero voltage. Output power of the inverter is regulated by varying the phase shift between switches Q1 and Q2. The resulting voltage across the tank is a quasi-square wave clamped at zero during the time corresponding to phase shift angle ϕ. If the switching frequency is kept constant and close to resonance, zero voltage switching (ZVS) will be lost for increasing value of ϕ because the load current becomes positive before Q2 turns on. The diode recovery problems are also aggravated. To prevent loosing ZVS, the controller increases the switching frequency to allow for more negative load current before Q2 turns on, ensuring full discharge of the MOSFETs output capacitance [1]-[2].

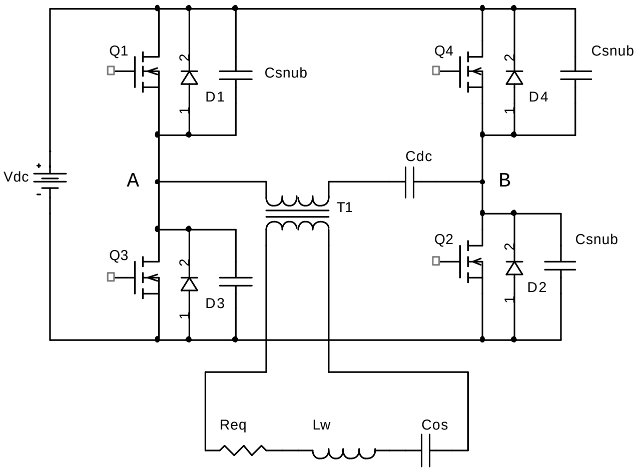
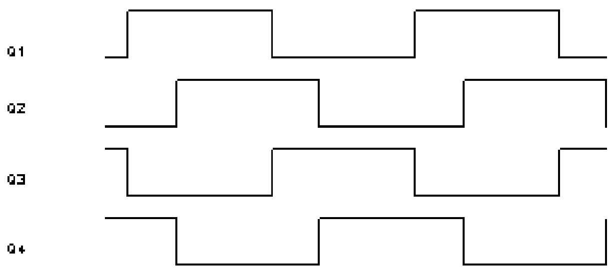


Fig. 2 Power MOSFET based Full-Bridge circuit of PSC-SRI. (Req and L_w are the load equivalent resistance and inductance respectively, C_{os} is



secondary resonant capacitor, Cdc is the DC current blocking capacitor and Csnub is the snubber capacitor across each switch)

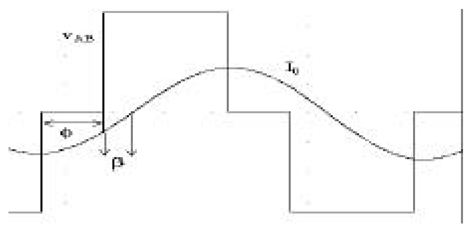


Fig. 3 Switch control signals for PSC-SRI.

Fig. 4 Inverter Waveforms to explain working of PSC-SRI

III. Design Details Of The Induction Heating System

The design consists of the evaluation of following parameters:

1) The output resonant Capacitor $C_{os.}$ 2) The turns ratio of impedance matching transformer.3) KVA Rating of the power switches. 4) The worst-case β_{min} 5) The maximum Phase shift angle ϕ_{max}

Table 1 shows the symbols used for different design parameters. The design procedure for the evaluation of the above parameters is mentioned below with the appropriate design steps and is illustrated with a sample practical example based on the brazing application, however, it can be extended for any induction heating applications.

3.1 *Design Steps*

Selection of Input Design Specifications decides the design Specifications from the input specifications depending upon the work-piece size and the required heating time.

TABLE . 1 DESIGN PARAMETERS

Abbreviations:

P_{out} : Output Power (Watts)
P_n : Normalised Output Power (Watts)
V_{in} : DC link voltage (Volts)
i_o : Resonant tank current on primary side of the HF Transformer
v_{AB} : The quasi-square wave voltage appearing at the output terminals of the Inverter Bridge
V_{cap} : The maximum peak value of Secodary side capacitor voltage
Ios : Peak value of secondary side tank current
L_w : Equivalent inductance of the coil and work-piece (μH)
f_o : Resonant Frequency of the tank circuit (kHz)
Z_{0p} : Characteristic impedance of the tank circuit referred to primary (Ohms)
Z_{0s} : Characteristic impedance of the secondary side tank circuit (Ohms)
C_{os} : Secondary Resonant Capacitor (μF)
Q_{min} : Minimum value of the Quality factor of the load
Q_{max} : Maximum value of the Quality factor of the load
C_{snub} : Snubber capacitor across each switch (μF)
C_{dc} : DC Blocking Capacitor connected in series with the primary (μF)
n_1/n_2 : Turns Ratio of Impedance Matching Transformer
β_{min} : The worst case value of the phase portion where tank voltage is positive and the tank current is negative
$R_{eq}(min)$: Minimum value of the equivalent resistance of the coil and work-piece referred to primary (corresponding to Q_{max} (Ohm)
ϕ_{max} : Maximum Phase shift (Degrees)
$C_t = C_{os}+C_{snub}$:Total output Capacitance of each switch (μF)

The Induction brazing is a through heating method. It mostly need medium power and frequency. The parameters such as output Power, input voltage, resonant frequency, coil inductance and coil Q factor range are treated as inputs to the design. The normalized power P_n is selected in the range of 2-3. Normally higher value of P_n is preferred since it causes the operation close to resonance and leads to higher transformer turns ratio, which in turn leads to lower secondary capacitor voltage.

A. Design of resonant capacitor C_{os}

The value of Cos is calculated by using values of f_0 and L_w

$$C_{os} = 1 / [(2.\pi.f_0)^2.L_w] \quad (1)$$

The peak voltage rating of the tank capacitor is given as

$$V_{c(peak)} = (n_2/n_1).(4.V_{in}/\pi).(Q_{max}) \quad (2)$$

The current rating is same as maximum coil current since it is connected in series with the induction coil.

(The turns ratio is found from step E below)

B. To find Secondary side Characteristic Impedance(Z_{os})

The characteristic impedance offered by secondary side resonant circuit is given as :

$$Z_{os} = \text{sqrt} (L_w / C_{os}). \quad (3)$$

C. To find primary side Characteristic Impedance(Z_{op}) :

The normalized power P_n is defined as :

$$P_n = P_{out} / [(V_{in}^2)/Z_{op}] \quad (4)$$

Therefore find Z_{op} from the above equation by substituting values for known parameters.

D. Transformer turns ratio (n_1/n_2)

$$n_1/n_2 = \text{sqrt} (Z_{0p} / Z_{0s}) \quad (5)$$

E. KVA Rating of the power Switches:

The KVA rating of each switch in a full bridge configuration is decided by calculating the maximum voltage appearing during its off state and the maximum peak current during its on state.

The maximum voltage appearing across each switch is the DC link voltage V_{in}. Therefore the voltage rating should be around 1.5 times V_{in}, where 50 percent safe margin is kept for inductive voltage spikes due to stray inductance in the circuit.

The resonant tank current in Series Resonant Inverter is approximately sinusoidal near resonant frequency due to filtering action of R-L-C circuit. Each switch conducts nearly half cycle of each current cycle. The RMS Inverter current on primary side of the matching transformer is calculated by calculating the RMS value(V_{AB}) of fundamental component of the quasi-square wave inverter output voltage v_{AB} and the total reflected impedance on primary side at resonant frequency. To simplify the calculation and to allow for safe margin due to transient over-current, the current is calculated at zero phase shift and zero β angle.

The RMS value of fundamental component of the Inverter output voltage with zero phase-shift is:

$$V_{AB} = 2. (1.4142). V_{in} / \pi \quad (6)$$

and the maximum RMS tank current is:

$$I_0 = V_{AB} / R_{eq(min)} \quad (7)$$

Thus the Current rating of the switch would be I_0 /2

The KVA Rating of each switch would be the product of V_{in} and I_0.

F. Calculation of b_{min}

β is the anti-parallel diode conduction period and during which the charge transfer takes place from one switch to other switch of the same leg.

Thus

$$\beta_{min} = \arccos [1- (2.\omega_s .q_t / I_p)] \quad (8)$$

where I_p : The peak load current at Q_{max} ;

ω_s : The radial switching frequency.

G. Calculation of the maximum phase-shift f_{max}

Let α : The phase angle between the fundamental component of the quasi-square tank voltage v_{AB} and the approximate sinusoidal load current i_0

$$.\alpha = \arg (Z_{in}) = \arctan [(\omega_n^2-1).Q / \omega_n] \quad (9)$$

Where ω_n : The normalized switching frequency and is given as ω_s / ω_0

Therefore the maximum permissible phase shift for the given Q factor without loosing ZVS is given as:

$$\phi_{max} = 2.(\alpha - \beta_{min}) \quad (10)$$

It was observed that the angle ϕ_{max} reduces with reduction in Q factor. Thus the output power control range by phase-shift control is greater for higher Q factor load and vice-a-versa.

H. Impedance Matching Transformer Considerations:

It is well known that the impedance of the induction coil with work-piece and the compensating capacitor together is very small and can not be connected directly across the inverter bridge. A high frequency transformer with appropriate turns ratio and KVA rating is used for matching the load impedance. The secondary and sometimes primary winding are made water-cooled. The transformer core is made from good quality ferrite sections with appropriate core size. The transformer core area and window area can be decided from Area Product Approach. However, the saturation-less operation should be ensured strictly since the saturation of the core may lead to loss of resonance and very high current spikes. All precautions are taken to reduce the transformer leakage reactance since it may reduce the power transfer and may change the resonant frequency as well as quality factor.

3.2 Loss Calculations:

The losses associated with the present Induction Heating System can be grouped into the following categories:

a) Losses in the Input Rectifier Bridge
b) Losses in the Resonant Inverter
c) Losses in the Matching Transformer
d) Losses in the Induction Coil and Capacitor Bank

The system efficiency can be calculated by computing all the above losses and the input power. The loss calculation is explained in detail in following sub-sections 3.2.1 – 3.2.4 .

3.2.1 Losses in Input Rectifier Bridge

For Single Phase Rectifier Bridge the rectifier power loss is expressed as follows:

$$P_{rect} = 2.\, V_{fd}.I_{in} \quad \text{Watts} \quad (11)$$

where, V_{fd} is the forward drop of diode and I_{in} is the RMS input line current.

3.2.2 Losses in the Resonant Inverter

Losses in the resonant inverter operating above resonance can be further divided into the following items:

- Switching losses consists of the switch turn-on and turn-off losses.
- Conduction losses in the switches:
- Conduction losses in the anti-parallel diodes
- Gate Drive and control circuit losses

3.2.2.1 Switching Losses

Switching losses in case of PSC-SRI is presented as below[4]:

1) Switch Turn-On Loss

In case of PSC-SRI operating above resonance, the switch turn on loss is negligible since the switch is turned on when the current through its anti-parallel diode reaches zero.

2) Switch Turn-Off Loss

the turn-off loss in each switch is given by :

$$P_{off(1)} = [\, I_f^{\,2}.t_f^{\,2}.f_{s(max)} / (24.C_t)\,] \quad (12)$$

where I_f : The current through the switch at the start of turn-off. Normally it is considered as 80% of the peak value of Inverter current
t_f : The fall time of the switch and can be found from the device data sheet
$f_{s(max)}$: The maximum switching frequency
$C_t = C_{oss} + C_{snub}$: The output capacitance of the each switch.

The total turn-off loss is the summation of individual switch losses.

3.2.2.2 Switch Conduction losses

In PSC-SRI, the inverter current is approximately sinusoidal near resonance and each switch is conducting for approximately half the switching cycle, the conduction loss per switch is given by:

$$P_{cond} = (I_{0(peak)} / \pi)^2 R_{(DS)on} \quad (13)$$

where $I_{0(peak)}$ is the peak value of the inverter current.
and $R_{(DS)on}$ is the MOSFETs on state resistance.

3.2.2.3 Conduction losses in anti-parallel diode

In full bridge configuration, there are four anti-parallel diodes across the four switches. Out of these four, two are conducting for the period β (diodes D_2 and D_4) and other two are conducting for the period $\beta + \phi$ of the resonant cycle (diodes D_1 and D_3). Therefore the total conduction loss in anti-parallel diodes is given as:

$$P_{d(anti)} = (I_{0(peak)} / \pi).\{2 - [\cos(\beta) + \cos(\beta+\phi)]\}.V_{SD} \quad (14)$$

where V_{SD}: the anti-parallel diode forward voltage drop

3.2.3 Losses in HF Transformer

The losses in transformer are :

- *Copper loss in the transformer winding*
- *Eddy current loss in the transformer core*
- *Hysteresis loss in the transformer core*

Copper loss in primary and secondary winding can be calculated by knowing their AC resistance and their respective currents. The skin effect is pronounced at high frequencies and should be considered while evaluating the winding resistances. At high frequencies, the eddy current loss in the transformer core is more dominant than the hysteresis loss. Practically, the total transformer loss is considered to be 1% of the total output power[4].

3.2.4 Losses in the Induction Coil and Capacitor Bank

The induction coil copper loss and the copper loss in secondary capacitor bank can be evaluated by knowing their resistances at no load condition. There is also some loss taking place in capacitor dielectrics. By practical approximations, the total loss in induction coil and capacitor is considered as 0.5 % of the total output power.

After calculating the total losses, the theoretical estimate of the system efficiency is given by:

$$\eta = (P_{in} - \text{losses}) / P_{in} \quad (15)$$

where P_{in} is total input power supplied to the system in watts.

3.3 Design Example

The theoretical design explained in sections 3.1 and 3.2 is illustrated with following example:.

It is intended to design an Induction Heating System for induction brazing of an automobile part. The input specifications are given as follows:

Pout = 5kW; V_{in}=300V; f_0=60kHz; Q_{min}=3; Q_{max}=20; P_n=3; L_w=1uH (for 3 turn induction coil); Single phase 220 volts, 50Hz Input Supply.

a) The Resonant capacitor value $C_{ois\ found}$ from (1) is calculated as 7.036µF. We choose a bank 15 capacitors, 0.47µFeach, so that the total C_{ois} is 7.05µF.

b) The matching transformer turns ratio is calculated from (3), (4) and (5).Therefore Z_{os} = 0.3766Ω; Z_{op} = 54 Ω; n_1/n_2 = 11.97.We choose n_1 = 12 and n_2 = 1.

c) The switch voltage rating is chosen as 500V and the current rating is calculated from (6) and (7). We get V_{AB}=270V; $R_{eq(min)}$ = 2.7Ω and I_0 =100A; I_{sw} =50A.Thus four power MOSFETs each with rating 500V/20A, giving total switch rating as 500V/80A are selected as one switch. The increased current rating is chosen for protection against initial start-up transients.

d) The β_{min} is found to be 14^0 .with f_s as 60kHz; q_r =4 µC and I_p =50A. The phase shift angle ϕ_{max} at Q_{min} and Q_{max} is found to be 40^0 and 76^0 respectively.

e) The estimated losses at rated conditions with maximum power are given as below:

P_{rect} = 40 Watts; with V_{fd}=0.8 and I_d=25Amp .

$P_{off(1)}$=7.85Watt for I_f=25A; $f_{s(max}$=75kHz; Coss=340nF; Csnub=10nF; C_r=13.4 nF; and t_f=232ns. Therefore for four switches $P_{off(total)}$ = 31.4 Watts.

P_{cond} = 58 Watts; The transformer loss = 50 Watts

The induction coil and the capacitor loss=25 Watts. Considering other Miscellaneous loss as 25Watts

Therefore the total power loss = 230 Watts.

Thus the total system efficiency at 220Volts and 25A input with 0.75 input power factor is estimated as nearly 94%.

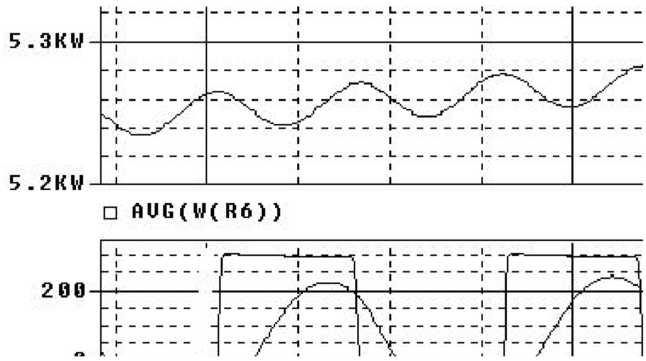
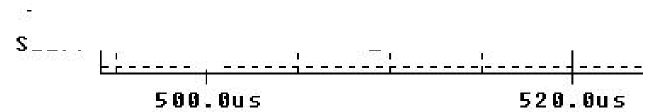


Fig. 5 Pspice Simulation Results of PSC-SRI based Induction Heating System , with Q=10; ϕ=10; fs=64k; V_{in}=300; ; LW=1µH; COS=7.05 µF



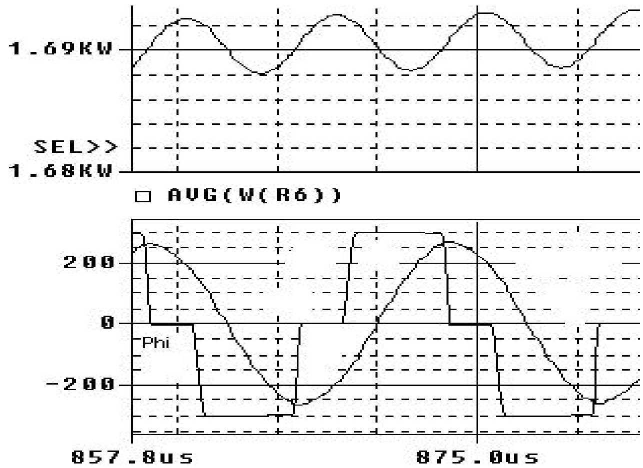


Fig. 6 Pspice Simulation Results of PSC-SRI based Induction Heating System , with Q=10; ϕ=60; fs=67k; V_{in}=300; Lw=1µH; Cos=7.05 µF

IV. CONTROL STRATEGY AND ITS IMPLEMENTATION

4.1 Control strategy

The impedance of the induction-heating load changes during a heating cycle. This effect is more pronounced at the curie temperature if the load is magnetic in nature. The change in impedance can be seen as the change in inductance and the equivalent resistance of the coil and work-piece, which effectively changes the resonant frequency and the quality factor Q.

Thus the control requirements are:

1) The inverter should automatically tracks on the new resonance conditions;
2) It should restrict the output power within the given range (power regulation).

Thus to meet both these requirements simultaneously, a combined phase shifted PWM and PFM is implemented. The two independent control variables are w_n and ϕ. The control

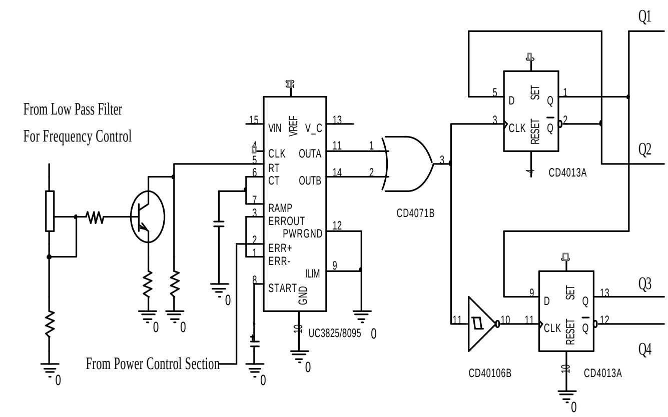


Fig. 7 The IC UC3825 circuit modified as PWM and PFM Controller for generating the switch control signals for PSC-SRI

strategy would be to maintain the β time fixed equal to β_{min} by frequency control (PFM), whereas the output power is regulated with the phase shifted PWM control. The phase shift is locked beyond ϕ_{max}, to ensure the ZVS for all the loading conditions[1]. The control scheme to implement the above control strategy is presented in Fig. 2

4.2 control Implementation

A control circuit is designed around a standard PWM controller IC UC3825 (fig. 5), which can be used as both PWM and PFM controller with some extra hardware. The outputs of the IC are used for generating the switch control signals shown in fig. 4.

The pulse-width and frequency of the pulse is controlled independently by the PWM and PFM control blocks respectively. The circuit implementation for these blocks is written in following sub-sections and their interconnection with PSC-SRI can be found from fig. 2.

4.2.1 PFM Control Block

This block is executing a function of Phase Locked Loop (PLL), which consists of a ZCD, phase detector, low pass filter and retriggerable monostable circuits. The function of this block is mainly to track the inverter frequency for the constant β time control. The reference setting for β time adjustment is fixed at β_{min}.

4.2.2 PWM Control Block

The input AC current is sensed and an analog signal is generated which is considered to be proportional to the input power drawn with constant input voltage. The measured power is compared with a adjustable reference power setting. The error signal is used to automatically adjust the actual power by phase shift control.

V. Experimental Results

The induction heating power supply was trially produced for maximum output power of 5kW at 50-100kHz based on design parameters mentioned in design example mentioned in sub-section 3.3. The PSC-SRI was built using power MOSFETs. Each switch was consisting four power MOSFETs IRFP460 (500V/20A) connected in parallel to meet the desired current rating. Figures 8 and 9 shows the

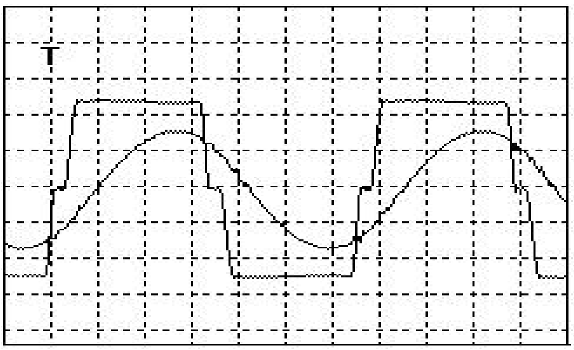


Fig. 8 Oscillogram of the inverter voltage VAB and inverter current i_0, Pn=5kW; fs=64kHz; $\phi = 10^0$, (Scales: Voltage150Volts/div., Current:20A/div., Time: 2us/div.)

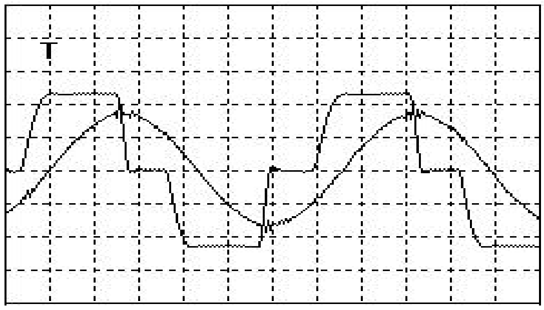


Fig. 9 Oscillogram of the inverter voltage VAB and inverter current i_0, Pin=1.71.6kW; fs=77kHz; $\phi=60^0$, (Scales: Voltage150Volts/div., Current:10A/div., Time: 2μs/div.)

different experimental waveforms at minimum and maximum phase-shifts respectively. The experimental waveforms can be compared with the simulated waveforms shown in figures 8 and 9.

VI. Summary

This paper described the design, development and control implementation of a 5kW, 50-100kHz solid-state power supply for induction brazing applications. Constant β time control for frequency control and phase shift control for power regulation was practically implemented with low cost general-purpose components. A prototype Induction Heating System was built and tested for 5kW output power and 50-100kHz switching frequency for industrial brazing. The designed parameters were simulated and verified using Pspice computer simulation package

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