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Current Source ZCS PFM DC-DC Converter for Magnetron Power Supply

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Abstract

This paper presents the design of zero current switching ZCS pulse frequency modulation type DC-DC converter for magnetron power supply. A magnetron serving as the microwave source in a microwave oven is driven by a switch mode power supply (SMPS). SMPSs have the advantages of improved efficiency, reduced size and weight, regulation and the ability to operate directly from the converter DC bus. The demands of the load system and the design of the power supply required to produce constant power at 4[kV]. A magnetron power supply requires the ability to limit the load current under short circuit conditions. The current source series resonant converter is a circuit configuration which can achieve this. The main features of the proposed converter are an inherent protection against a short circuit at the output, a high voltage gain and zero current switching over a large range of output power. These characteristics make it a viable choice for the implementation of a high voltage magnetron power supply.

Key Words : DC-DC converter, series capacitor, compensated transformer, leakage inductance, resonant converter, magnetron power supply

1. Introduction

Microwave technology was developed during the Second World War, when vacuum tubes termed magnetrons were invented and perfected. These magnetrons were capable of generating many kilowatts of electromagnetic power at previously unattainable frequencies. Microwave energy is widely used in industry and home applications.

Microwave heating and drying has several advantages over conventional thermal heating/drying methods, such as; instantaneous rapid heating, efficient and accurate control of heating and drying rates, significant energy savings, drying time can be shortened by 50[%] or more, occupies less space and reduces handling time, improves product quality and, in some cases, eliminates case hardening, internal stresses, and other problems of quality such as cracking. As a magnetron of a commercial microwave oven requires 4[kV] for its operation, a high voltage supply is required. For most household microwave ovens, this voltage is provided by a half-wave

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doubler's power supply circuit. In this type of circuit, half of the voltage, 2[kV], is supplied by the transformer, and then is doubled to 4[kV] by a capacitor diode combination. A transformer within the power supply portion of the system raises the voltage from the power line (220[V]) to that required by the supply circuit. The microwave output power from a magnetron can be varied by a number of techniques [1].

Most commercial microwave ovens apply "on-off" power control of the voltage supply to change the power output of the magnetron in an "on-off" mode (Duty cycle control). Different power levels can be achieved by different intervals of the "on" and "off" time. This method has also been extended to research experiments on the drying of bio-products. Many researchers are seeking for the best "on-off" intervals to achieve the best drying result for the specific products. Even some specially designed feedback systems also use the "on-off" control of the power supplied to the magnetron to achieve temperature control in the drying process. Other power control methods have seldom been used until now[2].

Several methods exist for providing high voltage power supply of stable power. The requirement is to provide substantially constant anode current independent of high voltage fluctuation or microwave work load impedance variation. For magnetrons with fixed magnetic field with permanent magnet, the power unit must have adjustable EHT (High voltage power supply) controlled to give constant anode current. The required anode current is set by a dc reference which compared with dc voltage developed across resistor R proportional to anode current. The difference voltage is amplified and fed to trigger circuit to switches.

The resonance circuit of the Power Supply contains a high frequency transformer, the secondary side of which is connected to the magnetron via a voltage multiplier consisting of a rectifier and voltage doubler circuit. To regulate this power, a feedback signal which is proportional to the power fed to the magnetron, a sensing resistor is connected in series with output of the rectifier and voltage doubler circuit. The output signal of the sensing resistor is compared in a control circuit with a reference signal to control the switch frequency and thereby the magnetron power.

Resonant converters have a sinusoidal waveform and are based on filtering out only the fundamental from the square wave. The resonant converter will be designed to operate above resonance due to the advantages presented in [3]: natural commutation of power switches, resulting of low switching losses, reduced components stresses, elimination of turn-on losses and di/dt inductors and increased switching frequency, resulting of reduction in the size of magnetic and filter components, etc.

This paper describes a High Voltage, High Power switch mode supply designed for supplying Magnetron anode. The demands of the load system and the design of the power supply required to produce constant power at 4[kV]. A typical arrangement of a magnetron power supply is shown in Fig. 1.

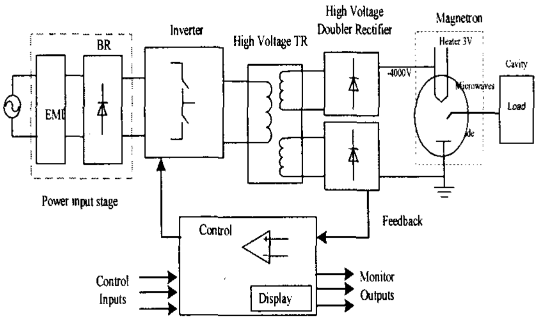


Fig. 1. Basic block diagram of high voltage power supply

2. Half-Bridge Series Resonant DC-DC Converter

2.1 Circuit description

A power supply arrangement for a microwave oven including a magnetron comprising: a switch mode power supply having a resonance circuit fed from a source of AC supply voltage via a diode bridge rectifier and EMI filter supplying a DC-DC converter. This DC-DC converter is composed of typical divided current source half-bridge inverter and two centre points capacitors C1 and C2 act as tuning capacitances in the resonance circuit. The high-voltage side includes a high-frequency transformer, multiple half-wave bridges, and voltage and current monitoring circuits. The secondary side of the transformer is connected to a rectifier and voltage doubler circuit consisting of two capacitors C3, C4 and two high-voltage diodes D3, D4. The tertiary side of the high frequency transformer connected to a rectifier and voltage doubler circuit consisting of two capacitors C5, C6 and two high-voltage diodes D5, D6. The two rectifiers are connected in series to sum the rectified voltage levels to obtain the final output voltage. The half bridge rectifier can be replaced by a center tap full wave configuration. The rectifier and voltage doubler circuit delivers the operating voltage to a magnetron. In order to solve the significant problems mentioned above, a single capacitive snubber assisted series-resonant ZCS-PFM DC-DC power converter with a high-frequency transformer link is proposed in Fig. 2, the secondary side voltage and current sensing circuits are shown in Fig. 3

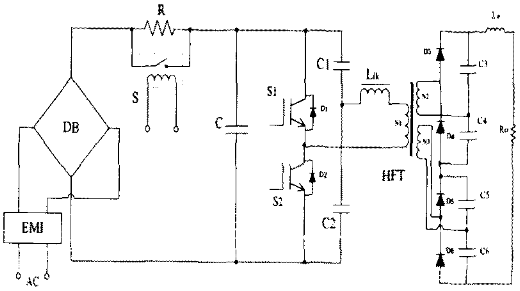


Fig. 2. Circuit configuration of series-resonant ZCS-PFM DC-DC power converter

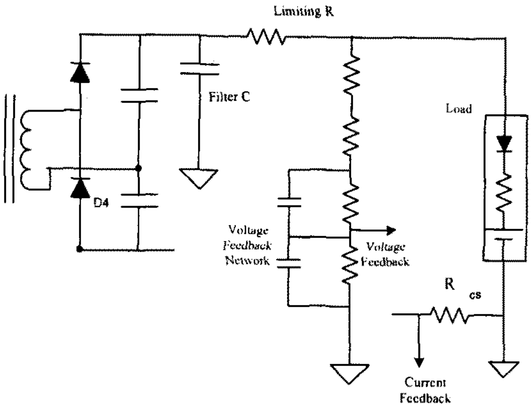


Fig. 3. Typical high voltage output stage

2.2 Feedback control scheme

In order to obtain a feedback signal which is proportional to the power fed to the magnetron thereby to regulate this power, a current sensor resistor is connected in series with the load in the rectifier and voltage doubler circuit. Then a current sensing device, producing a signal corresponding to the DC-mean value of the anode current is required. The output signal of the current sensor is compared in a control circuit with a reference signal and the result of the comparison is used to control the switch frequency and thereby the power fed to the magnetron M is regulated. The power delivered by the resonance circuit to the magnetron is dependent upon the switching frequency. The signal strength of the feedback signal has to correspond to the DC mean value of the anode current and must not be influenced by disturbances caused by irregularities in the anode current.

Another way to sense the current through the high voltage circuit is to use current transformer. A current transformer, which only can transfer the AC-content of the current, can be used in order to get a measure of the dc-mean value of the current and thereby the power fed to the magnetron. To determine the DC-mean value without knowing the initial zero level, this is a condition for being able to use a current transformer for producing a feedback signal, as the transformer cannot transfer the DC-level.

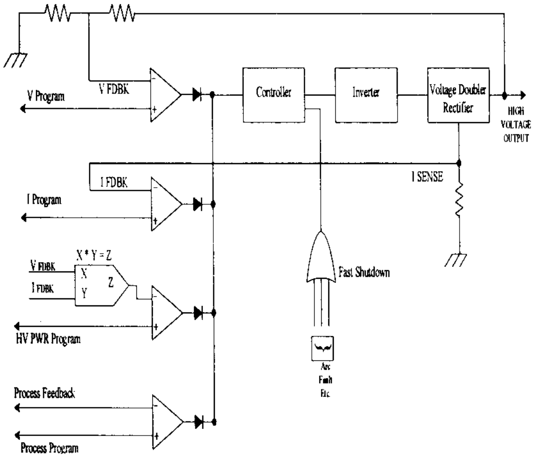


Fig. 4. Power supply control loops

Furthermore the current transformer has the great advantage that it provides galvanic insulation. The anode current has a very irregular waveform and contains strong disturbances. Every second pronounced peak is to be compared with the diode current peak, which show a much more regular and non-disturbed character. Instead of the rectifier and voltage doubler circuit, the current transformer being connected in series with one of the diodes in the voltage multiplier. Control circuits are the glue to keep all of the power stages working together. The basic requirement which every control circuit must meet is to precisely regulate the output voltage and current as load, input power, and command requirements dictate. This is best accomplished by a feedback control loop. Fig. 4 shows how feedback signals can be used to regulate the output of the power supply. Conventional regulation of voltage and current can be achieved by monitoring the output voltage and current respectively. This is compared to a desired (reference) output signal. The difference (error) between the feedback and reference will cause a change in the inverter control device. This will then result in a change of power delivered to the output circuits.

3. Modeling and simulation

3.1 Equivalent circuit model of the magnetron

Typical Input voltage vs. input current characteristics of magnetron is shown in Fig. 5. In the oscillating state of the magnetron, its input side DC voltage can be considered nearly constant since it is represented by a linear v-i characteristic [4] with small slope as indicated in Fig. 5. The electrical equivalent circuit model of the magnetron can simply represent by using pure resistances R0 and R1, an ideal diode D, an ideal battery VZ (cut-off voltage) and an ideal switch as shown in Fig. 6 As illustrated in this figure, the position of the ideal switch in the equivalent circuit of the magnetron is selected whether the voltage between anode and cathode is higher than the cut off voltage or not. For the semiconductor manufacturing production for industrial applications, the stable microwave power is required, and the magnetron is used under a condition of the continuous oscillation. Therefore, the only stable oscillation state is considered for the converter operation in this purpose.

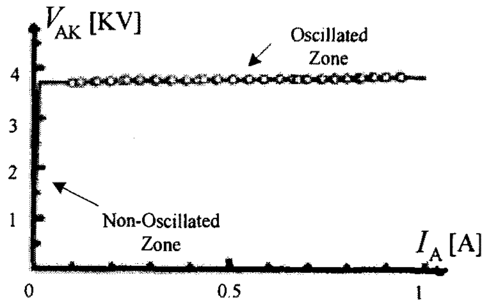


Fig. 5. Input voltage vs. input current characteristics of magnetron.

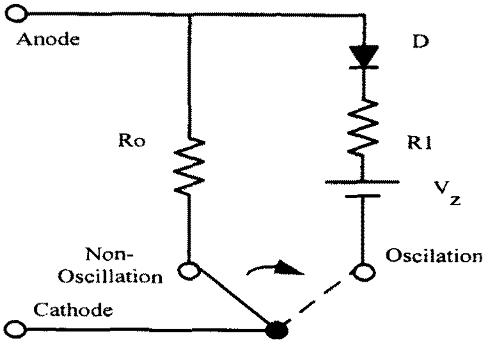


Fig. 6. Electrical equivalent circuit model of magnetron

3.2 High frequency transformer modeling

The series resonant converter design was modeled and calculated using the PSIM simulation software under short circuit and open circuit conditions of the load[5].

The two-winding transformer, in the model, was an ideal transformer. This model had negligible magnetizing inductance or leakage inductance. An extra inductor was placed in series with the primary winding of the transformer to simulate the leakage inductance of the high frequency transformer which was a resonant component in the load leg of the circuit. For the simulation of the open circuit and short circuit conditions two additional switches were placed in the converter model. One allowing a short circuit to occur across the load and the other is in the load leg causing an open circuit[6].

4. Operation Principle

The output of the power input conditioning stage is typically a DC voltage source. This DC voltage provides the energy source for the Inverter stage. The Inverter stage converts the DC source to a high frequency AC signal. Many different inverter topologies exist for power supplies. However, the high voltage power supply has a few factors which may dictate the best approach.

Typically, the Inverter generates a high frequency AC signal which is stepped up by the HV transformer. The reason for the high frequency generation is to provide high performance operation with reduced size of magnetics and energy storage capacitors. A problem is created when a transformer with a high step up ratio is coupled to a high frequency inverter. The high step up ratio reflects a parasitic capacitance across the primary of the high voltage transformer. This is reflected at a (Ns:Np) 2 function. This large parasitic capacitor which appears across the primary of the transformer must be isolated from the Inverter switching devices. If not, abnormally high pulse currents will be present in the Inverter. The high-voltage transformer has two secondary windings to reduce the parasitic resonance caused by the secondary inductance and self capacitance. Another parameter which is common to high voltage power supplies is a wide range of load operations. Due to the presence of high voltage, insulation breakdown, i.e. tube arcing, is commonplace. The inverter robustness and control loop characteristics must account for virtually any combination of open circuit, short circuit and operating load conditions. The microwave power from the magnetron is proportional to the anode current of the magnetron. Therefore, the output power of magnetron can be regulated by controlling its anode current with a feedback loop. The inductance is comprised of the transformer leakage inductance of 3[μH]. The resonant frequency fo is given by (1), and the characteristic impedance of the resonant circuit Z, is found from (2). Equation (3) shows that the on-time of the switches is equal to 1.99[μS], or one-half the resonant period. Three hundred nanoseconds of dead time are provided while the inverter switches at the maximum frequency. Thus the maximum switching frequency fs is 166[kHz] as given by (4) with dead time td =1.1[μS].

$$f_o = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

$$Z_o = \sqrt{\frac{L}{C}} \tag{2}$$

$$t_{on} = \frac{1}{2}T_o = \frac{1}{2f_o} \tag{3}$$

$$f_{\max} = \frac{1}{2(t_{on} + t_d)} \tag{4}$$

The inverter switches may be in one of three different configurations at any given time: 1) S1 may be closed (on) while S2 is open (off), 2) S2may be on while S1 is off, or 3) all of the switches may be off. The anti-parallel diodes (also known as freewheeling diodes) D1-D2, provide a path for the resonant current when the corresponding switches around which they are connected are off. During switching configuration 1), the inverter voltage V_{ab} is equal to +VBus, and the resonant current I_R flows through S1 in the positive direction. During switching configuration 2, V_{ab}=-VBus, and the resonant current is negative and flows through S2. During configuration 3, the value of V_{ab} depends on which pair of freewheeling diodes, if any, is conducting. If D1 and D2, are conducting, Z_R is negative, and V_{ab} = +VBus. If D, and D, are conducting, I_R is positive and Kb = -V_{ab}. If I, = 0[A], then none of the diodes is conducting. The operation of the proposed converter may be divided into four modes based on which switches and diodes are conducting. An equivalent circuit is drawn for each mode assuming that all resistances are negligible, all switches and diodes are ideal, and the transformer is ideal. Mode 1 occurs when switches S1 is conducting and the resonant current I_R is positive. The equivalent circuit for the operation modes is depicted in Fig.8. The load capacitor has been reflected through the ideal transformer and is designated as C_L; the voltage source $V_{3(t)}$ represents the charge stored on the energy storage capacitor at the beginning of the mode. In mode2, this occurs when D1 conduct, the resonant current is negative. As the resonant current is now negative, the polarity of the voltage source $V_{3(t)}$ is the opposite of mode 1 because of the operation of the output rectifier. Mode 3 is characterized by switches S2 is conducting and a negative resonant current and is described by the equivalent circuit. When diodes D2 conduct, the resonant current is positive and the circuit is operating in mode 4. Because the resonant current is positive, the polarity of the voltage source $V_{3(t)}$ is the same as it is in mode 1.

In the steady-state analysis of series resonant converters supplying constant power loads, the transformer, output rectifier, and load are modeled as a constant voltage for all four modes. The solution for the voltages and currents in any of the equivalent circuits in Fig. 7 may be obtained using standard circuit analysis techniques. The current $i_{R(t)}$ in mode 1 can be determined as follows:

$$i_R(t) = \frac{V_{bus} - v_2(t_0) - v_3(t_o)}{Z_o}\sin[\omega_o(t-t_o)] + i_R(t_o)\cos[\omega_o(t-t_o)],$$
$$to < t < tx \tag{5}$$

where the characteristic impedance Z, and resonant frequency wo are given by(6), and t, and t, are the start time and end time, respectively, for mode 1.

$$Z_o = \sqrt{\frac{L}{C_{eq}}} \quad \omega_o = \frac{1}{\sqrt{LC_{eq}}} \tag{6}$$

C_{eq} is the series combination of capacitors C and C_f. The reflected filter capacitance C_f is equal to the product of the C_f and the turns ratio of the transformer squared. As a result, in high-voltage applications C_f is much larger than the resonant capacitor C_r. This is an important reason for employing the series resonant converter in this application. The voltage across the resonant capacitor for mode 1 can be found from :

$$v_2(t) = v_2(t_o) + \frac{1}{\omega_o C}\begin{pmatrix} \frac{V_{bus} - v_2(t_0) - v_3(t_o)}{Z_o}(1-\cos[\omega_o(t-t_o)]) \\ + i_R(t_o)\sin[\omega_o(t-t_o)] \end{pmatrix} \tag{7}$$

The operation of the proposed converter is shown in Fig. 7. As shown in Fig. 7, the gate pulse signal sequences of IGBTs are designed to regulate the pulse frequency under on-time constant condition. The IGBTs are turned on with ZCS and turned off with hybrid ZVS & ZCS in all power regulation range when the switching frequency of this DC-DC converter is less than half of the resonant frequency decided by the resonant capacitor and the leakage inductance of high-frequency transformer. If the switching frequency is more than half of the resonant frequency, bridge current of this converter becomes continuous waveform and this converter operates in continuous current mode. However, in case of using a high-frequency transformer with a leakage and magnetizing parasitic circuit parameter, it is actually difficult to realize the discontinuous current mode in spite of easy zero current soft commutation. In order to implement this operating mode, it is necessary that the magnetizing current through the high-frequency transformer primary winding is nearly zero. The resonant frequency is 251[kHz] with 0.1[μF] capacitor and total series inductance 3[μH]. The currents and voltages for the other modes are of the same form as those for mode 1. The only difference is the sign of some of the voltage terms. For instance, the sign of Vi is positive for modes 1 and 2 and negative for modes 3 and 4. The sign of $V_{3(t)}$ is positive in modes 1 and 4 when the current is positive and negative in modes 2 and 3 when the current is negative. The current flow through the resonant circuit is varied by changing the ratio of the switching frequency to the resonant frequency. This ratio may be held constant or it may be varied.

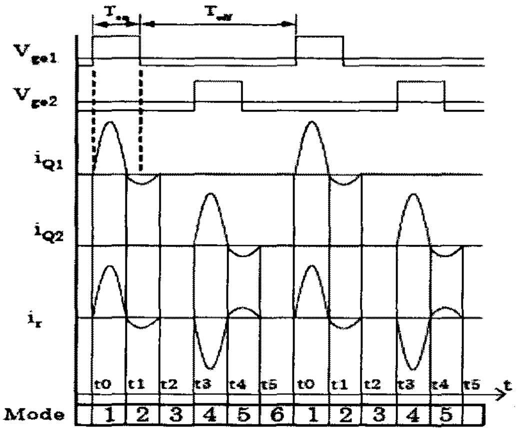
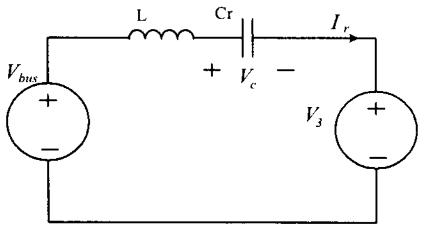
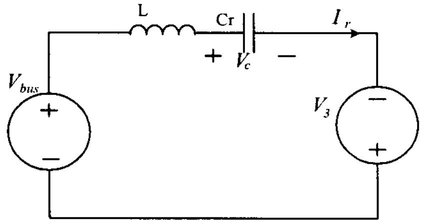


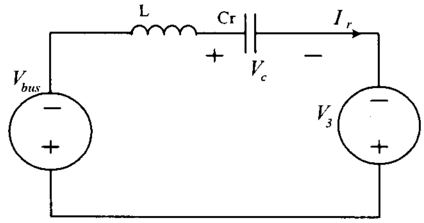
Fig. 7. Operating waveforms in discontinuous mode



Mode 1



Mode 2



Mode 3

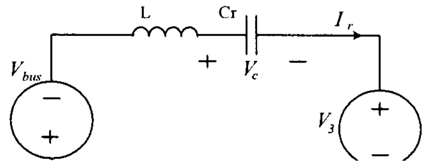


Fig. 8. Equivalent circuits for operation modes

The variable frequency scheme begins with a ratio that limits the current to a safe value at the beginning of the operation. To increase current flow through the resonant circuit as the output voltage builds up, the switching frequency is moved toward the resonant frequency. Examination of (1) indicates that the current for mode 1 is described by two sinusoidal components. If switches S1 and S2 are turned on for a sufficient time period, the current will reach zero and the devices will turn off at zero current, thus reducing switching losses. Zero-current switching is possible as long as the switching frequency is less than there sonant frequency. To ensure zero-current switching in the proposed DC-DC converter the on-time of switches S1, and switch S2, is fixed to be equal to one-half of the resonant period To, which is the reciprocal of the resonant frequency. This on-time remains constant while the switching frequency is varied with respect to the resonant frequency to control current flow through the resonant converter.

5. Simulation Results

The current flowing through IGBT switches rises gradually at turn-on and ZCS turn-on commutation can be achieved completely. Fig. 9 shows the simulated currents in the circuit when a short circuit has occurred across the load and Fig. 10 shows the output voltage across the load and the magnetron load current. When the short circuit condition occurred the circuit is driven at 50[kHz]. The resulting load current had a maximum value of 250[mA]. The switch current is much higher than this since it is on the primary side of the isolation transformer.

The steady state operation waveforms in a discontinuous current mode in the series resonant DC-DC converter are illustrated in Fig. 7. In this case, the current through transformer primary winding is discontinuous.

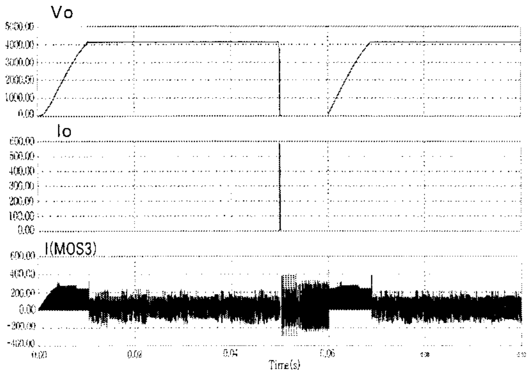


Fig. 9. Simulated currents when a short circuit occurs

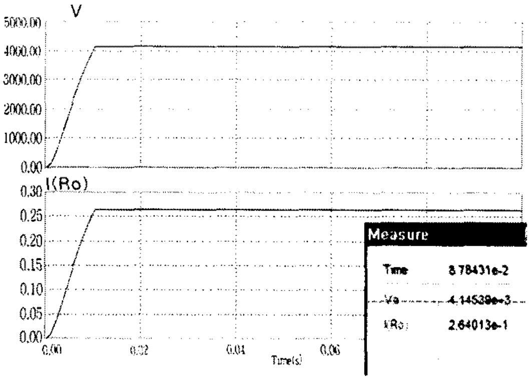


Fig. 10. Output voltage and load current

6. Conclusion

A power supply for microwave oven has been presented. The power supply is an active rectifier followed by a series resonant converter. The series resonant converter was chosen due to its ability to operate at high frequency and limit voltages and currents under open circuit and short circuit conditions, respectively. A full design procedure has been developed which allows the position of the resonant frequencies of the resonant converter to be specified by the designer together with the circuit resistance value at one of the resonant frequencies. the circuit design procedure determines the component values required in the primary and secondary sides of the circuit.

A series resonant circuit was designed to deliver 1[kW] to a magnetron load through a transformer operating at a frequency of 85[kHz]. The circuits was then simulated under short circuit and open circuit conditions and conformed to British Standards. The circuit was then constructed. The resonant circuit was supplied by an active rectifier from the AC mains. This had near unity power factor operation.

In this paper, a transformer parasitic parameter and a lossless inductive snubber assisted series-resonant ZCSPFM DC-DC converter has been proposed in order to improve the significant problems of the hard switching commutation at turn-on and turn-off of the active power switching devices in series-resonant PFM controlled DC-DC power converter with a high-frequency high-voltage transformer link.

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Biography

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