Resonant Power Supplies: Their History and Status

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ABSTRACT

A power system processes electrical power by converting the input of one form to the required output of another form. The hardware that converts this power processing is called a power supply, regulator, DC-DC converter, or battery eliminator.

The successful operation of any electrical or electronic equipment depends upon proper and reliable functioning of its power supply. The stringent demands on performance, weight, volume, reliability and cost make the design of the power supply a truly challenging exercise. The power supply must deliver the regulated power at the required voltage and current. This can be anywhere from a fraction of a watt to a few thousand watts, and few volts to thousands of volts, dc or ac, a few cycles to a few thousand cycles. It is essential to have very high efficiency. Important objectives are low losses and low mass. The last decade has witnessed significant advances in Power Electronics resulting in the development of reliable, light weight and high efficiency power systems.

The energy source for most converters is ac. Sources of dc are batteries and solar cells. Most of today's electronic equipment runs on dc. Sometimes more than one dc voltage is needed. Some ac converters deliver constant-frequency power to loads such as gyros. On the other hand, boiler feed-pumps in power plants require variable frequency.

Types of Converters

The power converter can be a dissipative or non-dissipative type (Fig. 1). Dissipative systems operate inefficiently, hence require large heat sinks. The dissipation varies as a function of input voltage and load fluctuations. This results in poor efficiency. However, they exhibit low EMI and ripple. The non-dissipative power systems operate in the switch mode resulting in high efficiencies.

In the dissipative regulator, the pass transistor is operated in active conduction mode and the conduction is controlled to make the voltage across the pass transistor always equal to the difference between the input voltage and the output voltage, even if there are variations in the input voltage. Diode voltage and emitter follower regulators are the simplest regulators one can conceive. These are normally used for low output current requirements, where efficiency is not important.

For today's high-power applications, dc is converted to ac by 1) chopping the dc into pulses from which the ac is assembled (switching mode), or by 2) pulsing a resonant circuit.

In the non-dissipative type, the pass transistor is switched between ON (saturation) or OFF (cut-off) mode minimizing the dissipation in the pass transistor. Once the dc power is converted into ac power it is easy to raise or lower the voltage with a transformer. In most of the practical applications, transformer isolation is essential and it is a must for safety. DC voltage, where required, can be obtained by rectifying and filtering the AC waveform.

In the switch mode converter, the dc input voltage is chopped at a high frequency to form square wave ac. This square wave voltage can be raised or lowered with transformers, and rectified and filtered to get DC at a voltage different from the input. The ratio of on-time to cycle time (duty ratio) of the square wave determines the amplitude of the output voltage, and hence can be varied to regulate voltage.

In the resonant mode approach, the dc input voltage is applied through controlled switches to an inductance-capacitance (LC) resonant circuit. The switches are driven with square waves of current or voltage, and by adjusting the frequency around the resonant point, the voltage on the resonant components can be controlled to any practical voltage level. Initially the inductor L and the capacitor C do not contain any energy, they start

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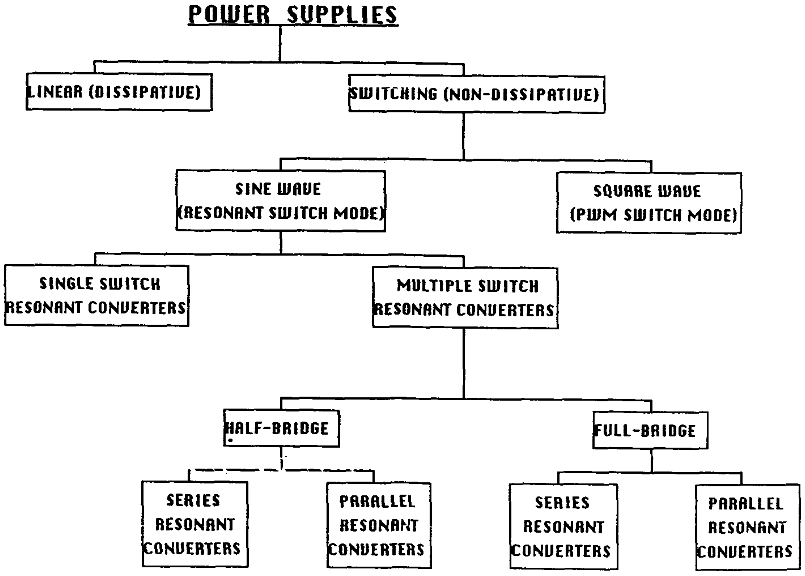


Fig. 1. Power Supply Classification Tree

afresh and resonate with approximately sine-wave current flowing through them and sine-wave voltage appearing across the capacitor. The ON and OFF states of the switches are controlled to maintain the resonant frequency of LC components. Output voltage can be controlled by changing the dwell time between pulses.

History of Resonant Power Supplies

Exploiting the resonance phenomena in power conversion is not new. Soon after vacuum tube was invented, class C amplifiers were developed to convert dc power into radio frequency power.

In the 1940s high-voltage self-excited vacuum tube power oscillators operating at radio frequencies powered tuned (single or double) step-up transformers for cathode ray tubes[1,2,3,4]. The heart of these power supplies is the self-excited power oscillator using a tetrode or a pentode with tuned step-up secondary. The secondary load was a voltage doubler, tripler, or quadrupler, depending on the output voltage required. The output ac sine wave is rectified and filtered to obtain DC voltage. Switching losses are minimized by making the switch turn-on or turn-off when the voltage across it was at its minimum value by the inertia (damping or Q) of the resonating LC tank circuit. Frequencies used in these power supplies ranged from audio to radio frequencies.

The output voltages ranged from 100 volts or more for Geiger Counters, ionization chambers and scintillation counters, to less than 1 kilovolt for iconoscopes, and 30 kilovolts and higher for projection kinescopes. These power supplies when working at radio frequencies are light weight and small when compared to the conventional high voltage supplies working from the 60 cycles power line. The achievable power output levels were limited by the oscillator power. The practically obtainable power levels were in the range of 50 watts for voltages up to 30 kilovolts. The achievable conversion efficiencies were in the range of 40% to 45%.

In television receivers [5,6,7], high voltage is derived from the deflection circuit, which operates at 15.750 kHz. The cathode ray beam in such equipment is ordinarily deflected by a saw-tooth wave of current that is passed through a magnetic deflecting coil. During the flyback interval, the current in this coil changes rapidly, developing a high voltage. This voltage can be stepped with a transformer, and rectified to obtain high dc voltage for the anode.

Before 1940, the high power vacuum tube was used principally in radio applications. After 1940, it was also used to generate radio frequency energy for industrial applications such as induction heating [9,10]. Either Colpitts or coupled-grid circuit configurations were used to generate radio frequency energy. These produce a high-impedance, constant-current variable-voltage output, hence require manipulation of load circuits to load the generator properly.

Coarse power control was obtained with an autotransformer (or tapped transformer) and fine control by varying the grid bias voltage. The generally accepted radio frequency generator for induction-heating is frequency ranged between 100 and 550 kHz.

Not available to the designers of vacuum-tube power converters were 1) detailed analysis to understand the static and the dynamic behaviour, 2) control approaches, and 3) high power supplies and higher conversion efficiencies.

In the following paragraphs we show how these lacking items are now being fulfilled.

PWM Switch Mode Power Supplies Vs. Resonant Power Supplies

In a pulse-width-modulated (PWM) switch mode power converter, the ac waveform is a square-wave which is rich in harmonics of the fundamental. Transformers can only be optimized for the fundamental frequency, and the harmonics heat up the core of the transformer contributing to losses. Furthermore, square wave generation inherently generates EMI, conducted as well as radiated, which needs to be attenuated carefully. As the switches turn-on with large initial currents and turn-off while carrying large currents, the power switches and the associated snubbers dissipate power. The switching losses increase as the switching frequency increases. The stresses on the bipolar switches can lead to second breakdown problem.

At high power levels, high-frequency square-wave power conversion circuits display parasitic induced behaviour which is difficult and expensive to control. Parasitic inductances cause excessive transient voltages. Parasitic capacitance, especially interwinding capacitance of the magnetic components, causes ringing of the voltages and currents initiated by the square wave switching. Reverse recovery becomes a severe problem, aggravated by the fact that the recovered charge characteristic of diodes does not scale linearly with device rating. EMI becomes more difficult to suppress.

In resonant converters, the current starts from zero when the switch is turned-on and ends in zero before the switch is turned-off. Because of this zero current switching, no snubbers and no complex turn-off circuitry is required. Thus the converter becomes simpler and more efficient. As the base drive is coupled to the collector current, the transistor switches turn-off naturally when the collector current becomes zero. This is called natural commutation. Because transistor switches are turned-off at zero collector current, the reverse-bias second breakdown is automatically avoided. As proportional drive can be used advantageously, and as the collector current becomes zero gradually, the storage time and the turn-off times become small and hence the transistors can be operated at a higher speed compared to the speed of operation of pulse-width-modulated switch-mode power converters.

Resonant converters can be operated at a relatively high frequency, making filtering components small. The waveforms are of half sinusoids (quasi-sinusoids), so the EMI generated is low. As the power switches (transistors and diodes) turn-on and turn-off at zero current, they dissipate minimum power. Furthermore, there are no voltage/current overshoots. Thus there are no stresses and almost no losses due to switching (although the saturation losses will be present in either converters). As the switches turn-off at zero current, no large di/dt and dv/dt (which can lead to switch failure due to second breakdown) are present.

Advantages & Disadvantages

The important differences between Resonant Power Supplies and pulse width modulated Switch Mode Power Supplies are presented in Table 1. The advantages of resonant converters outweigh their disadvantages.

RESONANT CONVERTERS

Resonant converter topologies can be classified, as shown in Fig. 1, into a) Single switch resonant converters, and b) Multiple switch resonant converters.

Single Switch Resonant Converters

There are different circuit configurations of single-switch resonant converters. Shown in Fig. 2 are two simple single switch resonant converters, a) Miller Resonant Converter, and b) Miller & Buchannan Resonant Converter. Fig. 2A shows the schematic of the power stage of the Miller Resonant dc-dc converter with non-isolated output. When the switch is turned-on, capacitor C1 charges to peak voltage and current through L1 reaches peak. When the switch is turned-off, the energy from the capacitor is transferred to output capacitor and load.

In the Buchannan & Miller circuit (Fig. 2B), the energy is transferred to the load two times in each cycle in the form of half sines, once when the switch is on and the other time when the switch is off. L1, C1 and L2 work as intermediate energy storing elements.

Multiple Switch Resonant Converters

Fig. 3 shows a selection of five multiple-switch resonant converters. Depending on the number of switches employed, these can be classified into half-bridge and full-bridge types. Fig. 3A and B show Half-bridge resonant converters and Fig. 3C and D show Full-bridge resonant converters. The main differences of these two types of resonant converters are presented in Table 2. In full-bridge resonant converter, the output voltage can approach the input voltage, whereas in the half-bridge converter the output voltage can approach only one half of the input voltage. Fig. 3E shows a half bridge resonant converter where the voltage dividing capacitors are used as a resonant capacitor. Again each has its own merits and demerits. Depending upon the particular application, the designer has to make trade-offs and select the type of converter.

Series and Parallel Resonant Converters

Whether the resonant converters are of half-bridge or full-bridge type, depending upon the connection of the load, they can be divided into two types, i.e., a) series resonant converters and b) parallel resonant converters. In a series resonant converter, the load is connected in series with the resonant elements (Cr, Lr) or a reactive element (Cr). In a parallel resonant converter, the load is connected in parallel with a reactive element (Cr). The current into the load is a series of pulses and the load is voltage fed. Because of this, for the same average load current, the rms load current can be much higher in the parallel resonant converter than it is in the series resonant converter. The main differences of these two types of converters are presented in Table 3. Each has its own merits and demerits. Again the selection of the topology depends on the particular application and the trade-offs.

Discussion on Resonant Converter Circuits

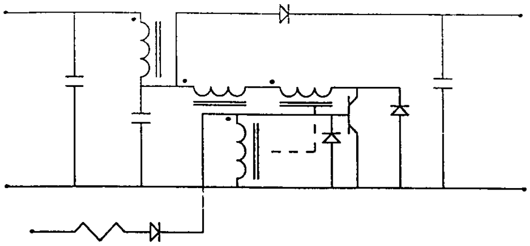
In single switch converters, the output ground is connected to the input ground. However, it is possible in the converter of Fig. 2B to isolate the output completely but this is not possible in the converter shown in Fig. 2A. On the other hand, a completely isolated output is possible in the five converters shown in Fig. 3. It is obvious that the output power rating or capability of a single switch converter will be lower than that of a multiple switch converter. This is because in the case of multiple switch converter, the power is shared or processed by

Table 1. Comparison of PWM Switch Mode Power Supplies & Resonant Power Supplies

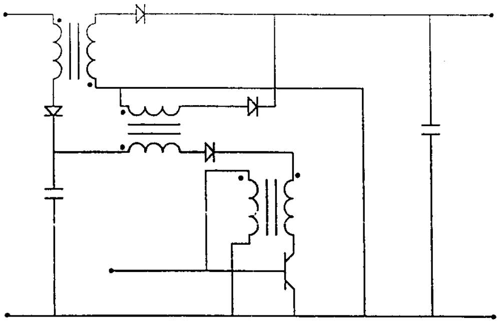
Parameter	PWM Switch Mode Power Supplies	Resonant Power Supplies
Advantages of Resonant Converters		
1. Switching losses	Turn-on & turn-off losses	Minimum or no switching losses. Requires smaller heat-sink. Results in higher efficiency, lower weight & volume.
2. di/dt & dv/dt	Exist & get worsened due to parasitics	* Low or insignificant di/dt or dv/dt, low or insignificant reverse recovery losses in diodes. Results in lower EMI, weight, volume & higher efficiency.
3. Second breakdown	Design has to take care of this problem	As the current is zero at turn-off, there is no second breakdown problem.
4. Operating frequency	Limited by turn-off times & switching losses	As turn-off times and switching losses are minimum, operating frequency is relatively higher. Hence filter components become smaller. Results in lower weight and volume.
5. Use of SCRs	Limited because of complex turn-off circuit requirements	# As turn-off is equivalent to SCR, at high power levels where bipolar and FETs cannot be used. SCRs can be used.
6. EMI	High	Low or minimum as the waveforms are of half sinusoids (quasi-sinusoids), the EMI generated is low and hence the corresponding filtering also becomes small.
Disadvantages of Resonant Converters		
7. Power Components & Ratings	Relatively smaller	Needs extra resonant inductor & capacitor. Requires components with relatively higher ratings. Hence cost increases.
8. Output Ripple	The rms current rating is approximately equal to the average output current	When rectified sine waves are filtered to get pure DC, filter size increases; but the rectifier diodes conduct for a small portion of the cycle. This current will be higher if the diode conducting period is less. To compromise the filter size can be reduced, but output ripple increases. For the same average output current, the rms rating of rectifier diodes and filter capacitors has to be higher.
9. Output Filtering	Rectified squarewaves result in almost pure DC; hence filtering is easy, small size filter can be used.	Rectified sinewaves do not result in DC. They are half sinewaves. Hence large size filter has to be used. However, these can be operated at relatively much higher frequency.
10. Pulse by Pulse current limit	Possible	Not possible as turn-off is carried out when current ceases to zero.
11. Shut-off	System can be shut-off at any instant.	System cannot be shut-off at any instant. Shut-off has to be synchronized with zero switch current as there are no turn-off snubbers provided to protect the switches from large di/dt, dv/dt, v, i (which occur if turned-off at maximum switch current which is contrary to the basic principle of operation).
12. Synchronization	Possible	Possible conditionally (only in particular topology and/or in particular mode of operation).
Common		
13. Base Drive	Constant base drive can be used in most of the cases unless there are large excursions in input voltage or output current	Proportional base drive is a must even if input voltage and output current are constant in order to see the real advantage.
14. Pulsating input and/or output current	Buck: non-pulsating output current; Boost: non-pulsating input current; Buck-boost: pulsating input & output currents; Cuk: non-pulsating input & output currents	Pulsating input and output currents; requires additional filtering (perhaps additional filtering may equal the reduction in filtering due high operating frequency in the order of 500 KHz or higher)

* *At higher operating frequencies, availability of faster power switching diodes is a limiting factor. By reducing di/dt of the current waveform through the diode, the energy losses can be reduced. This enables the use of low power faster switching diodes in high frequency high power applications.*

\# *Though at higher power levels, SCR's can be used, the switching frequency has to be lowered. Although present thyristors offer higher power capabilities than transistors, their losses are high, their operating frequency is limited, and additional protection and commutation circuitry is required.*

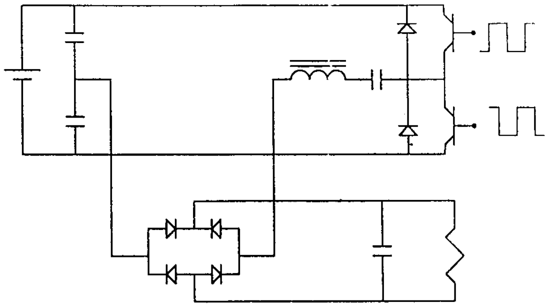


A. Miller Resonant Converter (Fig. 1 of Paper 1)

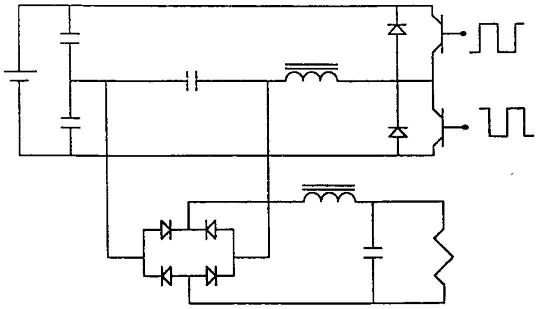


B. Miller & Bachannan Resonant Converter (Fig. 1 of Paper 2)

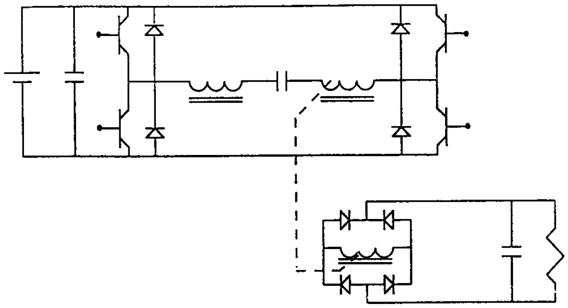
Fig. 2. Single Switch Resonant Converters,



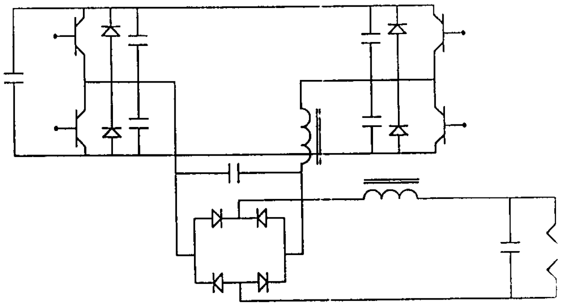
A. Half-Bridge Series Resonant Converter (Fig. 1a of Paper 11);



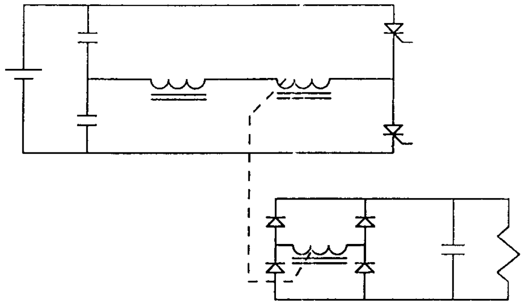
B. Half-Bridge Parallel Resonant Converter (Fig. 5a of Paper 11);



C. Full-Bridge Parallel Resonant Converter (Fig. 1 of Paper 40);



D. Full-Bridge Parallel Resonant Converter (Fig. 1 of Paper 8);



E. Half-Bridge Series Resonant Converter (Fig. 2 of Paper 6); Wherein the Voltage Dividing Capacitors are Used as Resonant Capacitor

Fig. 3. Multiple Switch Resonant Converters,

all the switches rather than by a single switch. Table 2 presents a comparison of half-bridge and full-bridge converters. Table 3 presents a comparison of series and parallel converters. Thus each converter configuration has merits and demerits.

CONTROL OF RESONANT CONVERTERS

In a resonant-converter power supply the output has to be regulated against input voltage variations and output load variations. This means that the output of the converter has to be continuously monitored, compared against a stable voltage reference, and the error signal with appropriate compensation has to be used to control the output.

Table 2. Comparison of Half-Bridge & Full-Bridge Converters

Parameter	Half-Bridge Resonant Converter	Full-Bridge Resonant Converter
Number of Power Switches	2	4
No. of Anti-Parallel Diodes	2	4
Resonant Inductor	1	1
Resonant Capacitor	1*	1
Voltage Dividing # Capacitors	2	0
Input Current (For Same Output Power)	Two times	1
Output Voltage †	Half of Input Voltage	Approximately Equal to Input Voltage

* *Sometimes voltage dividing capacitors are used as resonant capacitor. Conventionally voltage dividing capacitors are much larger than resonant capacitors.*

\# *Assuming only one power source for both cases. Voltage dividing capacitors are not required if two isolated power sources are available for half-bridge converter.*

† *Without any transformer.*

Table 3. Comparison of Series and Parallel Converters

Parameter	Series Resonant Converter (SRC)	Parallel Resonant Converter (PRC)
Inductors	2	1
Inductance	50% Smaller	1
Peak Inductor Current	50% Greater	1
Capacitors	2	2
Voltage Rating of Capacitors	50% Smaller	1
Anti-Parallel Diodes	Fast Recovery Type Required	No Anti-Parallel Diodes Required
Electrolytic Bypass Capacitors	2	None
DC Chokes to Create Current Source	None	2
Start-Up & Shutdown	Controlled by Inverter Switches	By Control of the DC Source

In the past decade, we have modelled and analysed the resonant converters which, although quite widely used, are not as well understood as the pulse-width-modulated switching converter. The state space averaging technique that has proven to be so fruitful in the analysis of pulse-width-modulated switching converters, is not applicable to resonant converters because the principal time constants are not long compared to the switching period. Nevertheless, the same kind of analytical results are required for resonant converters, in particular the dc to dc conversion ratio. These analyses produced input-to output and control-to-output transfer functions for steady-state and dynamic conditions. Just like PWM converters, the resonant converters also operate in either continuous or discontinuous conduction mode depending upon the component values, the input and output voltages, the load and the operating frequency.

There are many methods to control and regulate the output voltage of which five well-known methods are described in the paragraphs that follow:

Alpha Control: In the alpha control method, the zero crossing of the resonant current is sensed, and the switch is turned-on after a variable time delay, thereby directly controlling the delay angle. This is also known as diode conduction angle control as the diode conducts during this delay.

Gamma Control: Instead of sensing the current zero crossing, this approach uses a voltage controlled oscillator to drive the switches. In this case, the sum of the delay angle and conduction angle is controlled. This method is more practical in achieving inherent short circuit protection in the resonant converters.

Frequency Control

In the frequency control method, the switches are driven at a frequency (fs) lower than, equal to or greater than the resonant frequency (fr) of the reactive components. In the frequency control there are many possibilities, some of which are listed below:

1. fs < fr the circuit rings for half cycle, one cycle, or several cycles depending on the implementation.
2. fs = fr the duty cycle of the input square wave is varied or a shunt saturable reactor is employed to regulate the output.
3. fs = K where K is a constant, fr is varied by changing the value of the inductor (Lr) by controlling the degree of core saturation using a control winding on the inductor. For many applications, a variable switching frequency is not acceptable. Thus, this control approach is favored where the switching frequency has to be constant and synchronized with an external source.
4. fs > fr output controlled by varying fs; however, in this case, the natural turn-off of the switch is lost because the switch turns-off while conducting non-zero current.

Capacitor Voltage Control: In the capacitor-voltage control, which is popular in parallel resonant converters, the switches are turned-on when the capacitor (Cr) voltage reaches the amplified control voltage.

State Plane Trajectory Control: In the state plane trajectory control, the switch is turned-on as a function of inductor (Lr) current, capacitor (Cr) voltage, amplified control (error) voltage and an elapsed time from the previous switch turn-on instant. This control is similar to all state feedback control employed in PWM switching regulators.

Discussion on Control Methods

First four approaches are good enough for most of the applications. Fast response and current protection are inherently present in the state plane trajectory control method but this method is complex. It may be noted that the current limiting is not same as in PWM switching regulators where pulse by pulse current limiting is achieved. In resonant converters, the switches turn-off themselves by feedback and they do not employ forced turn-off. Also as there are no turn-off snubbers, for the switches are never turned-off when the current through them is not zero. Thus the current limiting in resonant converters is not similar to pulse-by-pulse current limiting achieved in current-programmed pulse-width modulated switching regulators.

Not recommended is achieving regulation by employing PWM switching preregulator. All the advantages of the resonant converter approach are lost because this system has PWM type switching regulator and the combination becomes bulky and inefficient.

HARDWARE

Many resonant converters have been recently developed because of their inherent advantages and excellent performance. Switching can be done with hyristors or transistors. Although present thyristors offer higher power capabilities than transistors, their losses are high, their operating frequency is limited, and additional protection and commutation circuity is required. Resonant power supplies developed to-date range in power from a few watts to about 30 KW, with an operating frequency up to 200 KHz and with an efficiency in the range of 85% to 96%.

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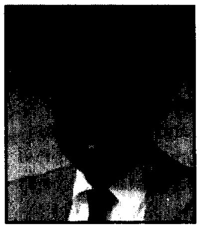

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Since 1983 he has been employed at the Fairchild Space & Defence Corporation. Currently, he is manager of the TOPEX Spacecraft Power System and is also acting Director for Spacecraft Design Department. His current interests are electronic power processing and spacecraft systems. Previously he was employed by the Indian Space Research Organization (ISRO) (1972-1979), the French Space Center at Toulouse, the California Institute of Technology (1979-1981) and Sundstrand Corporation (1981-1983) where his work centered on electronic power processing. He has over 60 technical publications, is the author of the books ***Switch Mode Power Supply Design*** and ***Satellite Technology & its Applications***, and holds five patents.

Dr. Chetty also teaches two short courses ***"Satellite, Power Systems,"*** and ***"Design and Analysis of Switching Regulators.*"** He received ISRO's Distinguished Achievement Award in 1975, the Most Valuable of the Issue Award from Electronic Design in 1974, the best Design of the Issue Awards from EDN in 1976 and 1978, and Fairchild's President Award in 1987. He was a member of the IEEE PESC program committee 1984-1986; Session chairman for IEEE PESC 1984; member of the IEEE Power Electronic Council 1986-1989; technical field editor for ***IEEE AES Transactions 1984-1989***; publicity standing committee chairperson for IEEE Power Electronics 1986-1989; and is currently a member of the Board of Governors for the IEEE AES Society.