Resonant Links: A New Family of Converter Topologies for Solid State Power Conversion

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Abstract This paper summarizes recent development on the resonant link power conversion family of power converters. These converters utilize a high frequency link to introduce zero voltage or zero current intervals. By switching at the zero crossings of the voltage or current, the converter switch losses can be greatly reduced permitting at least an order of magnitude increase in the converter switching frequency. The converters can synthesize nearly sinusoidal currents on both input and output converters and can also maintain unity fundamental power factor at the system input.

Introduction

The availability of high power gate turn-off devices such as the Bipolar Junction Transistor (BJT), the insulated gate bipolar transistor (IGBT) and the gate turn off thyristor (GTO) have contributed to remarkable advances in power power frequency conversion in recent years. The most widely used and highly developed frequency changers are the variable amplitude (six step) and fixed amplitude (pulsed width modulated or PWM) dc voltage link inverter which synthesize variable frequency and variable voltage ac output from a dc voltage input. The second class of highly developed frequency changers is the variable amplitude dc current link converter. A third class of frequency converter, which is still in its infancy is the direct ac/ac converter which eliminates the need for a dc link but requires reverse blocking devices for satisfactory operation, a still elusive device property at the present time. These dc link based power conversion systems as well as the direct ac/ac converter have several inherent limitations. One important drawback is the excessive switching loss and device stress which occur during the switching intervals. As a
result, the devices require a relatively large Safe Operating Area and the reliability of the system may be compromised unless snubbers are employed. The typical switching frequency in medium size 10-50 kw PWM inverters is only about 5 kHz. Larger converters require lower switching frequencies or cannot even be contemplated because of the loss issue. Because of the relatively low switching frequency it is difficult to realize dramatic gains in important system attributes such as faster system response, increased output frequency, improved power densities and reduction in audible and electrical noise particularly when the motor is operating at high speeds.

In recent years remarkable progress has been made in the development of high power density ac/ac converters which incorporate resonant-link schemes rather than the more conventional dc link. These converters, called "resonant link converters", utilize high speed devices such as fast recovery transistors, thyristors and GTOs to achieve a relatively high switching frequency and thereby markedly reduce the output current distortion compared to dc link schemes. In addition, these new converters also have high power density made possible by very low switching losses. The purpose of this paper is to summarize the state of the art in this important new branch of high power electronics.

**Principle of Soft Switching Converters**

Soft switched converters are of two types. A zero current switch (ZCS) refers to device turn-on and turn-off occurring with virtually no current in the device. This type of switching requires the use of purely inductive "snubbers" with no snubber resent mechanism. Turn-on losses are now dependent only on the size of the snubbing inductor which limits the rate of rise of current in the device. Turn-off losses, while device dependant, are relatively small since turn off of the device uses only natural commutation (natural turn off of the device when the anode current drops below the holding current).

Zero voltage switching (ZVS) converters use purely capacitive snubbers which requires that device turn-off occur in conjunction with an anti-parallel diode (usually in another branch of the circuit) which carries the current after turn-off. Turn-off losses are now dependent only on the size of capacitance which limits the rate of rise of voltage across the device.
Turn-on losses, while device dependant, are also modest when the turn on of the device takes place under a zero voltage link condition. The two types of switching elements are shown in Fig. 1.

Series Resonant AC Current Link Power Conversion

In general, switching schemes for high power resonant link converters can be classified according to whether they involve a resonant ac voltage or current impressed on the link or incorporate a pulsating dc component, i.e. the link is "dc resonant". Figure 2 shows a schematic illustration of the simplest configuration, the series resonant ac current link. Historically, this type converter was the first to be developed [1]. However, the initial conception involved a complicated magnetic structure which prevented application to high power ratings. In a more recent, and simplified realization, a single-phase ac current link operating at a fixed frequency of 20 kHz or higher serves as the interface between two six pulse bridges [2]. Shunt capacitors on the input and output serve to decouple the series resonant link from the source and load impedance. Since 4-layer devices turn off when the current becomes less than the holding current, this converter structure requires only thyristors in its implementation, an important advantage. Because the current in the link reverses, the switches are implemented with inverse parallel thyristors. The bridges operate from the bi-directional high-frequency, series resonant current of the link to synthesize low frequency (including dc or zero frequency) voltage or current source outputs as appropriate by means of suitable control of the bridges.

It is important to mention that the resonance of this converter is set solely by the link L and C and is essentially independent of the load parameters. This type of operation is in contrast to more traditional "resonant converters", used for example in induction heating, in which the load forms a portion of the resonant circuit.

With such constraints on the switching of the converter switches, one half cycle of the high frequency current becomes the basic unit of synthesis of the low frequency output signals. Figure 3 illustrates the basic switching operation of the converter. In general, converter switching is restricted to the zero crossing points of the link current so that the switching losses, which dominate the converter losses at these high frequencies do not
become excessive. Half cycles of the resonant link current are selected by the line side and load side converter so as to synthesize a sine wave of the appropriate frequency. Start up of the resonant link can readily be accomplished through proper control of the converter connected to the source. The major disadvantage of this converter is the need for 12 thyristors per converter to carry the bi-directional ac current of the link. Also, the voltage rating of the series resonant inductor and capacitor must be in the range of 2-3 times the voltage rating of the output, resulting in relatively high cost. Recently, the switch count of such a converter has been reduced to six as shown in Fig. 4, but at the cost of three additional, relatively large capacitors per bridge [3]. The concept continues to be pursued for variable speed power generation such as in small pumped hydro and wind turbines [2].

Parallel Resonant AC Voltage Link Power Conversion

Circuit duality plays an important role in power electronics and the duality of conventional dc voltage link and dc current link converters are well known. Current resonant links also have duals which possess similar properties as the conventional dc current link converters. Figure 5 shows the circuit dual of the series resonant ac current link which has been investigated in detail at the University of Wisconsin for use in a high frequency link power distribution system such as for aircraft or aerospace applications [4-7]. In the case of this converter, the inductance L and capacitance C form a parallel resonant link. Switching of the devices of each converter occurs at zero voltage rather than zero current intervals. Figure 6 shows the switching strategy for this converter. Note that the waveforms are essentially identical to Fig. 3.

It can be noted that since current is flowing through solid state switches when the voltage crosses through zero, the switches of this converter must be self commutated. Also, since the switches undergo voltage reversals while they are turned off due to the ac nature of the link, the switches must possess bi-directional voltage blocking capability. Hence, each bridge must be implemented with switches consisting of 12 transistor or GTOs in series (to implement the bi-directional current conducting requirement) together with 12 diodes (to implement the bi-directional voltage blocking
requirement). Alternatively six transistors embedded in a diode bridge arrangement can be utilized.

Figure 6 shows a typical voltage and current waveforms observed across one converter switch. The waveforms clearly demonstrate the zero current switching nature of the parallel resonant ac link converter. The high switch number together with the high current rating of the resonant link inductor and capacitor are the main disadvantages of this type of technology.

**Parallel Resonant DC Voltage Link Power Conversion**

An alternative to permitting the voltage link to reverse polarity is to bias the link with a dc voltage as shown in Fig. 7 [8]. This advancement in the resonant link technology was also developed at the University of Wisconsin shortly after the introduction of the resonant ac voltage link. In this case the link resonates at the tank frequency defined by L and C, in effect, a parallel resonant process. Capacitor C₀ is a conventional electrolytic capacitor used to provide the dc bias to the link. The link voltage now takes the approximate form of a biased cosine wave. Again the switches of both converters operate only when the link voltage reaches zero. In order to reduce the effects of the stray capacitance, the link capacitor C can be distributed across the poles of both converters or even across the switches themselves. Because the voltage of the link does not actually reverse polarity, the switches need not block reverse voltage. Hence, the converter switches need be implemented only with a transistor and inverse parallel diode; the normal switch configuration for a self commutated voltage source inverter.

The major concern for successful operation of this scheme is to ensure that the link voltage reaches zero during each resonant pulse. It can be shown that if losses are included, the voltage across the capacitor C is a damped sine wave which does not reach zero as predicted ideally. A zero voltage interval can, however, be ensured by giving the link inductor L an initial current condition. The initial condition can be accomplished if the link resonant capacitor is briefly shorted by simultaneously triggering both top and bottom legs of one phase of the converter before the capacitor is released and an oscillation cycle commences.
A potential disadvantage for such a converter is the relatively poor utilization of the semiconductor switches since the RMS value of the output voltage is roughly half the equivalent voltage of a dc voltage link PWM converter for the same switch voltage rating. This difficulty can be overcome by incorporating an active clamp which limits the link voltage to a predetermined value as shown in Fig. 8 [9]. In this circuit, diode D turns on and clamps the bus voltage at a predetermined value. With D conducting, the device S is turned on in a lossless manner. The current eventually transfers from the diode to the device S. The charge transferred to the capacitor \( C_C \) with D conducting is recovered during the interval when S is on. When the net charge transferred equals zero, S is turned off and the LC circuit resonates until the dc bus voltage reaches zero and C is again shorted. At this point the resonant cycle is reinitiated. In this manner it is possible to reduce the voltage stress from approximately 2.5 to 1.2-1.4 times the link dc capacitor voltage. Hence, the switch elements become only marginally greater than the equivalent switches of a dc link converter. Typical idealized waveforms for the case of voltage clamping is shown in Fig. 9.

The dc offset in the link is a major advancement of the resonant ac voltage link of Fig. 7 since the voltage bus is supported primarily by the voltage of the dc capacitor \( C_0 \) so that the characteristic impedance of the resonant L and C can be reduced to very small values compared to the corresponding elements of the resonant ac voltage link. Switching frequencies of the order of 60 kHz can be reached with devices losses not exceeding those of a conventional PWM inverter switching on the order of 5 kHz. The primary disadvantage of this circuit is the need for the voltage clamp which adds significant cost to the inverter compared with the normal dc voltage link type inverter. However, when issues other than cost, for example high efficiency and low weight, are of concern, this new type of converter promises to be a very attractive new alternative in converter topology.

**Series Resonant DC Current Link Power Conversion**

The dual of the Parallel Resonant DC Voltage Link is the Series Resonant DC Current Link converter shown in Fig. 10 [10]. This topology, which also was developed at the University of Wisconsin, utilizes
a dc bias current which is added to the link by employing a dc inductor $L_0$. The link current now takes the form of a displaced cosine wave. Again, zero current intervals are used to turn off the conducting thyristors in much the same manner as the series resonant ac current link system. However, since the current now remains unidirectional, the converter switches can be implemented with single thyristors. Hence, each converter becomes no more complicated than the conventional thyristor bridge. In order to increase the switching frequency to as large a value as possible, fast turn off devices must be employed so that the cost of the bridge is somewhat greater than a simple phase controlled bridge. The switching waveform is

When the losses in the system are considered the link current does not return to zero after each oscillation interval in much the same manner as the dc resonant voltage link. The problem can be solved in this case by properly regulating the current in inductor $L_0$ and the instant of turn-on of the next thyristor to ensure that the link current reaches zero after each cycle of oscillation. It is apparent that this converter suffers from the dual of the disadvantage of the dc resonant voltage link. That is, the RMS ac output current is relatively small compared to the current switch rating. However, in this case the problem is less serious since thyristors are used for the switch elements so that sufficient current carrying capability can easily be accommodated with relatively modest cost.

If necessary, the problem of switch utilization can be eased by incorporating a current clamp as shown in Fig. 11 [11]. In this case a dc biased inductor ("swinging choke") can be utilized as the resonant inductor. The dc bias current is conveniently implemented by using the dc current in the bias inductor $L_0$. Waveforms obtained from measurements on of the dc link current for a typical motor load is shown in Fig. 12 for two different resonant switching frequencies.

Since the series resonant dc current link converter does requires only simple thyristors, high applications for this strategy are particularly attractive including dc motor drives [12], rectifiers for superconducting energy storage [13] and large ac motor drives [14]. The future of this circuit depends heavily on availability of suitable thyristors with fast turn-off capability (less than 20 msec). The major disadvantage of the circuit is
the voltage rating of the resonant capacitor which must be on the order of two per unit.

**Variations in Circuit Topology**

Over the past several years activity in resonant link converter has increased exponentially and circuit topology variations have appeared for both the dc voltage resonant and dc current resonant topologies. Figure 13 shows a typical modification of the basic dc resonant voltage link (Fig. 7) in which the resonant capacitor is shorted by an additional switch [15]. In this manner the link voltage can be limited to safer values than for the basic circuit and required zero crossing of the voltage can be ensured without the need for "precharging" the resonant link inductor.

In Figure 14 is shown a modification of the basic dc current resonant link in which the current flow to the load is diverted by means of a bypass thyristor [16]. Use of the by pass thyristor allows the current pulses to be "trimmed", i.e. varied in size so that the current fundamental component can be more accurately synthesized without the "lumpiness" created by fixed amplitude current pulses. The principle of pulse splitting is illustrated by Fig. 15. It is shown in Ref. 17 that the pulse splitting concept can be realized without the need of an additional thyristor. This modification is illustrated in Fig. 16. In this case half the resonant inductance is placed in the legs of the converter bridge. Current is diverted from the load when both top and bottom switches of the same leg are turn on. A circuit employing both pulse splitting (Fig. 14) and clamping (Fig. 11) has been reported in Ref. 18. Figure 17 shows typical high fidelity waveforms which can be achieved with such circuits.

It has been shown by Park and Cho that capacitors on the ac side of the converter rather than the dc (link) side of the converter can be used to form a series resonant with the dc link inductor. In this case the bias inductor and dc link capacitor can be eliminated [19]. An extension of this principle which resonates both the line and load side capacitors with the link inductor is shown in Fig. 18. Figure 19 shows a typical line side current waveform which can be achieved. Research on this topology is actively being pursued at the University of Wisconsin.
Modulation Strategies

The quantum nature of resonant link power conversion has necessitated the development of specialized schemes for regulation of the output current or voltage. Figure 20 shows the block schematic of a typical modulation scheme used for resonant voltage link systems based on the concept of sigma modulation which relies upon integration of the current error [5]. In this scheme, the area under the reference signal is compared with the area of the synthesized voltage signal. If the comparison indicates that the integral of the synthesized signal is more (less) than the desired value then the controller causes the next half cycle pulse to be applied so that the integral is increased (decreased). In this manner, voltages having a fundamental component of dc, sinusoidal ac or any other smooth waveform may be synthesized using a single integrator, a comparator and a few logic gates. This simple implementation results in the density of the half cycle pulses in the synthesized voltage to be modulated in close accordance with the amplitude of the reference signal.

Figure 21 shows a typical spectrum of the voltage obtained by such a modulation strategy using, in this case, the resonant ac voltage link. It can be noted that very low level harmonics exist evenly over the spectrum from the fundamental to twice the link frequency (in this case 40 kHz). This spectrum is in marked contrast to many types of dc link converters in which the harmonic spectrum has characteristic "blips" at well defined multiples of the fundamental. Similar results can be shown to be possible for the dc resonant ac voltage link configuration except that the basic switching frequency is one full cycle rather than a half cycle resulting in a "blip" at 20 rather than 40 kHz.

The importance of current regulation in ac motor control has prompted a close look at current regulation in such drives [20,21]. Figure 22 shows the current waveform for the ac resonant voltage link system using a simple bang-bang controller. While this simple type of current controller is very adequate at low frequencies, the need for more sophisticated current regulators increases as the motor frequency rises.

An alternative method is evident when it can be noted that in zero voltage or zero current switching schemes, the switching instant and pulse duration is specified. Hence, the problem of current modulation reduces to
finding the next optimal combination of switch states at each switching instant a switching strategy impractical for conventional pulse width modulated dc link converters. If the load current for the next switching instant can be predicted for all possible switching states before the switching instant, the switching pattern can be selected which minimizes specified error function. If only current regulation is required, the error function may be simply the sum of the absolute current regulation errors of each phase or, alternatively, the square of the individual errors. Figure 23 shows the block diagram of a mode selection controller based on this principle which realizes substantial improvement in the current waveform at high frequencies. A typical waveform for this controller is shown in Fig. 24 and can be compared with Fig. 22.

Field Oriented Controller

A complete system diagram for a field oriented induction motor controller utilizing high frequency link technology, in this case a resonant dc current link topology, is shown in Fig. 25 and illustrates the complexity which must be dealt with when applying resonant link technology. The current of the source side converter is controlled by a link voltage regulator which regulates the link voltage by balancing the active power flow between the source and load. The current regulator at each converter regulates the current in both magnitude and phase. The induction machine is controlled by a current regulated field oriented controller equipped with a speed regulation loop. The current regulator of the field oriented controller utilizes an inner voltage loop within the basic current regulator required by the field orientation principle to ensure stability.

The input power converter is controlled as shown in Fig. 26. The power estimator provides an estimate of the current value of active power to the voltage regulator by calculating the average load side power and the system losses based upon measurement of the current operating conditions. A typical trace showing the transient characteristics of the drive is shown in Fig. 27. In particular, the trace shows system performance for a step change in torque command from 0 Nt-m to 8 Nt-m and then back to 0 Nt-m. Again the dc resonant current link converter of Fig. 7 is modeled. It is apparent that the high effective switching frequency of the converter permits very rapid changes in motor current results, in turn, in an
extremely fast acting torque controller. Figure 20 shows an experimental trace of the system for the condition where the motor is operating under a steady load condition and demonstrates the feasibility of operation with the supply current having a nearly sinusoidal waveform at unity power factor.

Figure 28 shows an experimental trace of the input voltage as well as the input and output current for the case of a resonant ac voltage link conversion system. Note that the input current is in phase with the input voltage. This important property is common to all of the circuit topologies that have been discussed in the paper and points to a major advantage of this technology compared to conventional thyristor bridge rectifiers.

Conclusions

This paper has summarized recent work on a new class of power converters, the resonant link power converter. These converters utilize the zero crossings of the link voltage or current to realize nearly zero loss switching. Of particular importance is the fact that these new converters do not necessarily require extremely fast turn off devices (i.e. IGBTs or MCTs) for satisfactory operation but can, in fact utilize low cost bipolar transistors and thyristors as the switching elements. Since the effective switching frequency is high, the currents at the input and output of the converter are nearly sinusoidal. These new converters promise to play an important role in the next generation of power conversion equipment.

References


Fig. 1 Soft Switching Elements (a) Zero Voltage Switching, (b) Zero Current Switching.

Fig. 2 Series Resonant AC Current Link Power Conversion System.
Fig. 3  Switching Strategy for Series Resonant AC Current Link Power Conversion.

Fig. 4  Modification of Series Resonant AC Current Link Converter Utilizing only Six Thyristors per Converter Bridge.
Fig. 5  Parallel Resonant AC Voltage Link Power Conversion System.

Fig. 6  Typical Voltage and Current Waveforms Observed Across One Converter Switch of Parallel Resonant AC Voltage Link Power Conversion System. Upper Trace: Switch Voltage: 125 V/div. Lower Trace: Switch Current: 5 A/div, Time: 25 ms/div.
Fig. 7 Parallel Resonant DC Voltage Link Power Conversion System.

Fig. 8 Parallel Resonant DC Voltage Link with Active Voltage Clamp.
Fig. 9  DC Link Voltage $V_{HF}$, Command Voltage $V_{LF}^*$ and Line to Line Output Voltage $V_{LF}$ Waveforms for System of Fig. 8.

Fig. 10  Series Resonant DC Current Link Power Conversion System.
Fig. 11 Series Resonant DC Current Link with Current Clamping Inductor.
Fig. 12 Typical Link Current Waveforms with Current Clamping a) Link Frequency $f_S = 2.1$ kHz, b) Link Frequency $f_S = 13.5$ kHz.
Fig. 13 Modification of DC Voltage Resonant Link by Utilizing an Additional Switch to Ensure Zero Crossing of Resonant Capacitor Voltage.

\[ L_1 = \frac{L}{2} \]

Fig. 14 Pulse Splitting Topology with Bypass Thyristor.
Fig. 15 Illustrating Control Method of Pulse Splitting.

\[ L_1 = \frac{L}{2} \]

Fig. 16 Pulse Split Circuit Obtained by Eliminating the Additional Thyristor of Fig. 13.
Fig. 17  Output Voltage and Current Waveform Obtained by Pulse Splitting Technique.

Fig. 18  Series Resonant Converter with AC Side Resonant Capacitors.
Fig. 19  Typical Line Side Current Waveform Obtained with Circuit of Fig. 18.

Fig. 20  Control Block Diagram for Area Comparison Pulse Density Modulation (Delta Modulation) and Resulting Line-to-Line Voltage Waveform. Voltage Scale 250 V/div. Time Scale 198.35 ms/div.
Fig. 21  Harmonic Spectra Associated with the Line Voltage Waveform of Fig. 13. Amplitude Scale: 20V/div., Frequency Range: 50 kHz.

Fig. 22  Response of Current Regulator Employing Bang-Bang Current Regulation. Traces: A Phase and B Phase Line Currents and Corresponding Reference Currents in Amperes, Frequency 143 Hz.
Fig. 23  Block Diagram of Mode Controller for Current Regulation.

Fig. 24  Response of Current Regulator Employing Mode Selection Current Regulation. Traces: A Phase and B Phase Line Currents and Corresponding Reference Currents in Amperes, Frequency 143 Hz.
Fig. 25  Diagram of Controller of the Output Converter of a Resonant DC Current Link Converter Feeding and Induction Motor Load.

Fig. 26  Complete Diagram of Control of the Input Converter of a Resonant DC Current Link Power Conversion System.
Fig. 27  Torque Response of System Employing Resonant DC Current Link. Traces: Electromagnetic Torque in Nt-M, Speed in RPM and Torque Command.
Fig. 28  Illustrating Unity Power Factor Operation of Line Side Converter During Motoring Operation. Traces: Peak of the Link Voltage: 130 V/div, A Phase Source Voltage, 40 V/div, A Phase Source Current: 5 A/div., A Phase Induction Machine Current: 5 A/div. All Grounds 4 Div form the Bottom. Time Scale 3.967 ms/div.