T.3: Resonant Immittance Converters and Their Applications in Power Supplies for Accelerator and Laser Subsystems

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Switch-mode power converters are being increasingly used in various subsystems for accelerator and lasers because of higher efficiency as compared to linear power supplies. Further, the size of isolation transformer and passive components in the filter are drastically reduced and transient response is significantly improved due to high frequency operation as compared to the line-commutated converters. However, these benefits come at the cost of higher complexity, more switching losses, higher switching stresses and electromagnetic interference (EMI), which are exacerbated with increase in switching frequency. Therefore, although the power devices are capable of being operated at higher frequency, these problems pose a practical upper limit on the switching frequency. Further miniaturization of power converter circuits is possible if they operate at still higher switching frequency, and to do this, a way to reduce or eliminate the switching losses and stresses must be conceived. Soft-switching is the technique that helps this cause by making the switch to change its state at an instant when either voltage across it or current through it is zero. Resonant converters (RCs), one of the techniques that offer soft-switching, have been a potential candidate in many power electronics applications. RCs also inherently have peculiar and useful characteristics that may not be exhibited by the other classes of power electronics converters. One of these is the immittance conversion characteristics (ICC), which is either inherently required or can be advantageously applied in various power supplies required for accelerator and laser subsystems as well as other demanding applications.

This article highlights the characteristics of a newly identified family of resonant converters, called as the resonant immittance converters (RICs) [1] and describes its potential applications.

RCs and RICs

A simplified block diagram of a dc-dc RC is shown in Fig. T.3.1. The input is either a voltage source or current source, implemented using bridge inverter to excite the resonant network (RN) with high frequency square-wave waveform. The output is a voltage or current sink, implemented using rectifier and filter. RCs are defined as [2] the ones in which, the power transfer from input to output is primarily via the fundamental component of switching frequency. Further the waveforms of the voltage or current response of RN to the excitation of source and load is piecewise sinusoidal.

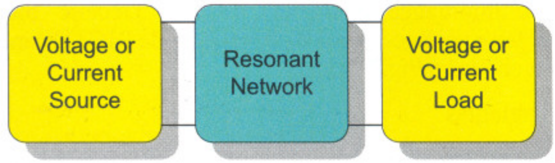

Fig. T.3.1: Simplified block diagram of RC.

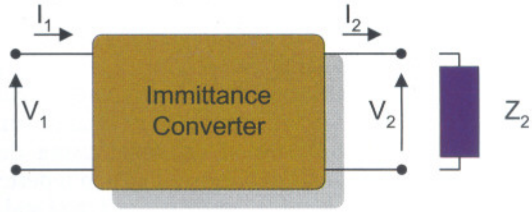

Fig. T.3.2: A two-port IC.

An immittance converter, IC, (abbreviation of impedance- admittance converter) is a two-port network, as shown in Fig. T.3.2, in which the input impedance is proportional to load admittance connected across the output terminals. Voltages and currents at the input and output ports of an IC (represented by V_1, I_1, V_2 and I_2, respectively) are related as given by the following expression [3]:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} 0 & \mp jZ_o \\ \pm j(1/Z_o) & 0 \end{bmatrix} \cdot \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix} \qquad (1)$$

where Z_o is characteristic impedance of the circuit. Input impedance, Z_1, of the network can then be derived as,

$$Z_1 \equiv \frac{V_1}{I_1} = Z_o^{\,2}\frac{I_2}{V_2} = \frac{Z_o^{\,2}}{Z_2} \qquad (2)$$

where $Z_2 \equiv (V_2/I_2)$ is a load impedance connected at the output port of the network. Thus the admittance at the output port is converted to the impedance at the input port. This conversion characteristic is called as ICC. From (1), the following relationship between the input-output voltages and currents is observed:

$$I_2 = \frac{V_1}{\pm jZ_o} \quad \text{and} \quad V_2 = \mp jZ_o I_1 \qquad (3)$$

The output current is proportional to input voltage and output voltage is proportional to input current. This feature of an IC enables the conversion of a constant voltage source to constant current source and vice versa.

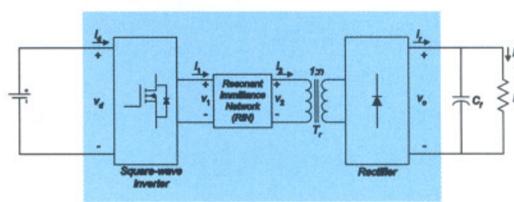

Fig. T.3.3: Block diagram of dc-dc Type-II RIC.

Those RCs, whose RN exhibits ICC, are termed as resonant immittance converters (RICs). Generic block diagram for a voltage-source or Type-II dc-dc RIC [1] can be drawn as shown in Fig. T.3.3.

RIC Topologies

It is well known that a quarter-wave distributed constant line exhibits ICC. This property has been explored in the past for various applications operating in megahertz-range [4]. While the length of distributed constant line is manageable for operation in megahertz-range, it becomes prohibitively long for power converters operating in kilohertz-range. Therefore some lumped-element IC topologies based on the transmission line approximation emulated using discrete inductors and capacitors have been studied and reported [3]. However, the efforts to identify, study, characterize and apply the lumped-element IC topologies has been largely discrete in nature. Therefore, for systematic investigation of RIC topologies, various topological structures of electric networks composed of maximum up to four branches and four reactive elements have been investigated [1] to examine the transmission or ABCD parameters. It is found that the condition for a network to be an IC is:

$$A = D = 0 \quad \text{and} \quad BC = 1 \qquad (4)$$

Only T-network, π-network, ladder network and the bridged-T network are found to satisfy the condition of (4). In all, 24 Resonant Immittance Networks (RINs) composed of reactive elements are synthesized from these network as shown in Fig. T.3.4 [5]. Note that the bridged-T type network (BT_1) is topologically equivalent to network T_8 in after star-delta transformation. The 9 topologies, namely, T_6, P_1, P_3-P_6, LA_1, LA_5 and LA_6 are suitable for conversion of a current source into a voltage source. They are termed Type-I RIC topologies. The rest 15 topologies, namely, T_1-T_5, T_7-T_9, P_2, P_7, LA_2-LA_4, LA_7 and LA_8 are suitable for conversion of a voltage source into a current source. They are termed Type-II RIC topologies.

Design Conditions and General Features

The RINs of Fig. T.3.4. exhibit ICC only if various reactances satisfy certain conditions leading to the generic condition of (4) These conditions are satisfied only at a particular frequency of operation and the circuits have different characteristics at other frequencies. To derive this operating point and the design condition the following terms are defined:

Angular resonant frequency: $\omega_o = 1/\sqrt{L_1 C_1}$ (5)

Normalized switching frequency: $\omega_n = \omega/\omega_o$ (6)

where ω is the angular switching frequency.

Ratio of inductances: $\gamma = L_2/L_1$ and $\alpha = L_3/L_1$ (7)

Ratio of capacitances: $\psi = C_2/C_1$ and $\beta = C_3/C_1$ (8)

Table T.3.1 summarizes the derived design conditions in terms of operating point $\omega_n = \omega_{ni}$ (the normalized switching frequency where a RIC topology exhibits ICC) and relationship among the values of reactive elements (in terms of α, β, γ and ψ).

It is observed that the transformer leakage inductance (important in low-voltage high-current power supplies) can be advantageously used as the part of the RIN in all RIC topologies when the transformer is either connected directly across the output port (e.g. in topology T_1) or inserted in between the RIN and shifting some of the components on the secondary side (e. g. in topology T_4 with C_1 placed on the secondary side). Some of the RIC topologies (T_2-T_4, T_7, T_9, P_1, P_2, P_4-P_6, LA_1-LA_6) absorb transformer leakage inductance and winding capacitance when the transformer is at the output

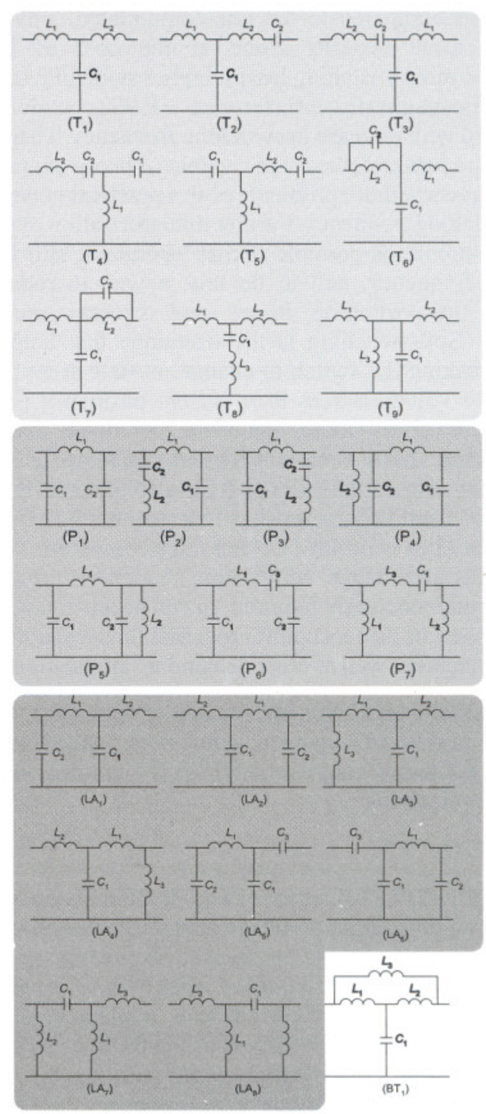

Fig. T.3.4: Synthesized RINs with maximum of 4 reactive elements.

Table T.3.1: Operating point and design condition of RIC topologies

RIC Topology	Operating point $\omega_n = \omega_{ni}$	Design condition	RIC Topology	Operating point $\omega_n = \omega_{ni}$	Design condition	RIC Topology	Operating point $\omega_n = \omega_{ni}$	Design condition
T_1	1	$\gamma = 1$	T_9	$\sqrt{\frac{\alpha+1}{\alpha}}$	$\gamma = 1$	P_7	$\frac{1}{\sqrt{1+\alpha}}$	$\gamma = 1$
T_2, T_3	1	$\gamma = \frac{1+\psi}{\psi}$	P_1	1	$\psi = 1$	LA_1, LA_2	1	$\psi + \gamma = 1$
T_4, T_5	1	$\gamma = \frac{1-\psi}{\psi}$	P_2, P_3	1	$\psi = \frac{1}{\gamma+1}$	LA_3, LA_4	1	$\alpha = \frac{1}{\gamma-1}$
T_6, T_7	1	$\gamma = \frac{1}{1+\psi}$	P_4, P_5	1	$\psi = \frac{1+\gamma}{\gamma}$	LA_5, LA_6	1	$\beta = \frac{1}{\psi-1}$
T_8	$\frac{1}{\sqrt{\alpha+1}}$	$\gamma = 1$	P_6	$\sqrt{\frac{\beta+1}{\beta}}$	$\psi = 1$	LA_7, LA_8	1	$\gamma = \frac{1}{\alpha+1}$

port (e.g. in topology LA_2) or inserted in the RIN (e.g. in topology T_7 with L_2, C_2 placed on the secondary side), rendering them useful for high-voltage power supplies. Topologies T_4, T_5, T_9, P_5, P_7, LA_4, LA_7 and LA_8 advantageously integrate magnetizing and leakage inductance into the RIN, these parasitic component being significant in a loosely coupled transformer used for inductive power transfer. It is advantageous if a resonant capacitor also does the dc blocking to prevent saturation of isolation transformer. Some of the RINs (T_2-T_5, P_6, P_7, L_5-L_8) offer inherent dc blocking of isolation transformer.

Topological Extensions

A) Type-II RICs with CC-CV Characteristics

While the load current is required to be constant in a CC power supply when the power supply is loaded, in many applications the output voltage of the power supply also needs to be within specified (safe) limits when the output terminals are open circuited. Therefore, inherent CC-CV characteristic is beneficial. Addition of two clamp diodes (D_{c1} and D_{c2}), as shown in Fig. T.3.5 from transformer primary to the dc supply rails, gives inherent CV characteristics to the half-bridge-driven Type-II RIC [6]. Experimental results on a 1 A, 500 W RIC operating at 100 kHz (using network T_1 as the RIN) with clamp diodes are shown in Fig. T.3.6. The converter is seen to operate in CC mode if R_L<500 Ω and in CV mode if R_L>500 Ω. The output power of the converter is also seen to be safely limited to maximum designed value over the entire operating range including two extremities - load short-circuit and load open-circuit.

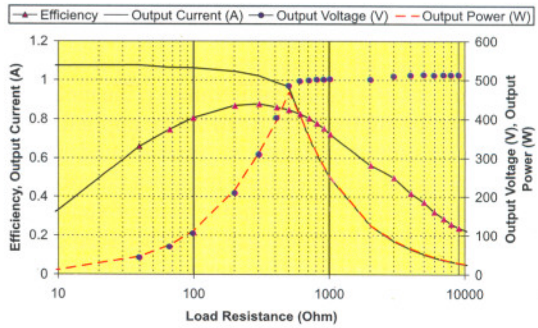

Fig. T.3.6: Experimental results on a T_1 RIC demonstrating inherent CC-CV characteristics.

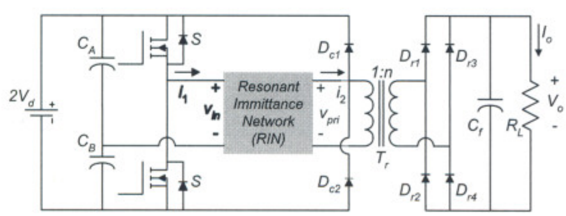

Fig. T.3.5: Half-bridge Type-II RIC with clamp diodes for in built CCCV characteristics.

B) Multi-phase Type-II RICs

Most of the conventional PWM converters and RCs operating with their input and output ports connected in series or parallel are inherently unstable and equal load sharing is not guaranteed unless it is forced by implementing a feedback control. Since a Type-II RIC is inherently a current source, it lends itself for easy paralleling without any additional care for equal current sharing, as illustrated in Fig. T.3.7.

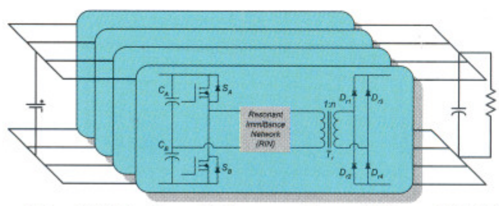

Fig. T.3.7: Parallel operation of Type-II RICs.

Operation of these paralleled converters can be phase-staggered to reduce input and output ripple amplitudes and to increase the ripple frequency. The dc components of individual modules directly add independent of the phase shift. However, harmonics can selectively get cancelled in the total current depending on the phase angle. The peak-peak ripple in the rectified output current normalized to its average value as a function of the phase shift is shown in Fig. T.3.8 for different values of the number of paralleled modules, *m*[7].

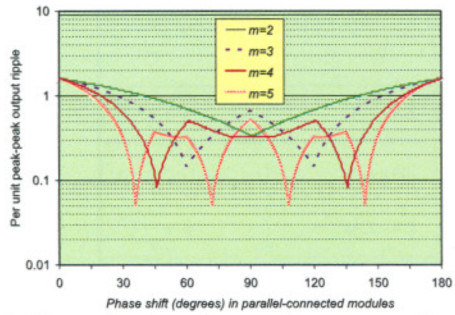

Fig. T.3.8: Normalized peak to peak output ripple current in multiphase Type-II RICs.

PWM Control

Since Type-II RICs behave as a current-source only when it is operated at a particular frequency, the method using variation of switching frequency can not be applied to control the output. The output current can be regulated and varied over a wide range by either varying the input dc voltage using another converter in the front-end or using fixed-frequency control methods. In the former case, two cascaded converters reduce overall conversion efficiency, increase complexity, component count and cost. Asymmetrical PWM (APWM) control is one of the fixed-frequency PWM control method and can be readily be used for controlling Type-II RICs. Generally four distinct operating modes, based on the commutation conditions of the switches, have been identified and named Mode-I through Mode-IV. Operation of the converters in these modes depends largely on the duty cycle, *D*, of the PWM and circuit *Q*. The mode-boundaries thus can be plotted on the *D-Q* plane, as shown in Fig. T.3.9 for topology T_1[8]. Since all the switches operate with ZVS in Mode-I and Mode-III, the converter can be designed to operate in these modes. Experimental waveforms of bridge output voltage and current demonstrating ZVS operation in

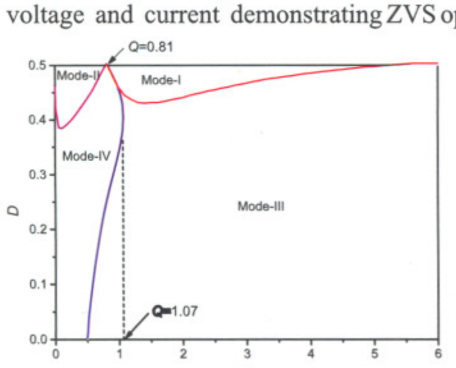

Fig. T.3.9: The D-Q plane showing boundaries among various operating modes in T_1 RIC.

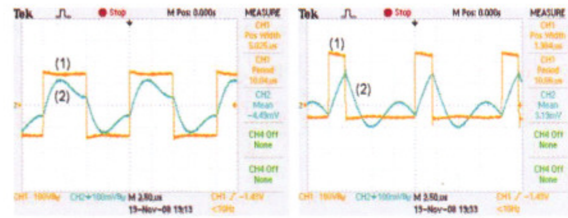

Fig. T.3.10: Bridge output voltage(1) and current(2) in Mode-I (left) and Mode-III (right) operation.

a 1 A, 500 W RIC (using network T_1 as the RIN) with APWM control operating at 100 kHz are shown in Fig. T.3.10. The results of Fig. T.3.11 confirm the close match between predicted and experimental values of output current, which is seen to be variable over a wide range.

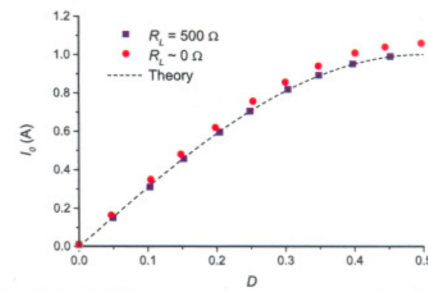

Fig. T.3.11: The control characteristic with APWM.

Applications of Type-II RICs

The property of Type-II RICs that it converts a voltage source into a current source is very useful in variety of applications wherein a CC source is either inherently required or can be advantageously applied. Beginning with application of Type-II RICs as a CC power supply, some of applications areas - particularly related to accelerator and laser subsystems - are described subsequently.

A) Type-II RIC as a CC Power Supply

The usefulness of Type-II RICs is illustrated in this section with one newly identified T3 RIC [5] as a CC power supply. The circuit diagram of half-bridge T_3 RIC is shown in Fig. T.3.12. As summarized in table T.3.1, topology T_3 exhibits immittance conversion characteristics when operated at ω_n=1 and, $\gamma = 1+1/\psi$. Under this condition, the converter current gain is given as,

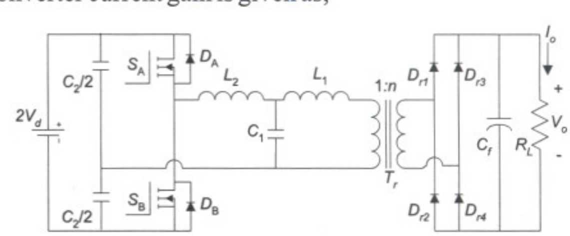

Fig. T.3.12: Circuit diagram of RIC topology T_3.

$$H\Big|_{\gamma=\frac{1+\psi}{\psi}} = \frac{nI_o}{\frac{V_d}{Z_n}} = \frac{8}{\pi^2}\left(\frac{j\psi\omega_n}{P}\right) \qquad (9)$$

wherein

$$P = 1+(1+\psi)\left(\omega_n^{\,4} - 2\omega_n^{\,2}\right) + j\,\tfrac{8}{\pi^2}\,\tfrac{(1+\psi)}{Q}\left(\omega_n - \omega_n^{\,3}\right)$$

Figure T.3.13 illustrates the plot of (9) for various values of Q and for ψ=1 and γ =2 demonstrating that H independent of load (that is, Q) at ω_n=1, thereby acting as a CC power supply.

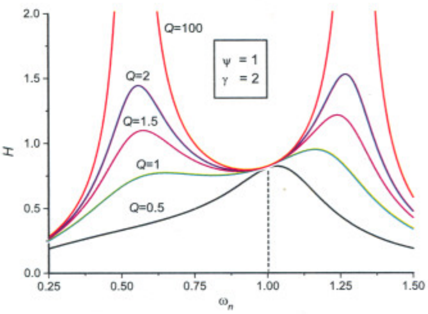

Fig. T.3.13: The plots of H in T_3 RIC.

Reactive components in a RC increase its size. Therefore, RCs are optimized for minimum size of RN taking (kVA/kW) rating of the RN as an index for its physical size, which in the present case is,

$$\frac{kVA}{kW}\bigg|_{\omega_n=1;\gamma=\frac{1+\psi}{\psi}} = \frac{\pi^2}{4}Q + \frac{16}{\pi^2}\left(\frac{1+\psi}{\psi}\right)\frac{1}{Q} \qquad (10)$$

The optimum value of Q is then derived as,

$$Q_{opt}\Big|_{\omega_n=1;\gamma=\frac{1+\psi}{\psi}} = \frac{8}{\pi^2}\sqrt{\frac{1+\psi}{\psi}} \qquad (11)$$

A half-bridge prototype was designed and built to experimentally validate the current source property of topology T_3. The converter has following specifications: input dc supply voltage ($2V_d$) = 220 V, I_o = 1 A, $R_{L,\max}$ = 250 Ω, f_s = 105 kHz and is designed with ψ=2. Fig. T.3.14 shows a photograph of the prototype. Open-loop output characteristic, rms value of i_{L2} and efficiency of the experimental prototype obtained by varying values of load resistance is shown in Fig. T.3.15. The measured rms value of i_{L2} is also seen to reduce with load as predicted in the analysis, thereby resulting in high efficiency over a wide range of operation.

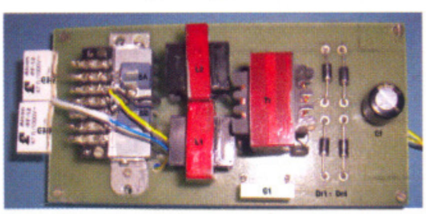

Fig. T.3.14: Photograph of prototype T_3 RIC.

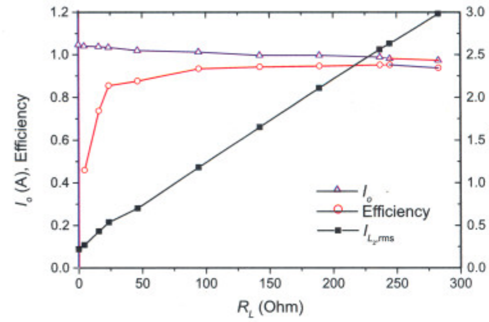

Fig. T.3.15: Experimental characteristics of T_3 RIC.

B) Capacitor Charging Power Supply

Various industrial applications require pulsed energy transfer. The required energy is provided to the pulsed loads by rapidly discharging a pre-charged capacitor. A special type of power supply required for charging of the capacitor is commonly termed as capacitor charging power supply (CCPS). The applications of a CCPS include flash-lamps for food sterilization and lasers, radio frequency modulators, high voltage pulse generators, plasma source implantation, non-thermal pollution gas treatment, pulsed magnets in particle accelerators etc. Topological variant of Type-II RICs with clamp diodes that exhibit inherent CC-CV behaviour is ideally suited for this application because of following reasons:

1. Type-II RICs are inherent CC source, it is not necessary to sense and regulate the current.
2. Reactive currents are minimum and conduction losses in the switches are low. Soft-switching reduces switching losses and EMI
3. Safe operation of the converter is inherently guaranteed eliminating the need of timing circuit to disable its operation when the energy storage capacitor is being discharged into the load.
4. The converter operation automatically and smoothly changes from CC to CV mode after the load capacitor is charged to rated voltage. This transition takes place passively due to conduction of clamp diodes.
5. Fixed-frequency operation.

A half-bridge T_1 RIC with clamp diodes has been developed [9] to charge a 2 μF capacitor from 0 to 500 V in 1 ms time. The input dc supply available is 200 V and switching frequency is 100 kHz. The circuit diagram is shown in Fig. T.3.16. Figure T.3.17 shows the principal circuit waveforms during charging and refresh mode of the charging cycle. The charging mode commences at t=t_1. The voltage across energy storage capacitor (waveform-1) builds inearly, confirming CC operation of the converter. At t=t_2, capacitor charges to 500 V smoothly without any overshoot. The current i_L (waveform-2) builds smoothly as the instantaneous output power of the converter rises. The transformer primary current (waveform-3) is constant indicating CC operation.

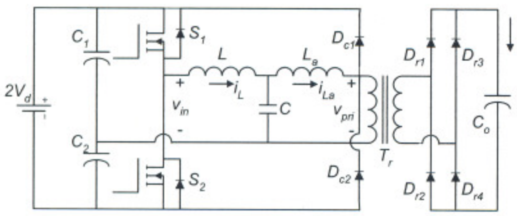

Fig. T.3.16: Circuit diagram of RIC topology T_1 with clamp diodes as a CCPS.

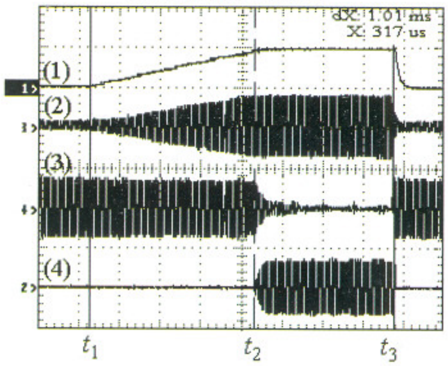

Fig. T.3.17:Principal cCircuit waveforms in a CCPS using Type-II RIC.

Clamp diodes are off during the charging mode. At $t=t_2$, capacitor is charged to 500 V and converter operation changes from CC to CV mode. Transformer primary current is no longer constant and decays quickly to zero. The clamp diode current (waveform-4) rises as they conduct and maintain the output voltage constant at 500 V. At $t=t_3$, discharge cycle starts and the converter changes its operation from CV mode to CC mode inherently and almost instantaneously as the clamp diodes stop conducting and transformer primary current builds to its CC value.

C) High Voltage DC Power Supply

High voltage (HV) dc power supplies are commonly required in laser and accelerator subsystems. As opposed to line-frequency-operated converters, high-frequency switch-mode converters offer a compact power supply with smaller filter and associated stored energy. However, design of a high-frequency HV power supply is complex because of high leakage inductance (L_{lk}) and significant winding capacitance (C_w) associated with the transformer. Since these parasitic components can easily be integrated as a part of RN, RCs are popularly applied for these applications. Type-II RICs can be an attractive alternative for HV power supplies due to the following merits:

1. Partial discharge and arcing can occur frequently in HV loads. Since Type-II RICs behave as an inherent CC source, semiconductor devices are inherently protected against these faults.
2. HV power supplies required for sensitive and expensive loads like klystrons need to have minimum energy storage in the output filter as stored energy is dissipated in the load in case of arcing. Fast closing switches operating in parallel to the klystron path (known as crowbars) are used for protection. To avoid false firing and reliability issues of crowbars, a crowbar-less power supply is preferred wherein stored energy in the power supply is kept less than the maximum energy handling capability of klystron. Multiphase Type-II RIC is a potential alternative for such applications since phase-staggered operation can reduce (or even eliminate) filter capacitor and the stored energy.
3. Some of Type-II RICs absorb L_{lk} and C_w in the RIN.

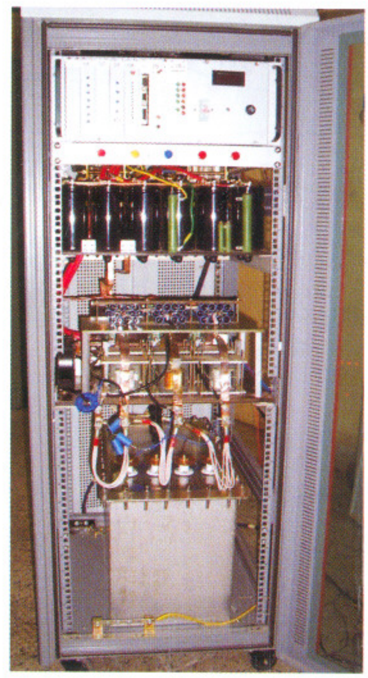

Fig. T.3.18:A photograph of 20 kV, 1 A crowbar-less HV dc power supply.

RIC topology LA_2 absorbs L_{lk} and $C\omega$ in the RIN [10], thereby rendering it as one of the suitable topologies for this application. A 20 kV, 1 A power supply has been developed with maximum stored energy of 5 J in the output filter capacitor using three stages of half-bridge LA_2 RIC operating in parallel and with a phase shift of 120 degrees. Each converter uses IGBT operating at 25 kHz. The phase-staggered operation of three converters results in ripple frequency of 150 kHz at the output allowing 27 nF filter capacitor with 5 J stored energy at 20 kV. Since this is much less than the maximum allowable energy dissipation limit in klystrons (20-25 J), crowbar-less operation is possible. Figure T.3.18 shows the photograph of the power supply.

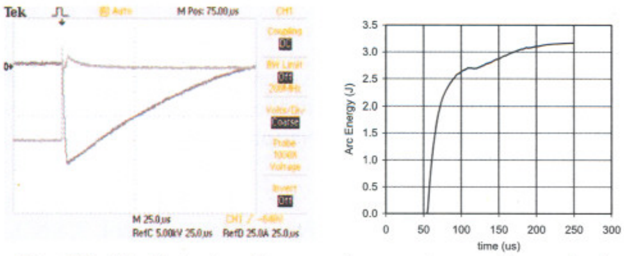

Fig. T.3.19: Output voltage and current waveforms during simulated arcing condition and calculated arc energy.

The power supply has been tested under simulated arcing conditions. Output voltage and current waveforms under arcing condition is shown in Fig. T.3.19 The energy dissipated in the arc is calculated from these waveforms. As shown in Fig. T.3.19, the arc energy is limited to 3.16 J at 15 kV. A detailed report on this activity will be published shortly.

D) Induction Heating Power Supply

The ICC of RICs is also useful in converting small value of effective load resistance in induction heating applications to the values suitable for available sources, thereby relaxing the stringent requirements on the matching transformer. A 25 kW/ 25 kHz induction heating power supply for MOVPE system in Semiconductor Laser Section, Solid State Laser Division, RRCAT has been developed [11] based on T_1 RIC topology. The system is required to heat graphite susceptor to 1200 °C. The application of this scheme offers many advantages: The converter offers high current gain, which in turn reduces the current rating of the secondary winding of the matching transformer and the feeder to coil. Coil current is constant irrespective of changes in effective load resistance due to temperature or work-piece change.

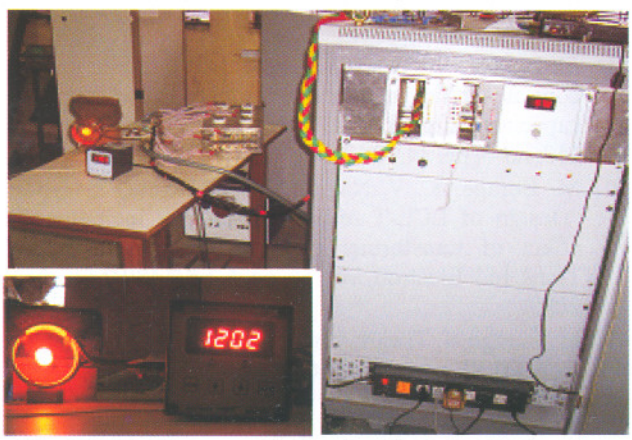

Fig. T.3.20: Photograph showing the induction heating power supply with a graphite block heated to 1200 0C in the inset.

Transformer design is further simplified since its turns ratio is no longer dependent on the Q of the resonant network. The work coil acts as one of the resonant inductor in the T_1 RIN and the second resonant inductor is integrated as the leakage inductance of the matching transformer. Water-cooled resonant capacitor is placed near the work coil to minimize the loop of high reactive current (700 A rms) circulating in the work coil. This way, only active current flows in the transformer secondary winding and the feeder to coil high (typically, 70 A rms), greatly simplifying their design. Figure T.3.20 shows a photograph of the power supply being tested in the lab to heat graphite block in air to 1200 °C.

E) Pulsed Current Sources

Many application demand pulsed current sources. For instance laser diode drivers [12], electrochemical processes, battery charging etc. Type-II RICs and multiphase Type-II RICs are very useful for such applications wherein various source-switch arrangements can be realized to deliver unipolar, biploar and dc-offsetted pulses of currents with great flexibility on the various parameters such as pulse width, pulse frequency, pulse amplitude, offset etc. For instance, the arrangement of Fig. T.3.21 can deliver unipolar pulses of current riding on a defined off-set current, which is very useful is characterizing laser diodes.

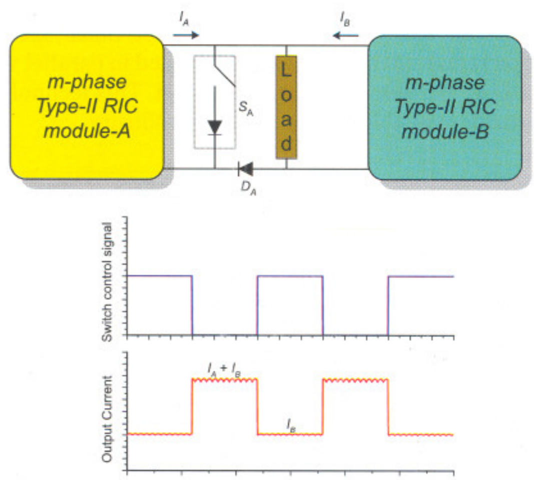

Fig. T.3.21: Switch-source arrangement with multiphase RICs as a pulsed current source.

F) Other Applications

Apart from the above-mentioned applications, Type-II RICs, by virtue of their current-source behaviour, give a promising alternative to the designers to develop various power sources required for electric arc welding, battery charging, illumination, electro-mechanical actuators, inductive energy transfer, fast and rugged chargers for ultracapacitors etc.

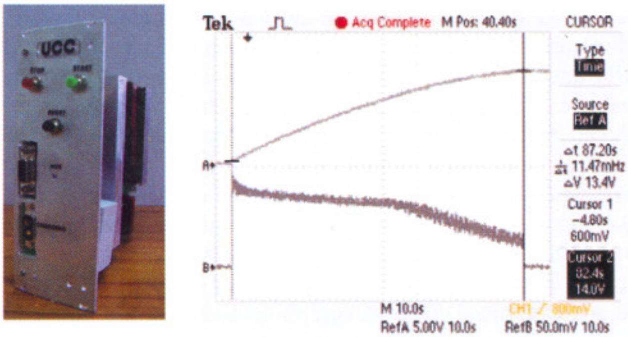

Fig. T.3.22: Photograph of ultracapacitor charger and charging voltage (top) and current (bottom) waveforms.

Ultracapacitors, also known as supercapacitors, offer many advantages over batteries such as large number of charge-discharge cycles, low ESR, high efficiency, high power density and low heating. Therefore, ultracapacitors are being increasingly used in portable electrical and electronic devices and transportation in conjunction with batteries. A compact, scalable, standard 4U card sized constant-current Ultra Capacitor Charger (UCC) using Type-II RIC topology T_1 has been developed [13]. The charger has been designed for ± 48 V DC input, 10 A output current, 15 V maximum charging voltage and tested with 58 F ultracapacitor. The same card can easily be re-configured for other specific application requirements and can be operated in parallel with other cards to increase the charging current. This technology has been made available for transfer to the industry.

Summary

The newly explored family of RCs, named as RICs, exhibit very peculiar and useful characteristics making them a promising alternative for the development of compact, efficient and rugged power converters for demanding applications in accelerators, lasers and industry.

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