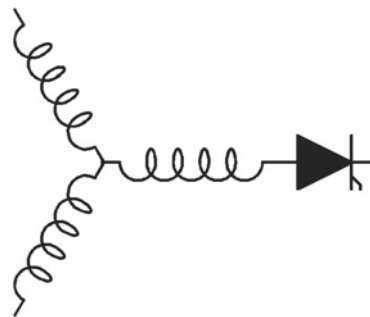


Research Report  
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## Converter Topologies for Induction Motor Drives

**T. A. Lipo**

Dept. of Elect. & Comp. Engr.  
University of Wisconsin-Madison  
1415 Engineering Drive  
Madison, WI 53706



**Wisconsin  
Electric  
Machines &  
Power  
Electronics  
Consortium**

University of Wisconsin-Madison  
College of Engineering  
Wisconsin Power Electronics Research Center  
2559D Engineering Hall  
1415 Engineering Drive  
Madison WI 53706-1691

## **SECTION V.1. CONVERTER TOPOLOGIES FOR INDUCTION MOTOR DRIVES**

THOMAS A. LIPO

*University of Wisconsin-Madison*

*1415 Johnson Drive*

*Madison, WI 53706 U.S.A.*

### **ABSTRACT**

Progress in the design of power electronic frequency converters has, in large part, been a result of the remarkable advances in the design of the power electronic switches themselves. Classification of the commutation process provides a convenient means to categorize the various converter circuits presently available for use in variable frequency induction motor drives. Five categories can be identified for realizing the commutation process in a three phase dc/ac converter: natural Commutation, resonant pulse commutation, device self commutation, resonant link commutation, quasi resonant link commutation. Based on this categorical procedure, the key converter topologies both in the past, present and future are summarized.

### **KEYWORDS**

converter topologies / inverters / resonant link / commutation / quasi-resonant link

### **1. Introduction**

Progress in the design of power electronic frequency converters has, in large part, been a result of the remarkable advances in the design of the power electronic switches themselves. In general, the primary driving parameter in switch development has been the time in which the switch regains its voltage blocking ability after the current in the device begins to be extinguished (turn-off time). In only thirty short years, the turn off time of practical high power switches have decreased from the several hundred microseconds in the thyristors of the sixties to a few tenths of a microsecond in modern IGBT and FET devices. That is, by a factor of one thousand!

The device turn-off time is of critical importance in a power electronic converter since it is inevitably required to produce either a sinusoidal voltage or current approximation across or through the load, from what is, effectively a dc source. Thus, the faster that the switches operate, the better the approximation of the desired waveform across/through the load. The process of transferring current from one conducting device to another is termed commutation and the effectiveness of the commutation process is clearly dependent on the turn-off time of the conducting device.

Classification of the commutation process provides a convenient means to categorize the various converter circuits presently available for use in variable frequency induction motor drives. Five categories can be identified for realizing the commutation process in a three phase dc/ac converter:

- Natural Commutation
- Resonant Pulse Commutation
- Device Self Commutation
- Resonant Link Commutation
- Quasi Resonant Link Commutation

Circuit constraints can be shown to have an important impact on feasible converter topology. Fig. 1a is a simplified representation of a dc/ac converter having two input and output terminals. In general, the operation of the switches should never create a sudden change of the current in a current source/sink nor sudden voltage changes across a voltage source/sink. It can be easily determined that if current sources/sinks are placed at both the input and output, energy conversion is impossible since currents cannot change in any of the input or output lines. Likewise, if voltage sources are connected to the input and output, energy conversion again can not occur since voltages can not change on any of the input or output terminals. Furthermore, circuit constraints impose the requirement that each line containing a current source/sink must be connected to one and only one voltage sink/source except for exceptional situation which do not occur in practice. Fig. 1b shows two possible realizations of these ideal converters. Note that inductances can be placed in series with current sources/sinks and capacitances in parallel with voltage sources but not vice versa. A pure resistance can be considered as both a current or a voltage sink in this context but it is important to note that a pure resistance can never be achieved in practice due to the inevitable inductance of the connecting leads.

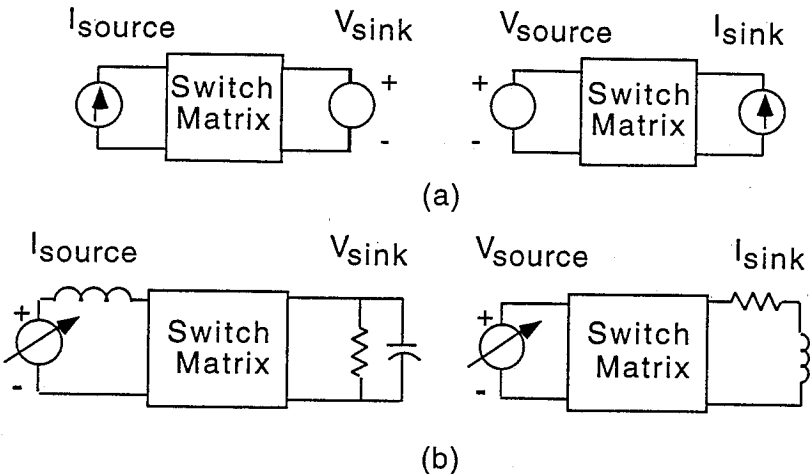


Figure 1. a) Ideal converters, b) Practical realizations

Based on these circuit constraints it can be observed that the two, so-called, bridge configurations of Fig.2 for connecting a dc source to an ac load can satisfy the requirements that are imposed. In particular, if,  $T_1, \dots, T_6$  are logic signals applied to switches  $T1, \dots, T6$  then in Fig. 2a, if

$$T_1 + T_4 = 1$$

$$T_3 + T_6 = 1$$

and

$$T_5 + T_2 = 1$$

then one and only one voltage source is applied to each current sink. In Fig.2b, if

$$T_1 + T_3 + T_5 = 1$$

and

$$T_2 + T_4 + T_6 = 1$$

then the current source is guaranteed to be connected to one and only one voltage sink.

Because of its good device utilization and absence of extra components such as interphase or intergroup reactors, the bridge configuration in either a current source or voltage source realization, forms the basic topology of nearly all three phase converter circuits presently used today. Thus the current/voltage source bridge topologies combined with the five means for commutation form a convenient framework by which converter circuits can be categorized.

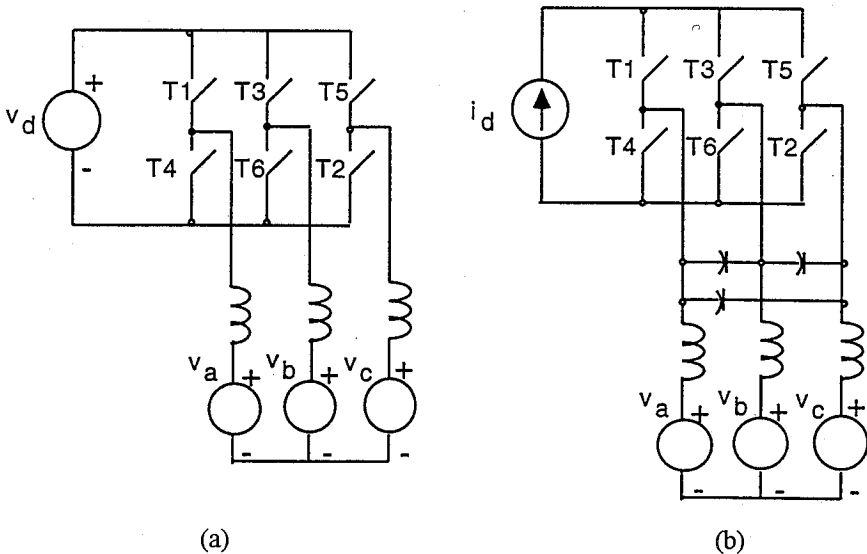


Figure 2. Converter constraints for three-phase a) voltage-fed and b) current-fed inverter circuits with a motor type load

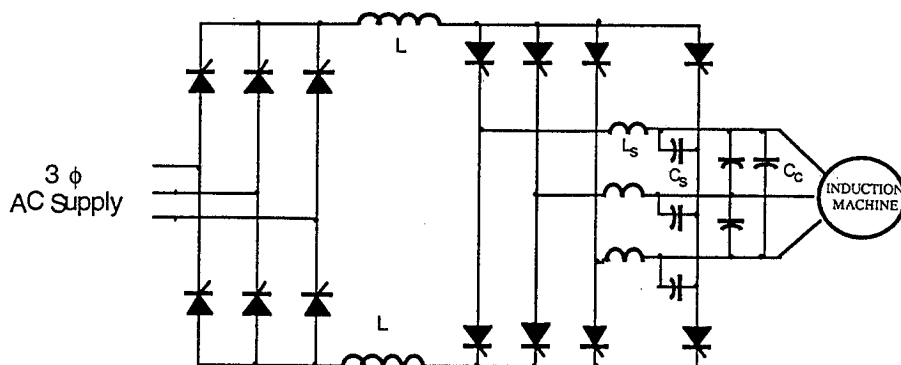


Figure 3. Naturally Commutated Converter Circuit for Induction Motor Drive

## 1. Naturally Commutated Inverters

Naturally commutated converters rely upon the natural behavior of the load to provide the energy needed to transfer current from one switch to another. This type of converter corresponds to the principle of operation of the Graetz bridge [1], the original bridge rectifier circuit which employed mercury arc valves such as ignitrons or excitrons. Natural commutation can only occur if the voltage of the ongoing phase is larger than that of the off going phase, which, in turn, implies that the voltage of each output phase must lead the current if power is to be consumed by the load. Hence, capacitors are inherently required to provide the necessary leading power factor condition if the load is an induction motor. The capacitors must be chosen to be sufficiently large to supply the reactive energy needed to magnetize the motor plus an additional amount to commutate the inverter switches. The most common naturally commutated inverter used for induction motor drives is shown in Fig.3. Note that since the current is extracted from the off-going phase by the external circuit capacitors  $C_s$ , thyristors can be used as the converter switches. The inductance  $L_s$  and capacitance  $C_s$  are used as a pulse commutation circuit (similar to those in the next section) to commutate the main thyristors during low frequency starting where the external capacitor's energy storage capability is too small to perform this function. This circuit has been widely applied in high power applications where the high voltage capability of thyristor technology can be exploited.

## 2. Resonant Pulse Commutated Inverters

Another means for sweeping the current away from a conducting thyristor is by means of a series resonant circuit placed in parallel with the switch. Resonant pulse commutation is, after natural commutation, the second oldest commutation method having come into widespread use shortly after the invention of the silicon controlled rectifier (thyristor) in the late 1950's. With the development of high power bipolar

transistor technology in the early 1970's, this technology has consequently faded from popularity. However numerous examples of continuous operation of such converters up to the present time can be found in industry. Both voltage-fed and current-fed inverter circuits can be identified. In the case of the current-fed arrangement the resonant capacitor is designed to resonate with an inductive load. Some of the most popular examples of such circuits are shown in Fig.4 and Fig.5 [2, 3, 4].

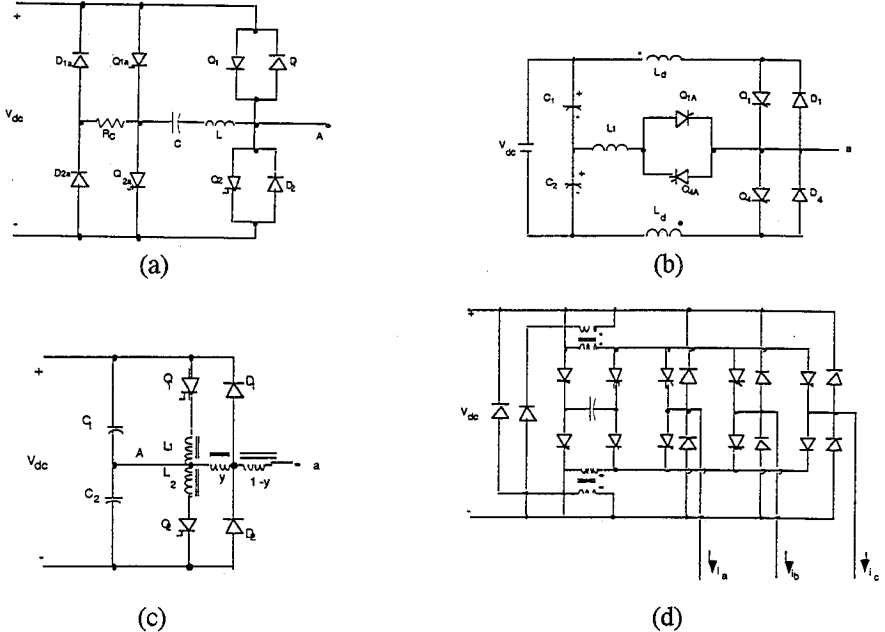


Figure 4. Voltage-fed circuit commutated converter circuits. a) Modified McMurray circuit (one-pole), b) AC switch commutation circuit (one-pole), c) McMurray-Bedford commutation circuit (one-pole), d) DC bus commutation inverter

#### 4. Self-Commutated Inverters

Progress in semiconductor device technology has been moving at a rapid pace ever since the appearance of the 'giant transistor' a bipolar transistor developed by Toshiba in the early 1970's. Today, the bipolar transistor technology of this era has been supplanted by modern insulated gate bipolar transistors (IGBTs) in most high power applications. Devices up to 1800 V and 350 A are presently available from a variety of manufacturers. Also, field-effect transistors have also improved markedly, particularly in their voltage handling capability to the point where 1000 V, 0.95  $\Omega$  MOSFETs are available for lower power applications. Finally, gate turn-off thyristors have been gradually improving every since their appearance over twenty years ago. Devices up to 4500 V and 3500 A are readily available and higher voltage devices are under development. Hence, self-commutated three-phase inverters are widely used from a few kilowatts to tens of megawatts and are the topology of choice for most applications.

Again, inverters of this type can be categorized into voltage-fed and current-fed topologies. Fig.6 shows both voltage-fed and current-fed arrangements. The GTOs in Fig.6b are both forward and reverse voltage blocking devices.

## 5. Multi-Level Inverters

Raising the operating voltage has traditionally been one of the primary means available to designers of high power components such as transformers, transmission lines, cables, etc. for improving the system efficiency. Cables and bus bars both on the input ac side and on the motor load side of an adjustable speed drive also account for an appreciable loss component making the use of higher voltages desirable. A considerable effort is underway to design inverters to operate in excess of 2000 V since power can then be taken directly from the distribution network without the need for a line side transformer. Also, the need for a transformer on the motor side to reduce cable loss can also be eliminated when the voltage is increased. Fig.8 shows several possible alternatives for raising the system voltage without increasing the voltage rating across individual switches [5,6].

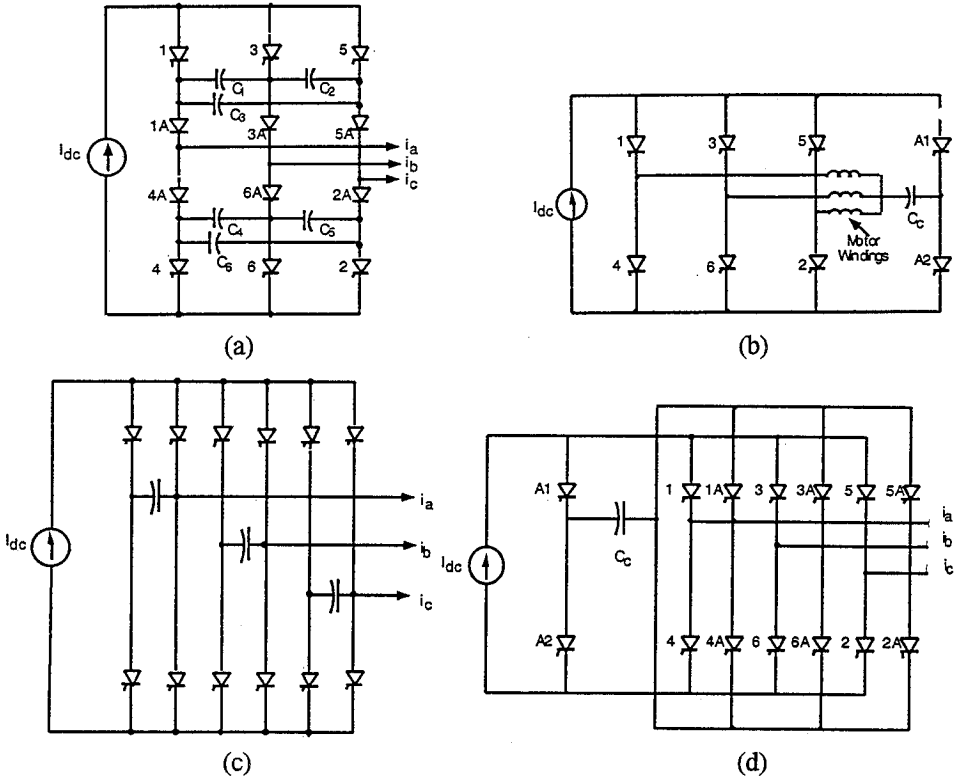


Figure 5. Current-fed circuit commutated converter circuits a) Auto-sequentially commutated inverter, b) Third harmonic commutated inverter, c) Double bridge circuit, d) Double bridge with dc side commutation

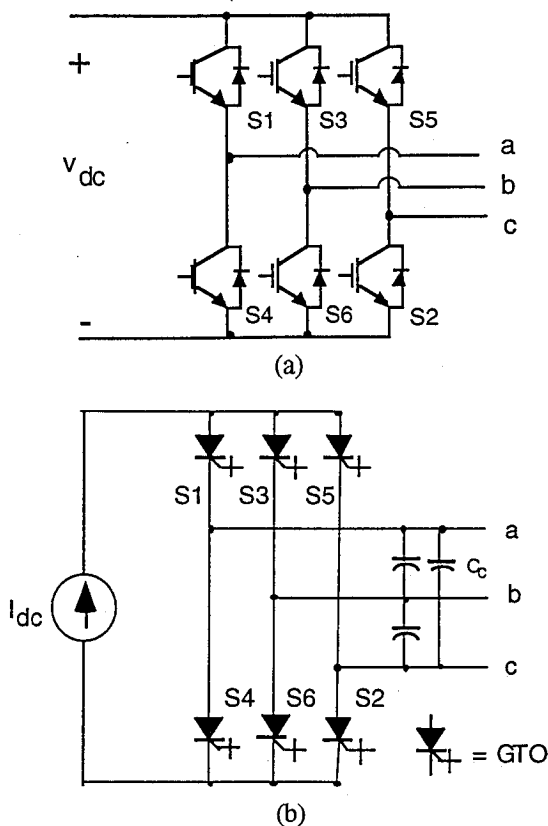


Figure 6. Self-commutated converter circuits a) Voltage-fed, b) Current-fed

## 6. Resonant Link Commutation

While self commutation is, by far, the preferred commutation technology today, it is not without its drawbacks. In particular, as the need to maintain low distortion of the motor (or line) current increases, attempts to switch the converter at progressively higher switching rates, causes the turn-off losses of the switching devices to increase to the point where the switch must be derated due to thermal limitations. Also, the fast turn-off of modern IGBT and FET devices ( $0.5 \mu\text{s}$  or less) produce rapid rise in the voltage across the switch (thousands of volts per  $\mu\text{s}$ ) which turns the device into an effective antenna for frequencies in kHz to MHz spectrum. Also, harmonics flow in the utility line contributing to harmonic pollution of the power line upstream from the motor drive. The fast rise of voltage across the off going switches is also believed to cause problems with the connected motor. For example, the steep voltage wave front traveling along a long feeder cable to the motor acts as a transmission line. When the wave front encounters the motor, the motor appears as nearly an open circuit resulting in reflected

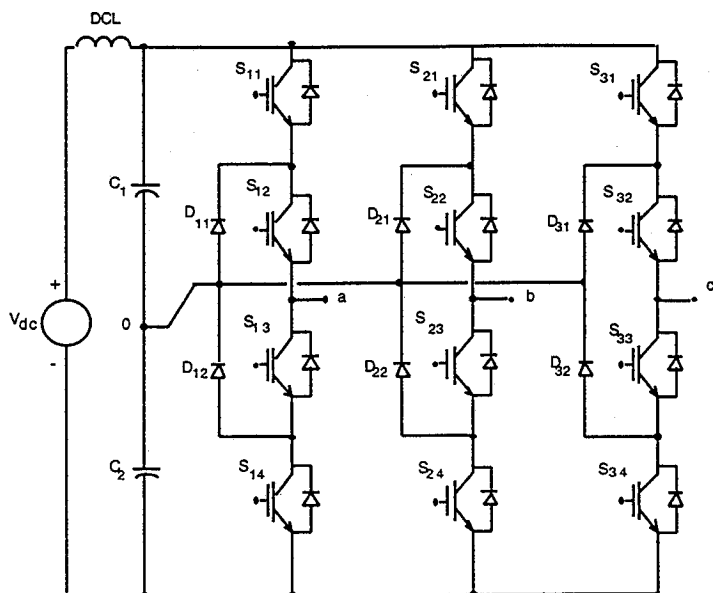


voltage which travels back to the inverter and results in a doubled voltage across the motor phases. Also, this steep voltage is impressed only across the first few turns of the motor phase. Capacitive type currents flow through the winding insulation to ground making deterioration of the insulation a concern. Finally, it has been reported that these capacitive type currents can flow through bearings which cause further deterioration in the bearing races [7].

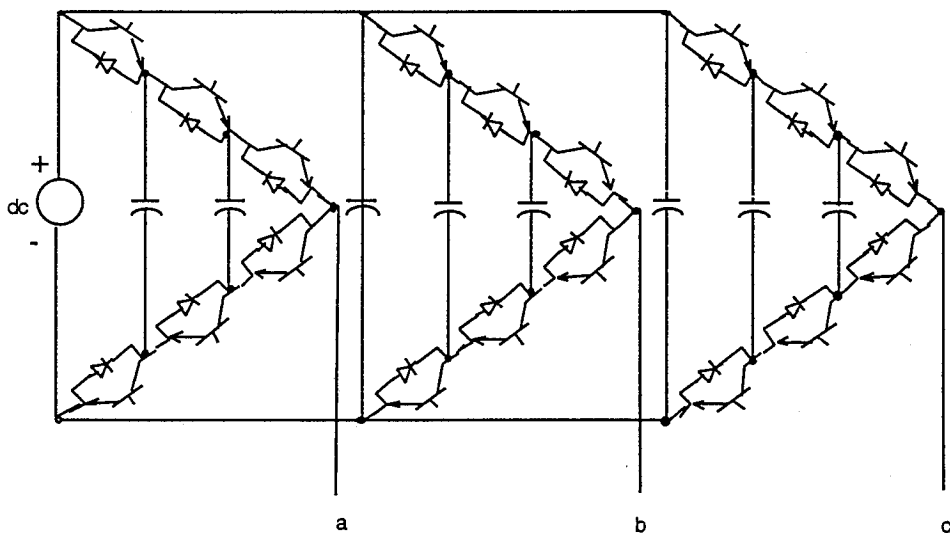
Many of these problems can be remedied if the rate of rise of voltage across the off going switch and the associated turn-off loss is reduced. The problem can be elegantly solved if the link feeding the inverter is designed to resonate, thereby producing instants of zero voltage and/or zero current on the link at which point the inverter switches can be closed or opened without switching losses. Fig.8 shows the basic family of resonant link topologies. In Fig.8a and b the link capacitor and inductor of the voltage and current-fed converters are replaced by parallel and series resonant elements, respectively. Operation of each switch (turn-on or turn-off) is initiated only when the link voltage (in Fig.8a) or the current (in Fig.8b) reaches zero. As can be noted, bipolar variation of the link voltage/current requires that the switches conduct current and block voltage in bi-directional fashion necessitating use of complicated switch elements.

The problem of needed bi-directional capability of the inverter switches can be remedied if the resonant voltage/current can be biased upward by an amount which makes the voltage/current feeding the inverter unipolar. Fig.8(c) and (d) show two such circuits. In this case the voltage (or current) reaches zero only once per cycle versus twice as in Fig.8a and b. Biasing is accomplished by means of an ac capacitor  $C_o$  in Fig.8c and a dc inductor  $L_o$  in Fig.8d. Hence, the resonant frequency must be doubled to obtain the same waveform quality. However, this is readily accomplished by decreasing both the resonant inductor and capacitor while keeping the characteristic impedance the same.

Advantages of these circuits include the fact that the rate of rise of voltage in the parallel resonant link and rate of rise of current in the current resonant link are limited by the choice of the resonant frequency. Voltage  $dv/dt$ 's of only a few hundred volts per  $\mu s$  can be readily obtained. One drawback of the resonant link principle is that the modulation of the output voltage/current is effectively quantized since complete half cycle or full cycle pulses must be chosen without violating the zero voltage/current switching principle. In turn, this leads to a voltage/current spectrum which is broadband in nature with a small but significant portion of energy at frequencies below the fundamental component of the output making filtering difficult. Also, the device rating must be geared to the maximum value of link voltage and current. Since the volt seconds (amp-seconds) that the link voltage supplies with offset sinusoidal pulses is only one-half that of a square pulse supplied by a dc voltage link, the voltage (or current) of the switches must be derated by a factor of two when compared with the hard switched self-commutated inverters of Section 4. Finally, control of the inverter switches must be done with great care since the energy storage capacity of the resonant components are very small. Selection of the improper switch could result in energy being returned to the link from the load rather than vice-versa, thereby creating a high instantaneous voltage transient on the link resonant capacitor and, therefore, the inverter switches.



(a)



(b)

Figure 7. Multi-level converter circuits a) Three level neutral point clamped converter, b) Flying capacitor onverter (showing 7 levels)

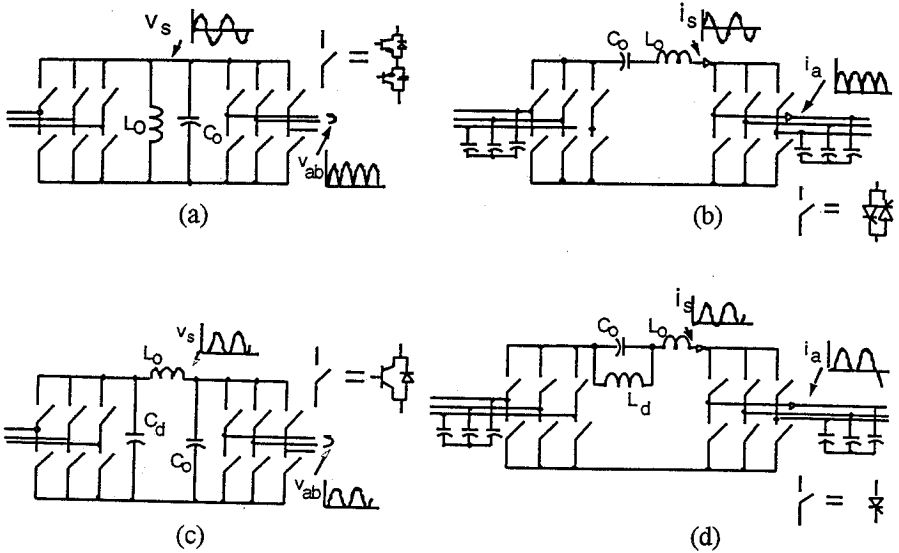


Figure 8. Resonant link converter family a) Resonant ac voltage link, b) Resonant ac current link, c) Resonant dc voltage link, d) Resonant dc current link

The problem concerned with high instantaneous voltage or current can be alleviated by utilizing clamping circuits to limit the excursion. Fig.9 shows several circuits which are used to limit the link voltage [7]. In Fig.9a an extra switch and capacitor are used to clamp the inverter voltage at  $V_o + V_1$ . The voltage is normally set from 0.2 to 0.4 $V_o$ , making the peak voltage across the inverter switches 1.2 to 1.4 $V_o$ . The main disadvantage with this approach is the high switching frequency of the auxiliary transistor which must operate at roughly six times the switching frequency of the main inverter switches which limits the application of this type of clamp to converters below 100 kW.

Another approach to limiting the link voltage in a parallel resonant dc link is to use a passive clamp as shown in Fig.9b. In this case, the clamp voltage  $V_1$  must be at least equal to  $V_o$  so that the voltage across the switches reaches 2.0 per unit. Hence, this type of clamp does not truly prevent the link voltage from rising to twice the nominal link dc capacitor voltage but only prevents overvoltage beyond this value arising from improper triggering of the conducting switches which dumps energy back onto the link from the load. However, because this approach is passive, it is appropriate for high power applications above 100 kW. One important limitation of this approach is the requirement to have very tight coupling of the two clamp windings since a progressively increasing leakage flux results in a progressively larger clamping above the 2.0 per unit value.

Analogous clamping circuits are available for the dc current resonant link [9, 10]. Fig.10 shows several clamped resonant dc current link circuits. In this case the current is clamped rather than the voltage. In general, resonant current inverters have not received the same degree of attention as resonant voltage link inverters due to the need

for fast turn off thyristors to provide switching with a high link resonant frequency in order to maintain good quality ac current waveforms. However, the possibility of using thyristors rather than self commutated devices makes this approach suitable for high power (multi-megawatt) applications.

Whereas resonant links resolve many of the problems associated with self-commutated converters, they are not without their drawbacks. Primary among these problems is additional cost imposed by the resonant link and clamp components. Hence, resonant link technology may never replace self-commutated approaches unless mandated by harmonic and/or EMI/EMC standards or  $dv/dt$  limitations across motor loads. Very few examples of practical industrial applications exist at this time. However, the reduced stresses across the converter switches together with the substantial reduction in heat sink requirement make this alternative promising in the future for specialized high efficiency, light weight, high power density applications.

## 7. Quasi Resonant Link Commutation

Other problems associated with resonant link circuits involve the losses in the link and the "quantum" nature of pulses supplied to the load. Since the link resonates

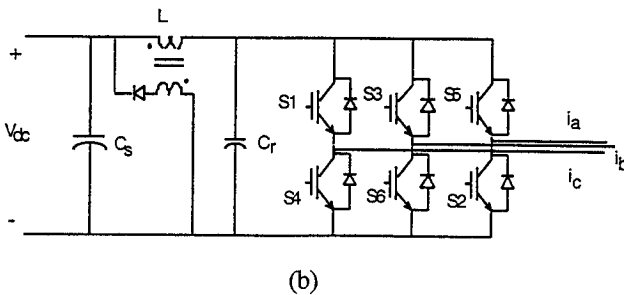
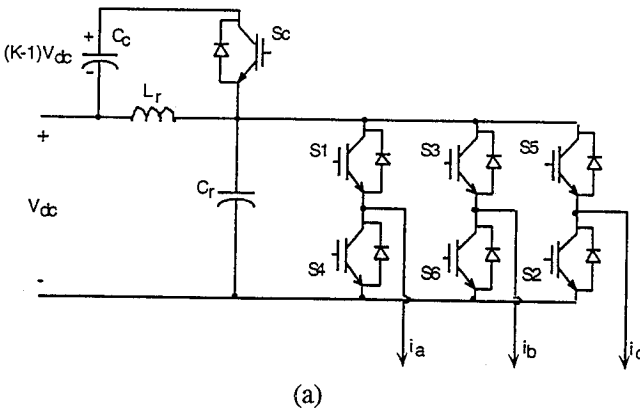
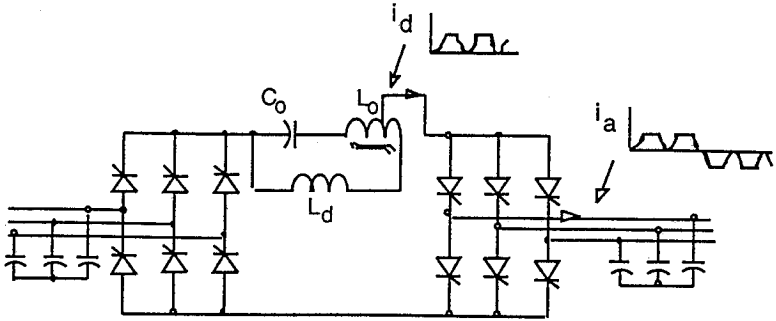
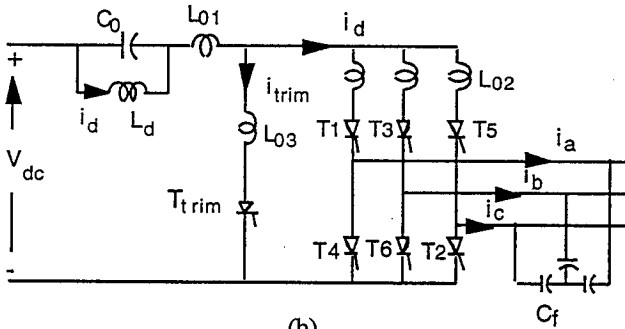


Figure 9. Resonant dc voltage link converter circuits a) Active clamped, b) Passive clamped

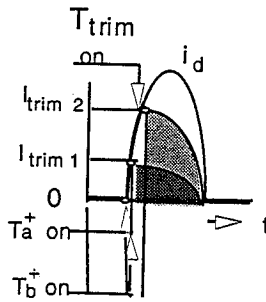
continuously, many switchings of the inverter are redundant, i.e. the same switches are chosen numerous times before another inverter switching pattern is required. The losses produced by the resonant link and clamping circuit during this period are therefore unnecessary. Also, since there is no means to adjust the width of the pulse (being fixed at the period of the resonant LC tank) the spectrum produced by the pulse selection



(a)



(b)



(c)

Figure 10. Resonant dc current link converter circuits a) Passive clamped, b) Pulse trim type, c) Principle of pulse trim type converter

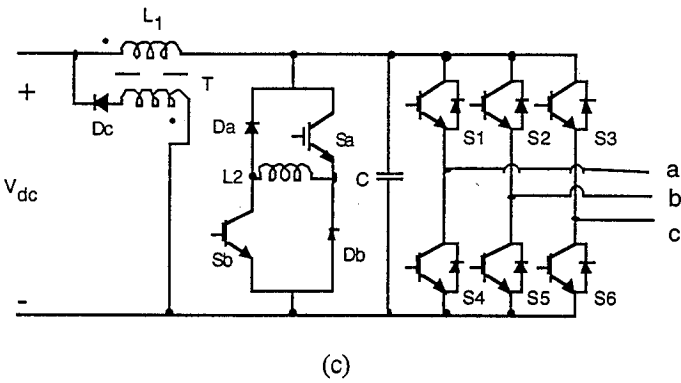
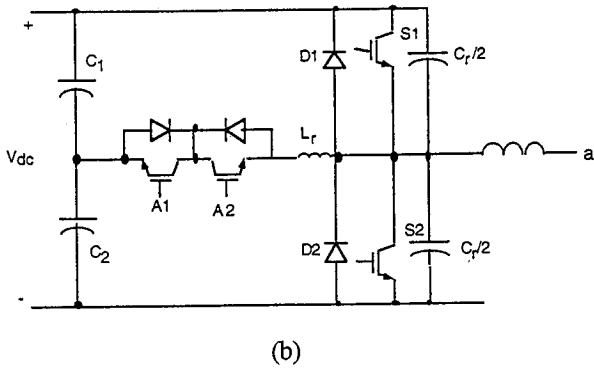
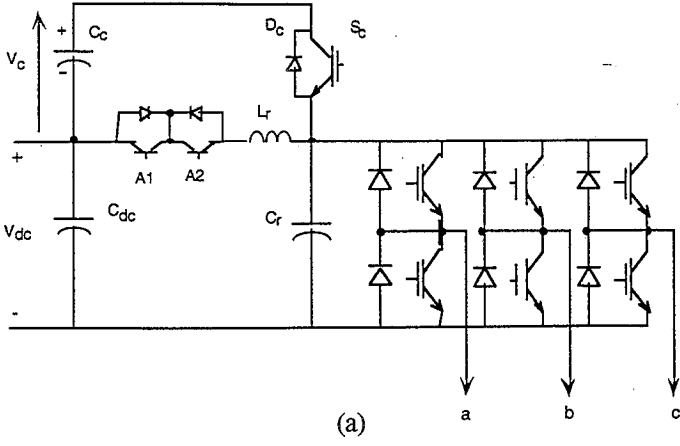


Figure 11. Quasi resonant voltage link converter circuits a) Active clamped, b) Auxiliary resonant commutated pole (one pole shown), c) Passive clamped

process results in sub-harmonics. Normally, the presence of these small 'trace' low frequency harmonics are of little concern. However, in some cases, application specifications are very stringent concerning the presence of these harmonics which is difficult to meet with resonant link technology. These problems can be alleviated by adopting a, so-called, quasi resonant strategy in which the link is called upon to resonant only when a change in inverter switching state is commanded by the controller. Hence, the inverter pulse width can be adjusted in much the same manner as for the self-commutated inverter scheme while the zero voltage or current switching of the resonant link commutation principle is retained. A variety of such circuits are shown in Fig.11 [10,11, 12, 13] and Fig.12 [14].

## 8. The Future

While it is difficult to predict the exact developments that will take place in the next decade it is clear that the remarkable progress of the past 30 years will continue, and must continue, if the scope of power electronic conversion technology is to expand its application base. Increasingly sophisticated system integration is clearly the path to follow towards reduced cost, improved reliability and smaller size and weight. Much of the progress to be achieved will depend upon improved switch structures, improved passive components such as capacitors and inductors, and system design aspects which are outside the scope of this section. However, some conjectures regarding topology can be attempted.

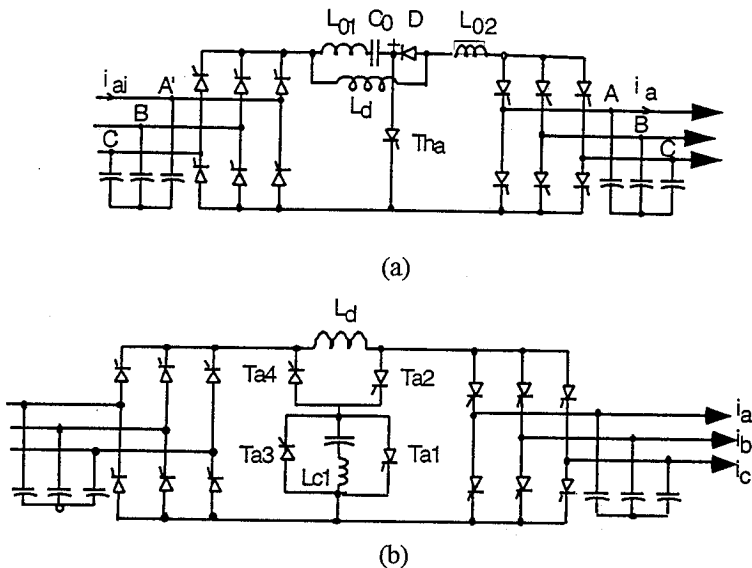


Figure 12. Quasi resonant current link converters a) Current clamped resonant current link, b) Notching current link converter

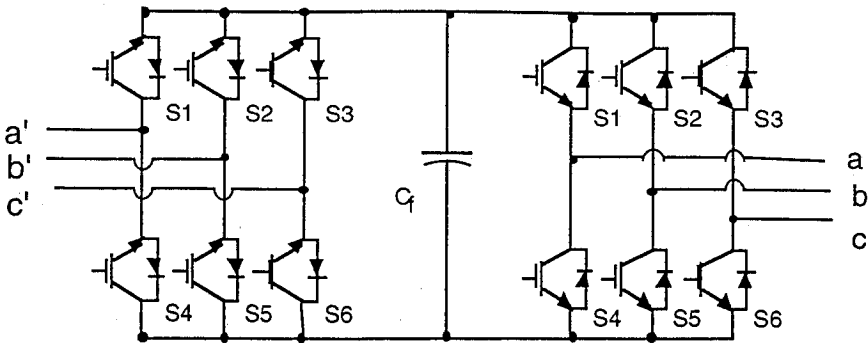


Figure 13. Double ended self-commutated rectifier/inverter

The drive towards reduced line side harmonics, as exemplified by IEEE Standard 519, will clearly have a major impact on motor drive design, particularly the line side converter. Fig.13 shows a circuit diagram of a double ended self-commutated bridge which has only recently been appearing in industrial drive applications. The presence of the self-commutated switches on the input converter together with modern pulse width modulation algorithms allows for the possibility of greatly improved current waveforms on the line side of the motor drive together with greatly simplified input side line filters. Line side converters of the resonant link or quasi resonant link type will make similar contributions to reduced harmonics on the line side. Coordination of the pulse width modulation strategy of both line and load side converters should make possible a marked reduction in the dc side filtering requirements, currently in the range of 1000 to 2500  $\mu\text{F}$ , to values in the range of 50 to 100  $\mu\text{F}$ . Since dc link electrolytic capacitors are large and bulky, replacement of these with simple film capacitors will certainly contribute greatly to a reduction in size and weight in converters, particularly as power rating increases. The inroads resonant link and quasi resonant link technologies will make on self commutated technologies is difficult to estimate. However, it appears that, as a minimum, these resonant technologies will take their place along side self commutation as an option for each new application and, in many cases involving high frequency, low weight and/or small size, will prove to be the preferred technology. In the opinion of the writer, high power applications (1 MW or more) offer the greatest potential for innovations in power electronic converter technology in the next decade. Quasi resonant approaches appear to be particularly suitable in such applications since the switch losses and thermal management are of particular concern. Multi-level converter technology appears to be another promising avenue for high power converters particularly in the medium voltage (> 2,000 V) category. If the next decade proves to be as interesting and stimulating as the past decade, we shall all look forward to the next challenge.



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### Thomas A. LIPO

Thomas A. Lipo (M'64-SM'71-F'87) is a native of Milwaukee, WI. He received the Ph.D. degree from the University of Wisconsin, Madison, in 1968. From 1969 to 1979, he was an Electrical Engineer in the Power Electronics Laboratory, Corporate Research and Development, General Electric Company, Schenectady, NY. He became Professor of Electrical Engineering at Purdue University, West Lafayette, IN, in 1979. In 1981, he joined the University of Wisconsin, Madison, where he is presently the W. W. Grainger Professor for Power Electronics and Electrical Machines. Dr. Lipo has received the Outstanding Achievement Award from the IEEE Industry Applications Society, the William E. Newell Award of the IEEE Power Electronics Society, and the 1995 Nicola Tesla IEEE Field Award from the IEEE Power Engineering Society for his work. Over the past 30 years, he has served the IEEE in numerous capacities, including President of the Industry Applications Society.