REVIEWS

High power AC motor drives: Status review and work at IISc

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Abstract | A variety of solutions are available today from industry for high power variable speed AC motor drive applications, starting from a power rating of a few 100 kW to several 10's of Megawatts. These drives can be classified on the basis of the electrical motor, the power converter and the control technique. The main drive types are reviewed. The salient features of each type of drive are pointed out along with their industrial applications.
Following this, some research at IISc which has applications in high power drives is described briefly.

Keywords: Medium voltage drives, multilevel inverters, induction motors, synchronous motors, load commutated current source inverters.

1. Introduction

High power AC motor drives with power rating ranging from just below 1 MW to several tens of MW are used in a variety of industrial applications[7,8,17,19,37]. To give a few examples:

- Compressors, pumps in oil and gas industry [up to 100 MW].
- Mill drives in metal industry [up to 25 MW].
- Boiler feed pumps, conveyors, fans, wind turbines in power industry [up to 40 MW].
- Hoists, crushers, excavators in mining industry [up to 15 MW].
- Marine propulsion [up to 20 MW].
- Extruders, pumps, fans, presses in chemical, cement and paper industry [up to 5 MW].

Table. 1 summarizes the combinations of power converter and motor that are popular for different applications.

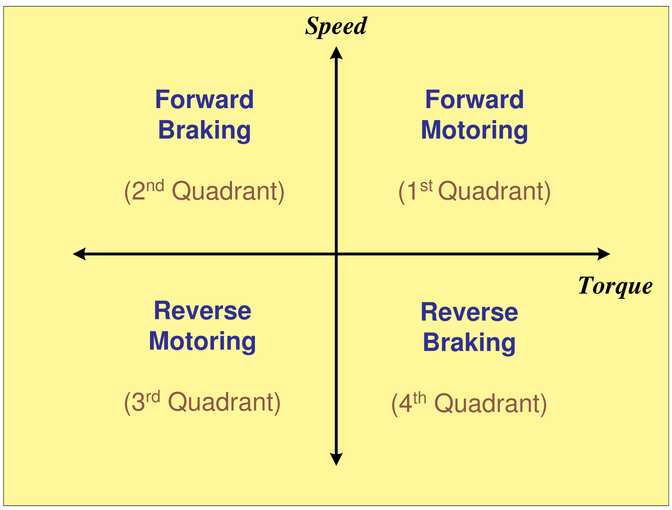
In general, drives can also be classified on the basis of their performance and range of operation. For example, applications such as hoists, rolling mills, traction/propulsion etc. require control of the motor developed torque in a very short amount of time, typically in milliseconds. Drives catering to such applications are known as "fast response" or "high performance" drives. Typically, they use a sophisticated type of control known as "vector control" which positions the stator magnetomotive force wave properly with respect to the flux wave. On the other hand, applications such as pumps or fans do not require frequent changes of speed and therefore they do not require quick control of the torque. Such drives are known as "low performance" drives.

The range of operation of a drive (in terms of the developed torque and speed) is described by means of a two dimensional torque speed plane (Fig. 1.). Drives which operate with positive torque and positive speed alone are known as single quadrant (1Q) drives. These necessarily are of the slow response type, since quick reduction of speed cannot be brought about by reversal of the torque i.e. "braking" operation is not possible. A fast response drive will necessarily have to be able to operate in two quadrants i.e. 1^{st} and 2^{nd} quadrant. Such a drive is referred to as a 2Q drive. Finally, a drive which can run in the forward as well as the reverse

Table 1:

Converter ⇒ ⇓ *Motor*	**VSI (2-level and 3-level)**	**GTO-CSI**	**Cyclo-Converter**	**Load Commutated CSI-LCI**
Induction Motor	Up to 5 MW ; **Appl:** Fans, Rolling mills ***High performance***	Not very popular	Low speed high power **Appl:** Tube mills ***High performance***	
Slip Ring Induction Motor	Rotor side control **Appl:** Wind generator ***High performance***			
Wound Field Synchronous Motor			Low speed high power **Appl:** Rolling mills ***High performance***	High speed high power **Appl:** Compressors, Large pumps ***Generally low performance***

Figure 1: The torque-speed plane.



direction and which can operate in the driving mode as well as the braking mode, is called a 4Q drive. It has the most complete range of operation.

With these notions, the various types of drives listed in Table. 1 will be briefly discussed below

2. Present day drive types

2.1. *Induction motor drives with voltage source inverters*

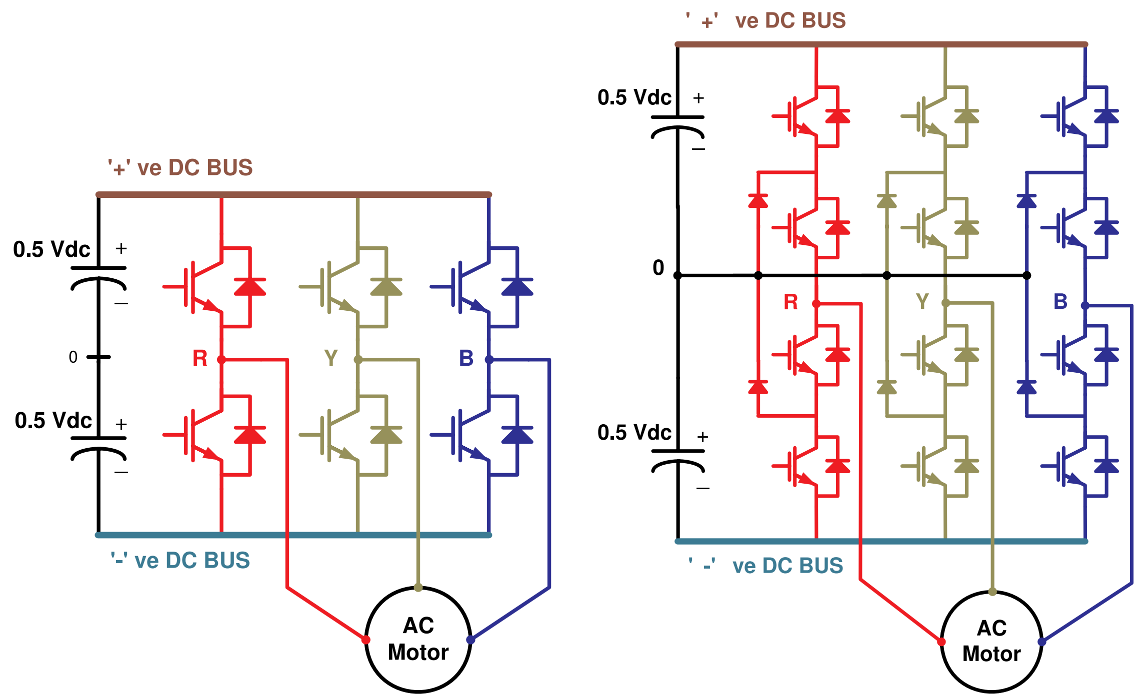
The induction machine is simple in construction and does not require any electrical contacts with the rotor [except for wound rotor type]. Therefore, it is practically maintenance free and can operate up to very high speeds e.g. 6000 to 10,000 r.p.m. is quite common in compressor applications. The power rating ranges up to about 5 MW. At such ratings, the motors tend to be designed for voltages in the range 1.1 to 4.16 kV and not at the normal 415 V. They are known as medium voltage motors.

2.1.1. *Variable speed operation—Basic issues*

The best method to control the speed of an induction machine is to vary the stator frequency, while maintaining the flux constant. Such an approach ensures that the full torque of the motor is available up to the rated speed. As a first approximation, the flux can be kept constant by keeping the ratio of the voltage magnitude to the frequency constant. This works well except at very low speeds viz. less than 10% of rated speed. Induction motor drives working on this principle are known as v/f drives. High performance drives utilize a more detailed model of the machine and a more elaborate control system – vector control – to regulate the flux and torque of the motor.

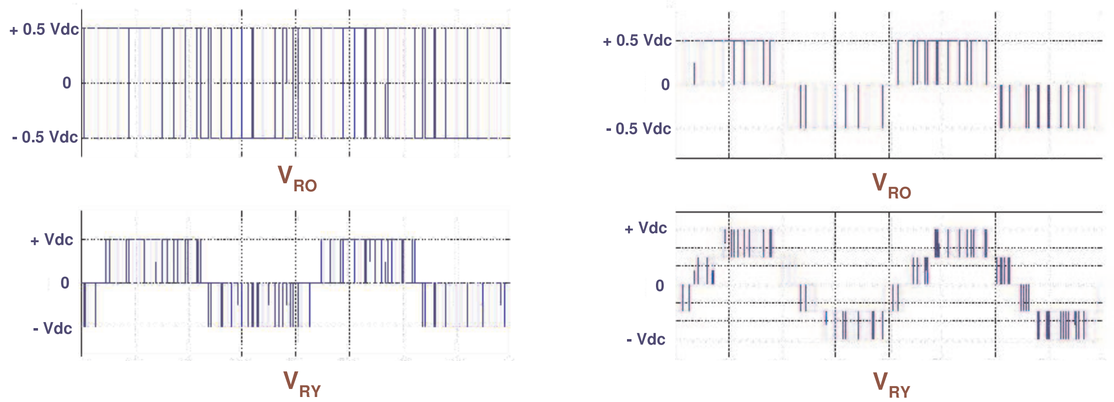
In either case, a source of power with variable voltage and variable frequency is required. Such a source is the "static inverter" which uses power semiconductor switches to create an AC voltage of controllable amplitude and frequency by switching ON and OFF a constant DC voltage across the load. Such an inverter is known as a Voltage Source Inverter (VSI) as it applies a voltage to the motor. Fig. 2 below shows the circuit diagram and the motor voltages for two types of VSI, namely 2-level and 3-level. The switching device used in these inverters is the IGBT – Insulated Gate Bipolar Transistor - which can be turned ON and OFF by applying a control pulse at the GATE terminal with respect to the EMITTER[16,18]. Since the emitters of the various switches are at different potentials, this

Figure 2: 2-level and 3-level Voltage source Inverters.



(a) Power Circuit of a 2-level VSI.

(b) Power Circuit of a 3-level VSI.



(c) Line to DC bus center-tap voltage (V_{RO}) and line to line (V_{RY}) voltage waveforms of 2-level VSI .

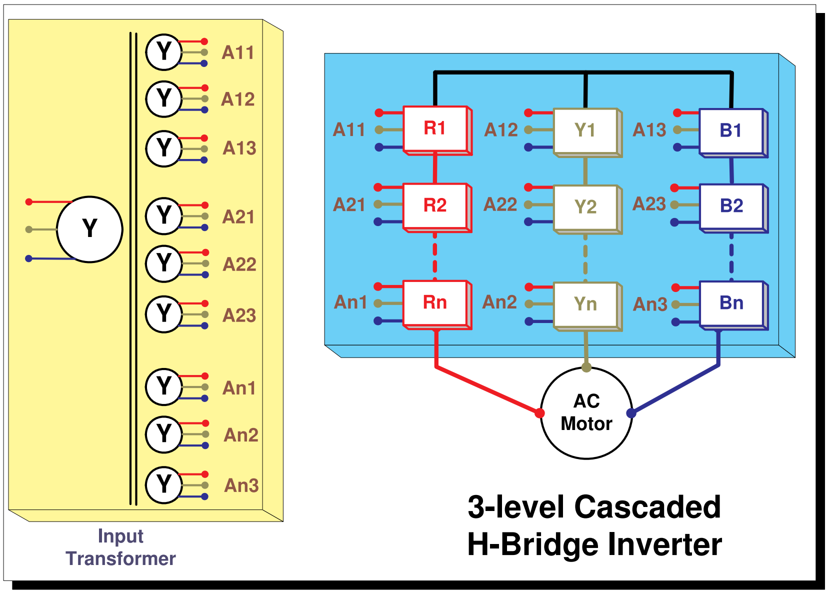
(d) Line to DC bus center-tap voltage (V_{RO}) and line to line (V_{RY}) voltage waveforms of 3-level VSI .

calls for transmitting the gate pulse from the control electronics through an isolation means—either optical or magnetic.

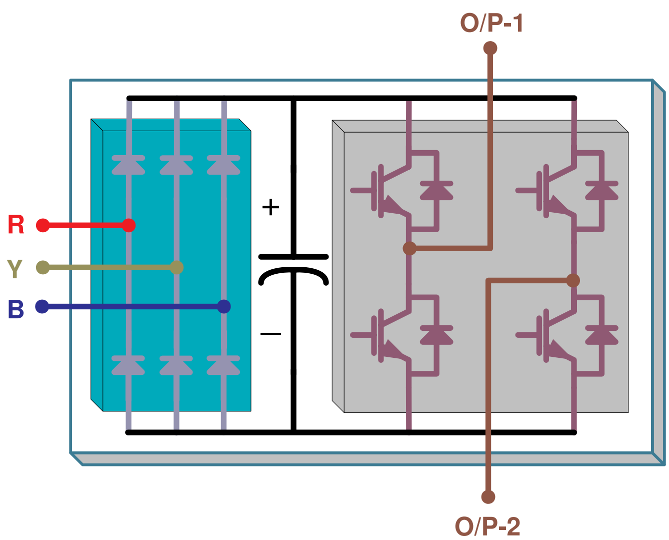
From the voltage waveforms of Fig. 2, it can be seen that the voltage across the motor contains not only the required "fundamental" sinusoidal components, but also pulses of voltage i.e. "ripple" voltage. The motor speed is controlled by varying the amplitude and frequency of the fundamental component of the voltage. As far as ripple in the voltage is concerned, the impedance offered by the induction motor at the ripple frequency is only due to the leakage inductance of the motor, which is less than 10% of the base impedance. Therefore, a considerable amount of "ripple" current is drawn by the motor from the inverter. This has several drawbacks:

- The copper loss in the stator winding increases.

Figure 3: H-bridge Inverter.



(a) Power circuit of the 3-phase multi-level H-bridge Inverter.



(b) One H-bridge cell.

- The peak instantaneous current to be handled by the IGBT increases.
- The motor develops pulsating torque near the ripple frequency which can adversely affect the mechanical components such as the bearings.

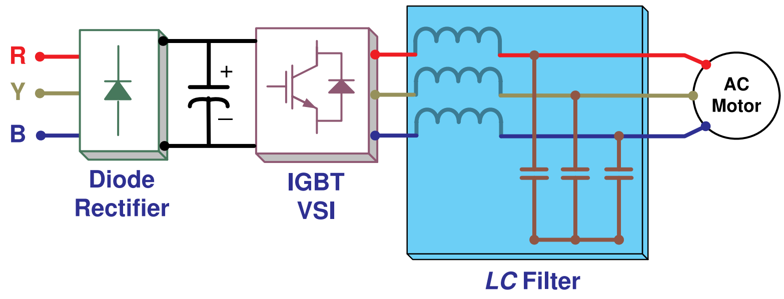
Moreover the voltage waveforms produced by the inverter has sharp edges. The rate of change of voltage with respect to time i.e. dv/dt is very high at these edges, of the order of 500–5000 V/μs. The consequences of such high dv/dt are:

- The motor insulation is stressed.
- Capacitive currents injected into the rotor flow to the ground through the bearings, reducing their life.
- Where there is a long cable between the inverter and the motor, there will be reflections which can result in doubling of the pulse amplitude at the motor end.

2.1.2. *Two-level versus multi-level VSI*

The above considerations have to be taken into account while selecting the IGBT device and the

Figure 4: Output Filter in a VSI fed drive.



inverter configuration. The voltage and current ratings of IGBTs have today reached 6600 V, 600 A. Although high voltage ratings are available, it is inadvisable to retain the 2-level configuration for higher voltage motors. This is because high voltage pulses will be applied to the motor causing dv/dt stresses.

The 3-Level inverter, on the other hand, allows the motor voltage to go up in steps, as can be seen from Fig. 2(b). This reduces the dv/dt stress for the same DC bus voltage V_{dc}. Also, using IGBTs of a given voltage rating, higher voltage motors can be catered to. Today, medium voltage induction motors rated at the MW level are generally controlled using three level inverters[7,13–15,20,29–30].

In theory, inverters of higher number of levels such as 5 and 7 level can also be constructed. However, the circuit assembly becomes very complex and issues such as keeping all the sections of the dc bus voltage equal have to be addressed. Therefore the 3-Level inverter remains the most popular choice at higher power levels and medium voltages.

A somewhat different inverter configuration uses series connections of single phase H bridge inverters in each phase to realize multiple voltage levels. A 3-level example is shown in Fig. 3. Each H bridge requires an isolated DC supply, so that the input transformer becomes very complex. But there is no limit to the output voltage that can be reached, while the IGBT ratings need not be more than 600 V. An 11 kV motor drive of this type is described in[12].

2.1.3. *Pulse-width modulation*

In VSI fed drives, the sinusoidal voltage needed by the motor is embedded as the average value in a stream of voltage pulses produced by the inverter. Inevitably, this required voltage is accompanied by other frequency components in the neighborhood of the switching frequency. The impedance offered by motor to these high frequency voltage components is basically due to the leakage inductance of the motor. Therefore, the motor current contains not only the fundamental components but also "ripple" at higher frequencies, which can be considerable in magnitude. In high power drives above MW rating, the switching frequency of the inverter is limited to a low value of about 500 Hz. [In lower power drives e.g. rated 10 kW or less, the switching frequency can be as high as 15–20 kHz]. The ripple current therefore tends to be high. The deleterious effects of the ripple in the current are mainly the followings:

- Additional copper loss in the windings.
- Higher peak currents to be handled by the inverter devices.
- Pulsations in the torque developed by the motor, which can effect the mechanical components such as gears, bearings etc.

Extensive work is reported in the literature on the subject of how to construct the voltage pulses of the inverters. The objectives are twofold.

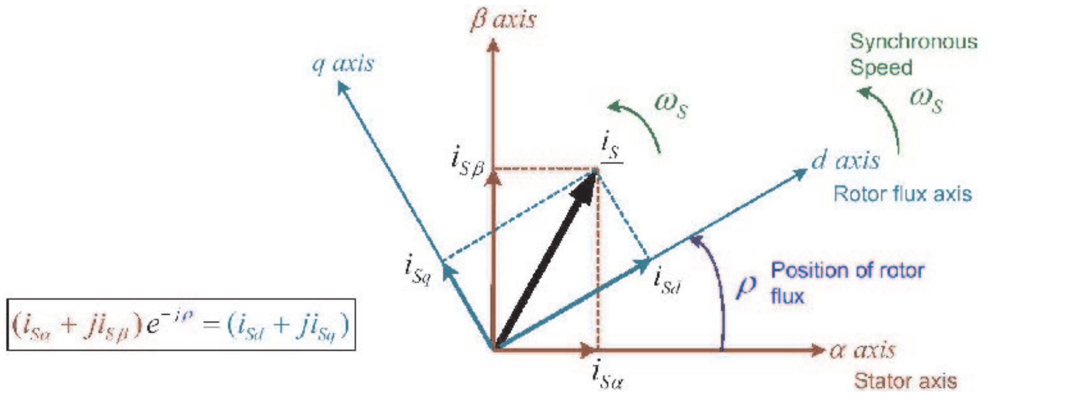
- Firstly, the required or fundamental component of voltage should be present.
- Secondly, the pulses should be "optimum" in some sense with regard to unwanted ripple components.

Various criteria have been adopted, such as : reducing the peak currents, reducing the overall r.m.s. value of the ripple current, reducing and eliminating torque pulsation at some selected frequencies etc. The topic is known as "Pulse-width Modulation" or PWM for short.[1,3–6,21–28]

2.1.4. *Output Filter*

As pointed out earlier, the presence of high dv/dt in the inverter voltage can have adverse effects on the motor insulation, bearing etc., especially if there is a long [few 10's of meters] cable connecting the inverter to the motor. In drive

Figure 5: Stator current components in the rotor flux frame of reference.



installations where this is particularly objectionable, the solution adopted is to connect a filter at the output of the inverter, as shown in Fig. 4. Because of the high currents and voltages involved and the corresponding kV A rating of the reactive elements, the filter circuit is usually limited to a second order *LC* filter as shown in Fig. 4.

The inverter can be a 2-level or a 3-level inverter. The issues in designing the filter arise from the low switching frequency in high power inverters. As an example, consider a 2-level inverter with a switching frequency of 500 Hz supplying a motor with a rated frequency of 50 Hz. The separation between the desired frequency and the unwanted frequency is only a factor of 10. The corner frequency of the filter has to be located at 150 to 200 Hz as a compromise between attenuating the switching frequency and allowing the highest fundamental frequency. Moreover, the filter inductor size has to be limited to about 10% of the base inductance with motor voltage and current as base quantities. A larger inductor would be uneconomical. The iron loss in the inductor is also a consideration. It leads to heating of the core and proper cooling has to be provided.

Use of a three-level inverter somewhat eases the problem of filter design. This is because the ripple frequency in the output voltage of a 3-level inverter is double the switching frequency of the devices. In the above example, the effective ripple frequency would become 1000 Hz, yielding a better motor voltage waveform for the same filter design.

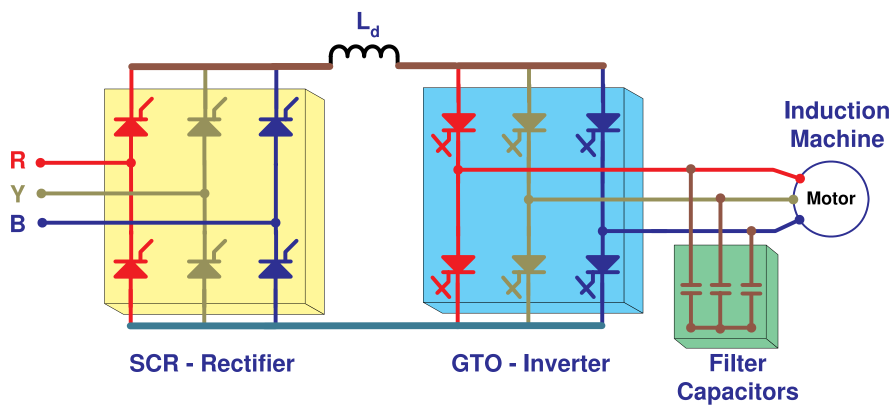
2.1.5. *Control*

Generally industrial drives are of the speed controlled type. In applications requiring precise control of the motor, a speed sensor is provided. The speed indicated by the sensor is compared with the set or reference speed. A speed controller acts on the error to set the torque reference for the motor. In many applications, such as pumps, fans etc., precise control of the speed is not required and the speed sensor is dispensed with. The speed reference is directly used to generate the torque reference. Such drives are known as "open loop" drives.

The inner core of the control deals with adjusting the motor voltage and frequency so that the developed torque matches the reference. In "low performance" drives such as pumps and fans where quick variation of the torque is not required, the control is based on steady state relationships between the torque and the voltage and frequency. It can be shown that torque is proportional to the square of the flux linkage – represented by the voltage to frequency ratio – and is also proportional to the slip frequency. By adjusting the frequency of the inverter output and simultaneously the magnitude of the voltage – so that the v/f ratio is constant – the torque of the machine can be controlled. However, the time taken to change the torque from one value to another typically takes several cycles of the stator frequency. Therefore, this method is suited only for drives which are not "high performance".

In applications such as machine tools, rolling mills, elevators, coilers etc. the torque has to be controlled in a fast and well damped manner. The flux linkage has to be preserved while attempting to control the torque, as otherwise coupling between torque and flux within the machine can give rise to slow and oscillatory response. The basic framework adopted in AC motors – including the induction motor – is to consider the components of the stator m.m.f. in a coordinate system that is rotating along with the flux of the motor. In the induction machine, the preferred flux for this purpose is the rotor flux—as against the stator flux and the air gap flux. Fig. 5.

Figure 6: GTO-CSI for Induction Motor control.



shows the stator current and its components along and perpendicular to the flux.

By controlling the two components i_{sd} and i_{sq} in a decoupled manner, the flux and torque of the motor can be controlled independently. The method involves sensing the actual stator currents of the motor, sensing the position ρ of the rotor flux using a model of the motor and transforming the stator currents to the d–q axis. Subsequently, current loops are closed around the stator to control the components of stator current. This method is known as "vector control" since the vector of stator current is controlled[1–4,9,31–33]. At the expense of increased complexity of implementation, it results in fast control of the torque of the machine, in times of the order of a few milliseconds. It is the commonly used technology today for most AC motor drives for high performance applications.

2.2. *Induction motor drives with GTO current source inverters*

In the early days, when the Silicon Controlled Rectifier [SCR or popularly thyristor] was the only power device available with high voltage and current ratings, the Current Source Inverter (CSI) emerged as an alternative to the VSI. This was because a separate "commutation" circuit was required in the VSI to turn off the SCRs, which made the VSIs difficult to design. The CSI was perceived as a more rugged alternative. However, the CSI operation was not without its difficulties. The CSI also required "commutation" capacitors to turn off the SCRs and the commutation time depended on the load current. Operation of the motor at low speed required PWM which was difficult to achieve with SCRs. Moreover, CSI operation is inherently closed loop in nature, unlike VSI operation with v/f control.

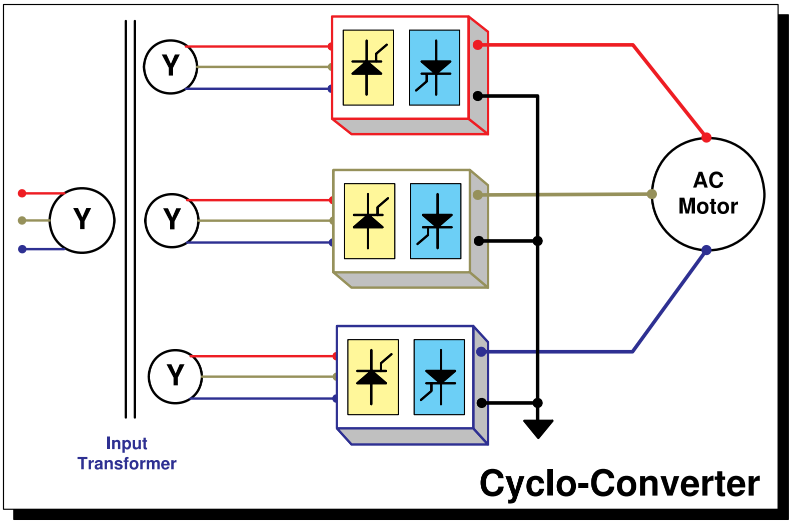
Because of the above reasons, VSIs slowly replaced the CSIs as the inverter of choice. Then a new device known as the Gate Turn-off Thyristor (GTO) was invented. As name implies, it is a thyristor with the ability to be switched off from the gate terminal. Although the device had high voltage and current rating comparable to the SCR, one of the difficulties in using it was the fact the "turn off gain" was low, of the order 10 or less. This meant that to switch off a main or anode current of 500 A for example, a negative gate current of about 50 A is required, albeit for times of the order of 100–200 μs. Therefore the design of the gate drive circuit was quite a challenge[1,3,6,34,37–38].

The GTO was used in VSIs as well as CSIs. Its use in CSIs was particularly interesting, since the commutation circuit could now be dispensed with. The circuit diagram of a GTO-CSI driving an induction motor is shown in Fig. 6.

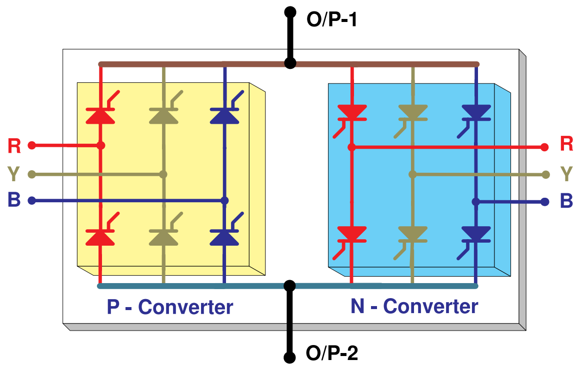
It can be seen that a bank of filter capacitors is required between the CSI and the motor. This capacitor bank converts the rectangular pulses of current coming out of the inverter into somewhat sinusoidal currents, in the process smoothening out the motor voltages also. However, the presence of the capacitor creates additional problems. The capacitor [generally 1 to 1.5 p.u.] can resonate with the main or magnetizing inductance of the motor; this limits the highest fundamental frequency that can be applied. The capacitor can also resonate with the leakage inductance of the motor. This requires that PWM should be introduced in the CSI to avoid generation of the resonant frequency. PWM operation of the GTO inverter is quite involved.

Because of the above difficulties, the GTO-CSI drive did not become very popular. Today, IGBT ratings have increased to match that of the GTO, with much less difficulties in the drive circuit.

Figure 7: 3-phase 6-pulse cyclo-converter.



(a) Power circuit of the 3-phase to 3-phase cyclo-converter.



(b) Power circuit of the 3-phase to 1-phase cyclo-converter.

Therefore the GTO itself has become obsolete. However GTO-CSI configuration has led to the evolution of other interesting configurations, which will be described in Section 3 of the paper.

2.3. *Cyclo-converter fed induction motor drives*

The cyclo-converter is a circuit which uses the SCR to convert AC power of one frequency (say 50 Hz) into AC power at another frequency (usually limited to about 1/3 of input frequency). Fig. 7 shows a 3 phase 6-pulse cyclo-converter[1,3,6,34–36].

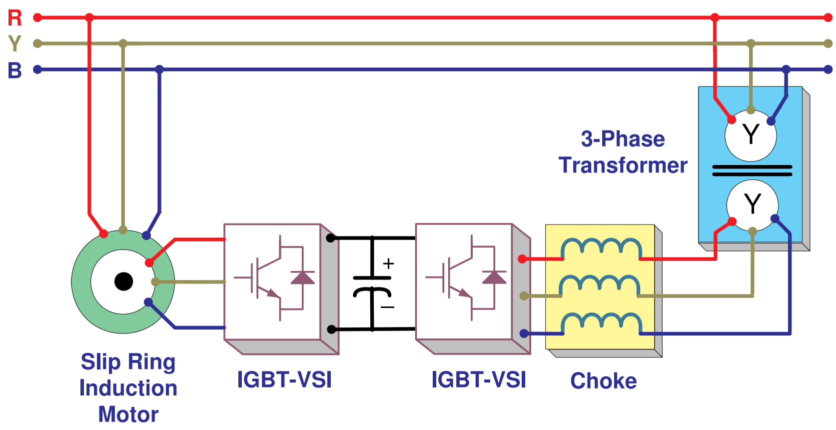
The three phases can be connected in star or delta. Note that each phase requires a secondary winding on the input transformer. The main advantage of the cyclo-converter is the fact that the turn-off of the SCRs is achieved by the process of line commutation. When a particular thyristor is turned ON it automatically turns off a previously conducting thyristor by applying a line voltage in reverse across it. The circuit is therefore extremely simple and can be scaled up to very high powers of the order of 10–20 MW. The large number of SCRs is not an issue at such power levels.

Cyclo-converters have a limitation that the output (or motor) frequency cannot be more than about a third of the input frequency, as otherwise the quality of the output voltage waveform becomes poor in terms of the harmonic content. This type of drive is therefore used in high power applications with low motor speed. Steel rolling mills and ball-mills in cement industry are examples. By enclosing current loops around the stator and applying vector control, high performance in terms of torque control can be achieved. One of the issues of the cyclo-converter drive is the complex waveform of the line current on the input side, which may require filters to be installed.

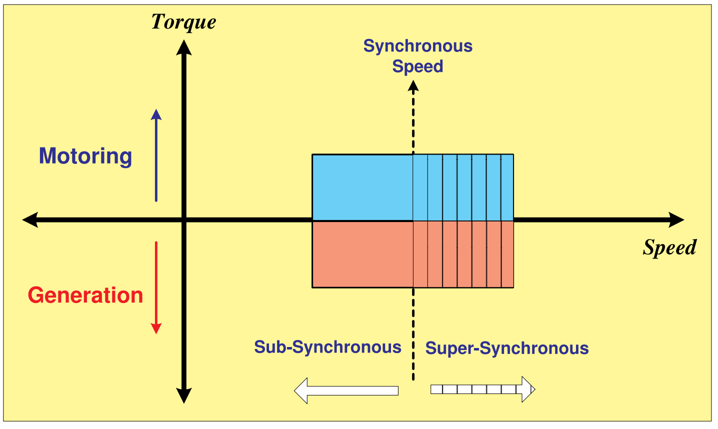
2.4. *Slip ring induction motor drives*

Slip ring induction motors have a three phase winding on the rotor whose terminals are brought

Figure 8: Rotor side control of Slip Ring Induction Motor Drive.



(a) Schematic.



(b) Operating Range.

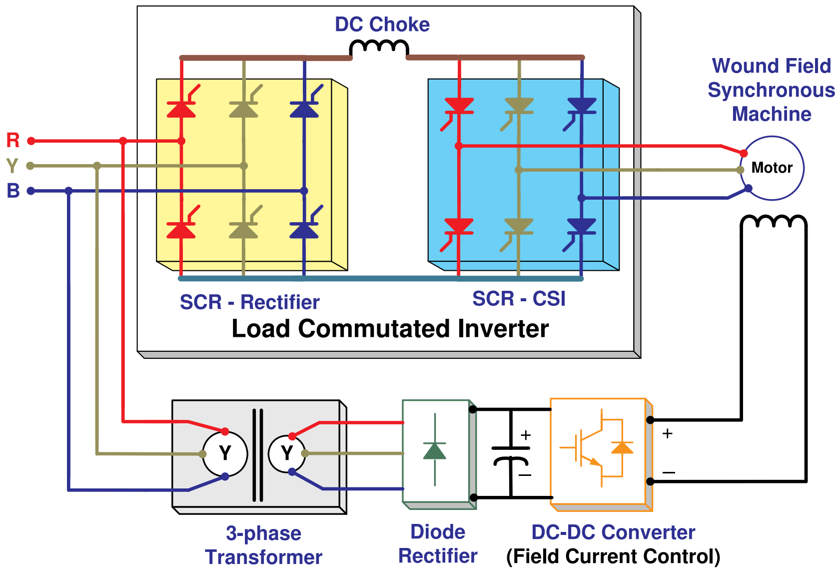
out through slip rings and brushes. They are typically built in the 100s of kW rating[1,43–47]. Traditionally they were used in applications such as wind tunnels, municipal water pumping etc. where the range of speed control is limited and close to the synchronous speed. The older systems used water rheostats connected to the rotor circuit for speed control, although this was a lossy method. Subsequently, SCR bridges were used on the rotor side to extract or inject power into the rotor at slip frequency, resulting in controlled operation at sub-synchronous as well as super-synchronous speeds. Today, one can build back to back IGBT based VSIs for this purpose. The schematic of such a slip ring motor controlled on the rotor side is shown in the Fig. 8(a) and the range of operation in Fig. 8(b).

Such a system has several advantages compared to the earlier SCR converter based systems.

- Since the machine operates over a limited slip range the power converter rating is equal to the maximum slip times the machine rating e.g. 30%.
- With IGBT converters, sinusoidal currents can be injected into the rotor, thus developing smooth torque.
- The line side VSI – also known as the front end converter – allows the regulation of DC bus voltage, as well as enabling the power factor of the entire system to be controlled.

This configuration has recently acquired significance in wind power generation. In this application, in order to optimally harvest the available wind energy, the electrical generator has to be a variable speed fixed frequency system. The slip ring machine, operating in the generator mode, ideally meets the requirement while at the same time being economical in terms of converter size. The rating of the windmill in such installations is typically 1 to 2 MW so the converter rating for 30% speed variation about synchronous speed is of the order of 300 to 600 kW. One of the advantages of using a slip ring machine in such a system is that the position and speed of the rotor can be estimated

Figure 9: Configuration of LCI fed Synchronous Motor Drive.



from the stator and rotor currents and hence there is no need for a mechanical position sensor. This is significant because the generator is mounted in the nacelle on top of the tower. Any position sensor would require cabling to bring the signals down to the inverter controls, making the system vulnerable to breaks in the cable and other faults.

2.5. *Wound field synchronous motor drives*

Synchronous machines are generally designed at medium (4.16 kV) to high (11/13.2 kV) voltages and power ratings in the tens of megawatts. Since it is not possible to build VSIs at these voltage and power levels, generally it is the SCR that is the device of choice in high power synchronous motor drives.

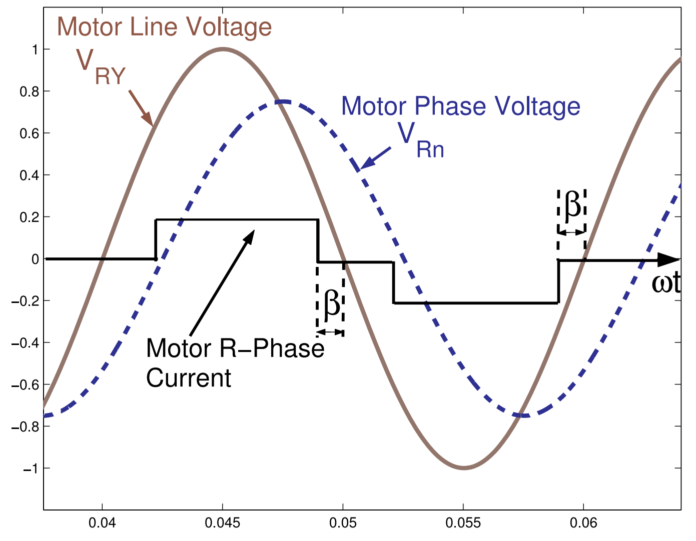
For low speed high performance applications such as rolling mills etc. the motor is designed with a large number of pole pairs and fed by a cyclo-converter. The output frequency limitation of the cyclo-converter is not a factor in such applications. Since the SCRs turn-off by line commutation, the power circuit is very simple. By closing current loops around the cyclo-converter and the stator, closed loop control of the torque can be achieved with quick dynamic response. The ripples in the motor voltage and current are still present and accepted as the price for circuit simplicity.

For high speed (e.g. 6000 r.p.m.) applications such as pumps, fans, compressors etc., the motor frequency may have to be actually greater than the line frequency (50/60 Hz). This obviously requires a power converter where the line side and motor side circuits are decoupled by energy storage elements. Again, since the SCR is the preferred device at the high power rating of the motor, the Load Commutated Current Source Inverter (LCI) is the preferred topology for such applications[1,4–6,39–42] . As can be seen from Fig. 9, the two circuits are identical SCR bridges, separated by a DC choke.

While the line side SCRs are turned off by line commutation, the machine side converter SCRs are turned off in a similar fashion by the internal induced voltages of the motor. For this purpose, a leading displacement factor has to be maintained at the motor terminals i.e. the current has to lead the voltage. This can be achieved by suitably adjusting the field current of the synchronous motor. The lead angle β of the current with respect to the voltage must be sufficient to ensure proper commutation. Fig. 10 shows typical voltage and current waveforms at the motor terminals.

It can be seen, for example, that at the instant when the positive pulse of current in the R-phase has to be shut down, the line to line voltage V_{RY} has to be positive so as to turn off the conducting SCR of the R phase. This requires the phase advance angle β. SCR turn-off times are of the order of 200 μs, so a value of $\beta = 10^o$ is sufficient even at the fundamental frequency of 50 Hz. At lower frequencies, of course, β will be even smaller, since the commutation time remains constant.

Figure 10: Motor voltages and currents.



The LCI configuration also has an extremely simple power circuit. One feature that can be observed from Fig. 10. is that the motor currents are rectangular. This results in 6^{th} harmonic torque pulsation and therefore the drive has to be operated above some minimum frequency; otherwise the torque harmonics may excite mechanical resonance. Sometimes the motor is provided with two sets of stator windings with 30° electrical shift between their axes. If the two stators are fed by two LCIs with a phase shift of 30° between their currents, the frequency of the dominant torque pulsation becomes 12 times the fundamental frequency. The two LCIs are connected in series on the DC side with a common DC current source.

In addition to the problem of torque pulsations, the LCI also needs special measures for starting. This is because, at low speeds, the machine induced electromotive force is not sufficient to turn-off the SCRs of the inverter. The solution adopted is that of "DC link current pulsing". Every time an SCR has to be turned-off in the inverter section, the rectifier has to be phased back so that the DC link current drops to zero. The new pair of conducting SCRs in the inverter is now turned ON and once again the DC link current is built up by reducing the firing angle of the rectifier SCRs to the proper value. Other than being cumbersome, the process results in pulsating torque. The drive is not suitable for applications requiring high torque at low speeds. This is the reason why, even though the circuit can operate in the regenerative mode, it is not regarded as a reversing drive.

3. WORK at IISc

Over the years, there has been significant research at IISc [specifically in the EE and CEDT Departments] which has relevance to high power AC drives. This work is briefly described below.

3.1. *Induction motor drives with VSIs*

As was pointed out in Section 2.1.2, the highest power output that can be handled by the conventional 2-level VSI is limited by IGBT ratings as well as dv/dt problems for the motor. Where it is applicable i.e. in the range of 500 kW–1 MW, the inverter has to be operated with limited switching frequency, of the order of 450 Hz. The generation of PWM waveforms at such low frequency is a challenge.

3.1.1. *Space vector PWM with low switching frequency*

By adopting the space vector framework, it has been shown that families of PWM patterns with low switching frequency can be generated. Deviating from the conventional Space Vector Modulation – SVM – new approaches such as adopting different voltage Vector Sequences for different samples of the reference vector, clamping one phase while switching the other two etc. can give rise to a variety of PWM patterns with interesting spectral properties. Such patterns have been systematically generated and extensively analyzed[48–57].

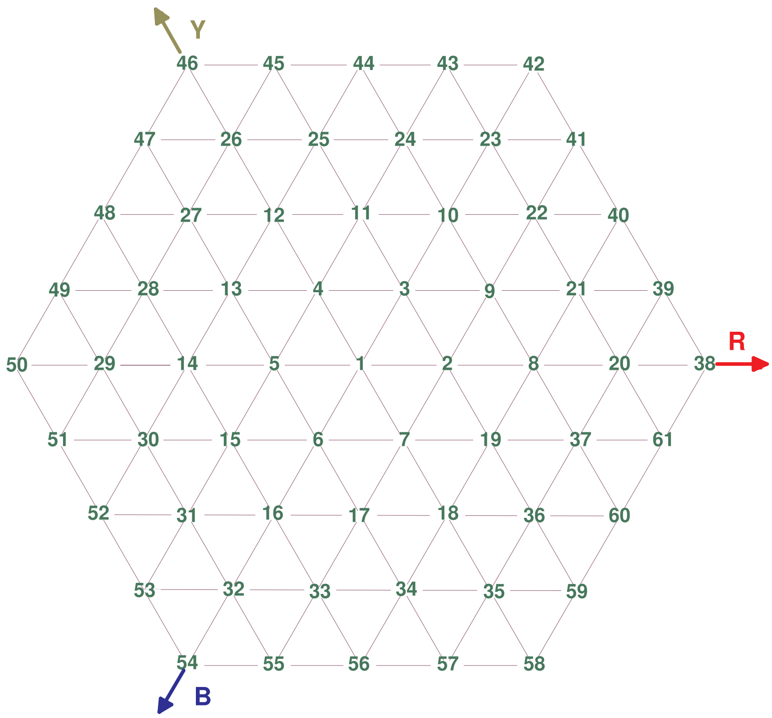
3.1.2. *Multilevel inverters and PWM techniques*

The use of three level VSI is now quite common in induction motor drives rated above a megawatt. The three level inverter can itself be constructed in different ways; the most commonly used being the so called Neutral Point Clamped-NPC-inverter, shown in Fig. 2(b).

While theoretically inverters with more levels in their voltage output can be constructed using the same approach, the circuit becomes complex and is not favored.

It has been shown that there are many alternative approaches to constructing multilevel inverters. These include combinations of two and three level inverters, motors with winding open at both ends etc. Considerable work has also been carried out on the generation of PWM sequences for such multilevel inverters. Fig. 11 shows the possible space vector locations for a 5-level inverter. The fact that many of the vectors can be produced by more than one state of the inverter switches gives rise to interesting possibilities such as avoiding common mode voltage. The problem of PWM generation for multilevel inverters has also been extensively studied[58–81].

Figure 11: Voltage Space Vector Locations for a 5-level Inverter.



3.2. *Slip ring induction machines*

3.2.1. *Grid connected operation*

As was described in Section 2.4 by connecting the stator of a slip ring machine to the 3-phase grid and controlling the rotor current through back to back VSIs, a variable speed constant frequency generator can be realized. Such a scheme is popular in wind power generation. The advantage of such a system over more conventional systems with squirrel cage induction motors has been clearly shown.

Moreover, the fact that the stator as well as the rotor currents can be directly sensed is of advantage in the control also. The position and magnitude of the rotor m.m.f. can be controlled without the knowledge of the rotor position i.e. sensor-less vector control is easy to implement. The control of the machine has been studied and sensor-less schemes have been implemented[82–85].

3.2.2. *Stand alone operation*

The use of a slip ring machine as the electrical generator rather than a fixed speed alternator gives rise to many interesting possibilities. In a standard diesel driven system, for example, the speed of the diesel engine can be reduced at light load, thereby saving of fuel as well as reducing emissions. The operation of such a stand alone system has been extensively studied and simple sensor-less control schemes have been developed to maintain the frequency[86–90]. Such a system can also be used as the backbone of a micro-grid with mixed power sources such as wind, solar, biogas, diesel etc. with the flexibility that the diesel engine speed can be allowed to vary.

3.2.3. *Double inverter fed slip ring induction motor drive*

Evolving out of the grid connected operation of the SRIM, a new configuration has been invented[91–94], as shown in Fig. 12 in its simplest arrangement.

The stator to rotor turns ratio of the machine is unity. The two inverters are of equal voltage and current rating and share a common DC bus. The system can be operated in a number of modes. In general, these modes can be classified into two varieties:

- Those where there is active power circulation between the two inverters, which may be termed sub-synchronous operation.
- Those where the active powers on the two sides are additive, which may be termed super-synchronous operation.

The net operating range of the system is shown in Fig. 13.

Some significant aspects can be noticed from this diagram. With the rating of the two inverters being 1 p.u. i.e. same as the rating of the motor, a total power of 2 p.u. can be extracted from the system by operating in the super-synchronous speed, since the stator and rotor powers are additive. The speed of the motor can also be extended beyond 2 p.u. by going into field weakening. This aspect is not discussed here. The system is fully four quadrant in nature. It is well suited for high performance applications going down to zero speed viz. rolling mills, coilers, winders, cranes, paper mills etc.

The control of the drive has also been extensively studied. It has been shown that best results are achieved if the flux of the machine is controlled from one side by maintaining constant v/f or equivalent, while the torque should be controlled from the other side by vector control or direct torque control.

Note that for a given rotor speed, the frequencies on the two sides should only obey the relationship that their difference should correspond to the speed. This allows freedom to vary the individual stator and rotor frequencies. Novel frequency profiles have been designed so that the frequency on either side never goes below a minimum, say 15 Hz. With this, the v/f approach gives good control of the flux. Moreover, the position of the flux can be obtained by simple integration, even at zero speed. Sensor-less control is therefore easily implemented enabling 100% torque to be developed even at zero speed.

Figure 12: Double Inverter Fed SRIM Drive.

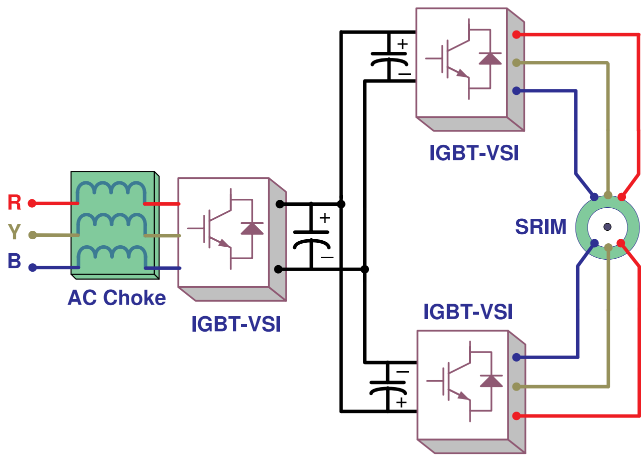
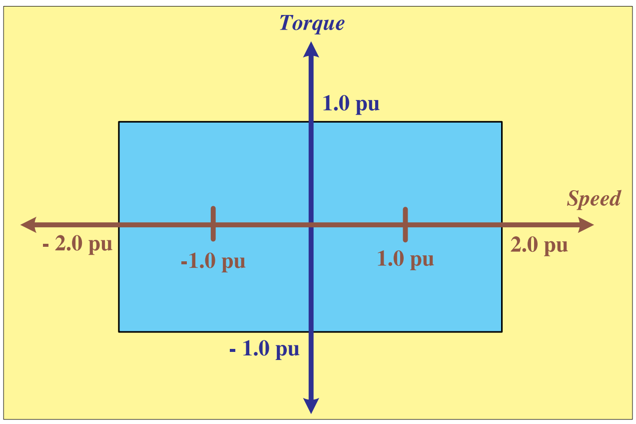


Figure 13: Operating range of the Double Inverter Fed SRIM.



3.3. *AC drives fed by LCI+VSI*

3.3.1. *Squirrel cage induction motor drives*

While discussing the GTO CSI drives in Section 2.2, it was pointed out that the presence of fixed capacitor filter at the output caused problems due to the resonances with the motor inductances. This required that the CSI be operated in the PWM mode, which is difficult.

3.3.2. *Synchronous motor driven by LCI+VSI*

A new configuration was proposed, where the fixed capacitor is replaced by an active filter consisting of a VSI and a reactor. This is shown in Fig. 14.

The advantages of this system over the earlier one are as follows. Since the VSI is an active converter, the filtering of the current waveform produced by the CSI can be maintained uniform irrespective of the fundamental frequency of the motor. Consequently the GTO-CSI can be operated in the simple 120° mode without any PWM. The harmonics in the 120° current waveform are compensated by injecting them from the VSI. Such a system was built and studied extensively[95–96]. The GTOs were replaced by IGBTs with series diode in the experimental system. It was shown that the motor voltage and current waveform become close to sinusoidal as ideally required.

The system of Fig. 14 still needs to use GTOs or other gate turn-off switches. Instead, if the VSI can inject the reactive power required by the induction motor as well as compensate the harmonics, the current source inverter can be constructed by using SCRs. The motor and the VSI circuit can be

Figure 14: GTO-CSI+VSI for Induction Motor Drive.

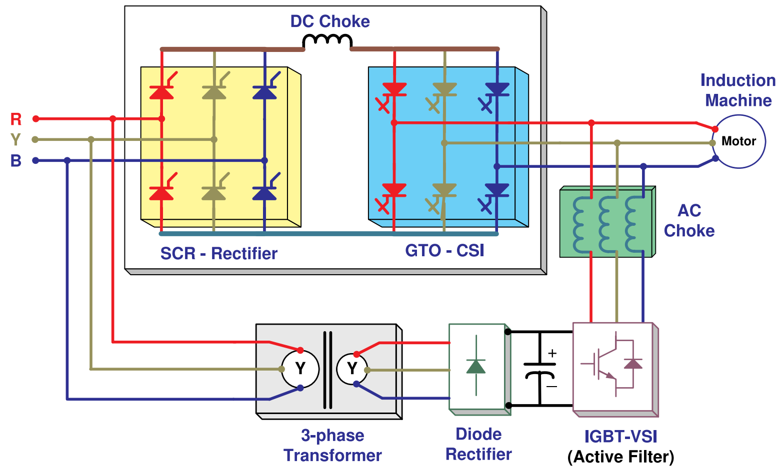
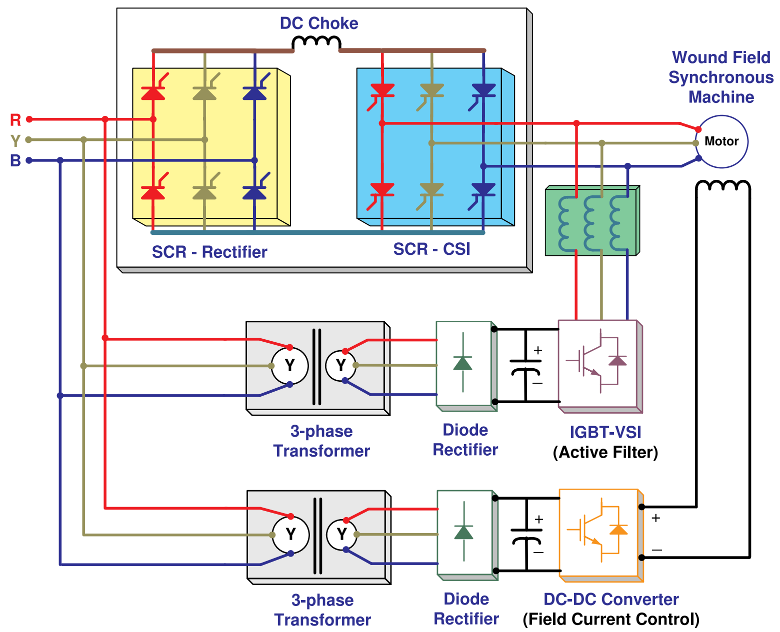


Figure 15: LCI+VSI for Synchronous Motor Drive.

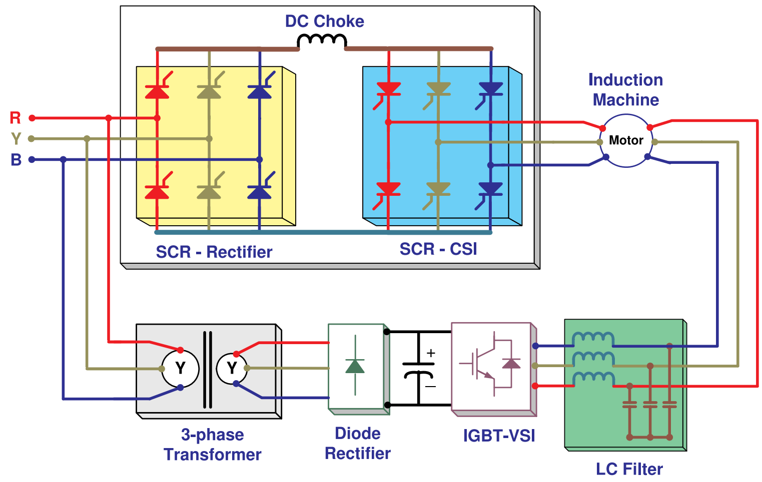


controlled to always present a leading displacement factor to the CSI. In that case, the SCRs get turned-off by the load voltages themselves, as in the case of a synchronous motor drive with LCI. Thus the LCI concept has been applied to the induction motor for the first time[97–98].

It should also be pointed out that the GTO has become obsolete and is being phased out by manufacturers. It is being replaced by devices such as IGCT (Insulated Gate Controlled Thyristor). Therefore, SCR based LCI is preferable.

The general philosophy of the LCI+VSI configurations can therefore be summed up as follows: the main active power of the drive flows through line/load commutated SCR circuits switching at fundamental frequency, while the harmonics and reactive power are alone handled by the VSI circuit. Since the reactive power requirement of high power motors is quite small (of the order of 20% or so) the kVA rating of the VSI is about 35% of the motor rating. However there are savings because of using SCRs in the main circuit. In

Figure 16: Configuration of IM drive with two stator windings.



comparison, an IGBT based VSI [generally 3-level] rated at the motor kVA has to be used with an output LC filter for the same application to obtain equivalent performance in terms of voltage and current waveforms, absence of common mode voltage etc. Since the switching frequency of such a high power IGBT will be limited, say 500 Hz, design of the filters is quite difficult.

Based on the above considerations, the LCI+VSI converter configuration can be applied to other motors as well. Extensive study has been made on a wound field synchronous motor drive (Fig. 15) fed by such converter configuration[99–100].

The synchronous motor differs from the induction motor in that the field current is independently adjustable. As was pointed out in Section 2.5, this is the basis for LCI fed synchronous machine drives: the field current is adjusted to make the motor operate at leading displacement factor, thereby enabling load commutation of the CSI. However, the field circuit is heavily inductive and slow to respond. Therefore, use of a VSI is still advantageous, in terms of injecting the reactive power required under dynamic conditions, until the field circuit is able to take over. Moreover, the compensation of the harmonic currents of the CSI is still a great benefit. The currents and voltages of the motor are close to sinusoidal.

The LCI fed synchronous machine also requires a special starting technique through dc link current pulsing. The presence of the VSI can be of help, since the motor can be started up smoothly by the VSI, even if the load torque is high [incidentally, this also applies to the induction motor drive]. Thus the addition of a VSI to existing LCI drives as a retrofit, can solve the problem of starting. The VSI can be disconnected from the motor once the speed reaches a minimum value, say 10%. This would also limit the kVA rating of the VSI.

The VSI can also be applied as a retrofit active filter to existing LCI drives, in order to filter out the current harmonics and improve the motor current and voltage. It has been shown that the VSI can be applied and removed "on-the-fly" while the motor is being driven by the LCI.

Thus the LCI+VSI converter can be a universal solution for SM drives.

3.3.3. *Induction motor drive with two stator windings*

The connection of both the LCI and the VSI at the motor terminals can give rise to difficulties, especially if the motor voltage is in the range of 6.6 to 11 kV. This is because the IGBTs in the VSI may not be rated for such a high voltages. The use of a transformer between the VSI and the motor can be considered; however it should be remembered that the motor frequency is variable.

A new configuration has been proposed to overcome the problem[101]. The motor is designed with two sets of stator windings, with their axes aligned. One winding, which is meant to carry the active power of the motor, is designed at a higher voltage and fed by an LCI. The other winding, which is meant to carry the magnetizing current — and thus the reactive power only — is designed at a lower voltage and fed by a VSI with an output filter. Fig. 16 shows the configuration.

In addition to providing the magnetizing current, the VSI also provides the reactive power required for load commutation of the LCI SCRs and the harmonics required to compensate those in the LCI current. These interactions are carried out through the magnetic coupling that exists in the machine. The electromagnetic torque of the machine is therefore smooth and does not contain 6th harmonic pulsations typically seen in an LCI drive.

4. Conclusion

High power AC motor drives are the enabling technology in many industrial processes. The types of motor, converter and control method are all of importance in selecting a drive for an application. The choices have been fairly stable for quite some time. Recent developments in power semiconductor devices, have made it possible to propose newer configurations, which allow one to move closer to the ideal of delivering sinusoidal voltage as well as current to the motor.

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Glossary

VSI	*Voltage Source Inverter* : A power circuit which converts an input DC voltage to output AC voltage of required frequency by appropriate switching action of semiconductor switches.
CSI	*Current Source Inverter* : A power circuit which converts an input DC current to output AC current of required frequency by appropriate switching action of semiconductor switches.
LCI	*Load Commutated Inverter*: An SCR current source inverter in which the turn OFF of the devices is achieved by the load voltage.
Cyclo-Converter	A power circuit which converts an AC voltage waveform, such as the mains supply, to another AC voltage waveform of a lower frequency. It synthesizes the output waveform from segments of the AC supply without an intermediate dc voltage or current link.
SCR	*Silicon Controlled Rectifier*: SCR or thyristor is a three terminal semiconductor device; the terminals are an Anode, a Cathode and a Gate. When a small current is passed through the Gate terminal to Cathode, the thysistor conducts, provided that the Anode terminal is at a higher potential than the Cathode. Once the thyristor is in conduction mode, the Gate circuit has no control and a commutation process is required to turn it OFF.
GTO	*Gate Turn-OFF Thyristor*: (GTO) is a special type of thyristor. GTOs, as opposed to normal SCRs, are fully controllable switches which can be both turned on and off from the GATE.
IGBT	*Insulated Gate Bipolar Transistor*: IGBT is a three-terminal power semiconductor device, namely, Emitter, Collector and Gate. It is a voltage controlled device as opposed to SCR and GTO which are current controlled device. The Gate terminal is isolated from the Collector and Emitter terminals. The IGBT is capable of switching at high switching frequency up to 20 KHz.
Commutation	Commutation is the process of turning OFF a thyristor
Line-Commutation	The turning OFF of the thyristor due to the natural behavior of line voltage, where a reverse voltage is applied across the device when the next SCR is turned ON, is known as line or natural commutation.
Load-Commutation	The turning OFF of the thyristor due to the behavior of connected load, such as leading power factor behavior in case of over-excited wound field synchronous motor, is known as load commutation.
Fundamental, Ripple	These terms refer to output voltage/current waveforms of the converter. The waveforms have multiple components. The component of interest is known as "fundamental" and the superimposed component present in the waveform due to switching action is known as "ripple".
Base Voltage, Base Current, Base Impedance,	For control and comparison of different electrical equipments within a system, per unitization process is carried out. All voltages, currents and impedance are divided by predefined values known as bases to obtain dimensionless numbers called per unit values.
PWM	*Pulse Width Modulation*: PWM is a method of constructing a sequence of voltage or current pulses which contain the required average value and which are optimum in some sense as far as the other frequency components are concerned.
3-phase, 6-pulse	A six pulse rectifier produces an output voltage waveform containing six identical segments in one cycle of the input AC voltage.
kW, MW	kW and MW are abbreviation for 10^3 watts and 10^6 watts of electrical power respectively. The prefix k stands for kilo and M for Mega.
Sub-synchronous, Super-synchronous	In AC motors, the speed of rotation of the flux when the motor is connected to a supply of rated frequency is known as the synchronous speed. The speed range of the motor lesser than the synchronous speed is denoted as sub-synchronous, whereas the speed range greater than the synchronous speed is denoted as super-synchronous.

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