

# PRESENT STATE AND A FUTURISTIC VISION OF MOTOR DRIVE TECHNOLOGY

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**Abstract—** One of the main driving force behind the industrial revolution was the invention of the electric motor more than a century ago. Its widespread use for all kinds of mechanical motion has made life simple and has ultimately aided the advancement of human kind.

The advent of the inverter that facilitated speed and torque control of AC motors has propelled the use of electric motor to new realms that was inconceivable just a mere 30 years ago. Advances in power semiconductors along with digital controls have enabled realization of motor drives that are robust and can control position and speed to a high degree of precision. Use of AC motor drives has also resulted in energy savings and improved system efficiency.

Yaskawa Electric Corporation has been at the forefront of technology, creating reliable drives that consistently push the envelope of engineering achievement. This paper reviews Yaskawa's role in the development and application of the inverter technology to AC motor drives and introduces some futuristic vision for the motor drive technology. The development of more efficient, more powerful electric motor drives to power the demands of the future is important for achieving energy savings, environmentally harmonious drives that do not pollute the electrical power system, and improving productivity. Yaskawa wants to be an integral part of this future and hopes to contribute significantly to achieve this.

## I. INTRODUCTION

The electric motor and its control have advanced considerably in recent years. This can be attributed to significant progress in the field of power electronics enabled by unprecedented progress in the semiconductor technology. The benefit of improvement in the motor drive industry has touched varied applications, from heavy and large industrial equipment such as rolling mills in steel making plants, paper mills, etc. to "Mechatronics" equipment used in machine tools and semiconductor fabrication machines. The AC motor controller comprises of the induction motor controller and the permanent magnet motor controller, both of which have played a key role in the overall progress of the motor drive industry. Fig. 1 shows a current inverter (induction motor controller) and AC servo drives (permanent magnet AC motor and their controllers). The controllers shown in Fig. 1 employ the latest that industrial technology has to offer [1] in power semiconductors using the most advanced motor drive control algorithms in the form of vector control. Such controllers are ubiquitous in varied industrial and commercial applications of the present day and age. As the use of AC motor drives becomes more widespread, it is difficult to ignore an important fact - the electric power used by electro-mechanical energy conversion equipment, of which electric motors form the bulk, exceeds 70% of the total industrial electric power produced. Given the fact that future residential

applications will soon be using motor drives in washing machines to HVAC applications, it is

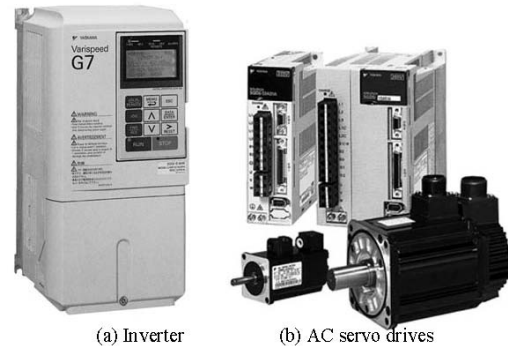


Figure 1: Typical AC motor drives. (a) 3-level Induction motor controller; (b) AC servo drives and servomotors.

important to concentrate R&D efforts in achieving higher efficiency and smaller size products that use less raw material, are less toxic to the environment, have a long MTBF, and are easy to recycle. Yaskawa Electric Corporation wants to be a part of such a future.

The concepts, ideas, and equipment used in the motor drives industry are easily applicable to harnessing energy from alternate sources, including Solar Energy and Wind Energy. Hence, it is not surprising to find power electronics to play an important role in these applications. The motor drives industry can thus become a key player in solving the future energy crisis and simultaneously contribute significantly to environmental preservation.

## II. AC MOTOR DRIVES

The present day industry categorizes AC motor drives into two distinct categories – Induction Motor Drives, and Permanent Magnet AC Motor Drives. The basic difference between the two types of drives is performance and cost. Induction motor still forms the work horse of today's industry. Applications that use induction motor may not need very high precision position and velocity control. Such applications typically use what is known in the industry as "General Purpose AC Motor Drives". However, the machine tool industry that caters to the semiconductor manufacturing and other sophisticated industries, require highly precise and controlled motion. Permanent magnet motors are the motor of choice because of their smaller size, higher efficiency, lower inertia, and hence higher controllability. Such motors are clubbed into the Servo Motor category and are controlled by Permanent Magnet AC Motor (PMAC) Drives and are typically more expensive than their induction motor counterpart.

### A. General Purpose AC Motor Drives – V/f Control

The power structure of the General Purpose AC Motor Drives is similar to the PMAC motor drives. Both of these

drives are referred to as Voltage Source Inverters, a term which will soon be clear. Since the power topology includes a large DC bus capacitor as a filter, and since it is the voltage that is modulated to provide variable voltage, variable frequency to the AC motor, such an inverter topology is called a Voltage Source Inverter and forms the integral part of most present day AC motor Drives. A typical schematic of the present day AC motor drive is shown in Fig. 2.

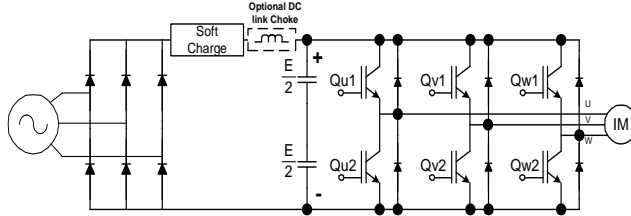


Figure 2: Schematic of a typical voltage source inverter based AC motor drive.

The general purpose AC motor drives typically provide constant flux into the induction motor. Since the motor flux is the ratio of the voltage to the frequency ( $V/f$ ) applied to the motor, this ratio is held constant to achieve constant flux operation. The motor current increases almost linearly with load. Conveyor belts and other frictional loads require such profiles.

For centrifugal loads like fans and pumps, the flux in the motor can be altered to follow a square function. By doing this, the power consumed by the motor becomes a cubic function of speed ( $P \propto f^3$ ) enabling significant energy savings. Even if the  $V/f$  is held constant in these types of applications, there is still significant energy savings compared to constant speed drives, where relatively large losses are associated with valve or damper control. Thanks to the square type torque characteristics of the load, voltage reduction at lower speed range is possible that improves efficiency further. The resulting improvement in efficiency is so significant that even the member countries that ratified the Kyoto agreement in the year 2000 agreed to convert fans and pumps from being operated directly across the line to be operated via AC motor drives to save energy and reduce the overall carbon foot print of a given plant. It is significant and important not only for those countries but for all people using centrifugal loads to convert the fixed speed fans and pumps to variable speed.

### B. High Performance AC Motor Drives – Vector Control

Though the majority of industrial applications require unsophisticated  $V/f$  control, there are quite a few applications that require higher performance. Such applications include machine-tool spindle drives, paper making machines, winders and pinch rolls in Iron and Steel industries, elevators, top drives for oil drilling, winders/un-winders, pick and place operations, printing, rolling mills, and other applications requiring high torque at low speed. Such performance was achievable in the past using DC motors, which are now being replaced by *vector controlled AC Motors*. The term vector control refers to techniques where the torque component of the

input current is controlled orthogonally to the magnetic field in the induction motor to result in optimal torque production. Such orientation based control is called Field Oriented Control. Similar to a DC machine, it is now possible to independently control the field flux and motor torque to achieve high performance from AC motors.

The basic idea of field oriented control is to transform the input time varying current flowing into the motor from three phase to time varying two phase components called  $\alpha$  and  $\beta$  components. These  $\alpha$  and  $\beta$  components are then transformed into two axis (d-axis and q-axis) that rotate synchronously with the air-gap magnetic field of the motor thereby making them stationary with respect to the rotating magnetic field of the AC motor (Fig. 3(a)). By maintaining the orthogonal relationship between the d-axis and q-axis components and by controlling the q-axis component, optimal torque is produced even at standstill condition. The transformation of the motor current from 3-phase to d-q axis requires instantaneous position and speed of the rotor, which is achieved using pulse encoders mounted on the shaft of the AC motor.

There are two fundamental approaches to field oriented control. They are: a. Direct Field Oriented Control, and b. Indirect Field Oriented Control [2].

In the direct field oriented control method, the position and magnitude of the air-gap flux in the AC motor is derived from measurement of motor input voltage and current. The measured flux is compared with a steady reference flux, and is fed into a flux regulator that forces the q-axis flux to go to zero to achieve complete decoupling between the two orthogonal axes. The d-axis value of the measured flux is also used to compute the measured electromechanical torque being produced by the motor, which is then compared with the reference torque. The torque regulator controls the torque producing component of the current to achieve desired torque at desired speed. The angle information from the encoder is directly used to perform the transformation from three-phase to two-axis and vice-versa.

The control philosophy in the indirect field oriented control is quite different from the direct field oriented control. Air-gap flux is not explicitly calculated in the case of indirect field oriented control. The motor slip is calculated based on measured current parameters. The calculated slip is used to calculate the slip angle, which is then added to the angle information from the encoder to achieve the correct position of the air-gap flux. The newly estimated angle is used for the transformations so that the d-axis motor current is aligned correctly with the air gap flux to achieve high performance torque control even at standstill. This is clearly one significant advantage of the indirect field oriented control over the direct field oriented control. However, the calculation of the motor slip angle requires information about the rotor parameters that is sensitive to temperature and other operating conditions. This sensitivity is more pronounced in higher power motors. At higher speeds, the resolution of the encoder and the computation time available for the microprocessor

to compute the slip angle are typical limitations with the indirect field oriented control method. This limitation does not exist with the direct field oriented control method and the use of both of this type of control – indirect field oriented control for standstill and low speed range and direct field oriented control for high speed range is a classical way of modern control, given the fact that the present day microprocessors are robust enough to do computations for both methods and switch over from one to the other depending on the state of a flag that is settable based on the speed of the motor. Typical control schematic for the two types of control along with the concept of coordinate transformation is shown in Fig. 3 [2].

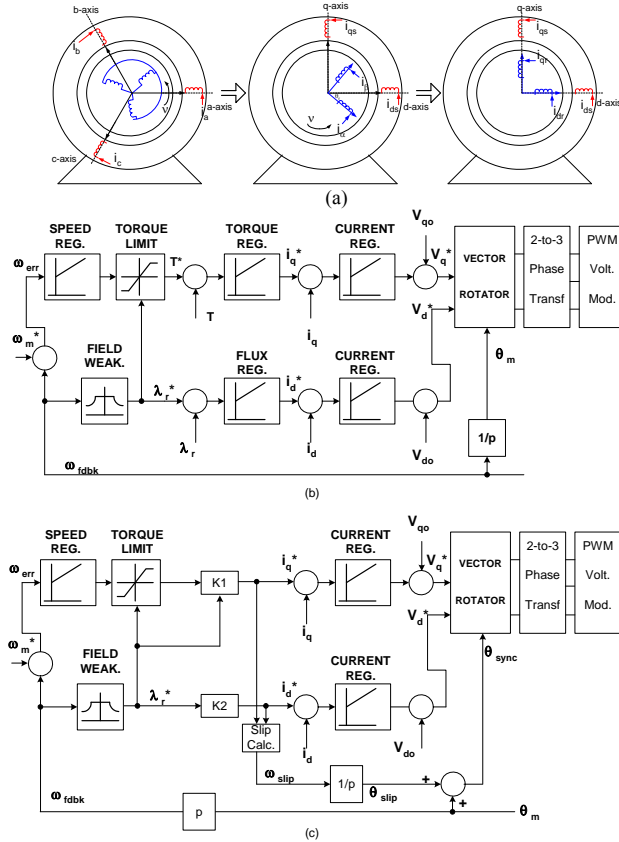


Figure 3: Schematic of typical induction motor control in modern AC drives. (a) 3-phase to 2-phase to 2-axis transformation, (b) Direct Field Oriented control and (c) Indirect Field Oriented control.

### C. High Performance AC Motor Drives – Sensorless Control

In the control schemes discussed above and shown in Fig. 3, the encoder feedback forms an integral part. Unfortunately, in many industrial applications, there is fear that either the signal wires carrying the encoder signal could break or the encoder itself could be rendered un-operational due to hostile environment like heat and humidity at the motor.

In other cases, the mounting of the encoder on the shaft may present an expense that the consumer is not prepared to bear. In either case, there is a need to achieve high performance from AC motors without the use of encoder signal.

The situation described above leads to a new breed of controllers called sensorless control. Some drive manufacturers call this type of control as “open-loop control”. The advent of sophisticated microprocessors with capability of performing real time highly-intense calculations has made this field of study very interesting and challenging.

Many researchers have worked on this topic and it still forms an important research and development topic at many major motor drive manufacturers. Two methods are gaining popularity. They are: a. using the motor itself as a sensor by injecting high frequency signal into the motor to reveal saliencies due to slot and teeth of the stator structure; and b. Flux observer based on a machine model that is updated as the motor temperature changes. In the latter case, operation at zero input frequency is not possible, while the exploitation of motor saliencies to identify the rotor position has been shown to be able to control the motor even at zero input frequency [3].

Practically speaking, zero shaft speed is adequate in many high performance applications like winders and top drives, where the drill bit is typically tightened and loosened when the bit needs to be changed. Hence, the flux observer, employed in Direct Torque Controlled (DTC) drives is more than adequate for such applications. Other flux observers that use standard PWM techniques are also sufficient provided the internal microprocessor used is fast enough to perform the needed calculations for the flux observer. Many researchers have worked in this area and quite a few motor drive manufacturers are coming out with sophisticated sensorless algorithms that push the boundaries consistently.

### III. ADVANCES IN POWER TOPOLOGY

Significant progress in semiconductor technology has facilitated higher switching frequency of PWM based voltage source inverters – the workhorse of the modern day AC motor drive. Carrier or switching frequencies in the range of 10-kHz to 15-kHz is quite common. This significantly contributes to improved controllability of voltage, current, and torque. It also helps in the reduction of acoustic noise. However, high-speed switching of IGBTs increases high frequency leakage currents, bearing currents, and shaft voltage. It also contributes to voltage reflection issues that result in high voltage at the motor terminals, especially when the motor is at distances farther than 20m from the drive. Researchers and engineers in the area of power electronics and ac motor drives have long recognized this and have developed many tools that are inserted in between the drive and the motor to handle such application issues.

#### A. Three-Level Neutral Point Clamped Inverter

Instead of adding a component in between the drive and the motor, modifying the power topology to reduce the problems described above is a much prudent approach. Yaskawa Electric Corporation was the first drive manufacturer to come out with a three-level drive structure for general purpose low voltage application [4]. The

three-level drive topology employed by Yaskawa is called the Neutral Point Clamped three-level inverter.

The neutral point clamped (NPC) three-level inverter was introduced first by A. Nabae, I. Takahashi and H. Akagi in 1980 and published in 1981 [5]. With this circuit configuration, the voltage stress on its power switching devices is half that for the conventional two-level inverter (Fig. 2). Because of this nature, it was applied to medium and high voltage drives. Early applications included the steel industry and railroad traction areas in Europe [6][7] and Japan [8].

In addition to the capability to handle high voltage, the NPC inverter has favorable features; lower line-to-line and common-mode voltage steps, more frequent voltage steps in one carrier cycle, and lower ripple component in the output current for the same carrier frequency. These features lead to significant advantages for motor drives over the conventional two level inverters in the form of lower stresses to the motor windings and bearings, less influence of noise to the adjacent equipment, etc. Combined with a sophisticated PWM strategy, it also makes it possible to improve the dynamic performance employing the dual observer method.

In order to benefit from the above features, general purpose pulse-width modulated (PWM) NPC inverters have been developed for low voltage drive applications [9], [10]. In this product, a unique technology is used to achieve balancing of the dc bus capacitor voltages [11]. Details are described in the following sections.

Figure 4 shows the circuit diagram of the NPC three-level inverter [4]. Each phase has four switching devices (IGBTs) connected in series. Taking phase U as an example, the circuit behaves in the following manner.

When IGBTs  $Q_{U1}$  and  $Q_{U2}$  are turned on, output U is connected to the positive rail (P) of the dc bus. When  $Q_{U2}$  and  $Q_{U3}$  are on, it is connected to the mid-point (O) of the dc bus, and when  $Q_{U3}$  and  $Q_{U4}$  are on, it is connected to the negative rail (N). Thus, the output can take three voltage values compared to two values for the conventional two-level topology. Relation between the switching states of IGBTs and the resulting output voltage with respect to the dc mid-point is summarized in Table 1.

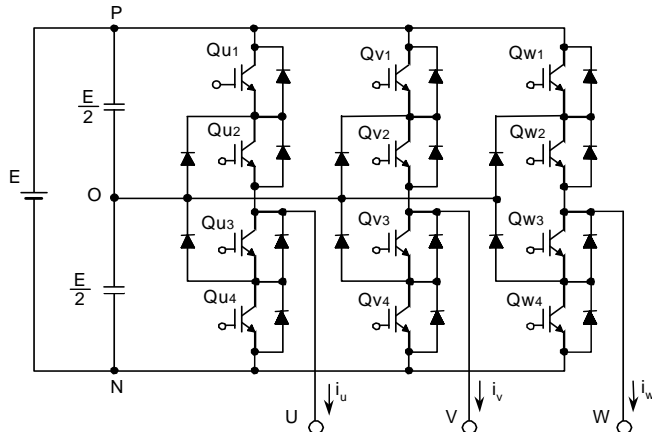


Figure 4: The neutral point clamped three-level inverter circuit topology.

DC bus capacitors need to be connected in series to get the mid-point that provide the zero voltage at the output. This is not a drawback since series connection of the dc capacitors is a common practice in general-purpose

Table 1: Relation between switching -States and output voltage

	$Q_{u1}$	$Q_{u2}$	$Q_{u3}$	$Q_{u4}$	$V_u$
Switching State	ON	ON	OFF	OFF	$+E/2$
	OFF	OFF	ON	ON	$-E/2$
	OFF	ON	ON	OFF	0

inverters rated at 400 – 480 V range due to the unavailability of high voltage electrolytic capacitors. The current from the inverter bridge into the capacitor mid-point is the only new issue for this topology, and maintaining the voltage balance between the capacitors is important and influences the control strategy.

In order to illustrate the output voltage waveforms, let PWM reference signal for phases U, V and W be,

$$e_U = A \sin(\omega t) \quad (1)$$

$$e_V = A \sin(\omega t - 120^\circ) \quad (2)$$

$$e_W = A \sin(\omega t - 240^\circ) \quad (3)$$

A is the modulation index. It is assumed that no third harmonic component is used to improve utilization of the dc bus voltage [4].

Waveforms of the output voltages vary by the modulation index and the phase angle. To illustrate the behavior of the output voltage, let the modulation index A be equal to 1.0, which means that full voltage command is applied, and let the phase angle  $\omega t$  be  $75^\circ$  for phase U. This condition is shown in Fig. 5, where the phase voltages in per-unit are expressed as,

$$E_U = 1.0 \sin 75^\circ = 0.966 \quad (4)$$

$$E_V = 1.0 \sin(75^\circ - 120^\circ) = -0.707 \quad (5)$$

$$E_W = 1.0 \sin(75^\circ - 240^\circ) = -0.259 \quad (6)$$

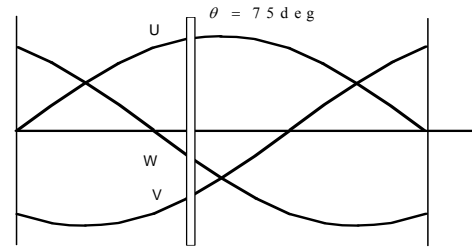


Figure 5: Phase angle chosen for waveform illustration

For the condition shown above, waveforms of the phase voltage with respect to the dc mid-point, the line-to-line voltage and the common-mode voltage are obtained for one cycle of the PWM carrier signal as shown in Fig. 6.

In Fig. 6,  $T_c$  is the period of the PWM carrier signal. Line-to-line voltage  $e_{u-v}$  is defined as,

$$e_{u-v} = e_u - e_v \quad (7)$$

It is the actual voltage applied to the motor terminals. Common-mode voltage  $e_{com}$  is defined as,

$$e_{com} = (e_u + e_v + e_w) / 3 \quad (8)$$

The common-mode voltage affects the leakage current, shaft voltage, and bearing current.

Measured line-to-line-voltage waveforms for two-level and three-level inverters are shown in Fig. 7. Measured common-mode voltages are compared in Fig. 8.

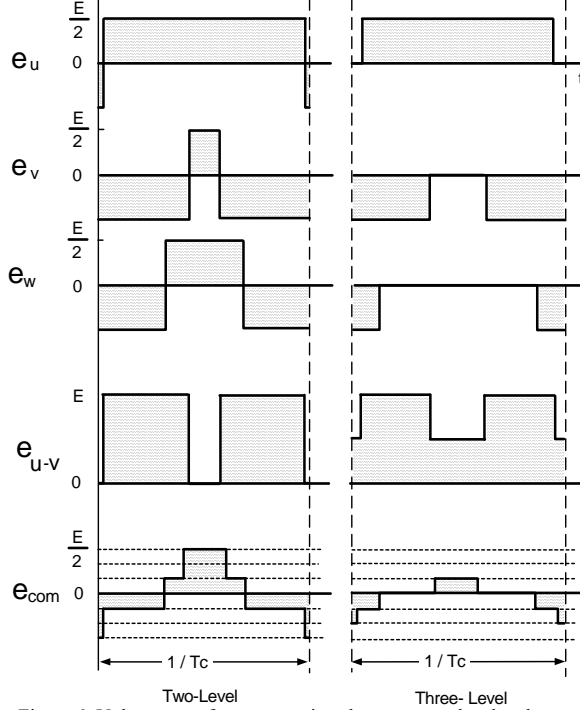


Figure 6: Voltage waveform comparison between two-level and three-level configurations.

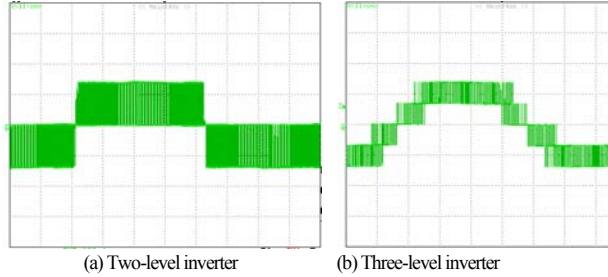


Figure 7: Measured line-to-line waveforms V: 500V/div, T: 2 ms/div

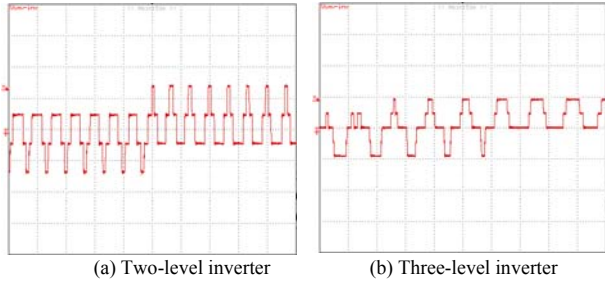


Figure 8: Measured common-mode voltage waveforms. V: 250V/div, T: 100 μs/div

The waveforms in Figures 7 and 8 are for a 460V, 7.5kW motor drive system. As shown in Figure 6-8, the three-level inverter has smaller voltage steps than the two-level inverter both in the line-to-line and common-mode voltages. In addition, the common-mode voltage amplitude of the three-level is lower than

that of the two-level in some phase angle ranges. These characteristics bring significant benefits to drive applications.

#### B. Features and advantages of three-level inverter

This section compares surge voltage at the motor terminals, leakage current, shaft voltage, and bearing current for two-level and three-level inverters.

##### Current waveforms

First, the ripple current component in the three-level inverter is lower for the same PWM carrier frequency due to the smaller and more frequent voltage steps. In other words, the carrier frequency can be lower for the same current quality compared to the two-level inverter, thereby reducing switching losses in the IGBTs.

##### Surge voltage at motor terminal

When the cable between the inverter and motor is long, voltages at the motor terminals are higher than those at the inverter terminals due to the steep voltage transient and distributed inductance-capacitance combination of the cable. High voltage appearing across the motor terminals may damage the insulation material of the windings. High rate of voltage change also creates non-uniform voltage distribution among winding turns, affecting the life of insulation material.

Since the voltage step of the three-level inverter is half that of two-level inverter, the peak voltage at the motor terminal is significantly lower than that of two-level inverter. Waveforms in Fig. 9 are based on the concept that the voltage can swing up to twice the input voltage when a step voltage is applied to an L-C resonant circuit. In Fig. 9 (a), the overshoot magnitude of E is added to the original voltage E, making the peak value as high as 2E. In Fig. 9(b), the voltage jump is 0.5E, which is added to the original voltage of E, resulting in the peak value of 1.5E.

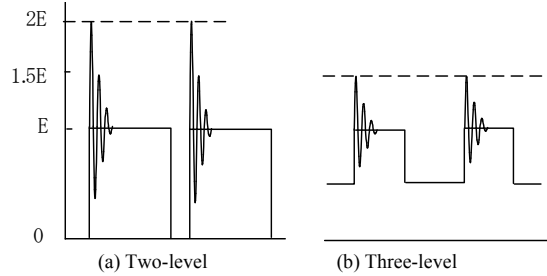


Figure 9: Voltage overshoot at motor terminals

Fig. 10 shows measured motor voltage waveforms when the cable is 100m long. These waveforms clearly show the difference in the peak voltages. High frequency ringing caused by the distributed parameters is also visible in these waveforms.

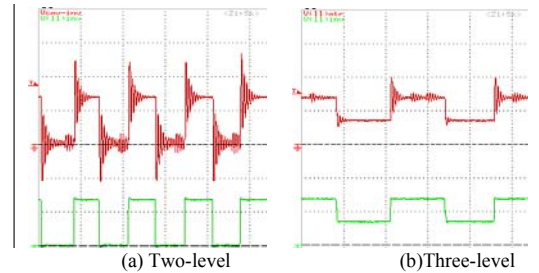


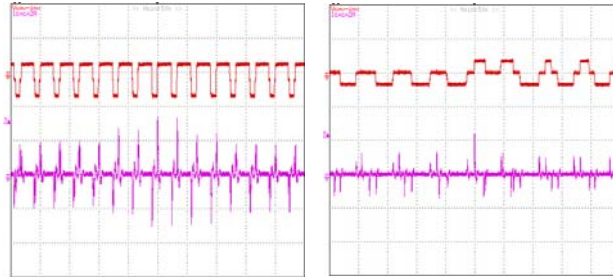
Figure 10: Measured surge voltage at motor terminals, V: 500V/div, T: 50 μs/div

### Leakage current

The high rate of the common-mode voltage causes leakage currents to flow from the conductors of the cable and motor windings to the ground through the parasitic capacitance in these components. This leakage current creates noise problems to equipment installed nearby the inverter. It is also strongly related to the EMI noise level.

Because of the smaller voltage steps of the common-mode voltage, the leakage current of three-level inverter is much smaller than that of the two-level inverter.

Fig. 11 shows a significant reduction in the peak leakage current level in the three-level case. The measurement was conducted with a 460V, 7.5kW motor and 100m cable.



(a) Two-Level

(b) Three-level

Figure 11: Leakage current

Upper scale: common-mode voltage, 500V/div

Lower scale: leakage current, 2A/div; T: 100  $\mu$ s/div

### Shaft voltage, Bearing Current

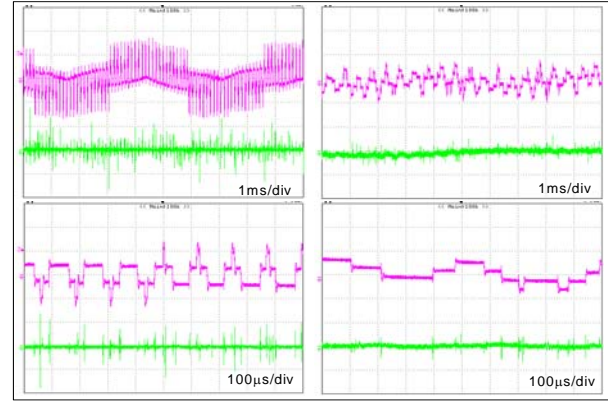
Bearing damages of the motors driven by inverters have been reported in cases where the shaft is not grounded. These problems are caused by the shaft voltage and bearing current created by the common-mode voltage and its sharp edges.

When the rotor of a motor is rotating with the bearings insulated by grease film, there exists capacitance between the rotor and the frame (ground). This capacitance is charged by the common-mode voltage through the capacitance between the stator winding and the rotor. Hence, the shape of the shaft voltage is similar to that of the common-mode voltage. Voltage edges of the shaft voltage cause current to flow through the bearing insulation. It leads to the breakdown of the insulation and discharge of the shaft voltage.

Since the change of the common-mode voltage is smaller in the three-level inverter, it has a significant advantage over the two-level version with regards to shaft voltage and bearing currents. Figure 12 shows the test results of shaft voltage and bearing current for two level and three-level inverters. In these tests, insulation material was inserted in between the bearing and its housing to facilitate observation of bearing current.

Although Fig. 12 shows that the bearing current in the three-level inverter case is significantly smaller, it is difficult to estimate the difference in the bearing lives. Actual long period tests were conducted to verify the superiority of the three-level inverter. Figure 13 shows that the use of three-level topology can result in a significantly longer bearing life.

Extreme conditions including temperature, type of grease, and motor speed were employed to perform the bearing life test of Figure 13. It should be pointed out that in practice, the normal bearing life would be longer than that shown here.



(a) Two-level

(b) Three-level

Figure 12: Shaft voltage and bearing Current

Upper in each frame: shaft voltage, 10V/div

Lower in each frame: bearing current, 20mA/div

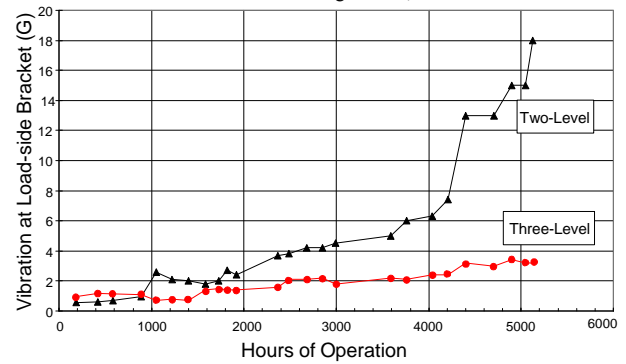


Figure 13: Result of bearing life tests  
0.7 kW, 2100 rpm



Figure 14: Varispeed G7, 400V, 1.5kW

Fig. 14 shows a 400V, 1.5kW unit. The units from 18.5kW up to 300kW have as standard a built-in DC reactor. This reduces the input harmonic current distortion. In addition, the units come equipped with a second rectifier bridge to facilitate twelve-pulse rectification. This can be achieved using a delta-delta-star isolation transformer for phase shifting. The input current THD can be reduced to about 12% using the twelve-pulse method.

### B. The Matrix Converter

The voltage source PWM inverter has been established as the major controller of motor drive systems. However, it is associated with issues pertaining to the input side or the ac power system side as well as the output side or the motor side as described in the preceding sections. Typical problems in two-level voltage source PWM inverters include the following:

- High levels of input current harmonics, which have an unfavorable influence on the electrical system,
- Interference with other equipment due to large common mode current, conducted and radiated EMI,
- Potential for motor insulation failure caused by surge voltage at the motor end, and
- Premature bearing failure in motors due to shaft voltage and bearing current.

In spite of the various advances made in addressing input and output power pollution caused by voltage source PWM inverters, there is still need for a converter that addresses both the input and output power pollution problems in an easier way without the need for large external peripheral equipment. Such a drive would then be able to achieve an environmentally harmonious system. One converter topology that shows promise in realizing this goal is the matrix converter [12].

The matrix converter (MC) is a direct frequency conversion device (AC to AC converter) that can generate variable magnitude variable frequency output voltage from the ac utility line. It is fully regenerative and has sinusoidal input current with unity power factor. Fig. 15 shows the basic topology of a matrix converter.

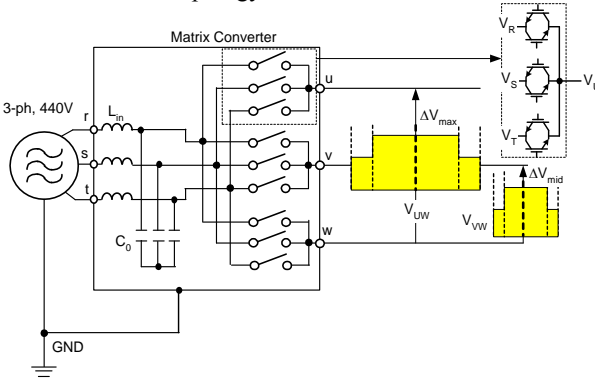


Figure 15: Schematic of a matrix converter with representative output line-line voltage patterns. Sizes up to 22-kW use reverse blocking IGBTs.

The concept of matrix converter was first presented by Venturini [13]. Since then, it has always been a topology that merited more attention. Lack of low cost, high performance semiconductors prevented the complete adoption of this topology. Thanks to the recent advances, it has been shown to be a very viable product. Yaskawa Electric Corporation is one of the first companies to commercialize this product. Three-phase MC consists of nine bi-directional switches, which allows PWM control of input and output currents. It does not require the intermediate DC link and the associated large capacitive filter, typical of voltage source inverters.

In practical implementation, understanding commutation procedure from one switch to another is very important. The commutation of current between switches should adhere to the following two constraints: a. Avoid input line-to-line short circuit; and b. Avoid output open circuits.

Several multi-step commutation strategies were introduced which adhere to the above two constraints [14]. The four-step commutation technique is perhaps the most popular and widely used. However, in all techniques, the applied gating signals and real turn on/off of bi-directional switch are different because the real turn-on/off time of each switch is affected by the direction of output current and the amplitude of the input voltage. Thus, during commutation sequence, unwanted voltage distortion can occur in the output voltage of a matrix converter similar to voltage distortion caused by dead-time between upper and lower switches of conventional voltage source inverter. Many researchers have worked on this topic and have proposed various reliable software/hardware implementation techniques [15]. In all techniques, the only possibility to deal with the distortion problem at low speed is to apply some means of compensation to accommodate for the loss of output voltage due to delay in commutation.

The input to the matrix converter is an ac voltage source, while the load on the matrix converter is an induction motor, which is inductive in nature. Since the current into the inductive load is switched from one phase to another, it can create interference and can stress the input ac source. To prevent this, ac capacitors are used at the input of the matrix converter, which then absorb the switching ripple current component. In order to prevent import of harmonics from external sources into the input capacitor, an inductor is used, the addition of which forms a low-pass input filter. The components of the input LC filter are chosen to filter the carrier frequency components of the matrix converter. The operation of the matrix converter in conjunction with the low-pass input LC filter results in a sinusoidal input ac current. The presence of an input LC filter provides a stable neutral point and facilitates further filter integration [12]. A summary of the advantages of a matrix converter over two-level voltage source inverter is given in Table 2.

Table 2: Comparison - two-level inverter vs matrix converter

Performance parameter	Two-level Inverter	Matrix Converter
Input Current THD	high	low
Common mode voltage step	large	small
Common mode current	high	low
Shaft voltage step	large	small
Bearing current	high	low

The output phase voltage in a matrix converter has three levels since it is constructed using the three available input phase voltages. Since the output voltage levels transit through the mid-level of the three available input voltages, the step change in the output voltage as well as in the common mode voltage is generally lower than in a conventional two-level voltage source PWM inverters.

Since, the matrix converter exhibits lower voltage step size in the common mode voltage waveform, it lends itself for easier filtering.

Fig. 16 compares the common mode voltage in a matrix converter with that in a conventional two-level inverter [12]. The common mode voltage steps are much smaller in the matrix converter resulting in potentially lower common mode current, shaft voltage and bearing current. Thus, the matrix converter topology lends itself to easier filtering. Integration of different filters to achieve a low noise drive that has lower ground current and higher safety margin is the thrust of this paper.

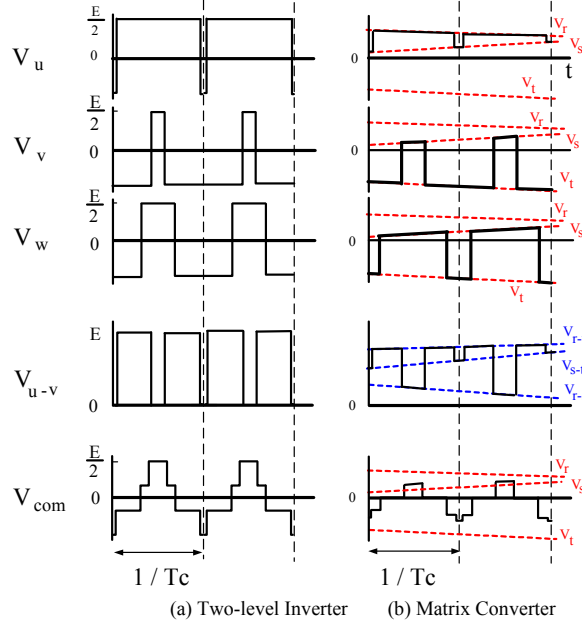


Figure 16: Common mode voltage in two different types of motor controllers, both employing three-phase modulation.

From the explanations provided thus far on the operation of the matrix converter, it can be said that the performance of the matrix converter is similar to a three-level inverter. Since the matrix converter is an inherently regenerative drive, it is fair to compare it with a back-to-back three-level voltage source inverter. Salient comparison points are:

1. Matrix converter uses 9 reverse blocking semiconductor switching devices, while a comparable three-level back-to-back voltage source inverter employs 24 devices.
2. A matrix converter does not need smoothing dc bus capacitor and the associated soft-charge circuit.
3. In case of a back-to-back voltage source inverter, two or three of the input phases are always connected together, resulting in large amplitude of switching frequency component at the input terminals. In order to reduce its influence on the power system, large smoothing inductors along with some passive components are needed. In the case of matrix converter, a given input phase is either connected to the motor or is left floating (turned-off). The switching frequency component amplitude that needs

to be attenuated thus is much smaller and results in a much smaller input filter.

4. Control scheme of a matrix converter is complex because of the absence of the dc bus capacitor, which is instrumental in separating the front end PWM rectifier from the motor side inverter in the case of a voltage source inverter. However, recent progress in control concepts has reduced the severity of this drawback significantly.

Various additional filters, which are required to achieve a low-noise motor drive system, can be easily integrated with the matrix converter. Fig. 17 shows a matrix converter with input and output filter configurations. In addition to the standard input low-pass LC filter, a small sized input EMI filter is added to provide filtering for conducted EMI.

The output section consists of a Normal Mode Filter (NMF) to provide sinusoidal output voltage waveform at the motor terminals. A common mode filter (CMF) is also employed at the output in order to attenuate the common mode voltage and hence the common mode current. Shaft voltage, which mimics the common mode voltage, also reduces and this helps reduce the bearing current.

Fig. 18 shows the actual unit of an environmentally harmonious power converter – a complete system that consists of the integrated filter and a matrix converter. The dimensions of the matrix converter integrated with the filters (Fig. 18) are: Width: 530mm, Height: 700mm, and Depth: 290mm. An equivalent back-to-back voltage source inverter with similar integrated filter would have occupied 37% more volume than the matrix converter.

### C. Medium Voltage Matrix Converter [16]

An interesting application of the matrix converter is its use in medium voltage drives. Matrix converters can be used to create appropriate voltage on a cell by cell basis. By intelligently phase shifting the carrier of each cell and combining them in the motor winding, multi-step medium voltage levels are achievable. By keeping the carrier frequency high enough, the phase shifted carrier voltage waveforms is seen to yield almost sinusoidal output voltage waveforms. Engineers at Yaskawa Electric have developed one such method that has gained popularity. The scheme and its associated vector diagram are shown in Fig. 19. The salient features of the medium voltage matrix converter are:

- Four quadrant operation
- Excellent input current waveform because of multiple phase-shifting winding of input transformer
- Flexible design:
  - Three cells in series yields 3.3kV, 200 to 3,000kVA system
  - Six cells in series yields 6.6kV, 200 to 6,000kVA system
- Excellent output voltage waveform due to multi-step configuration attainable by phase-shifting carrier frequency.

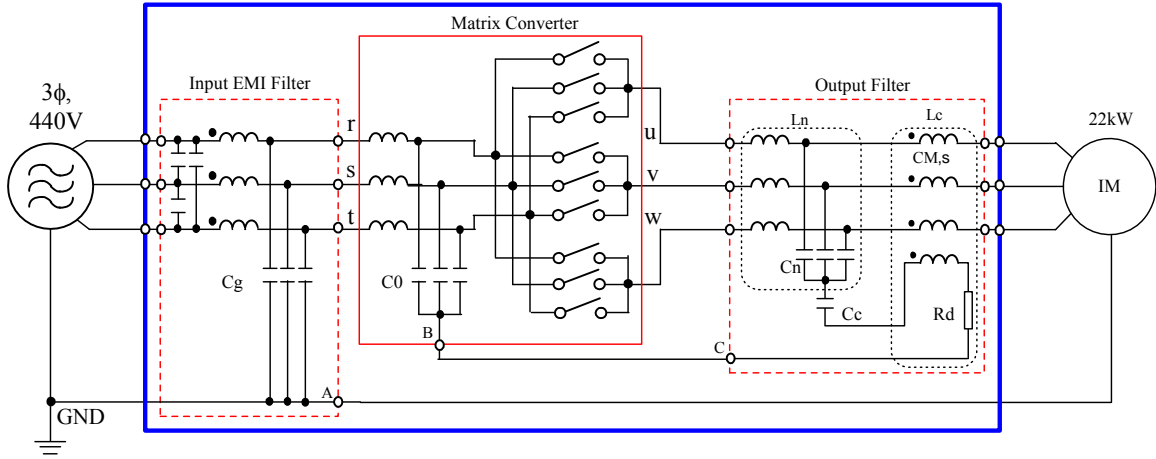


Figure 17: Schematic of a matrix converter with input and output filters to achieve environmentally harmonious drive system [12].



Figure 18: A 400V, 22kW environmentally harmonious matrix converter.

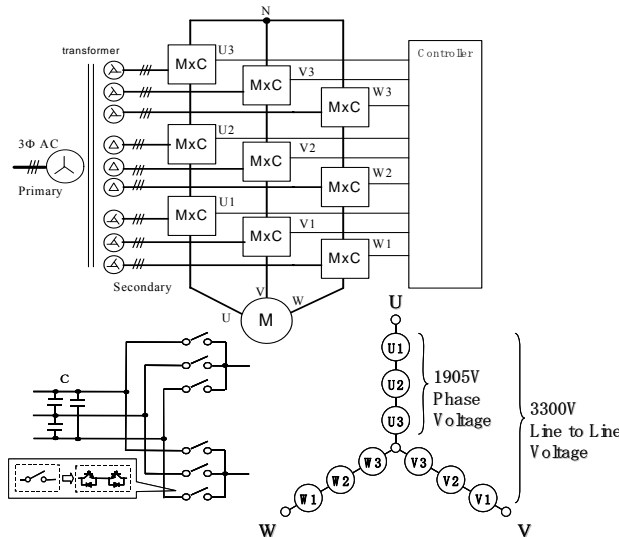


Figure 19: Schematic of medium voltage matrix converter drive with its associated vector representation [16].

#### IV. FUTURE OF MOTOR DRIVES

The progress made by the power semiconductor industry starting from 1960s onward, has directly influenced the progress of the Motor Drives industry. Following this

direct link, one can confidently say that the research work and experiments going on with newer switching semiconductors like GaAs (Gallium Arsenide), SiC (Silicon Carbide), and GaN (Gallium Nitride) devices will soon dominate the motor drives industry. Higher switching speeds at lower power loss will be achievable. Major changes to the cooling system are expected to revolutionize the motor drive industry.

##### A. SiC Devices – Advantages and Challenges

Silicon Carbide device can be operated at extremely high temperature without paying the penalty of increased losses and deteriorating performance typical of traditional Silicon based devices. SiC devices have been reported to operate easily at 150-deg C and higher. Some researchers have pushed it to operate even at 250-deg. C [17]. Higher operating temperature definitely reduces the volume and cost of the cooling system. The other player in the SiC market is the PFC (Power Factor Correcting Equipment) industry. Most electronic gadgets use power supplies and by using SiC devices, the overall efficiency can be greatly improved and because of its ability to operate at high frequencies and high temperature, the size of the cooling system can be greatly reduced. Higher operating frequency would mean smaller passive components that interact with the switch. The switch-mode power supply transformer can be reduced in size and the overall cost of the equipment can be lowered.

In spite of the advantages that SiC devices provide, there are some important issues that still need to be addressed. First and foremost is the cost. The yield of defect free parts is very low and the cost of the material itself is about 75% of the cost of the entire product for SiC based Schottky barrier diode [17]. This is much different from traditional Si based devices, where the cost of the material is in the 10% to 20% range of the total product cost. The next important fact that needs to be addressed is the difficulty of achieving a stable oxide layer. This prevents its use as a controlled switch. MOSFETs and IGBTs need this oxide layer to control the bulk of the transistor. Since, there has been manufacturing problems associated with the oxide layer, SiC based IGBTs or MOSFETs are still being developed. However, JFETs and

bipolar transistors (BJTs) do not need the oxide layer and there are some manufacturers that are planning to introduce JFETs and BJTs that use SiC devices. Typical amplification factor ( $\beta$ ) of 20 is achievable in case of power BJTs that use SiC devices [18].

### B. GaN Devices – Advantages and Challenges

Gallium Nitride (GaN) devices can withstand high voltages without showing degradation [19]. These devices have been shown to be able to be switched at high frequencies at high voltages making them very attractive in power systems engineering and large power motor drives. GaN has recently been grown on Silicon base wafers, both 4" and 6" type. This is a remarkable improvement because it reduces defects and allows its widespread use in Power Electronics. Given the fact that the power density of GaN devices is typically six or more times that of Silicon devices, makes it a very promising high power switching device. GaN devices can be operated at high temperature as well. Hence, prevailing opinion among researchers is that GaN devices may be better suited for both high voltage and high power applications – this holds promise for the power generation and distribution industry. The cost of GaN devices is also not expected to be much more than currently used Silicon based power devices. This is a positive point for GaN devices. However, it is too early to find out how the devices will be adapted to Power Electronics and Motor Drives. GaN based hetero-structure FETs are being developed but mainly for the RF industry. It may take a few more years before the details are worked out for use in motor drives.

Though both SiC and GaN devices can be operated at high temperature and high frequencies, it is important not to forget that the ancillary circuits that are needed to turn ON and OFF these devices also need to be able to handle the high temperature environment. Hence, progress in these areas also needs to be addressed.

### C. Permanent Magnet Motor Drives

Permanent Magnet (PM) motors are becoming very popular in many industrial applications including elevators and pumps. The residential market will soon be using motor drives for sump pumps, well water, HVAC, etc. All these applications are ideally suited for PM motors. Many of these applications do not need tight control of position, or do not require servo type performance. The main intention of using these motors in residential and other unsophisticated applications is primarily to reduce size and achieve higher efficiency. Most of these applications will require sensorless control capability. Drive manufacturers including Yaskawa Electric Corporation have products that can operate PM motors in open loop fashion [20]. To achieve acceptable performance, the motor parameters need to be known with a fair degree of accuracy. In the absence of such information, the drives will need to be equipped with "auto-tune" features that are sophisticated enough to determine the needed values of d and q axis inductances,

and motor resistances, etc. Given the advances in microprocessors used in general purpose drives now a days, this task is relatively easy. However, the challenge will be to perform such tasks without employing high end processors. The future research is currently being focused on such areas.

High performance PM motor drives that use encoders can benefit immensely if similar performance is achievable without the use of encoders. The IPM (Interior Permanent Magnet) motor is better suited for sensorless control. A saliency-based sensorless drive of adequately designed IPM motor for robot vehicle was demonstrated by Yaskawa Electric at Kitakyushu international airport in April 2006 [21]. The motor is deliberately designed to meet the requirements of robot application and lends itself better for saliency based sensorless control. The speed and position of multiple wheel-motors are synchronously controlled by the drive amplifiers and a single motion controller over the speed range from zero to maximum speed for the robot vehicle application. Two types of robot vehicles, one being a two-wheeled differential drive and the other being an omni-directional drive, were demonstrated to transport human and objects. The sensorless technique used in the robot vehicles injects high frequency signals into the motor to detect the initial magnetic pole position and then to track the poles as they rotate. The intended use is to help security personnel in airports, malls, etc., and also to assist in transporting bags within the airport premises. A photo of such a cart is shown in Fig. 20 and the actual motor that is included within the wheel is shown in Fig. 21. In the demonstration at Kitakyushu airport, the two-wheel differential drive type was driven by human, and the omni directional drive type was automatically controlled on the trajectory from a distance of 25 m. The absolute position of the robot could be corrected by the laser range-finder attached to the robot (omni direction drive). This was introduced as an after thought because of slipping of tires on polished surface of the airport and the need to achieve precise position information for transporting bags.

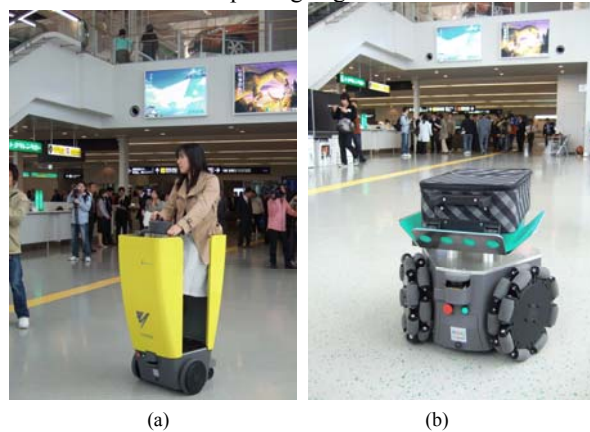


Figure 20: Developed "RoboPorter<sup>®</sup>": (a)Transporter for human, (b)Automatic transporter for objects.

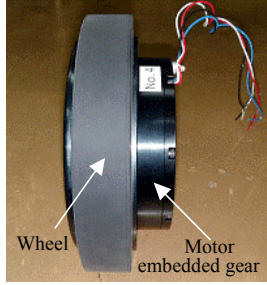


Figure 21: Photo of the proposed motor installed in wheel

#### D. Linear Motors

Efficient wafer transportation technique is key to achieving higher throughput in the ever-growing semiconductor manufacturing industry. Automatic wafer handling system that reduces the risk of dust contamination, invariably use linear motors. The modern semiconductor fabrication machines are large and require linear motors with relatively long stroke length to accomplish efficient wafer transportation. Efficient wafer transportation technique is important for achieving higher throughput.

There are two types of permanent magnet synchronous linear motors, Moving-Magnet type and Moving-Coil type. The Moving-Magnet (MM) type has magnets on the moving table whereas the Moving-Coil (MC) type has windings on the moving table. In the moving magnet type, the losses in the windings increase as the length of the stroke increases and hence, are not preferred for applications requiring long travel. On the other hand, in the moving coil type linear motor system, there is a need for a large number of high-cost magnets that must be distributed all along the guiding track of the entire stroke length, making it an expensive system.

Recently, there have been some development activities in moving magnet type linear motor drive systems for use in long stroke applications. In one such development effort, the stationary body is divided into multiple sub-sections. Each section is driven by an independent (dedicated) servo-amplifier. In this configuration, the losses in the coil are reduced because only the section that provides thrust need be powered. However, the need for multiple dedicated servo-amplifiers makes the system expensive. In addition, there is need to have a total system controller that can coordinate the excitation of various sections, thereby making the system complicated and expensive.

Engineers at Yaskawa Electric have developed a novel method that uses a moving magnet type linear motor for long stroke applications equipped with a method of electronic winding change used for rotating motors, shown in Figs. 22 and 23 [22]. This technique was also used to extend speed control range of induction motors and permanent magnet motors [23].

Segmented core structure is used by Yaskawa and others for fabricating the high performance servo motors. This improves the winding density and improves the space

factor by at least 2 compared to traditional laminations. Further, the use of Neodymium-iron-boron (Ni-Fe-B) high

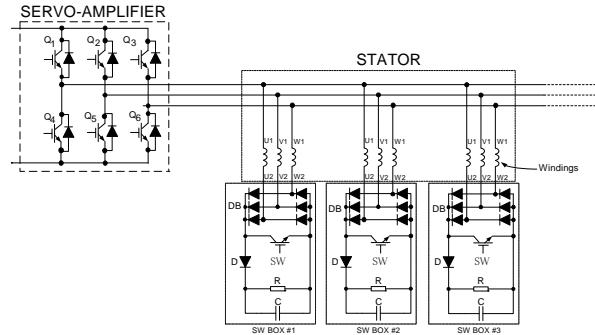


Figure 22: Circuit configuration for winding change technique.

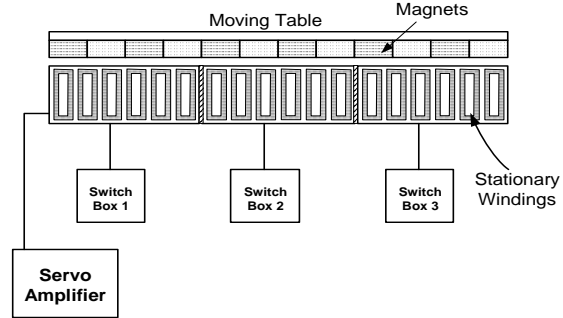


Figure 23: Structure of Yaskawa's moving magnet type linear motor.

performance magnets resulted in size and weight reduction of almost 25% and higher torque per amp capability.

The future of servo motors and drives is very bright. However, it is closely tied with the availability of higher performance rare earth magnets that can operate at alleviated temperatures without deteriorating in performance. Cost of these rare earth magnets is also important and typically the cost comes down when the usage increases. Higher power motors typically adopt the buried interior permanent magnet (IPM) structure because of higher mechanical stability compared to the surface permanent magnet (SPM) structure. IPM motors up to 400kW have already been developed and tested. These are primarily used in wind power applications and other high power pumping applications.

#### E. Renewable Energy Sources and Power Electronics

Power electronics plays a major role in the efficient conversion of mechanical energy to usable electrical energy when it is used in a wind turbine system. Advances in wind-turbine technology have made the wind energy a feasible alternative to the traditional coal and hydro energy. However, it is still more expensive than coal or hydro power. By connecting multiple wind turbines to a common grid, the efficiency of large scale production is achieved. Such facilities are called wind farms and they are gaining in popularity, due to the urgent need for environmentally friendly sources of energy.

The matrix converter may perhaps be an ideal drive for use in wind turbines. A permanent magnet motor can

be employed as the main generator, which would feed electrical energy to the matrix converter, which would then transform the voltage and channel the energy back to the electrical grid with little or no harmonic distortion. As mentioned earlier, large power permanent magnet motors are available and these can be used in conjunction with matrix converter to connect to the grid.

Since wind turbines are not considered as emergency power supplies, the ride-through capability of PWM inverters with large DC link capacitors is not required in matrix converter based turbine systems. Speed range of such a system also does not have to be wide. Typically 20% speed range (around the base speed) is more than satisfactory for meeting the maximum energy capture requirement and for suppressing the turbulence due to wind gusts. Lower power permanent magnet-matrix converter combination is also feasible and should be given serious thought. A possible arrangement is shown in Fig. 24. A transformer may be necessary to connect to the grid.

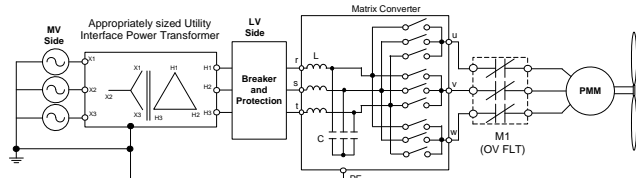


Figure 24: Schematic of possible use of matrix converter in wind turbine application.

For MW power rated turbines, the matrix converter can be used in the rotor circuit of a doubly fed induction motor. This will enable a lower power matrix converter to be used for harnessing large amounts of wind energy. The three-level inverter would also be a good candidate for such an application.

## V. CONCLUSIONS

In this paper, the present status of the motor drives industry is presented. All aspects of the motor drives industry has not been covered because the topic is too involved and too vast to be covered here. Salient products and their features have been discussed in broad terms. It is emphasized that providing an efficient means of converting electrical energy to mechanical motion may perhaps have the key to reducing our energy dependency. Alternately, efficient means of converting mechanical energy to electrical energy by the use of power electronics in wind turbines is another area that humankind can benefit from.

The challenge to present engineers and the motivation to future engineers lies in developing techniques, topologies, and control methods that will result in more efficient conversion process, both electrical energy to mechanical energy and vice versa.

## REFERENCES

- [1] T. Sawa, and T. J. Kume, "Motor Drive Technology – History and Vision for the future," Keynote speech at the 35th IEEE Power Electronics Specialists Conference, 2004, Aachen, Germany
- [2] V. R. Stefanovic, R. M. Nelms, R. W. De Doncker, L. J. Garces, F. Profumo, T. A. Nondahl, and R. D. Lorenz, "Microprocessor Control

- of Motor Drives and Power Converters," Tutorial Course, IEEE IAS Annual Meeting, 1992
- [3] J. Holtz, and R. D. Lorenz, "Sensorless Control and Complex Vector Control Analysis of AC Drives," Tutorial Notes, IEEE IAS Annual Meeting, 1999.
- [4] H. P. Krug, T. J. Kume, and M. Swamy, "Neutral Point Clamped Three-Level General Purpose Inverter – Features, Benefits, and Applications", Vendor Session Paper at the 35th IEEE Power Electronics Specialists Conference, 2004, Aachen, Germany
- [5] A. Nabae, I. Takahashi, and H. Akagi, "A new neutral-point-clamped PWM inverter," IEEE Trans. Ind. Applications, vol. 17, pp. 518-523, Sept./Oct. 1981.
- [6] R. A. Timer, "PWM Frequency Converters in the metal Industry," EPE Firenze 1991.
- [7] V. Cascone, L. Mantica and M. Oberti, "Three level inverter DSC control strategy for traction Drives," EPE Firenze 1991.
- [8] K. Nakata and K. Nakamura, "A three-level traction inverter with IGBTs for electric trains," IEEE Tokyo Section, Denshi TOKYO, No. 33, 1994, pp. 188-191.
- [9] E. Watanabe, et al., "New Inverter Drive Technology," Yaskawa Technical Review Vol. 65, No. 2, 2001, pp. 104-111
- [10] H. Takasaki, et al., "High-performance & Environmentally Friendly General Purpose Inverter Varispeed G7," Yaskawa Technical Review Vol. 65, No. 2, 2001, pp. 122-126
- [11] K. Yamanaka, A. M. Hava, H. Kirino, Y. Tanaka, N. Koga and T. Kume, "A novel neutral point potential stabilization technique using information of output voltage vector and currents," IEEE Trans. Ind. Applications, Vol. 38, No. 6 November/December, 2002 pp. 1572-1579.
- [12] T. J. Kume, K. Yamada, T. Higuchi, E. Yamamoto, T. Sawa, and M. Swamy, "Integrated Filters and their Combined Effects in Matrix Converter," IEEE Trans. on Industry Applications, Vol. 43, No. 2, March/April 2007.
- [13] M. Venturini, "A New Sine Wave in and Sine Wave out Power Conversion Technique that Eliminates Reactive -," Proc. Powercon 7, 1980, pp. E3-1 ~E3-15
- [14] N. A. Alesina, and M. Venturini, "Analysis and Design of Optimum Amplitude Nine Switch Direct AC-AC Converter," IEEE Trans. on Power Electronics, Vol. 4, pp. 101-112, Sept. 1989.
- [15] J. K. Kang, H. Hara, E. Yamamoto, T. J. Kume, and M. Swamy, "Output Voltage Distortion in Matrix Converter by Commutation of Bi-directional Switches," IEEE International Electric Machines and Drives Conference, 2003, Madison, Wisconsin USA
- [16] Y. Ueda, M. Ikeda, R. Suenaga, K. Imanishi, E. Masuda, and E. Watanabe, "Development of Medium Voltage Matrix Converter," IEEE Annual Meeting, 2007.
- [17] P. Roussel, "SiC Power Devices – if we only had a switch...," Vol. 2, Issue 5, Semiconductor Today – Compounds and Advanced Silicon, June 2007
- [18] J. Scofield, H. Kosai, B. Jordan, S. H. Ryu, S. Krishnaswami, F. Husna, and A. Agarwal, "High Temperature DC-DC Performance Comparison Using SiC JFETs, BJTs, and Si MOSFETs," Vols. 556-557 (2007), pp991-994, Material Science Forums, Trans Tech Publications, Switzerland.
- [19] G. Robinson, "Gallium Nitride nears use in RF Semiconductors," <http://www.eetimes.com/story/OEG20021017S0091>
- [20] "V1000 Product Brochure," Yaskawa Electric Corporation, <http://www.drives.com>
- [21] K. Ide, M. Takaki, S. Morimoto, Y. Kawazoe, A. Maemura, M. Ohto, "Saliency-based Sensorless Drive of an Adequately Designed IPM Motor for Robot Vehicle Application," PCC Japan Annual Meeting, 2007.
- [22] A. Maemura, S. Morimoto, K. Yamada, T. Sawa, T. J. Kume, and M. Swamy, "A Novel Method for Extending Stroke Length in Moving Magnet Type Linear Motor Drive System Employing Winding Changeover Technique," International Power Electronics Conference (IPEC), Tokyo, 2005
- [23] M. Swamy, T. J. Kume, A. Maemura, and S. Morimoto "Extended High Speed Operation via Electronic Winding Change Method for AC Motors," IEEE Transactions on Industry Applications, Vol. 42, No. 3, May/June 2006