A Present State and Futuristic Vision

OF MOTOR DRIVE TECHNOLOGY

Mahesh Swamy and Tsuneo Kume

Management Summary

One of the driving forces behind the industrial revolution was the invention—more than a century ago—of the electric motor. Its widespread use for all kinds of mechanical motion has made life simpler and has ultimately aided the advancement of humankind.

And the advent of the inverter that facilitated speed and torque control of AC motors has propelled the use of electric motors to new realms that were 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. The use of AC motor drives has also resulted in energy savings and improved system efficiency.

This paper reviews the development and application of inverter technology to AC motor drives and presents a vision for motor drive technology.

Introduction

The electric motor control has advanced considerably in recent years. This can be attributed to significant progress in the field of power electronics enabled by unprecedented progress in 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 the mechatronics equipment used in machine tools and semiconductor fabrication machines. The AC motor controller is comprised 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. Figure 1 shows a current inverter (induction motor controller) and AC servo drives (permanent-magnet AC motor and their controllers). The controllers shown in Figure 1 employ the latest that industrial technology has to offer (Ref. 1) in power semiconductors, using the most advanced motor drive control algorithms in the form of vector control. Such controllers are ubiquitous in today's varied industrial and commercial applications. As the use of AC motor drives becomes more widespread, it is difficult to ignore an important fact—i.e., the electric power used by electromechanical energy conversion equipment, of which electric motors form the bulk, exceeds 70% of the total industrial electric power produced. Given that future residential applications will soon be using motor drives in, for example, washing machines and HVAC applications, it is important to concentrate R&D efforts on achieving higher efficiency and smaller-sized products that use less raw material, are less toxic to the environment, have a long MTBF (mean time between failures) and are easy to recycle.

The concepts, ideas and equipment used in the motor drives industry are easily applicable to harnessing energy from alternate sources, including solar and wind energy. It therefore is not surprising to find that power electronics 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.

AC Motor Drives

The present-day industry categorizes AC motor drives in 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 motors are still the workhorse of today's industry. Applications that use induction motors may not need high-precision positioning and velocity control. Such applications typically use what is known in the industry as general-purpose AC motor drives. However, the machine tool, 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 therefore higher controllability. Such motors are grouped in the servo motor category, are controlled by permanent-magnet AC motor (PMAC) drives and are typically more expensive than their induction-motor counterparts.

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 that 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 as 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 today's AC motor drive is shown in Figure 2.

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, a voltage reduction at lower speed range is possible that further improves efficiency. 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 operation via AC motor drives to save energy and reduce the overall carbon footprint of a given plant. It is significant not only for those countries but for all people using centrifugal loads to convert the fixed-speed fans and pumps to variable speed.

High-performance AC motor drives—vector control. Though the majority of industrial applications require unsophisticated V/f control, there are quite a few that require higher performance. Such applications include machine tool spindle drives, paper-making machines, winders and pinch rolls in the iron and steel industries, elevators, top drives for oil drilling, winders/unwinders, 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—that 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 directed 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 α and β components. These α and β components are then transformed into two axes (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. 3a). 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 three-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:

- Direct field-oriented control
- Indirect field-oriented control (Ref. 2).

In the direct field-oriented control method, the posi-

continued

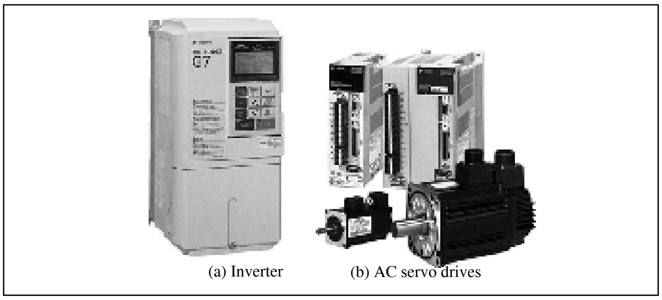


Figure 1—Typical AC motor drives: (a) three-level induction motor controller; (b) AC servo drives and servo motors.

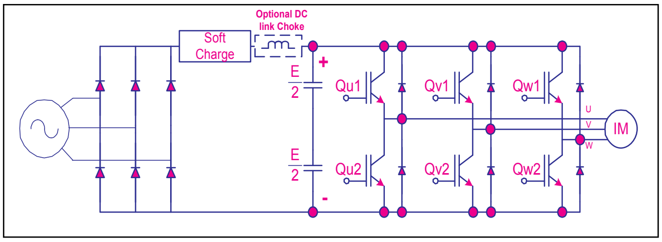


Figure 2—Schematic of a typical voltage-source, inverter-based AC motor drive.

tion and magnitude of the air-gap flux in the AC motor are 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.

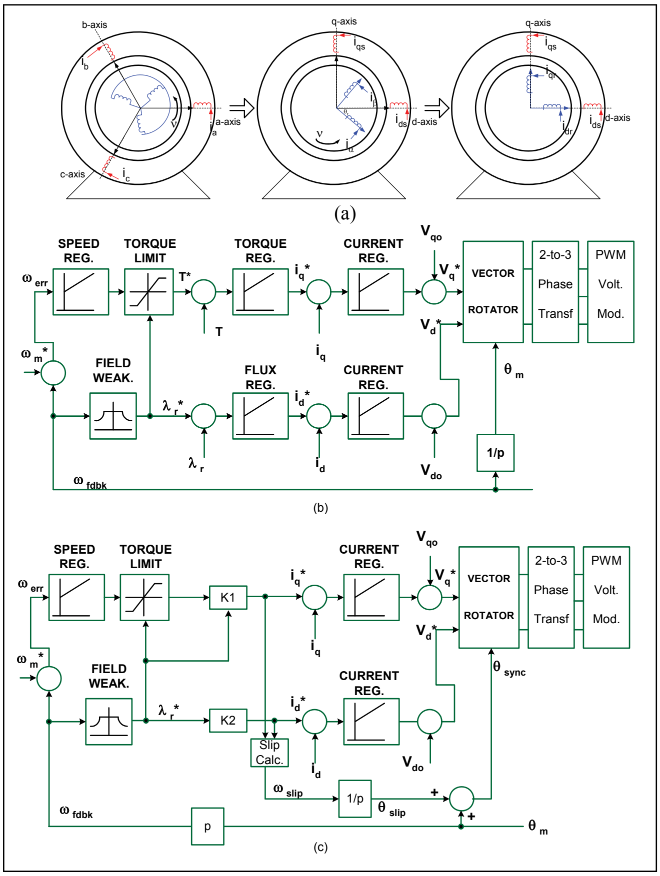


Figure 3—Schematic of typical induction motor control in modern AC drives: (a) three-phase to two-phase to two-axis transformation; (b) direct field-oriented control and (b) indirect field-oriented control.

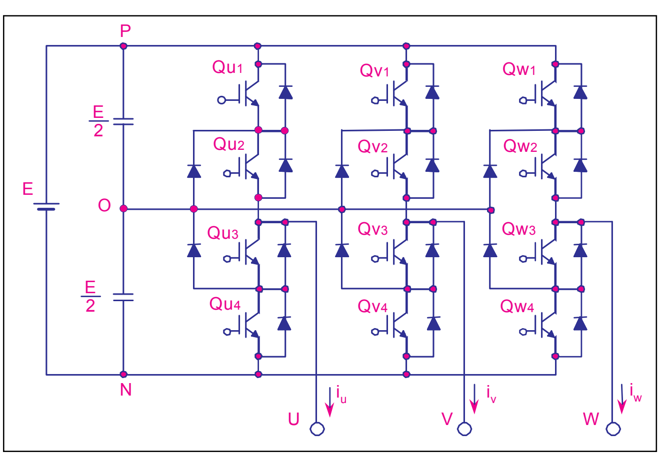


Figure 4—The neutral point clamped three-level inverter circuit topology.

The control philosophy in the indirect field-oriented control is quite different from 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 a 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/or the use of both types of this control—i.e., 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 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 motor speed. A typical schematic for the two types of control along with the concept of coordinate transformation is shown in Figure 3 (Ref. 2).

High-performance AC motor drives—sensorless control. In the control schemes discussed above and shown in Figure 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 inoperative due to a 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 "open-loop control." The advent of sophisticated microprocessors with the 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 remains an important research and development discussion at many major motor drive manufacturers. Two methods are gaining popularity. They are:

- Using the motor itself as a sensor by injecting a high-frequency signal into the motor to reveal saliencies due to the slot and teeth of the stator structure
- 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 effective in controlling the motor, even at zero input frequency (Ref. 3).

Realistically, 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 introducing sophisticated sensorless algorithms that push the boundaries consistently.

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 are 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 20 m 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 between the drive and the motor to handle such application issues.

Three-level, neutral-point clamped inverter. Instead of adding a component between the drive and the motor, modifying the power topology to reduce the problems described above is a much more prudent approach. Yaskawa Electric Corporation was the first drive manufacturer to introduce a three-level drive structure for general-purpose, low-voltage applications (Ref. 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 first introduced by A. Nabae, I. Takahashi and H. Akagi in 1980 and published in 1981 (Ref. 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, it was applied to medium- and high-voltage drives. Early applications included the steel industry and railroad traction areas in Europe (Refs. 6–7) and Japan (Ref. 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 (Refs. 9–10). In this product, a unique technology is used to achieve balancing of the DC bus capacitor voltages (Ref. 11). Details are described in the following sections.

Figure 4 shows the circuit diagram of the NPC three-level inverter (Ref. 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 QU1 and QU2 are turned on, output U is connected to the positive rail (P) of the DC bus.
- When QU2 and QU3 are on, it is connected to the mid-point (O) of the DC bus, and when QU3 and QU4 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. The relation between the switching states of IGBTs and the resulting output voltage with respect to the DC mid-point is summarized in Table 1.

DC bus capacitors need to be connected in series to get the mid-point that provides 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 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, consider PWM reference signal for phases U, V and W as:

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

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

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

A is the modulation index. It is assumed that no third harmonic component is used to improve utilization of the DC bus voltage (Ref. 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, meaning that full voltage command is applied, and let the phase angle ωt be 75° for phase U. This condition is shown in

continued

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

Figure 5, where the phase voltages in per-unit are expressed as:

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

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

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

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 Figure 6.

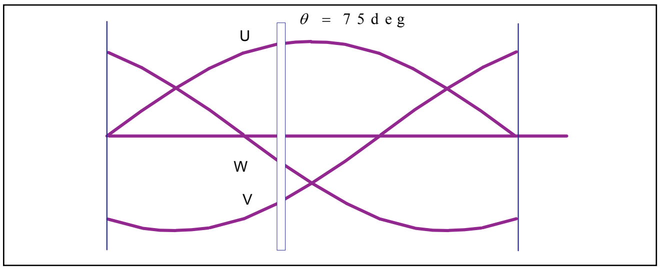


Figure 5—Phase angle chosen for waveform illustration.

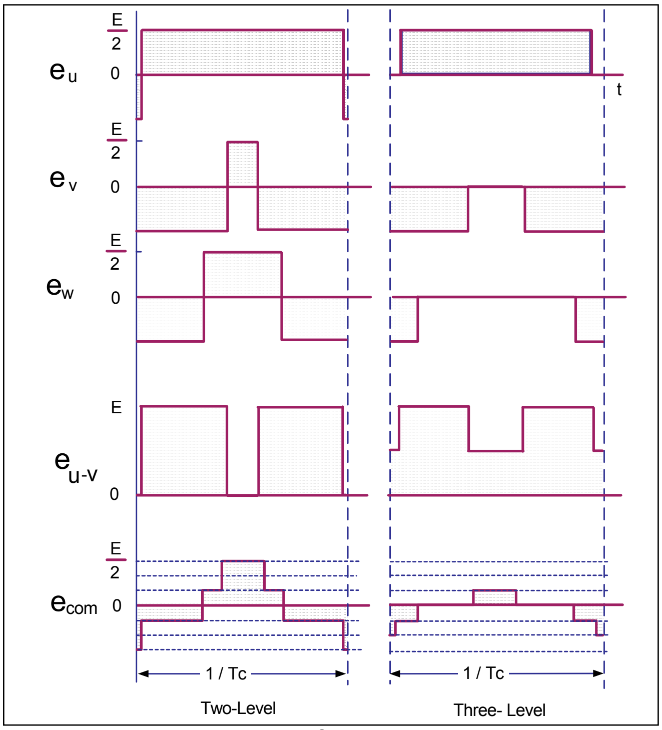


Figure 6—Voltage waveform comparison between two-level and three-level configurations.

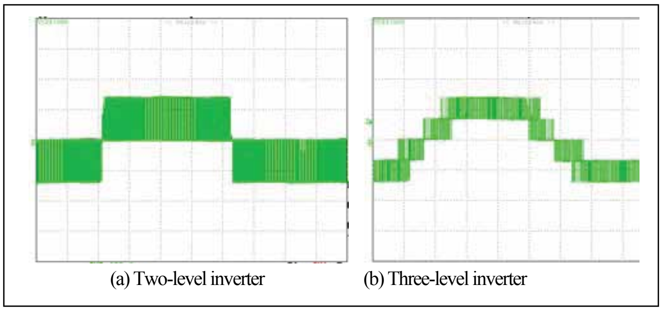


Figure 7—Measured line-to-line waveforms—V:500 V/div; T: 2 ms/div.

In Figure 6, *Tc* 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 Figure 7 and measured common-mode voltages are compared in Figure 8. The waveforms in Figures 7 and 8 are for a 460 V, 7.5 kW motor drive system. As shown in Figures 6–8, the three-level inverter has smaller voltage steps than the two-level inverter—in both 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.

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. A high rate of voltage change also creates irregular 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 the two-level inverter. Waveforms in Figure 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 Figure 9a, the overshoot magnitude of *E* is added to the original voltage *E*, making the peak value as high as 2*E*. In Figure 9b, the voltage jump is 0.5*E*, which is added to the original voltage of *E*, resulting in the peak value of 1.5*E*.

Figure 10 shows measured motor voltage waveforms when the cable is 100 m 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.

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 in equipment installed nearby the inverter. It is also strongly related to the EMI noise level.

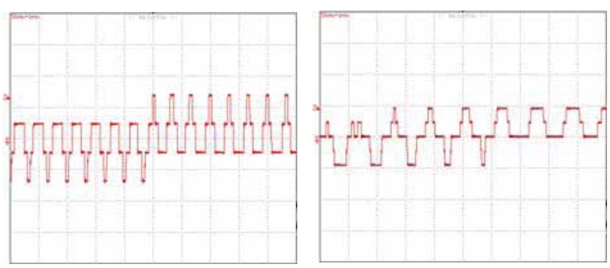
Because of the smaller-voltage steps of the common-mode voltage, the leakage current of the three-level inverter is much smaller than that of the two-level version.

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

Shaft voltage, bearing current. Bearing damages of 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.

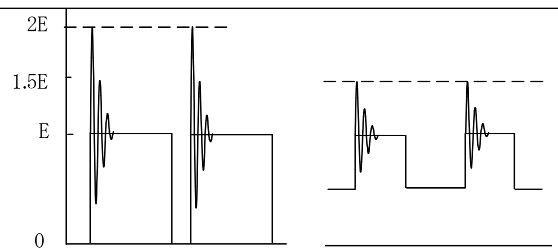
When the rotor of a motor is rotating with the bearings insulated by film grease, there exists capacitance between the rotor and the frame (ground). This capacitance is charged by the common-mode voltage through the capacitance between the stator winding and the rotor. Hence, the shape of the shaft voltage 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.

continued



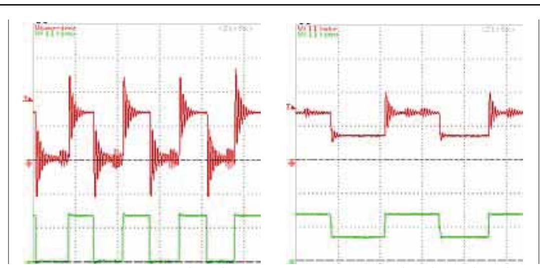
(a) Two-level inverter (b) Three-level inverter

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



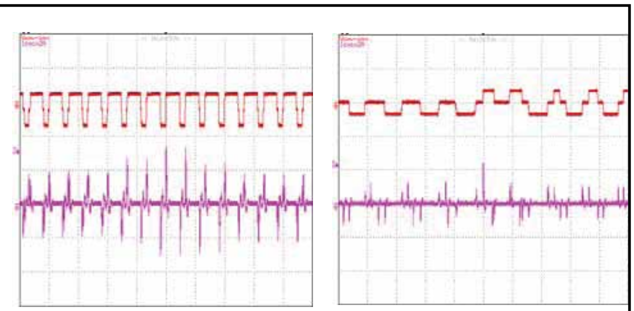
(a) Two-level (b) Three-level

Figure 9—Voltage overshoot at motor terminals.



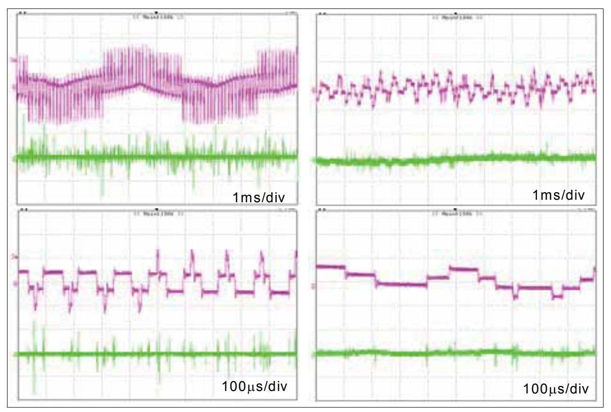
(a) Two-level (b)Three-level

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



(a) Two-Level (b) Three-level

Figure 11—Leakage current—upper scale: common-mode voltage, 500 V/div; lower scale: leakage current, 2 A/div; T: 100 μs/div.



(a) Two-level (b) Three-level

Figure 12—Shaft voltage and bearing current—upper in each frame: shaft voltage, 10 V/div; lower in each frame: bearing current, 20 mA/div.

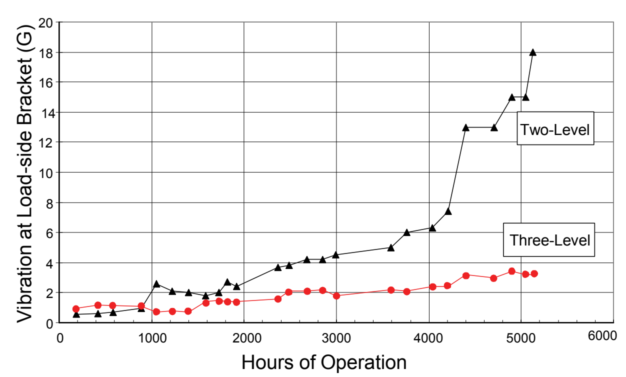


Figure 13—Result of bearing life tests—0.7 kW, 2,100 rpm.

Figure 14—Varispeed G7, 400 V, 1.5 kW.

Since the change of the common-mode voltage is smaller in the three-level inverter, it has a significant advantage over the two-level model 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 between the bearing and its housing to facilitate observation of bearing current.

Although Figure 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 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.

Figure 14 shows a 400 V, 1.5 kW unit. The units from 18.5 kW up to 300 kW 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.

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:

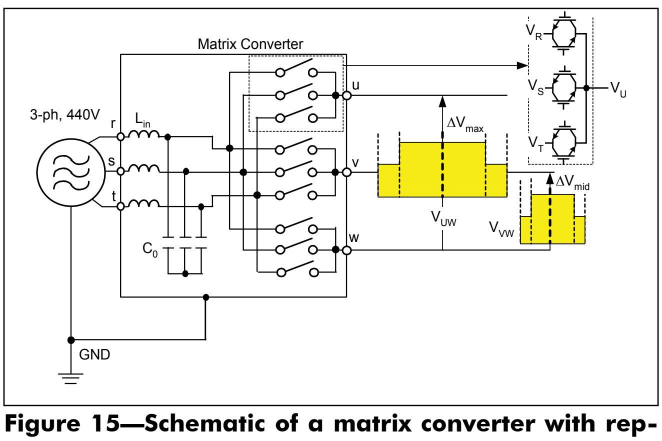


Figure 15—Schematic of a matrix converter with representative output line-to-line voltage patterns; sizes up to 22 kW use reverse-blocking IGBTs.

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

- High levels of input current harmonics that 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
- 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 remains a 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 (MC) (Ref. 12).

The 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. Figure 15 shows the basic topology of a matrix converter.

The concept of a matrix converter was first presented by Venturini (Ref. 13). Since then, it has always been topology that merited more attention. Lack of low-cost, high-performance semiconductors prevented the complete adoption of this topology. But owing to recent advances, it has been shown to be a very viable product. Yaskawa is one of the first companies to commercialize this product. Three-phase MC consists of genuine, bi-directional switches that allow PWM control of both input and output currents. It does not require the intermediate DC link and the associated large capacitive filter that is 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:

- Avoid input line-to-line short circuit
- Avoid output open circuits

Several multi-step commutation strategies were introduced that adhere to the above two constraints (Ref. 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 the bi-directional switch are different because the real turn-on/off time of each switch is affected by the direction of the output current and the amplitude of the input voltage. Thus, during the commutation sequence, unwanted voltage distortion can occur in the output voltage of a matrix converter, similar to voltage distortion caused by dead-time between the upper and lower switches of a conventional voltage-source inverter.

Many researchers have worked on this topic and have proposed various reliable software/hardware implementation techniques (Ref. 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 the 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 that is inductive in nature. Since the current into the inductive load is switched from one phase to another, it can create interference and 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 (Ref. 12). A summary of the advantages of a matrix converter over two-level voltage source inverter is given in Table 2.

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 conventional two-level voltage source PWM inverters. The matrix converter exhibits lower-voltage step size in the common-mode voltage waveform, thus allowing easier filtering.

Figure 16 compares the common-mode voltage in a matrix converter with that in a conventional two-level inverter (Ref. 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. Integration of different filters to achieve a low noise drive that has lower ground current and a higher safety margin is the thrust of this paper.

From the explanations provided thus far on the operation of the matrix converter, it can be said that its performance is similar to that of 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:

- Matrix converter uses nine reverse-blocking semiconductor switching devices, while a comparable three-level, back-to-back voltage-source inverter employs 24 devices.
- A matrix converter does not need a smoothing DC bus capacitor and the associated soft-charge circuit.
- In the 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 the 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 a 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.
- The control scheme of a matrix converter is complex because of the absence of the DC bus capacitor that 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

continued

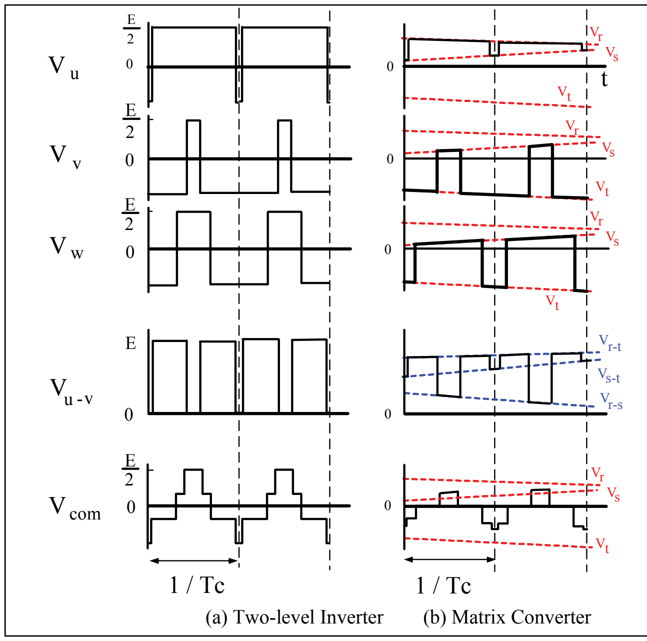


Figure 16—Common-mode voltage in two different types of motor controllers, both employing three-phase modulation.

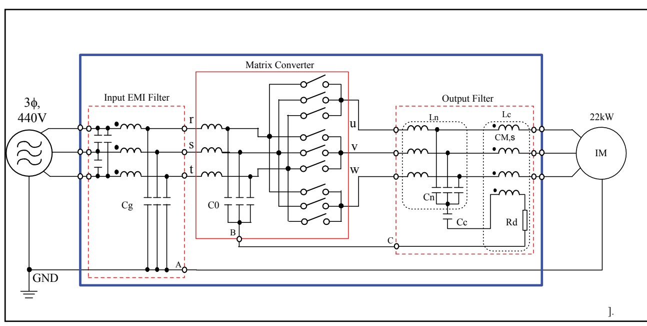


Figure 17—Schematic of a matrix converter with input and output filters to achieve environmentally harmonious drive system (Ref. 12).

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

of this drawback significantly.

Various additional filters that are required to achieve a low-noise motor drive system can be easily integrated with the matrix converter. Figure 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; this helps reduce the bearing current.

Figure 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: 530 mm; Height: 700 mm; and Depth: 290 mm. An equivalent back-to-back voltage-source inverter with similar integrated filter would have occupied 37% more volume than the matrix converter.

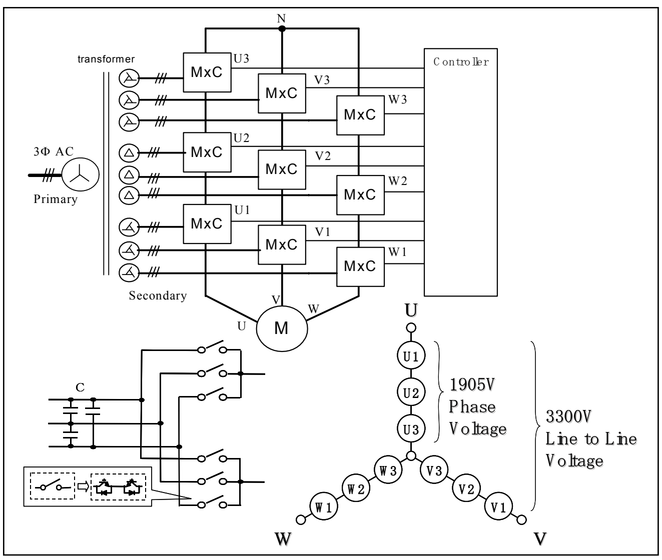


Figure 19—Schematic of medium-voltage matrix converter drive with its associated vector representation (Ref. 16).

(a) (b)

Figure 20—Developed "RoboPorter": (a) transporter for human; (b) automatic transporter for objects.

Medium-voltage matrix converter (Ref. 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 are 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 Figure 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 3.3 kV, 200 to 3,000 kVA system
  * Six cells in series yields 6.6 kV, 200 to 6,000 kVA system
- Excellent output-voltage waveform due to multi-step configuration attainable by phase-shifting carrier frequency

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 and experimentation are 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.

SiC devices—advantages and challenges. A 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°C and higher. Some researchers have pushed it to operate even at 250°C (Ref. 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 equipment 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 an SiC-based Schottky barrier diode (Ref. 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 have 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. A typical amplification factor (β) of 20 is achievable in cases of power BJTs that use SiC devices (Ref. 18).

GaN devices—advantages and challenges. Gallium nitride (GaN) devices can withstand high voltages without showing degradation (Ref. 19). These devices have been shown to be able to be switched at high frequencies and high voltage—making them very attractive in power systems engineering and large-power motor drives. GaN has recently been grown on silicon-based wafers, both 4" and 6"type. This is a remarkable improvement because it reduces defects and allows 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, 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. And, the cost of GaN devices is not expected to be much more than that of currently used silicon-based power devices. This, too, is a positive point for GaN devices. But it is too early to understand 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 to not forget that the ancillary circuits that are needed to turn these devices on and off also need to be able to handle the high-temperature environment. Hence, further progress in these areas needs to happen.

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 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, have products that can operate PM motors in open-loop fashion (Ref. 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, motor resistances, etc. Given the advances in microprocessors now used in general-purpose drives, this task is relatively easy. But the challenge is in performing such tasks without employing high-end processors. The future research is currently 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 an adequately designed IPM motor for a robot vehicle was demonstrated by Yaskawa at Kitakyushu international airport in April 2006 (Ref. 21). The motor is deliberately designed to meet the requirements of robot applications and lends itself more to 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 a two-wheeled differential drive, the other an omni-directional drive, were demonstrated to transport humans 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 Figure 20 and the actual motor that is included within the wheel is shown in Figure 21. In the demonstration at Kitakyushu airport, the two-wheel differential drive type was human-driven, and the omni-directional drive type was automatically controlled on trajectory from a distance of 25 m. The absolute position of the robot could be corrected by the laser rangefinder attached to the robot (omni-direction drive). This was introduced as an afterthought because of the tire slippage on the polished surface of the airport and the need to achieve precise position information for transporting bags.

Linear motors. An efficient wafer-transportation technique is key to achieving higher throughput in the ever-growing semiconductor manufacturing industry. Automatic wafer-handling systems that reduce 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.

continued

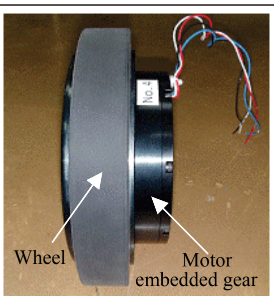


Figure 21—Photo of the proposed motor installed in wheel.

There are two types of permanent-magnet synchronous linear motors: a moving-magnet (MM) type and moving-coil (MC). The MM type has magnets on the moving table, whereas the 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 so 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 stoke 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.

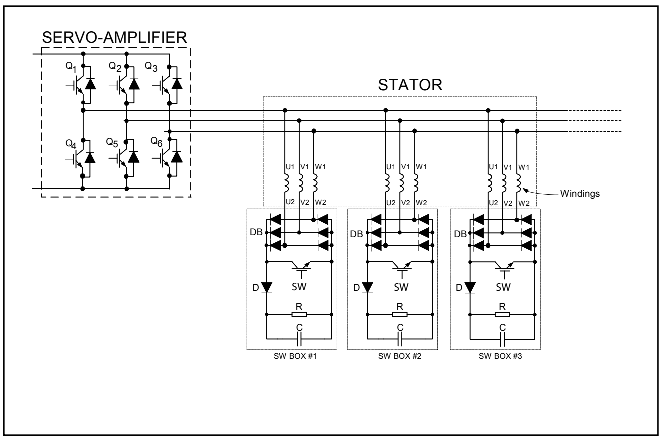


Figure 22—Circuit configuration for winding change technique.

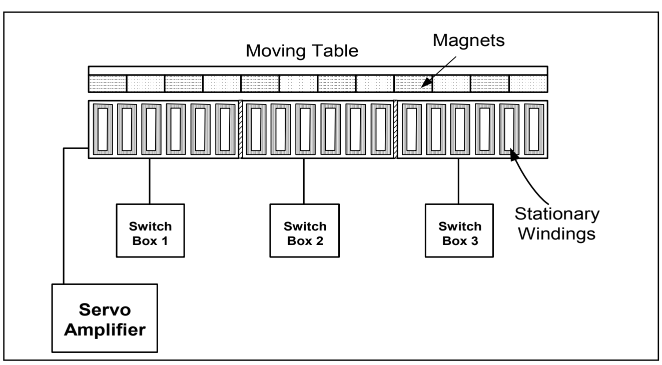


Figure 23—Structure of Yaskawa's moving-magnet-type linear motor.

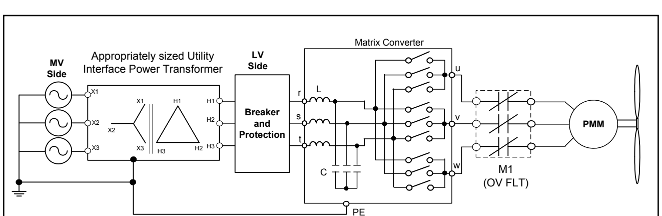


Figure 24—Schematic of possible use of a matrix converter in a wind turbine application.

Engineers at Yaskawa 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 (Ref. 22). This technique was also used to extend speed control range of induction motors and permanent-magnet motors (Ref. 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 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 400 kW have already been developed and tested. These are primarily used in wind power applications and other high power pumping applications.

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 a 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. The 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.

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.

Conclusions

In this paper, the present status of the motor drives industry is presented. All aspects of the motor drives industry have 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 in which humankind can benefit.

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 processes, both electrical energy to mechanical energy and vice versa.

References

1. Sawa, T. 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. Stefanovic, V.R., 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. Holtz, J. and R. D. Lorenz. "Sensorless Control and Complex Vector Control Analysis of AC Drives," Tutorial Notes, *IEEE IAS Annual Meeting*, 1999.
4. Krug, H.P., 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. Nabae, A., 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. Timer, R.A. "PWM Frequency Converters in the Metal Industry," *EPE Firenze,* 1991.
7. Cascone, V., L. Mantica and M. Oberti. "Three-Level Inverter DSC Control Strategy for Traction Drives," *EPE Firenze* 1991.
8. Nakata, K. 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. Watanabe, E. et al. "New Inverter Drive Technology," *Yaskawa Technical Review,* Vol. 65, No. 2, 2001, pp. 104–111.
10. Takasaki, H. et al. "High-Performance and Environmentally Friendly General Purpose Inverter Varispeed G7," *Yaskawa Technical Review*, Vol. 65, No. 2, 2001, pp. 122–126.
11. Yamanaka, K., 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, Nov/Dec, 2002, pp. 1572–1579.
12. Kume, T.J., 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 Elements" *Proc. Powercon* 7, 1980, pp. E3/1–E3/15.
14. Alesina, N.A. 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.Kang, J.K., H. Hara, E. Yamamoto, T. J. Kume and M. Swamy. "Output Voltage Distortion in Matrix Converter by Commutation of Bidirectional Switches," *IEEE International Electric Machines and Drives Conference*, 2003, Madison, Wisconsin USA.
16. Ueda, Y., M. Ikeda, R. Suenaga, K. Imanishi, E. Masuda and E. Watanabe. "Development of Medium Voltage Matrix Converter," *IEEJ Annual Meeting*, 2007.
17.Roussel, P. "SiC Power Devices: If We Only Had a Switch," Vol. 2, Issue 5, *Semiconductor Today–Compounds and Advanced Silicon*, June, 2007.
18. Scofield, J., 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, pp 991–994, *Material Science Forums, Trans Tech Publications*, Switzerland.
19. Robinson, G. "Gallium Nitride Nears Use in RF Semiconductors," *http://www.eetimes.com/story/OEG20020107S00*91.
20. V1000 Product Brochure, Yaskawa Electric Corporation, *http://www.drives.com*.
21. Ide, K., M. Takaki, S. Morimoto, Y. Kawazoe, A. Maemura and M. Ohto. "Saliency Based Sensorless Drive of an Adequately Designed IPM Motor for Robot Vehicle Application," *PCC Japan Annual Meeting*, 2007.
22. Maemura, A., 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. Swamy, M, T. J. Kume, A. Maemura and S. Morimoto. "Extended High-Speed Operation via Electronic Winding Change Method for AC Motors," *IEEE Transactions on Industry Application*s, Vol. 42, No. 3, May/June 2006.

Dr. Tsuneo Kume *received a bachelor's degree in electrical engineering from Waseda University, Tokyo, in 1960, and he joined Yaskawa Electric Corporation, Kitakyushu, Japan, the same year. He received master's and Ph.D. degrees in electrical engineering in 1968 and 1970, respectively, from the University of Missouri-Columbia. After returning to Yaskawa Electric, he started working on variable frequency inverters. Kume developed the first general-purpose transistor PWM inverter in 1974 and the first vector-controlled PWM inverter in 1979. Since then, he has continued his R&D activities in power electronics both in Japan and the United States. He is an active member of IEEJ and a Life Fellow of IEEE.*

Dr. Mahesh Swamy *received his bachelor's degree in engineering in 1983 from MMM Engineering College in Gorakhpur, India, and his master's degree in engineering from the Indian Institute of Science in Bangalore, India, in 1987. He received a Ph.D. degree in 1991 from the University of Victoria, British Columbia, Canada. In 1992 he joined Energy Management Corp., Salt Lake City, as a senior research engineer, where he worked on industrial AC motor drives. In 1996 he joined MTE Corp. as the director of engineering. Since 1997, he has worked with the R&D group at Yaskawa Electric America, Inc. His interests are in inverter drives and power electronics. Dr. Swamy is an active member of the IEEE Industry Applications Society and Power Electronics Society.*