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Speed Control of Three Phase Induction Motor by VVVF method using G7/A-1000 Drive

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Abstract: 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. he 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. 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. Yukawa wants to be an integral part of this future and hopes to contribute significantly to achieve this.

***Index Terms**: AC, Efficient, Yukawa, significantly, facilitated.*

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 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.

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(a) Inverter (b) Ac Servo drives

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

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 significant of 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.

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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.

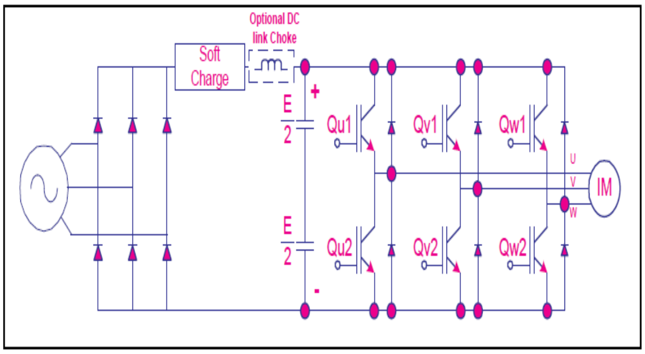

Figure 2: Schematic of a typical voltage source inverter based AC motor drive.

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 motor can be altered to follow a square function. By doing this, the power consumed by the motor becomes a cubic function of speed (Pocf) 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 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 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 x and f3 components. These c and J3 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.

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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 modem 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].

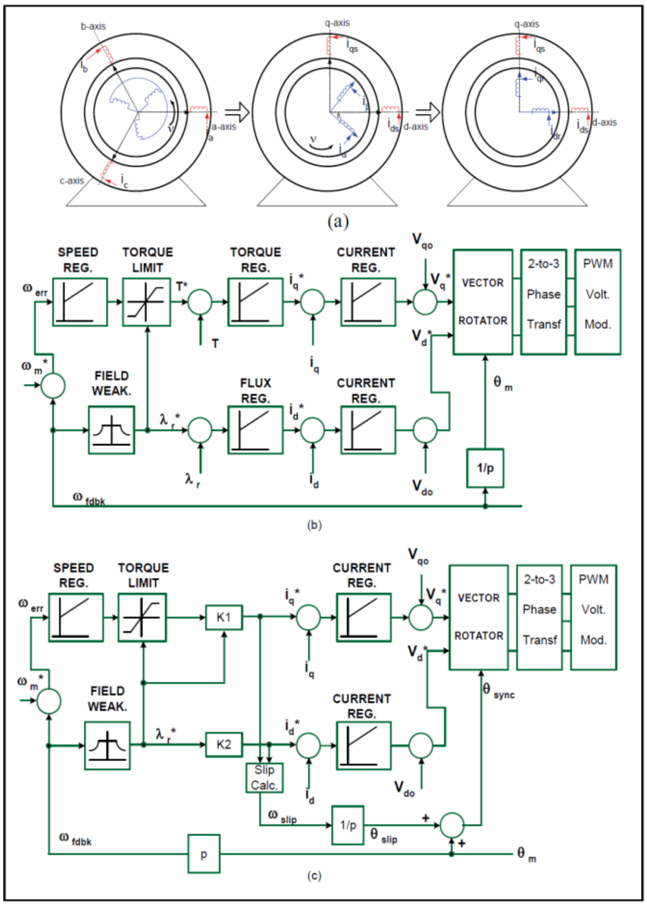

Figure 3: Schematic of typical induction motor control in modem AC drives. (a) 3-phase to 2-phase to 2-axis transformation, (b) Direct Field Oriented control and (b) Indirect Field Oriented control.

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 modem day AC motor drive. Carrier or switching frequencies in the range of lO-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 Ya.skawa 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 Qui and Qu2 are turned on, output U is connected to the positive rail (P) of the de bus. When Qu2 and Qu3 are on, it is connected to the mid-point (0) of the de 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.

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Relation between the switching states of IGBTs and the resulting output voltage with respect to the dc mid-point is summarized in Table 1.

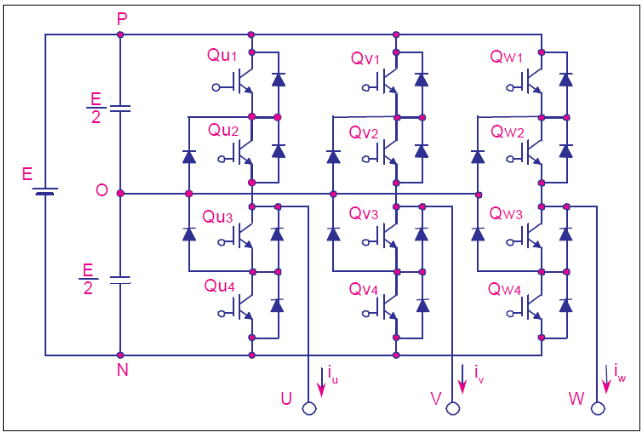

Figure 4: The neutral point clamped three level inverter circuit topology.

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 switch in -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 waveform let PWM reference signal for phases U, V and W be,

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

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

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

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 ωt 75° for phase U. This condition is shown in Fig. 5, where the phase voltages in per-unit are expressed as,

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

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

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

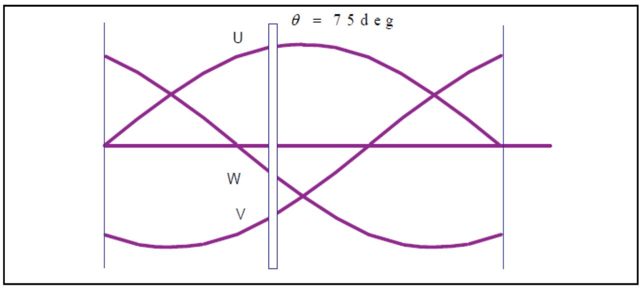

Figure 5: Phase angle chosen for waveform illustration

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, 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 Fig. 7.

Measured common-mode voltages are compared in

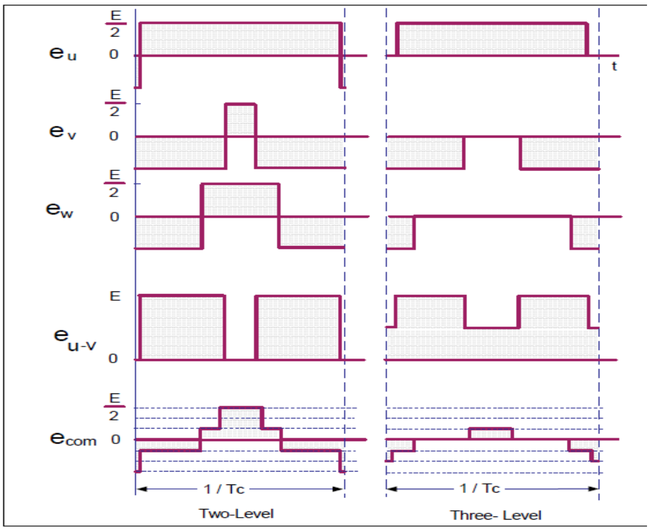

Figure 6: Voltage waveform comparison between two-level and three-level configurations.

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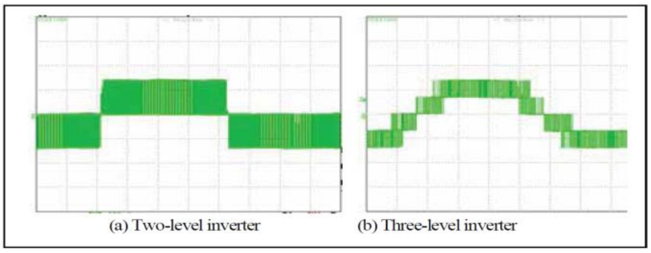

Figure 7: Measured line-to-line waveforms V: 500V/div, T: 2 100 μs/div

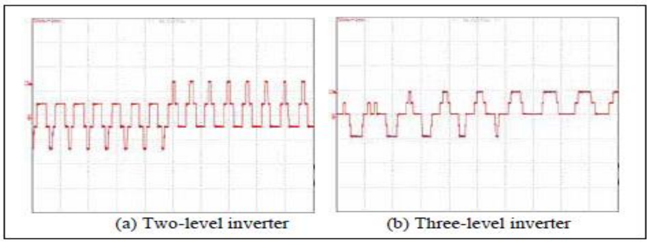

Figure 8: Measured common-mode voltage waveforms V:250V/div, T:100 μs/div

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 l.5E.

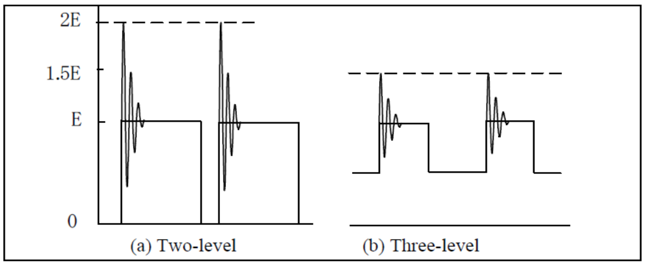

Figure 9 : Voltage overshoot at motor terminals

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.

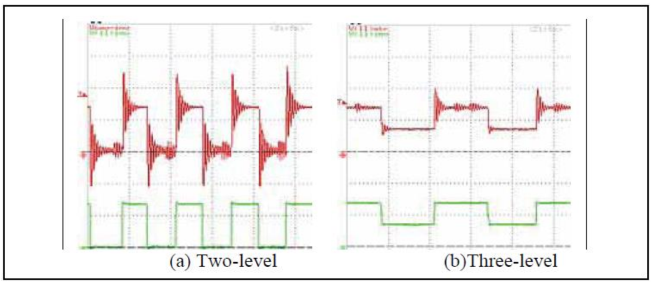

Figure 10: Measured surge voltage at motor terminals, v:500V/div, T:50μs/div

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.

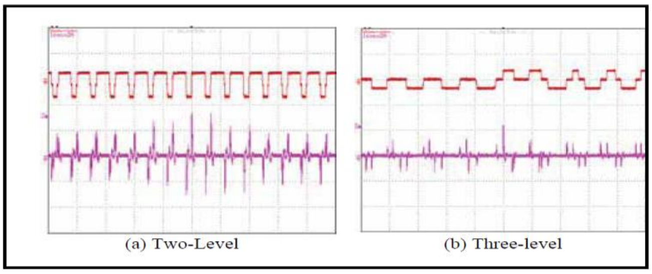

Fig. 11: Leakage current

Upper scale : common – mode voltage, 500 V/div
Lower scale: leaking current, 2A/div, T:100 μs/div

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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.

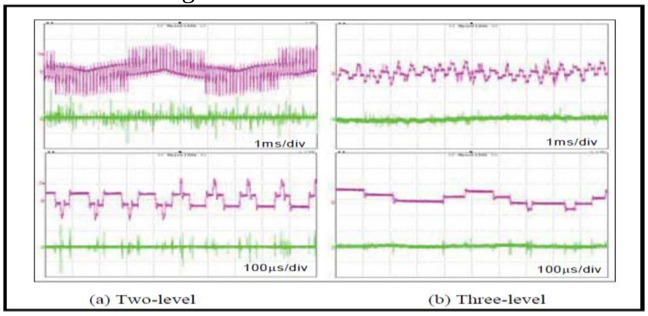

Figure 12: Shaft voltage and bearing Current Upper in each frame: shaft voltage, 10V/div Lower in each frame: bearing current, 20mA/div

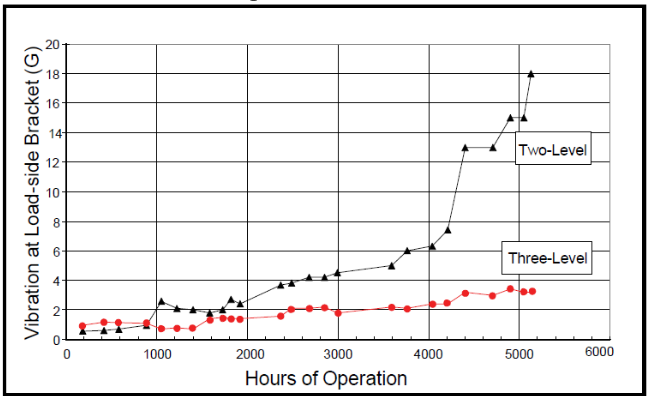

Figure 13: Result of bearing Life tests 0.7kW, 2100 rpm

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.

V. CONCLUSION

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.

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