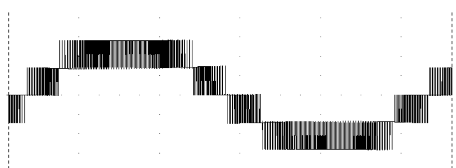
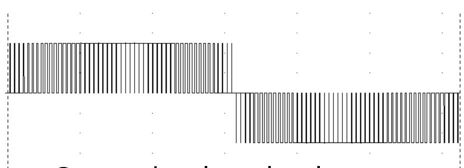
Product Application Note

Yaskawa G7 AC Drive
The World's First 480V 3-level Inverter

Applicable Product: G7
Rev: 05-06



G7 three-level output waveform



Conventional two-level output waveform

INTRODUCTION TO 3-LEVEL INVERTER TECHNOLOGY

This paper introduces the G7 Drive technology by Yaskawa that solves technical issues associated with industrial and commercial applications that increasingly require simplified set-up and improved maintainability. The 480V G7 Drive adopts a Neutral-Point Clamped (NPC) 3-level inverter technology [1]. The basic behavior of the NPC technology has significant advantages over a conventional 2-level inverter. In particular, 3-level inverters have smaller output voltage steps that help in the mitigation of problems related to surge voltages at the motor terminals, motor shaft voltage and bearing current, leakage current, as well as others. The features and benefits of the G7 Drive with 3-level control are presented in this paper along with measured waveforms.

BASIC CIRCUIT CONFIGURATION AND ITS BEHAVIOR

Figure 1 shows the circuit configuration of the 3-level inverter. Each phase has four switching devices (IGBTs) connected in series. The applied voltage on its power switching devices is one-half of the conventional 2-level inverter. This topology was traditionally used for medium voltage drives both in industrial and traction applications. In addition to the capability of handling higher voltages, the 3-level inverter has the following favorable features; lower line-to-line and common-mode voltage steps, more frequent voltage steps in one carrier frequency cycle, and a lower ripple component in the output current for the same carrier frequency. These features lead to significant advantages for motor drives over conventional 2-level inverters in the form of lower voltage stresses on the motor windings and bearings along with less influence (electrical noise) to the adjacent equipment.

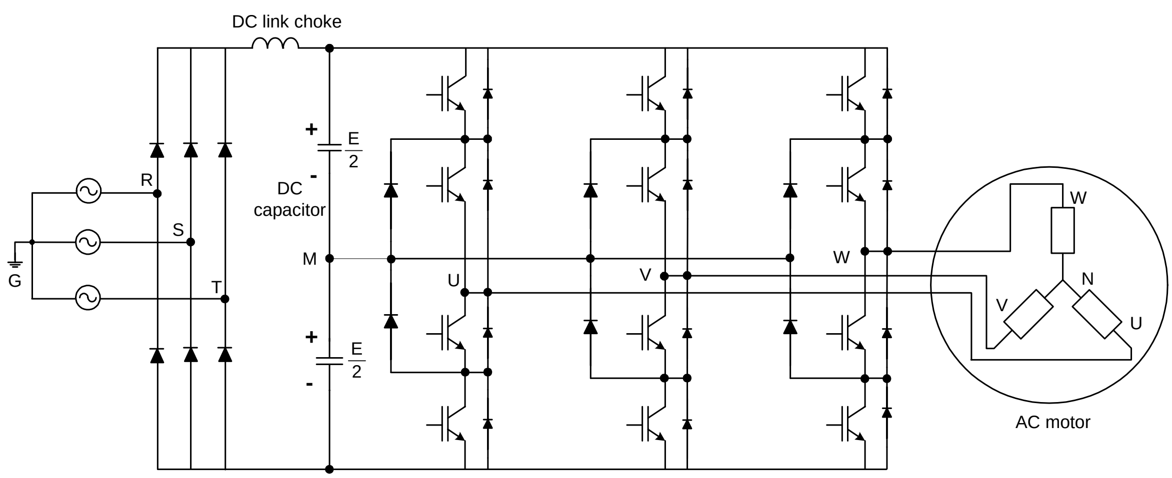
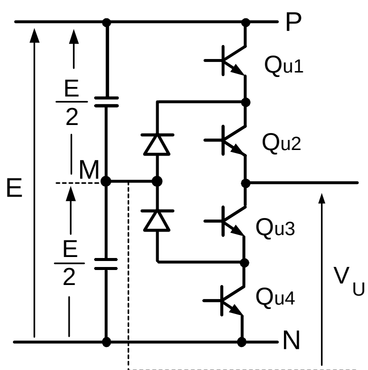


Figure 1. A 3-level inverter-driven AC machine

OUTPUT VOLTAGE AND SWITCHING STATES

Taking phase U as an example, the behavior of the 3-level inverter is described in Figure 2. 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 (M) 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 produce three voltage values compared to two values for the conventional 2-level topology. The relationship between the switching states of the IGBTs and the resulting output voltage with respect to the DC bus mid-point is summarized in the table in Figure 2.

The DC bus capacitors are connected in series to establish the mid-point that provides the zero voltage at the output. This is not a drawback since the series connection of the DC capacitors is a common practice in all general-purpose 480V inverters due to the unavailability of high voltage electrolytic capacitors. In NPC 3-level inverters, maintaining the voltage balance between the capacitors is important and influences the control strategy. In the G7 product, a unique technology is used to achieve balancing of the DC bus capacitor voltages [2].



	Qu1	Qu2	Qu3	Qu4	Vu
Switching states	ON	ON	OFF	OFF	+E/2
	OFF	ON	ON	OFF	0
	OFF	OFF	ON	ON	-E/2

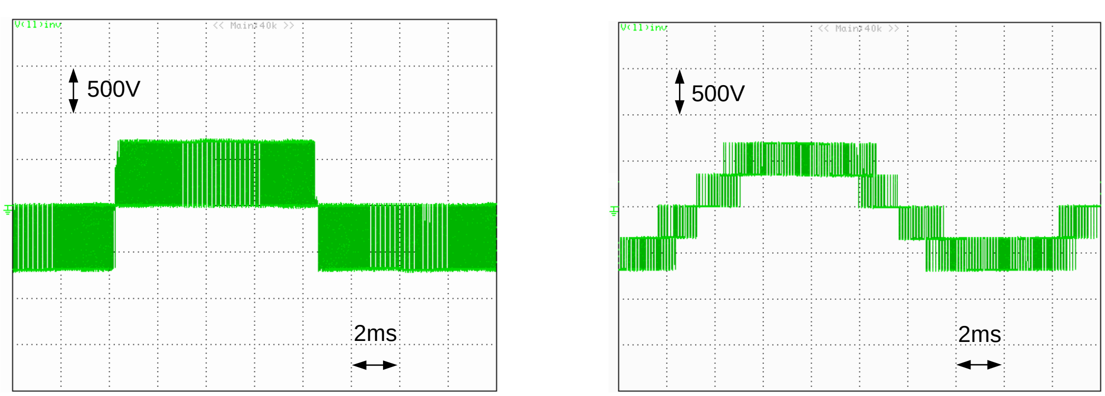
Figure 2. Relationship between the switching states of the IGBTs and the resulting output phase voltage

FEATURES AND ADVANTAGES OF 3-LEVEL INVERTER

This section compares the surge voltage at the motor terminals, leakage current, shaft voltage, and bearing current for 2-level and 3-level inverters.

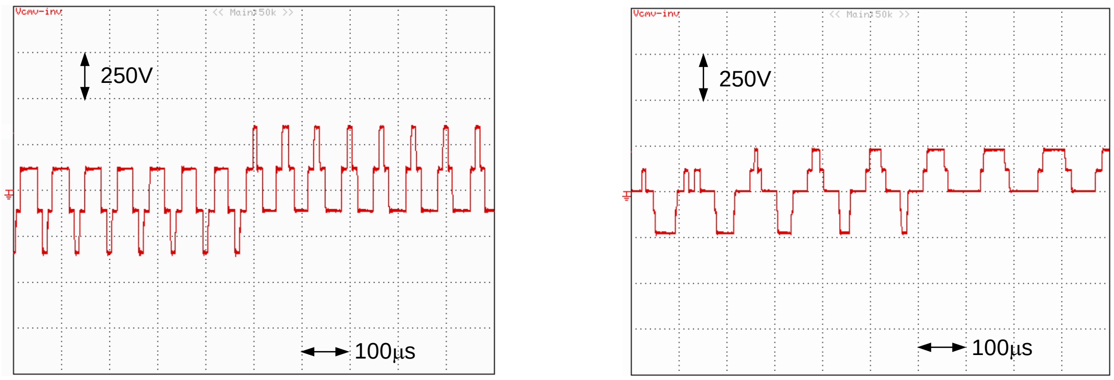
Multi-step voltage waveforms

Figure 3 shows that the 3-level inverter has smaller line-to-line voltage steps than the 2-level inverter. Figure 4 shows that the 3-level inverter also has smaller common-mode voltages steps. In addition, the common-mode voltage amplitude of the 3-level inverter is lower than the 2-level inverter in the high output voltage range. These characteristics bring significant benefits to drive applications.



(a) 2-level inverter (b) 3-level inverter

Figure 3. Line-to-line inverter output waveforms



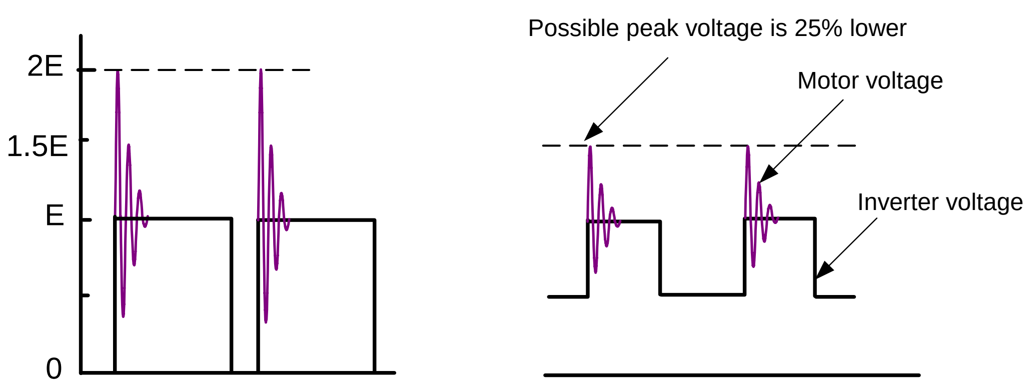
(a) Two-level inverter (b) 3-level inverter

Figure 4. Common-mode voltage waveforms

SOLUTIONS FOR THE MOTOR FAILURE ISSUES

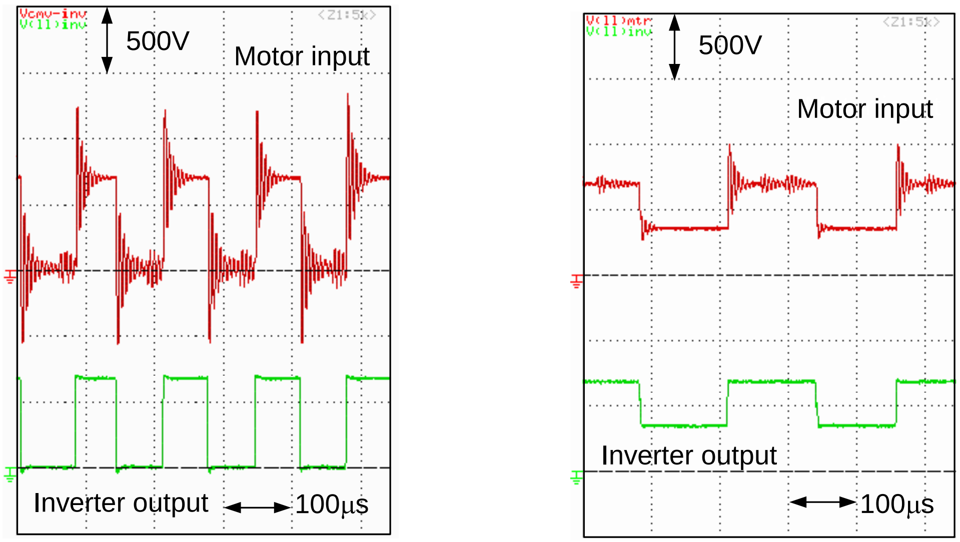
Surge voltage at the motor terminal

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. The 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 3-level inverter is one-half that of the two-level inverter, the peak voltage at the motor terminal is significantly lower than for a 2-level inverter. Waveforms in Figure 5 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 5(a), the overshoot magnitude of E is added to the original voltage E, making the peak value as high as 2E. In Figure 5(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 6 shows measured motor voltage waveforms when the cable is 100 meters long. The waveform in Figure 6(b) clearly shows the difference in the peak voltages. The high frequency ringing caused by the distributed parameters is also visible in these waveforms.



(a) 2-level inverter (b) 3-level inverter

Figure 5. Voltage overshoot at the motor terminals



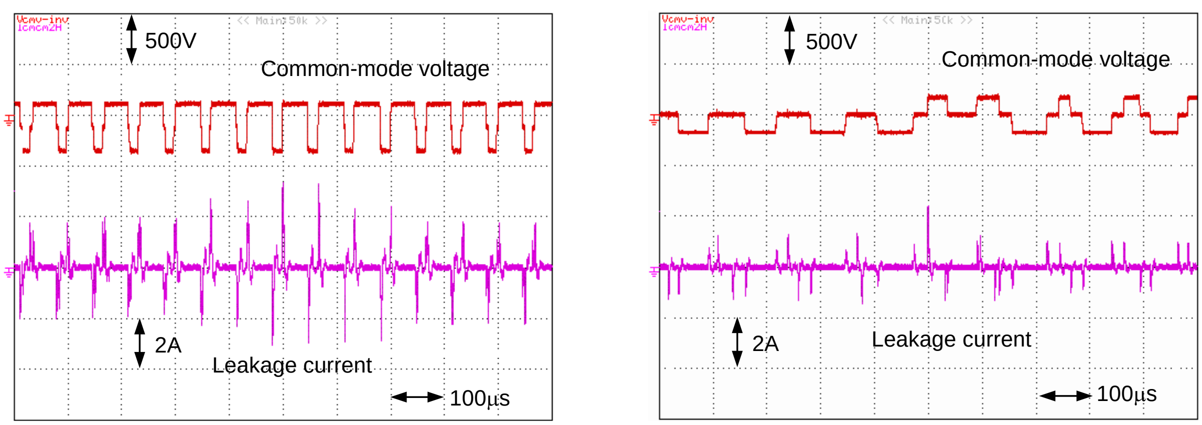
(a) 2-level inverter (b) 3-level inverter

Figure 6. Measured surge voltage at the motor terminals

Leakage current

High dv/dt 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 capacitances in these components. These leakage currents create noise problems to equipment installed near the inverter. It is also strongly related to the EMI noise level.

Thanks to the smaller voltage steps of the common-mode voltage, the leakage current of the 3-level inverter is much smaller than that in a 2-level inverter. Figure 7 shows a significant reduction in the peak leakage current level in the 3-level case. The measurement was conducted with a 460V, 10Hp motor and a 100-meter cable.



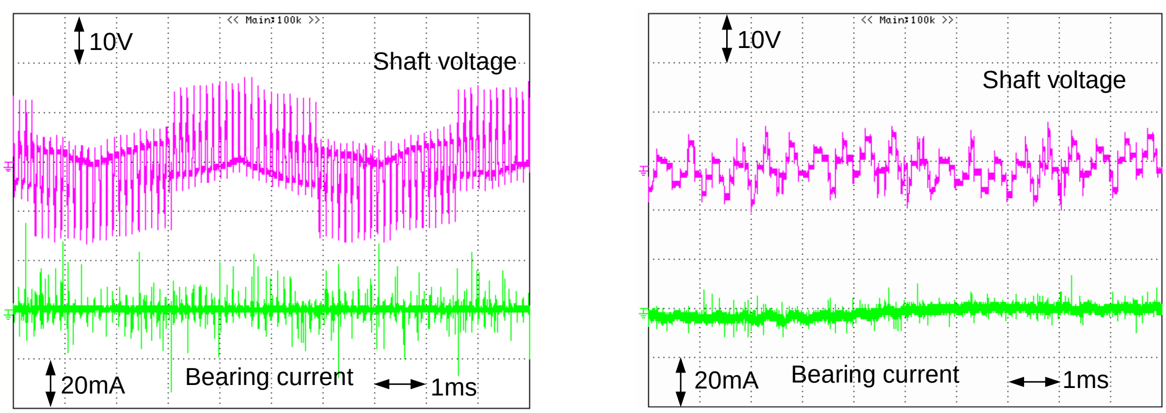
(a) Two-level inverter (b) 3-level inverter

*Figure 7***.** Leakage currents and common-mode voltages

Shaft voltage and bearing current

Bearing damage of motors driven by inverters has been reported mainly in cases where the shaft is not grounded. These problems are caused by the shaft voltage and additional bearing current created by the common-mode voltage and its sharp edges. When the rotor of a motor is rotating and a thin film of grease insulates the bearings, a capacitance exists between the rotor and the frame (ground). The common-mode voltage through the capacitance between the stator winding and the rotor charges this capacitance. This results in a shaft voltage that has a shape similar to the common-mode voltage. The sharp voltage edges of the shaft voltage cause the grease insulation to break down and current to flow through the bearings. This leads to repeated discharge of the shaft voltage as current through the bearings.

Since the common-mode voltage changes are smaller in the 3-level inverter, this has a significant advantage over the 2-level inverter with respect to the shaft voltage and bearing currents. Figure 8 shows the test results of the shaft voltage and bearing current for a 2-level and a 3-level inverter. Although Figure 8 shows the bearing current in the 3-level inverter case is significantly smaller, it is rather difficult to estimate the difference in the life of bearings. Actual long period tests were conducted to verify the superiority of the 3-level inverter. The tests simulated extreme conditions including temperature, types of grease, and motor speed. The results of the bearing life test are shown in Figure 9. It should be pointed out that in practice, the normal bearing life would be longer than that shown here. Figure 9 clearly proves that the use of a G7 Drive with 3-level topology can result in a significantly longer motor bearing life.



(a) Two-level inverter (b) 3-level inverter

Figure 8. Shaft voltage and bearing current of a 2-level and a 3-level inverter

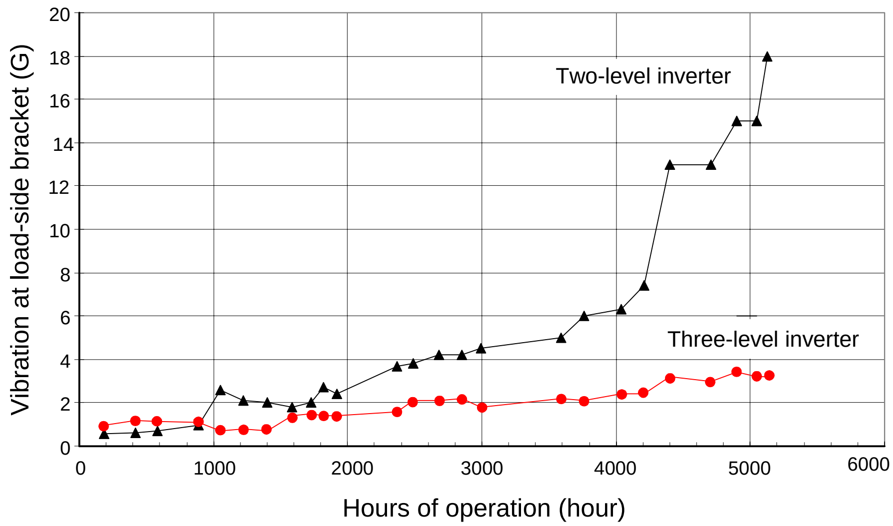


Figure 9. Results of the bearing life tests (1Hp, 2100rpm)

THE G7 3-LEVEL INVERTER

This section introduces the high dynamic performance of a G7 drive that is based on the 3-level technology. Combined with a sophisticated space vector PWM strategy and faster scan time, it is possible to employ the latest control technologies to improve dynamic performance.

Current Waveforms

The ripple current components in the 3-level inverter are 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 2-level inverter, thereby reducing switching losses in the IGBTs.

High Dynamic Performance AC Drive

Figure 10 shows a simplified control block diagram of the G7's Open Loop Vector control mode with the new dual flux observer resulting in excellent torque control characteristics. Using this method, it is possible to reach a torque of more than 150% of nominal torque at 0.3Hz as shown in Figure 11(a). The dual flux observer also helps in achieving accurate torque control. The torque limiting function limits the output torque to protect machines and materials against sudden changes in load as shown in Figure 11(b).

The reference tracking feed-forward control in the speed control block assures a fast response even in the Open Loop Vector control mode. The use of an encoder for actual motor speed feedback provides even better control and higher response in both speed and torque control. Figure 12(a) shows an example of the quick response to an abrupt change of the speed reference. Figure 12(b) illustrates when the load suddenly changes. The speed remains constant even when a step change in load is applied.

To achieve this high performance, the G7 Drive has a built-in auto-tuning function that calculates the motor parameters starting with only motor nameplate data. The G7 can perform either a static or rotational auto-tune to acquire the necessary motor information.

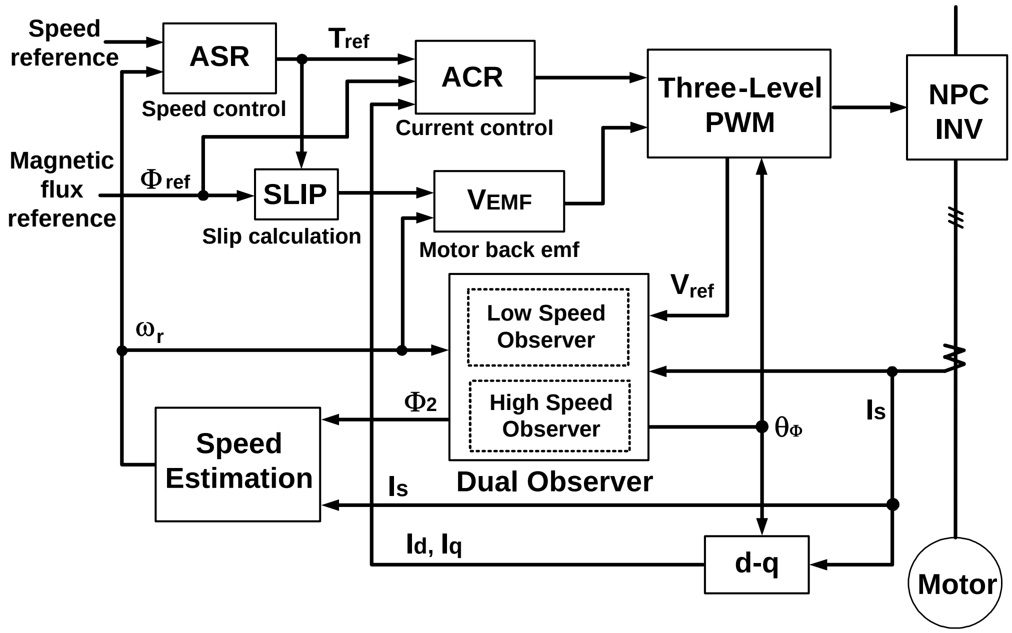
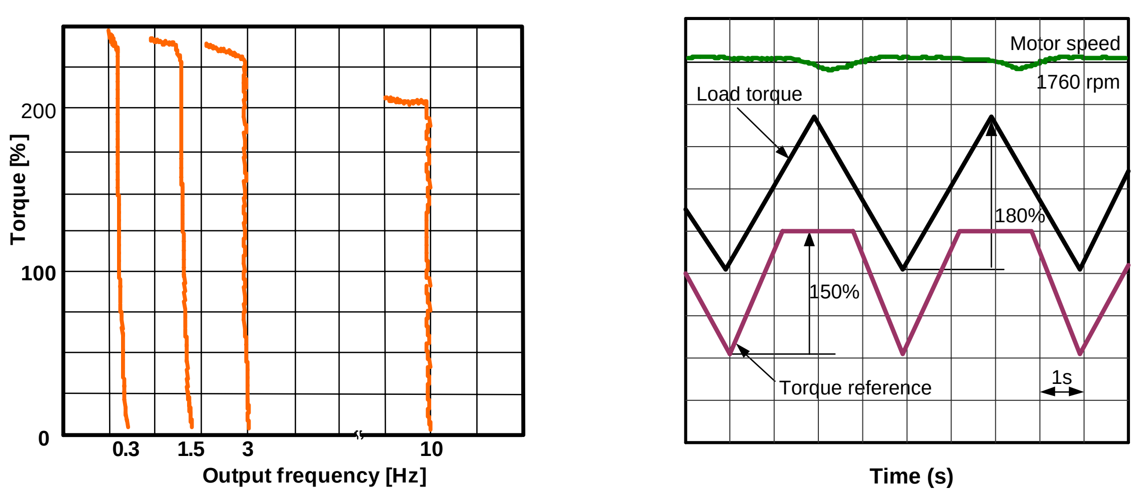
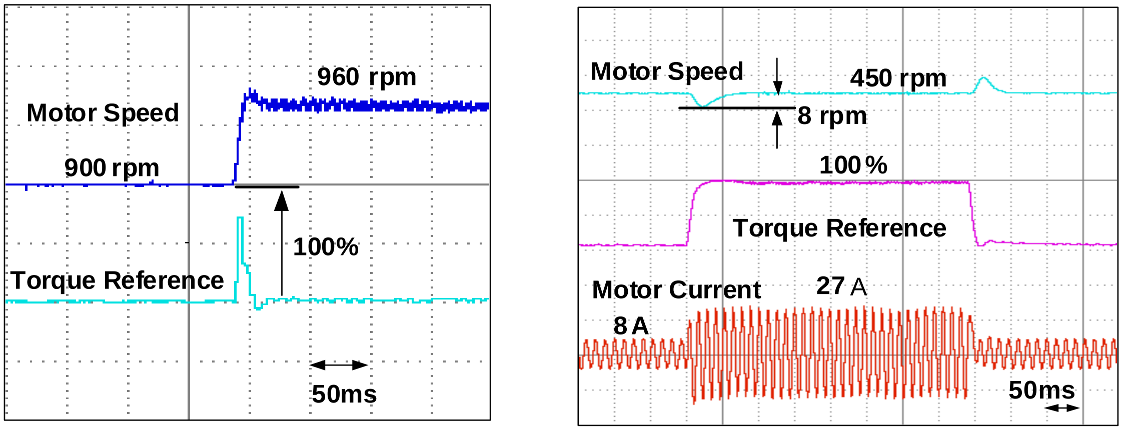


Figure 10. G7 open loop vector control block diagram using dual flux observer



(a) Torque characteristics in the low speed region (b) Torque limiting function

Figure 11. Torque control performance of the G7 drive



(a) Step speed-command response (b) Step load-torque response

Figure 12. High dynamic performance of the G7 drive

G7 DRIVES AND APPLICATIONS

G7 product line-up

The G7 Drive is designed for worldwide application. The G7 Drive has UL/cUL approval for the North American market as well as CE certification for the European market. It is available from ½ to 150Hp at 240V and ½ to 500Hp at 480V. The 3-level topology is only available in the 480V models (All 240V drives already have a DC bus height that is half that of a conventional 480V drive. Therefore, there is not a large need for the 3-level topology in 240V drives).

The G7 Drive (240V and 480V) from 25 to 500Hp has a built-in DC link choke (reactor). This DC link choke reduces the input harmonic current distortion and improves power factor. In addition, these units are equipped with a dual input rectifier bridge to facilitate twelve-pulse rectification. This can be achieved using a delta-delta-wye isolation transformer for phase shifting. The input current harmonic distortion (THD) can be reduced to approximately 12% using the twelve-pulse method.

Typical applications

Based on all the features and benefits of the 3-level topology and the dynamic, precise speed and torque control discussed above, many potential markets and applications can be identified. Typical applications requiring precise motor control capability include winders, spindle drives, elevators, crane hoists, sectionalized systems, etc. Long motor lead applications can be found in most large industrial plants and in the application of fans and pumps. Lead lengths of 300 meters or more are common in the pumping of water and oil. Such applications benefit from the use of the 3-level topology due to the lower surge voltage and minimal need for output filters.

Modernization projects requiring the need to keep existing motors also benefit from the use of the G7 Drive. In applications with large motors, where the motor manufacturer recommends insulated bearings, it is possible to use motors with standard bearings when a G7 Drive is employed.

A cost benefit can be achieved by using the G7 Drive. In building automation applications, where the acoustic noise of a running motor operated by an inverter needs to be low, it is possible to use the low audible noise capability of the G7 Drive. Most building automation applications are fans and pumps for air conditioning and heating systems. In most fans, the shaft of the motor remains electrically isolated resulting in shaft voltages and bearing currents that are at high levels. Such applications can take advantage of the G7 3-level topology.

CONCLUSION

This paper has introduced a G7 Drive 3-level technology for use in 480V applications. The features and benefits of the NPC 3-level topology have also been presented. In summary, the 3-level topology provides benefits that result in reducing motor surge voltages and bearing currents, lowering leakage current (common-mode noise), and reducing audible noise. These all reduce motor-drive installation issues.

The low motor surge voltage reduces the stress on the motor insulation system and provides an advantage in modernization projects where the user would prefer to use an existing motor. The output waveform of the G7 can provide benefits in voltage step-up applications by reducing the size and cost of the output filter components required in these applications.

The lower bearing currents avoid the need to employ costly mitigation methods such as insulated bearings, shaft brushes, or common-mode filters to minimize bearing failure. The G7 greatly increases motor bearing life.

In addition, electrical and acoustic noise is also reduced due to the higher frequency spectra of 3-level topology with respect to the voltage impressed across the motor windings. The noise level is comparable to the noise levels of the motors being supplied by line power.

This G7 drive is the ultimate performance solution with increased speed and torque response to provide servo-like performance from an induction motor. The world's first 480V 3-level inverter topology eliminates or minimizes the installation problems associated with IGBT switching and protects the entire motor-drive system.

REFERENCES

1. H.-P.Krug,T. Kume, M. Swamy,"Neutral-point clamped 3-level general purpose inverter - features, benefits and applications," IEEE Power Electronics Specialists Conference, pp.323-328, 2004.

2. 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, pp.1572-1579, 2002.