TOSHIBA INTERNATIONAL CORPORATION

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Monthly Informative Application Guidelines, with respect to *Motors & Drives* to keep you better INFORMED.

APPLICATION GUIDELINE #20

(Open Loop/Sensor-less Flux Vector Control)

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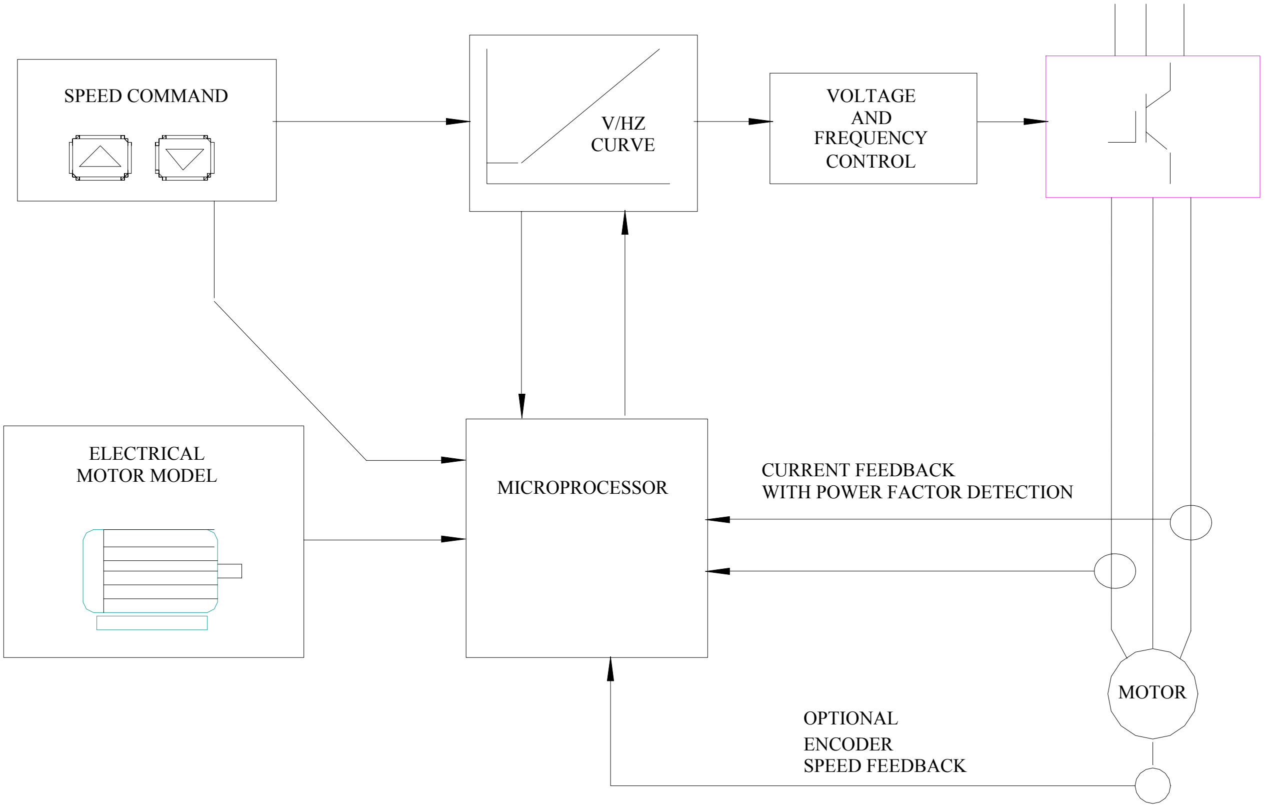
Modern general purpose low voltage (up to 600V) drives utilize various control schemes, many of which have capability of several types of control by simply making changes in the software.

The traditional topology is volts per hertz (V/f) control. V/f control is still valid for a great many applications including variable torque loads, multiple motors on one drive and applications that require overspeeding (above rated motor frequency) to name a few. Performance of V/f drives has been increased dramatically in the last few years with the use of Insulated Gate Bipolar Transistors (IGBTs) plus features such as dynamic voltage boost. With the advent of powerful and inexpensive microprocessors, vector control has become more popular for applications that need either better speed regulation and/or optimum torque, especially at lower frequencies. Vector control drives are available in either “open loop” configurations (drives that do not require direct speed feedback) and “closed loop” configurations (drives that do need encoder speed feedback).



Generally speaking, for sensor-less vector control, a drive needs the knowledge of the induction motor programmed in the software. By reading the back EMF current and comparing it to the applied voltage, the VFD calculates the 'rotor speed' and therefore 'slip'. Once the speed is known, the drive compensates for the slip by increasing output frequency to get good speed regulation and directly controls the flux current by increasing or decreasing the applied voltage for excellent torque control. The following explains how it achieves this in a little more detail.

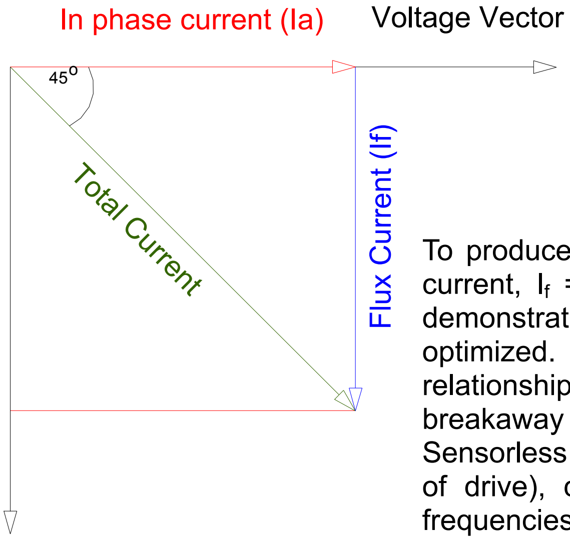
Vector control or true torque control treats an AC machine similar to the way that a DC drive controls a DC machine. Current draw from a motor can be broken down into two components:

1. Excitation, magnetization or flux current (similar to field current of a DC motor)
2. In phase current (similar to armature current of a DC motor)

The vector sum of these two components equals the total current the motor draws.

Excitation or flux current can be easily controlled by varying the voltage to the motor. Increasing the voltage increases flux current and decreasing the voltage decreases the flux current. The in phase current is dependent on the load. The larger the load, the greater the in-phase current. Independent control of the voltage means that the microprocessor has direct control of motor flux. Increasing flux reduces motor slip and conversely, decreasing flux increases motor slip. Motor slip is very linear with load in both motoring and generating modes (until the motor approaches its breakdown torque point) providing that flux remains constant. Precise control of flux therefore, allows slip to be correlated to motor torque. If slip is known, the drive can accurately compensate for slip by increasing the drive's output freqency thereby maintaining very tight speed regulation.

If desired, the flux can be manipulated at below base speed to increase torque output for a given, finite amount of current. First consider that an adjustable speed drive (ASD) is a current limited device. Torque of either an AC or DC motor can be expressed by the equation:



$\mathbf{T = K \times I_f \times I_a}$;where:
T = Torque
K = A constant
I_f = Magnetizing, flux, or excitation current
I_a = In phase current
(The above equation is valid as long as the motor does not saturate.)

To produce the maximum product of $I_f \times I_a$ with the minimum total current, $I_f = I_a$ or the phase angle between I_f and I_a is 45^{O}. This demonstrates that by manipulating the flux current, torque can be optimized. The G3 drive takes advantage of this current / torque relationship at low speeds in order to provide the maximum breakaway torque possible for a given size of drive. Conclusion: Sensorless flux vector control (available with the Toshiba G3 series of drive), can provide both optimum torque – especially at low frequencies – plus very good speed regulation.

The following additional info has been included for interest sake. Independent control of frequency and flux can allow design engineers to provide optimum torque performance in addition to extremely tight speed regulation. To properly grasp how voltage and frequency can be independently controlled, fundamental switching control should be understood. Fig. 2 below shows a standard 6 transistor inverter section which has 6 switching states: 0^{O}, 60^{O}, 120^{O}, 180^{O}, 240^{O}, 300^{O} plus 2 combinations which produce no output voltage. The 8 states have been labeled

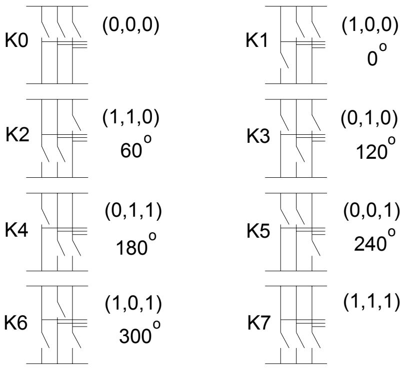


Fig.2: Eight possible switching states

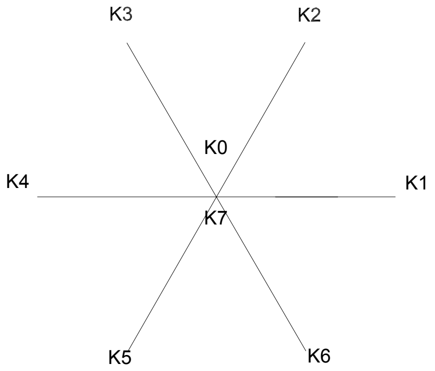


Fig.3: Position of Voltage Vector in each state

K0 through K7. States K1 through K6 are active and represent an output voltage vector. These 6 states cause current to flow through the motor windings. During states K0 and K7 the line to line voltage will be zero because all three phases are configured the same. The vector diagram above (Fig.3) shows the position of the rotating voltage vector as it moves in relation to each of the switching states. Switching state K1 represents the voltage vector pointing to the right. Switching state K2 represents the vector at 60^{O}, K3 at 120^{O}, K4 at 180^{O}, K5 at 240^{O}, K6 at 300^{O}. States K0 and K7 represent zero voltage at the center of the vector diagram.

Switching sequentially through these six vectors would provide poor performance therefore a technique to provide intermediate vectors between these six available states is required. A method for controlling the magnitude of these vectors is also required. Switching for a portion of the duty cycle in state K0 or K7 can control the voltage magnitude. If for example 50% voltage is required at zero degrees, the drive would switch between state K1 for 50% of the time and either K0 or K7 for 50% of the time.

If a voltage vector is required at a phase angle between states K1 and K2 the drive switches for a period of time in state K1 then for a period of time in state K2. The magnitude of the voltage vector is controlled by switching for a period of time in either of states K0 or K7. As shown in Fig.4, the desired voltage vector $V_{ref} \times T_s$ is determined by:

$$V_{ref}T_s = V_kT_k + V_{k+1}T_{k+1}$$

In other words, V_{ref} over switching period T_s is realized by switching between two states (V_k and V_{K+1}). The time required to switch between these states is determined by the following equations:

$$Tk = \frac{a \times \sin(60^{O} - \gamma)}{\sin 60^{O}} \times Ts$$

$$Tk+1 = \frac{a \times \sin(\gamma)}{\sin 60^{O}} \times Ts$$

$$a = \frac{V_{ref}}{V_{DC}}$$

$$T_0 = T_s - T_k - T_{k+1}$$

Where:

γ is the desired phase angle of the voltage vector

V_{ref} is the desired voltage vector

T_0 is the time spent in an inactive state (K0 or K7)

T_S is the total switching period time

V_{DC} is the DC bus voltage

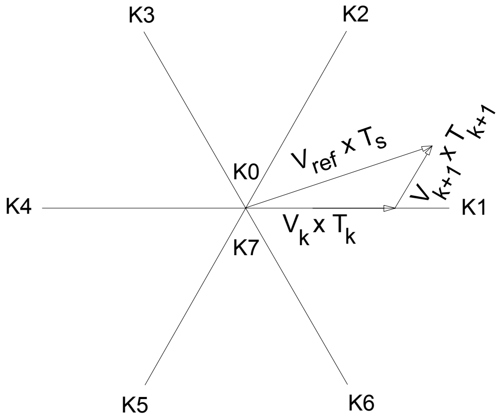


Fig.4: Intermediate Voltage Vectors

As can be seen, this switching control technique provides complete control of voltage vector phase angle and voltage magnitude. <u>Whether open or closed loop vector control is utilized, the control method is the same and the end result (i.e. improved torque performance and better speed regulation) is the same</u>. Closed loop vector, because of the actual versus calculated rotor position, affords the opportunity for improved speed regulation, typically in the area of 0.01% versus 0.1% for open loop control. The drive's microprocessor looks at the desired frequency and generates a PWM waveform that matches the speed requirement. Motor current magnitude and phase angle are monitored and sent to a 3 phase to 1 phase converter (which minimizes the number of calculations required and therefore speeds up the calculation process). The signal from the 3 phase to 1 phase converter is then fed to a torque and flux comparitor that provides flux feedback to the microprocessor. The comparitor feeds torque information to the portion of the feedback loop that contains the motor model. The torque current is used to determine motor slip. Actual motor speed information is fed to a regulator that adjusts the frequency signal to compensate for the slip. This new speed reference signal is fed to the microprocessor. This information process happens almost instantaneously resulting in speed regulation which is 0.1% from no load to full load. Several techniques are used to streamline the calculations that need to be done but this is beyond the scope of this discussion.