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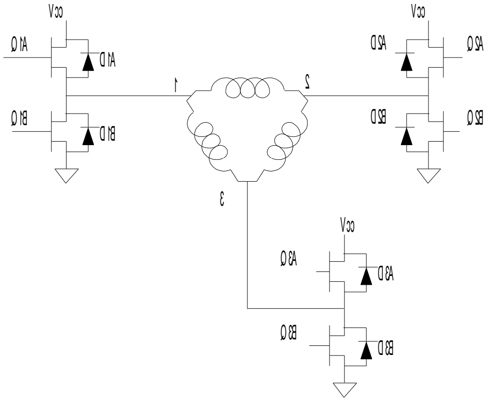
Subject: Brushless DC servo motor operation

Draft

Figure 1 shows a 3-phase motor connected to a single power supply via three totem pole drivers. This is the arrangement used by Kollmorgen and by IDC. Since the power supply is often floating, the open ground symbol in Figure 1 indicates that "ground" might not be earth ground. Any of the motor terminals can be connected to Vcc or ground, depending on which transistors and diodes are conducting.



The torque supplied by the three windings is given by $T_1 = K_T \cdot I_{12} \cos\theta$, $T_2 = K_T \cdot I_{23} \cos(\theta + 120°)$, and $T_3 = K_T \cdot I_{31} \cos(\theta+240°)$, where K_T is the torque constant and I_{12}, for example, denotes current flowing from Terminal 1 to Terminal 2. If the three currents are given by: $I_{12} = A \cos\theta$, $I_{23} = A \cos(\theta+120°)$, and $I_{31} = A \cos(\theta+240°)$, the torque will be constant (independent of θ) and will have a value of $3K_T A/2$. If we consider low speed or zero speed operation, we can neglect the back EMFs and treat the windings as simple resistors, each of resistance R. To get these specified currents to flow, we must have

$$
\begin{aligned}
V_1 - V_2 &= A \cos \theta/R \\
V_2 - V_3 &= A \cos(\theta+120°)/R \\
\text{and} \quad V_3 - V_1 &= A \cos(\theta+240°)/R.
\end{aligned}
$$

(Note that the third equation is redundant; it follows from the first two).

Since these equations are in terms of voltage differences, we are free to add any equal bias to the three voltages. It is convenient to bias the (algebraically) lowest voltage to zero. Suppose, that for the current value of θ, V_3 is lower than V_1 and V_2. We can therefore connect Terminal 3 to ground (by turning on Q3B). This lets us use the positive bus voltage to derive the positive voltages needed for Terminals 1 and 2. Rather than use the transistors as linear "dropping resistors", they operate as switching regulators. Suppose the voltage that must be applied to Terminal 1 is one quarter of the bus voltage. Transistor Q1A will be pulsed with a duty cycle of .25. When Q1A is on, current flows into the inductances presented by the windings. When Q1A is off, the current "free wheels" through D1B. Terminal 2 is likewise supplied current that alternates between Q2A and D2B. When θ reaches the point at which Terminal 1 must be at a lower voltage than the other two terminals, Q1B is turned on and Q3A and D3B begin operating as a buck converter for Terminal 3. Terminal 2 continues to be fed through Q2A and D2B. Remember that the motor contains a position encoder that so that the electronics box knows which transistor to keep on and which transistors to pulse. A sine lookup table determines the normalized pulse duty cycles. In addition, the electronics box scales the normalized pulse widths by *A* to satisfy the (external) torque command.

Regeneration

Electronic braking is provided by the same switching electronics. To see how this works, consider the example given above, where Terminals 1 and 2 are "active" while Terminal 3 is grounded. Suppose the carriage house is not moving - the currents into Terminals 1 and 2 provide just the necessary torque to counteract gravity. Now suppose we start to move the carriage house down hill very slowly, without acceleration. As it turns, the motor will produce induced EMFs in its windings. These induced voltages will have the polarity to aid the power supply. Since the torque requirement hasn't changed (no acceleration), the duty cycle must be reduced slightly to keep maintain the same currents. So far, we're not recovering any energy, we're simply spending less to power the (resistive) motor windings. The necessary duty cycle reduction will be done automatically by the controller's current feedback loop.

Now suppose the speed is increased. Again, the duty cycle will be reduced. At some speed, the duty cycle goes to zero. Q1A and Q2A never turn on, since, at this speed, the induced EMF is just enough to produce the required torque. This speed is the "self-damped" descent rate of the system. At this speed, potential energy is being converted into heat in the windings at just the rate needed to produce the necessary torque.

Finally, suppose that we want to increase the speed even more. Now we will have more power being developed (via loss of potential energy) than is needed to maintain the necessary torque. The duty cycle has gone to zero; now we need a *negative* duty cycle to counteract the excessive induced voltage. This can be provided by pulsing Q3B off and simultaneously pulsing Q3A on to connect Terminal 3 to the power supply instead of ground. The (large) power supply voltage causes the current to begin a rapid decrease. Before it decreases too much, Q3A and Q3B are toggled and the current builds back up through Q3B. This increasing current stores energy in the motor inductance. When Q3 again toggles, this stored energy is pumped into the power supply. During regeneration, the circuit works as a step-up (boost) converter while, otherwise, it works as a step-down (buck) converter.