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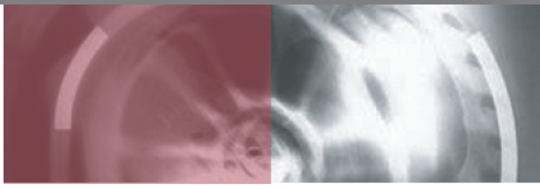
White Paper

Technical



Sensorless Theory of Operation

Sensorless Drive Theory of Operation

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Introduction

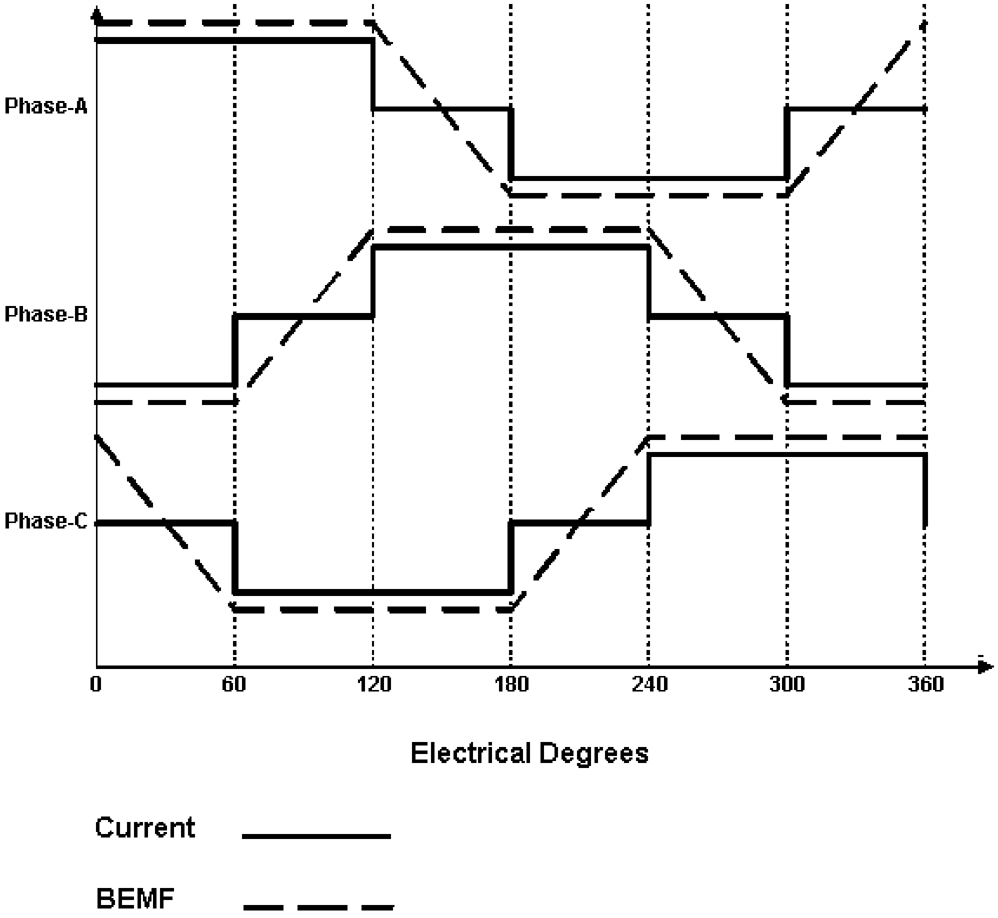
The DPDLite™ controller is capable of spinning certain BLDC motors without the need for sensors to provide commutation information. Once the shaft of the motor is spinning sufficiently fast the induced speed voltage caused by the time varying magnetic flux linking the stator windings can be measured by the controller. The magnetic flux is produced from the permanent magnets contained in the rotor. The DPDLite™ makes use of DriveStart (DOS application) to determine initial sensorless startup parameters, then, DPWin (a PC based tool) is used to fine tune start up and commutation. DPWin allows the user to save parameters for later retrieval. DPWin also allows configuration of the DPDLite™ for stand-alone operation.

Sensorless Startup

The first thing the DPDLite™ must do is ascertain the motor's present rotor position. To do this the controller issues a series of current pulses to various rotor positions and measures the variation in saturation inductance from phase to phase (this also allows the controller to successfully operate with slotless motors or other motors with low inductance). The motor will remain stationary during this process. Once the rotor position is determined the DPDLite™ will force commutation by issuing a current pulse to the known rotor position and then to the other five rotor positions in sequence. The startup time is a function of load and commutation timeout. The DPDLite™ will continue to force commutation in this manner until the shaft of the motor is spinning fast enough to produce measurable induced speed voltage at which point the DPDLite™ switches to six-step trapezoidal commutation. Acceleration during startup is constrained only by the controller's ability to detect back electromotive force.

Sensorless Commutation

Six-step trapezoidal commutation means only two of the three motor coils are energized at any one time. The coils that are energized are the two that yield the maximum developed electromagnetic torque. For wye-connected motors, the third coil is off and the speed voltage is sensed at that phase post. Each of the three coils is on for 120 electrical degrees and is then off for 60 electrical degrees. This pattern is repeated every 180 electrical degrees with the current switching direction every 180 degree segment. A typical phase current waveform is shown as follows.



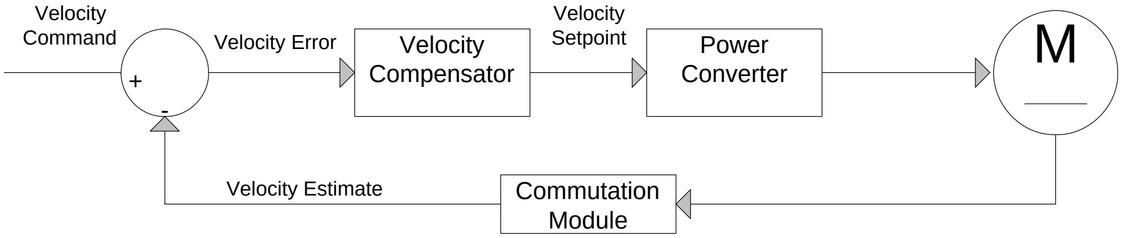
The speed voltage induced in the off phase undergoes a polarity reversal during the time the phase is off. A simplified time domain waveform would look something like that shown in the figure above as back electromotive force (BEMF). It is measured from the phase post to ground. The bias voltage is the voltage of the neutral point of the wye connection.

Ideally, the controller should shut off a coil as the induced speed voltage across that coil is undergoing a polarity reversal. The coil should then be re-energized once the voltage has changed polarity and that coil can contribute to torque production. In order to do this the controller samples the voltage of the off phase once the current in that phase has dropped to zero. Once it detects that the rotor flux is generating a speed voltage of the proper polarity it shuts off the coil that is just beginning to go through this voltage reversal process and energizes the one that just finished this process.

The controller uses the volts per rpm (Ke) of the motor in order to determine how much flux there is per pole. By integrating the induced speed voltage in the off phase and waiting for the proper amount of flux to accumulate, the controller forces commutation at the proper time.

PID-based Velocity Control

The velocity loop is a control loop outside the current loop which ensures the desired velocity setpoint is achieved and maintained. PID stands for "proportional, integral, derivative." These three terms describe the basic elements of a PID controller. Each of these elements performs a different task and has a different effect on the functioning of a system. The velocity loop block diagram is shown below.



Except for the motor, all of the blocks are parts of the controller. In the velocity control loop two main tasks must be achieved:

Maintaining the output the motor's actual velocity, as close as possible to the input, the velocity setpoint. This is called "steady state response". Respond properly to changes in the velocity setpoint. This is called "dynamic response".

To achieve these two goals a second order infinite impulse response approximation of a classic PID control loop will be used. Without entering a broader discussion of digital filter design PID control revolves around the error between the velocity setpoint and the actual velocity. The actual velocity value is derived internally from the commutation time, or more simply, the time between energizing a new coil configuration. Each term of the PID loop uses this error in a different way. The proportional term, Kp, is multiplied by the error between the setpoint and actual velocity. The integral term is multiplied by the accumulated error value over time. Lastly, the derivative term is multiplied by the rate of change of the error term. These terms are combined with the present setpoint according to the formula below to produce the velocity setpoint. The velocity loop update rate is 1 kHz.
Current Setpoint[n]

$$= Kp * error_{[n]} + \sum_{k=0}^{n} Ki\, error_{k} + Kd[error_{[n]} - error_{[n-1]}]$$

Where,
error = Velocity Command - Velocity Estimate

Low speed operation of the controller is limited by the back electromotive force constant (Ke) of the motor, current and velocity loop tuning, system inertia and damping. A motor that produces insufficient back electromotive force at low speeds will disrupt the commutation algorithm and stall the motor. Poorly tuned current and velocity loops limit the controller's ability to respond to large changes in system conditions. The mechanical damping and frictional effects of a system have greater effects at low velocities.

High-speed operation of the sensorless drive is limited by the commutation time between sectors. The DPDLite™ makes use of phase advance to improve high-speed operation but the commutation time cannot be less than 400 microseconds.

The controller's ability to regulate velocity and handle torque disturbances is a function of motor velocity, tuning, and system inertia. The DPDLite™ internal velocity estimator is a function of the commutation time. A motor that rotates at a high velocity produces more velocity updates than a slower moving motor. Therefore, the DPDLite™ is able to respond more quickly to torque disturbances or changes in actual velocity. As previously mentioned tightly tuned current and velocity loops allow the DPDLite™ to respond more quickly to changes in actual velocity or torque demand. Generally, the larger a rotational system's inertia the easier it is to regulate velocity provided the desired velocity setpoint can be reached. The downside to systems with large inertia is a reduction in the bandwidth of the velocity loop. The DPDLite™ can respond to torque disturbances of up to 100% provided that the disturbances occur at a frequency less than the bandwidth of the velocity loop.

The DriveStart Assistant

DriveStart is an additional tool outside of DPWin that Agile provides to users of the DPDLite™ product to assist them with the determination of the sensorless startup parameters. Providing the DPDLite™ with accurate startup parameters will ensure 100% reliable sensorless startups. DriveStart is a DOS-based console application that provides the user with step-by-step instruction to perform three tests on the motor and takes approximately five minutes to complete. The first test is a measure of how large the variation in inductance from phase to phase in the motor is. If the minimum threshold of 4% of the DPDLite™ rated current is not met the DPDLite™ algorithm is not capable of starting the motor. The second test is a flux per pole calculation and determination of the motor's back electromotive force deadband. If these first two tests pass the controller will attempt a startup of the motor. The motor will run for approximately one minute and then the user is provided with the following parameters as a starting point to fine-tune the startup in DPWin:

- Back EMF deadband
- Ping period
- Commutation timeout
- Flux per pole
- Minimum starting current

The user inputs these parameters in DPWin and repeats the startup procedure. The sensorless parameters can then be adjusted to ensure that motor commutation is optimum and startup is robust by examining the back EMF and current waveforms with the oscilloscope tool in DPWin. Once the sensorless tuning process is complete and the parameters finalized they can be saved to DPDLite™ flash memory for easy recall