September 1996

Application Brief 42020

The Smart Start™ Technique for BLDC Motors

GENERAL DESCRIPTION

The ML4428 provides sensorless commutation plus on-chip PWM speed control for brushless DC motors. During start-up and at low speeds the Smart Start™ rotor position detection technique commutates the motor. At higher speeds an integrating back EMF sensor, combined with an on-chip VCO and sequencer, form a phase locked commutation loop. The ML4428 provides on-chip braking and power failure detection. In 12V applications it can drive external P and N channel FET's directly. External Interface circuitry allows driving of higher voltage motors.

THEORY OF OPERATION

In a 3 phase BLDC motor, each phase is 120 degrees apart in spacing, as in Figure 1.

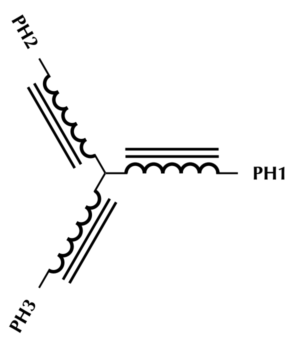

Figure 1. BLDC Motor Phases

The rotor is made up of a permanent magnet or series of magnets. In the simplest case the rotor is a single magnet. This type of motor is called a two pole motor because a magnet has two poles: north and south.

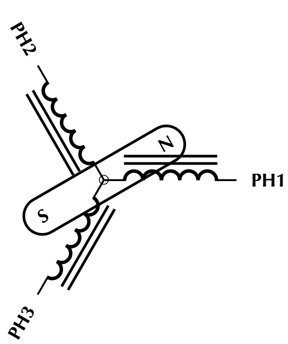

Figure 2. Two Pole Motor

Torque is produced because of magnetic interaction between the permanent magnet and the magnetic field generated by the coils. Torque only occurs if the two fields are in the correct position with respect to each other. Ideally the peak torque occurs when the fields are 90 degrees apart and falls off as the fields move together. In order to keep the motor running, then, the field produced by the coils must shift position as the rotor moves to catch up with the coil field.

In order to examine what happens during commutation of the motor it is necessary to know where the magnetic field is in space for each of the commutation steps. In what is commonly called "six-step" operation full voltage is applied to one phase, another is grounded, and the third is left floating. The actual phases connected to power and ground are changed to keep the magnetic field produced by the coils leading the field produced by the permanent magnet. It is called "six step" because this leads to six possible states for the magnetic field space flux vector. The space flux vector is just the magnetic field direction and magnitude. The current flow during each of the six steps is shown in Figure 3.

During step one phase 1 is switched to the motor supply voltage, phase 3 is switched to ground, and phase 2 is floating. Therefore, the current flow is from phase 1 to phase 3. By noting the direction of current flow in the diagrams in Figure 3 you can see which phases are connected to the motor supply and ground for each step. The secret to BLDC operation is to know where the rotor is, and to energize the proper state to give maximum torque in the desired direction for any rotor position.

A plot of the magnetic field for each of the states shows that there are six discrete positions corresponding to each of the possible states shown in Figure 3. Figure 4 is a plot of the states with the vertices of the hexagon showing the field position. When the rotor approaches the commutation point, which is usually 30 degrees before a vertex, the commutation circuitry switches the magnetic field to the next state. (The states between the vertices do not exist, and the lines connecting the states are not significant.)

THE SMART START™ TECHNIQUE

In any inductor made with a core, for example of iron, increasing the current in the inductor will cause the iron to move closer to saturation, therefore providing less inductance. Figure 5 shows a curve of flux linkage versus current for a typical motor winding. The slope of the curve is the inductance. As you can see, at higher current levels, the inductance falls off rapidly.

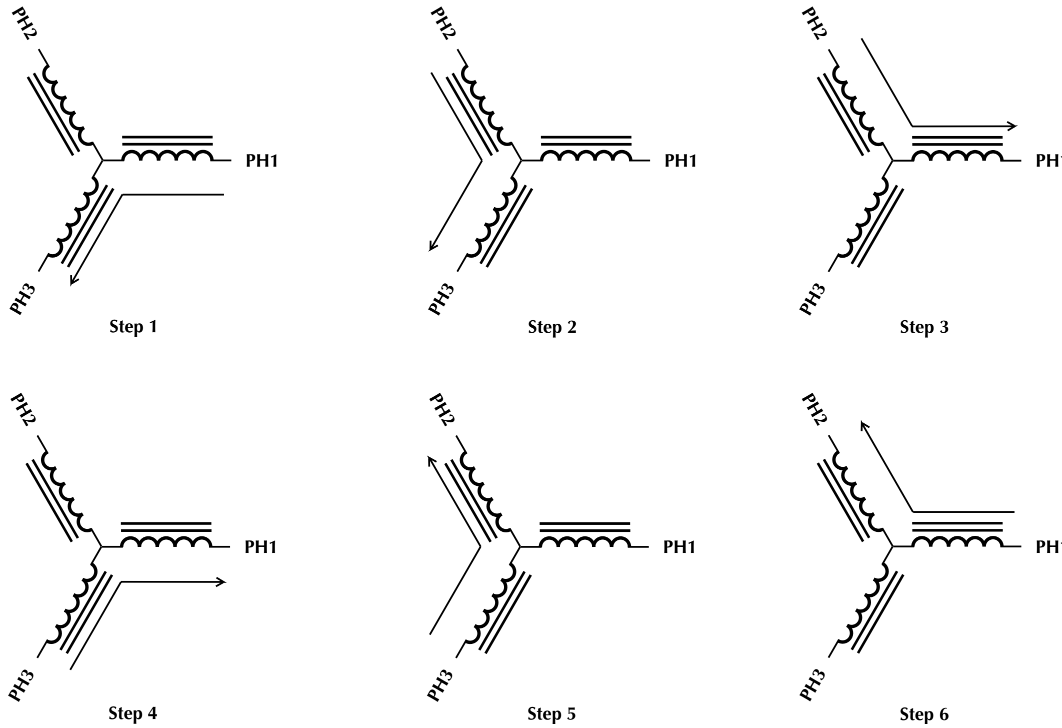

Figure 3. Current Flow Direction

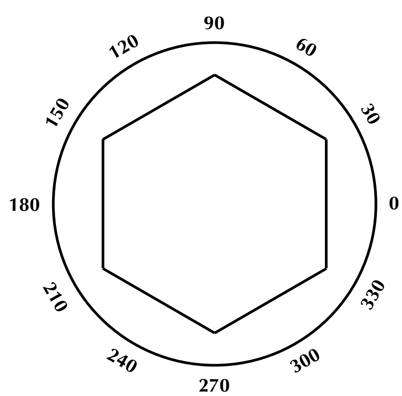

Figure 4. States

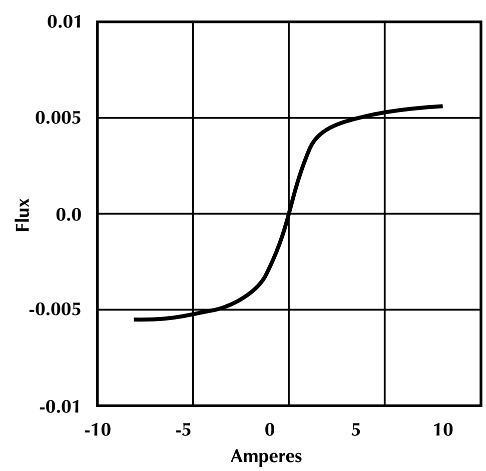

Figure 5. Flux Linkage vs. Current

Eventually, when all of the magnetic domains are lined up in the same direction, there is almost no more flux generated for increasing current, and the inductance drops dramatically. The Micro Linear Smart Start™ technique relies on the fact that a permanent magnet (the rotor) will also move an iron core closer to magnetic saturation. If the inductance is measured, more saturation means less inductance. If a current is added to the winding around the core, the current will either add to the saturation causing the inductance to decrease further, or subtract from the permanent magnet's MMF, causing inductance to increase. If you apply a voltage to a phase for a fixed period of time, and measure the peak current produced, then reverse the polarity, and repeat the measurement, by comparing the relative peaks you can determine the polarity of the permanent magnet. That is, you can tell whether you added to the magnetic field and decreased the inductance (higher peak) or subtracted from the field and increased the inductance (smaller peak). This tells you the rotor position to within 180 electrical degrees. Repeating the sequence 2 more times will narrow the position to 60 electrical degrees, which is sufficient to know which phase to energize for proper commutation.

DETAILED OPERATION

In order to find the position of the rotor by measuring the core saturation, and whether the added flux due to the energized winding brings you closer to saturation, you would like to apply a pulse such that it creates a magnetic field in the direction of only one winding. In order to do this, two phases are held to ground and one is switched to V_{MOTOR}, or two are switched to V_{MOTOR}, and one is held to ground. In this way, the components of the fields from the two common phases which are not in the direction of the single phase will cancel, as shown in Figure 6. Note that in Figure 6, the Y components of PH2 and PH3 cancel.

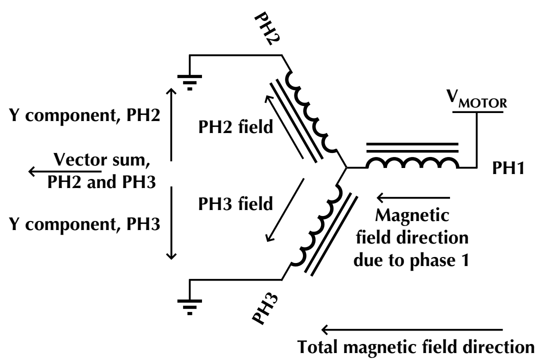

Figure 6. Motor Components

The Smart Start™ technique applies the full motor voltage across the selected windings for a fixed period of time. The time is set by the CSNS capacitor, and should be long enough to give at least 1V of signal across the current sense resistor. If the time is too long, the iron will saturate too much, and the current peaks will be too high. If the time is too short, the iron will not show enough difference in inductance with current direction to give a reliable measurement. Some experimentation may be necessary to find the correct value for CSNS.

The following explains the rotor position sensing in more detail. Referring Figure 7, if you take an inductor, and apply an external field with a magnet, the magnet will move the core material closer to saturation, causing the inductance to decrease.

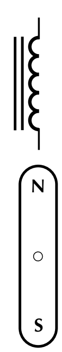

Figure 7. Inductor and Magnet

Now, if you apply a voltage across the inductor, the resulting current will either add to the external field and further decrease the inductance, or subtract from the external field and cause a net increase in inductance. If you apply the voltage for a fixed time, and measure the peak current, then reverse the polarity for the same time and measure the current again, the larger peak will indicate the current that is in the same direction as the external magnetic field (less overall inductance). Therefore you know the polarity of the external field. If this is a rotor in a motor, you have found the rotor position to within 180 electrical degrees. (Either the net external field is due to the north pole, or the south pole.) This is illustrated in Figure 8.

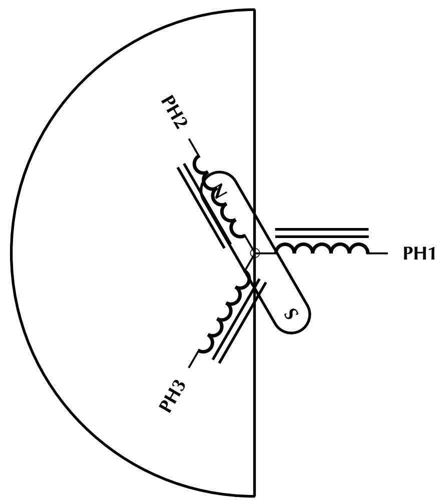

Figure 8. Rotor Position

In this diagram, the field in the direction of phase 1 has determined that the north pole is in the left half plane, since current that would produce a field in the same direction as the south pole gave the higher peak, when both polarities were energized as described above. By doing the same for phase 2, you can narrow the position further.

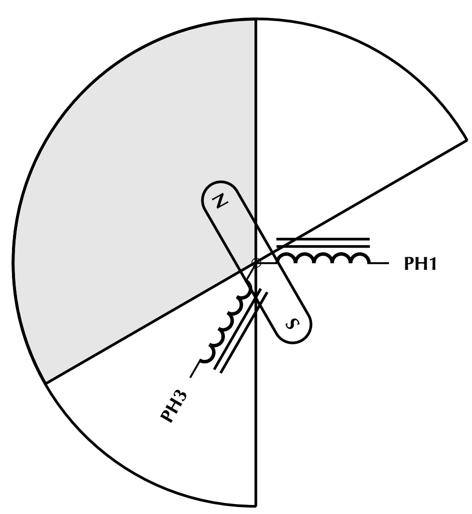

Figure 9. North Pole Location

Now the position of the north pole must be located inside the shaded area. By repeating the test for phase 3, you can narrow the position enough to know which state to energize to properly commutate the motor (see Figure 10).

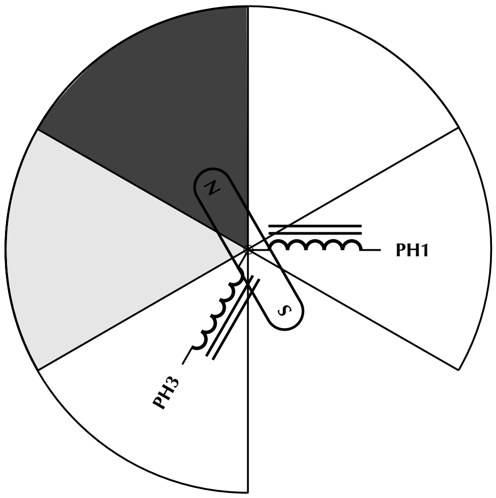

Figure 10.

Note that there is the possibility for ambiguity if the rotor is right on the edge of one of the semicircles. This is a "don't care" situation because the phase that is energized is the same whether the rotor is on one half of the boundary or the other. Figure 11 shows what the sense pulses should look like when measured at the current sense resistor.

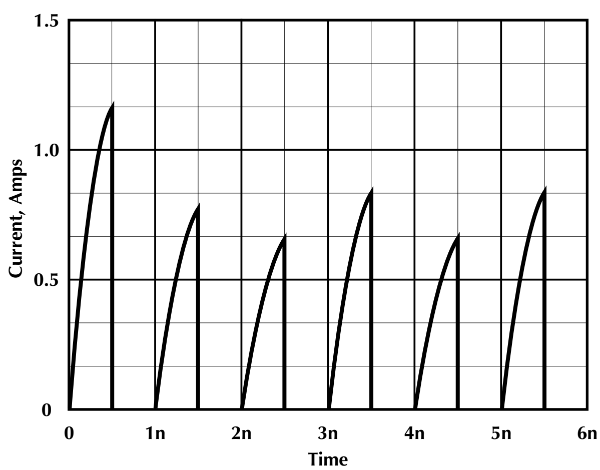

Figure 11. Sense Pulses

Now, just by comparing the pairs of peaks, and assigning a 1 (one) if the first peak is greater, and a 0 (zero) if the second peak is greater will result in a 3 bit binary code. This code uniquely determines the proper state to energize. Based on the states in Figure 3, with phase A on the X axis, the state table mapping would look like the following table.

Rotor Angle	Position Code	State to Energize
-30 to 30	100	State 2
30 to 90	110	State 3
90 to 150	010	State 4
150 to 210	011	State 5
210 to 270	001	State 6
270 to 330	101	State 1

(Depending on where you place the x and y axis relative to the motor windings, and how you define the states, many different state table possibilities exist. Also, "Reverse" requires a different mapping.)

Note that the motor's saturation characteristic must provide enough of a change so that the circuitry can resolve the difference in the heights of the peaks. This means that the technique will not work with all motors, especially the air core type motors, or motors with a cylindrical rotor (The magnetic field is distributed smoothly over a wide angle, i.e. there is no saliency.)

After deciding which state to energize, the ML4428 energizes the state for an initial time, T_{INIT}. This time is set by the resistor R_{INIT}, and should be long enough to start the rotor moving, but short enough to ensure that the rotor does not skip past the next state. (Again, some experimentation may be necessary to find the right value for R_{INIT}.) After T_{INIT}, the Smart Start™ circuitry senses the rotor position again, and if the rotor has crossed a commutation boundary, it energizes the next state. If not, the same state is energized again. At the same time, the drive time is shortened, so that the rotor can accelerate. The drive time is proportional to the voltage on pin 20, which ramps up during the Smart Start™ algorithm.

When the rotor reaches a certain speed, the time it takes to do the sensing becomes a large portion of the available drive time to the motor. This makes the technique unsuitable for running at higher speeds. For this reason, once the motor has reached a certain speed, corresponding to 0.5V on pin 20, the circuitry automatically switches to sensing the back EMF in order to commutate the motor. This combination of techniques gives the end user nearly all of the benefits of having sensors attached to the motor, without actually needing sensors.