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Sensorless Motor Control Method for Compressor Applications

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ABSTRACT

The new industry trend for developing highly efficient compressors is to use a Brushless DC (BLDC) motor with a 6-step, 120-degree drive and a Hall sensor. Traditionally, designers have used full vector control for industrial applications that require very high performance and efficiency. To keep the advantage of BLDC motor efficiency without increasing total cost, designers have also developed and applied a more economical 6-step, 120-degree drive that doesn't use a sensor. We have reviewed the performance of all three types of motor control methods using various criteria, and have analyzed factors that affect the overall efficiency of a compressor application. Our criteria included speed, torque, torque accuracy, response, efficiency and noise.

After understanding the limitations of the 120-degree control methods, we have developed a sensorless 180-degree sinusoidal motor control approach that uses the One-Shunt Current Detection (OSCD) method. During sinusoidal pulse width modulation (pwm) generation, our sensorless controller design measures the current in the shunt at a specific time using a specialized timer channel, then reconstructs the waveforms of the phase currents. That data is processed by the microcontroller, which adjusts the frequency and amplitude of the drive signals to obtain the desired compressor performance.

Our BDLC motor controller design with sinusoidal drive and one-shunt current measurements is cost effective and enables implementations that are very efficient. This paper explains our methodology and describes test results for a sensorless motor controller that satisfies the requirements of compressors used in home appliances.

1.0 INTRODUCTION

To build appliances that are more energy efficient, manufacturers are slowly beginning to use brushless direct-current (BLDC) motors instead of standard AC induction motors. However, the adoption of BLDC motors has been slow, due to a lack of cost-effective control techniques. Traditional vector-control approaches use position and current sensors to achieve high response, low noise and good accuracy at high torque, as shown in figure 1. However, the sensors needed to obtain such responsive control are expensive, adding tens of dollars to the bill-of-

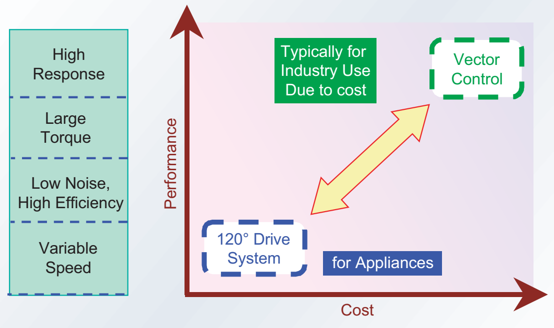


Figure 1. Cost performance trade-off for Vector & 120 Deg control

material (BOM) cost. As a result, motor controllers of the vector-control type are typically limited to industrial applications in which performance is a primary concern.

Home appliances, by contrast, are very cost sensitive, so they generally use a lower-performance, 120-degree control method, with or without a sensor. This type of controller provides a variable speed feature, but offers much less performance. In particular, it provides neither high response nor high efficiency, especially in traditional sensorless implementations, thereby causing appliances to remain limited in features and functions.

For our study, we selected a compressor application typical of those used in home appliances and analyzed its performance requirements in terms of the eight key criteria. Subsequently, we evaluated the 120-degree control methods, taking vector control as the reference method. After investigating and understanding the limitations of the 120-degree control methods, we developed a 180-degree sensorless control technique that achieves good energy efficiency, yet can be implemented economically.

In this paper we describe our 180-degree sensorless motor control method, discuss our initial results, and compare the performance we achieved in various areas to that of alternatives. Specifically, in Section 2 we discuss the traditional vector and 120-degree BLDC control methods and their relative merits, also covering performance requirements. In Section 3, we explain our one-shunt current control approach, detailing the measurement method. In Section 4, we present the initial test results of our 180-degree sensorless control technique in several performance areas and show how the data compares to the other methods. Finally, in Section 5 we briefly summarize the future development activity we plan to pursue.

2.0 BLDC MOTOR CONTROL METHODS

Figure 2a shows a typical application in which the vector control method is used to control the BLDC motor. The implementation uses a position sensor and two current transducers to control the flux level in the coils and, thus, the torque on the rotor. In this full vector control method, the information from the position sensor is used to determine the alignment of the rotor d-q frame in the stator u, v, w frame.

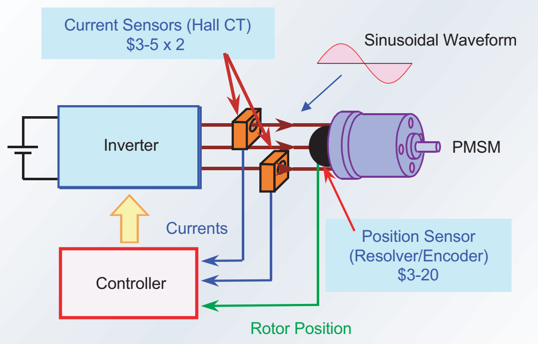


Figure 2a. Typical vector control requires position sensor and two current transducers adding cost to the BOM

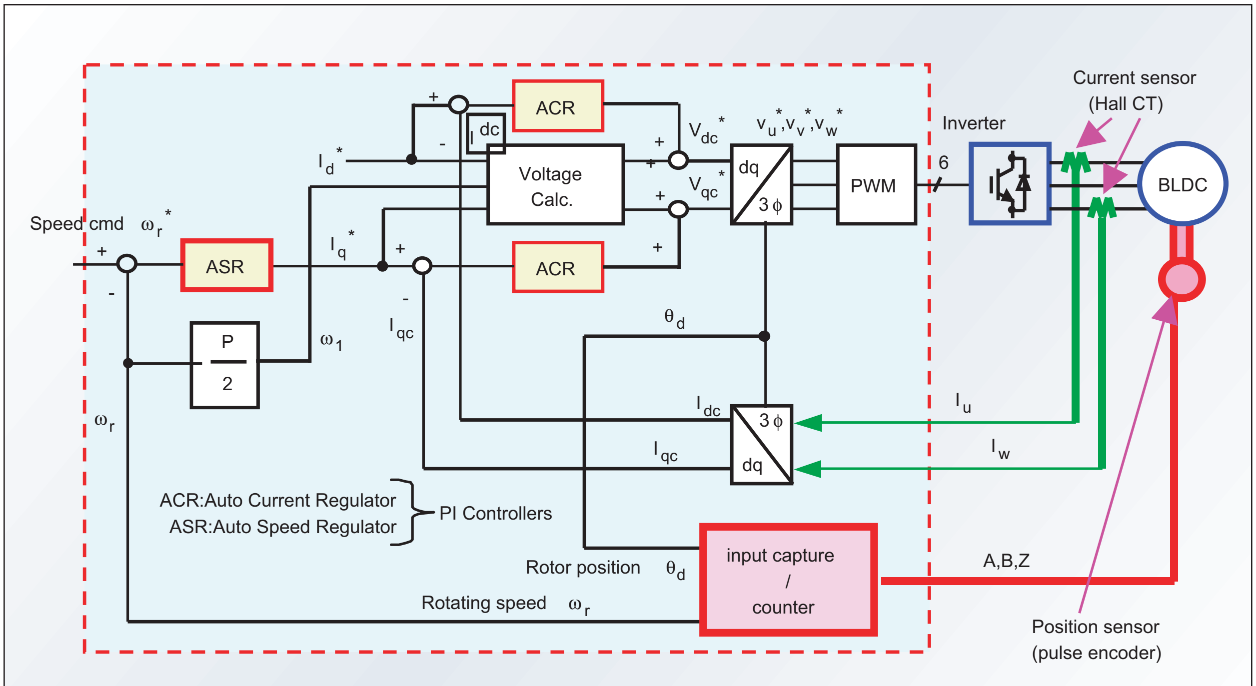


Figure 2b. Vector control algorithm executed in MCU to control torque and flux

Figure 2b shows the circuits that manage the currents in the d and q directions to maintain the flux and generate the torque needed to keep the speed within the motor's specified accuracy. This controller design can respond quickly to correct any speed errors that occur.

To make the overall calculations necessary for reaching and maintaining the correct motor speed, vector-control designs use a proportional-integral (PI) type automatic speed regulator and automatic current regulators. The pulse-width modulation (pwm) used for the DC bus is based on the currents in the rotor d-q frame. This BLDC control method enables accurate speed control in situations where the load on the motor changes continuously.

In summary, motor controllers based on the vector-control method provide high response, good torque accuracy, high efficiency and low noise. However, because they add cost to the final implementation, their use is mainly confined to industrial applications where the system performance requirements justify higher costs.

Another, less expensive way to control a BLDC motor so that it runs at a given speed is to use the 120-degree, 6-step modulation method (figure 3). In this approach, the current in each stator coil is maintained 120 degrees positive, 60 degrees free, 120 degrees negative, and 60 degrees free for any given electrical cycle. At every 60 degrees, a state change is performed to turn ON and OFF an IGBT or power MOSFET. This state

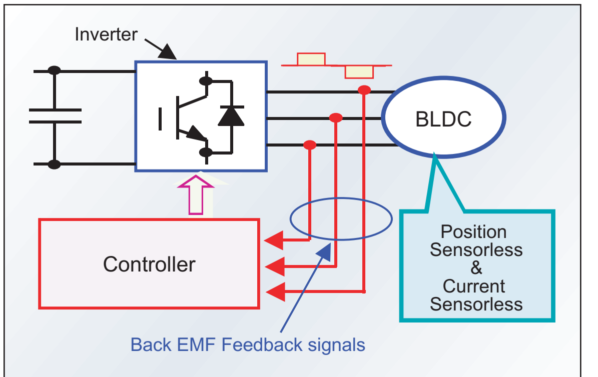


Figure 3. Sensorless 120° 6-step control method

machine is well described in many handbooks [1,2] and in several white papers.

This control method can use position-sensor feedback to accurately perform a state transition, or — in the sensorless version — it can use the back-EMF signal to perform a delayed transition. Regardless of whether the controller uses a sensor (typically a Hall-effect type) or is sensorless, it computes the speed of the motor from the time between two signals and uses a PI type speed regulator to maintain the proper motor speed. The sensorless 120-degree method is preferred by many appliance manufacturers because it costs less to implement.

To better understand the design choices that engineers at appliance makers must make, Hitachi R&D team members investigated the performance of the sensorless 120-degree, 6-step modulation control method with respect to eight performance criteria, taking vector control as the reference method. Here are the criteria Hitachi R&D lab analyzed:

1. **High speed:** *Can the control method achieve and maintain the maximum speed at which the motor must operate?* The motor might have to operate at 6000 or more rotations per minute (RPM), for example. (For a compressor to create high pressure, for instance, the motor may have run at 100 Hz or more, which corresponds to this high RPM. By contrast, if the compressor has to produce only a minimum pressure differential, the speed of the motor may drop to less than 600 RPM.)
2. **Large torque at low speed:** *When the motor is running at low speeds, say 600-900 RPM, can the control method create a large torque value?* This criterion is a factor in determining how quickly the controller can respond to changes in speed and flux when the motor operates at low RPM.
3. **Large torque at high speed:** *Can the control method create large amounts of torque at high speeds?* To maintain high speed, the controller usually runs a high carrier frequency, so only a short time is available for performing all necessary computations. For example, the controller has only 50μs to make calculations when the carrier frequency is 20 kHz, but 250μs when the carrier frequency is 4 kHz. Moreover, at high carrier frequencies, the pulses in the pwm waveforms are narrow and may not be able to create sufficient stator coil current to develop high motor torque. To be effective, the control method

must have the ability to do both: complete all necessary calculations, while also creating high current in the motor coils. Moreover, the control algorithm used must be able to identify such situations.

4. **Torque accuracy at low speed:** *Can the control method maintain high accuracy in torque at low speed?* This accuracy is a direct reflection of the torque ripple created by the motor controller.
5. **Torque accuracy at high speed:** *How well can the control method maintain high accuracy at high speeds?* This criterion is a measure of the controller's ability to recognize fast, yet small, changes in the BLDC motor's speed and torque.
6. **Response:** *How quickly can the control method make changes in motor speed and torque?* For example, if the desired speed rises from 1000 RPM to 2000 RPM, how long does it take the controller to achieve the desired speed? Rapid changes in the load on the motor will cause rapid variations in the measured speed, so the control method must have the ability to respond quickly.
7. **Efficiency:** *How much power does the control method require?* The efficiency of the controller is directly connected with the efficiency of the motor and the motor's output power. If the motor readily can handle dynamic changes in the load, then the control method is very efficient and both the controller and motor will use less power/energy. For appliances, power usage is an important measure of overall product performance. Good energy efficiency is a definite plus.
8. **Low noise:** *How much noise does the control method generate when it is controlling the speed of the BLDC motor?* This criterion is a measure of the controller’s ability to control the torque ripple, or to create a smooth modulation using the power module. Noise can be reduced if the controller can use a higher carrier frequency, but higher frequencies require faster, generally more expensive processors that have sufficient computation capability. This criterion is interrelated with other criteria and impacts the user's perception of the appliance. Consumers buying refrigerators or air-conditioners usually want products that operate quietly.

Figure 4 plots the data for the eight previously described criteria in color coded curves for the three BLDC motor control methods. We took the vector control method as a reference because it provides the highest levels of performance in all of the criteria, assigning its performance a normalized value of 5.0. In our analysis, the 120-degree control method (sometimes called 120-degree drive) with a position sensor is deficient in all areas due to the very nature of state changes and the characteristics inherent in its modulation

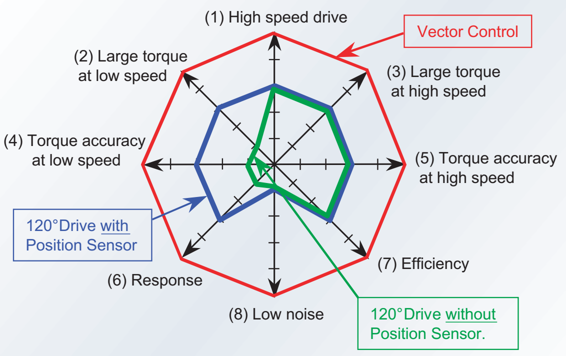


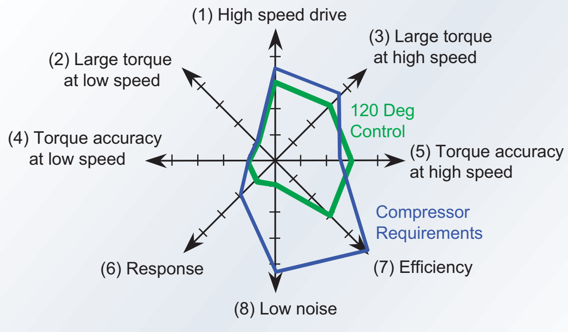
Figure 4. Comparison of 120° sensor and sensorless control with vector control.

technique. This method uses a 120-degree positive, 60-degree free, 120-degree negative, and 60-degree free technique for a given electrical rotation, so torque ripple is built in and performance is reduced. The electrical frequency is related to the number of pole pairs in the motor and the mechanical rotation, and the state-change time is limited, especially at high frequency.

For example, at 100-Hz mechanical rotation with 6 pole-pair motor, the state-change frequency of the 120-degree control method is only 3600 and the modulation is primarily trapezoidal. For the same 100-Hz mechanical rotation, a controller implementing the vector control method will use a 20 kHz carrier frequency to modulate the pwm voltages. Motor speed is varied by changing the slope of the trapezoid with pwm counts, and the accuracy with which the speed can be regulated generally depends on the granularity of the pwm counter. With 120-degree control methods, the desired control precision may not be achieved. Moreover, efficiency is low because the motor's stator coils are supplied with power during only two-thirds of the electrical rotation and thus cannot do any useful work one-third of the time. Response is also slow because full power cannot be applied.

The 120-degree control method that doesn't use a sensor has worse performance. It exhibits degradations in the areas of response, torque at low speed, and accuracy at low speed. These deficiencies typically result in a very poor control of appliance compressors with BLDC motors.

To provide application insight, we analyzed the requirements of appliance compressors in each of the eight performance criteria (figure 5). Compressors generally do not run at 6000 or more RPM, nor do they have a high-speed drive requirement. Therefore, for this application we rate the first criterion at about 70 percent, giving a value of 3.5 on our normalized scale. In light of this assessment, our third criterion also has the same value. These



Note: 120° control is deficient in all but two criteria which have very low importance.

Figure 5. Comparison of 120° sensorless control and compressor performance requirements.

two requirements are well below the ability of the vector control method, but higher than the performance obtainable from either of the 120-degree control methods. Moreover, appliance compressors do not run at low speeds. Therefore, the second criterion for this application has a very low value too — around 20 percent or 1.0 on our scale.

Compressors are basically considered to be constant-load devices. They don't have to cope with the dynamic large changes in load that industrial BLDC motor drives can experience. Nevertheless, appliance compressors do encounter smaller load changes that may become dynamic at times and must be able to handle these fluctuations. The 120-degree control method lacks the required performance, provides relatively poor efficiency and is too noisy. For these reasons we started looking into new control methods that can achieve the required performance using cost-effective sensorless implementations.

3.0 "TYPE A1" CONTROLLER

A key weakness of the 120-degree control method, with or without a sensor, is that the stator coils of the motor do not perform useful work for one third of each rotation. Also, the modulation scheme used generates high torque ripple, which adds into the noise the compressor creates. To avoid these pitfalls, we incorporated two new features to our control scheme, which are shown in figure 6. This method was called "Type A1" internally at the Hitachi R&D Laboratory and we will use that designation in this paper. Please note that most of the development activities were performed by Hitachi R&D lab members.

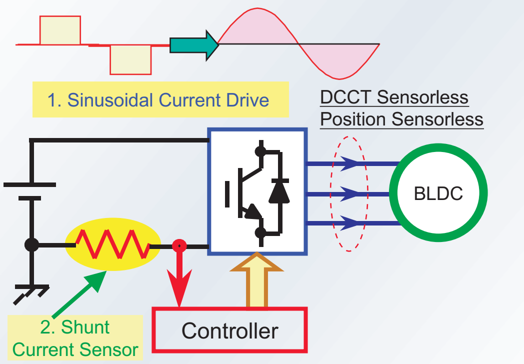


Figure 6. Two significant changes to 120° control method

The first major feature of our Type A1 method is that it uses sine wave modulation so that the motor can perform useful work throughout the entire rotation. Higher efficiency is achieved because balanced currents are created in all coils. The sine wave modulation scheme requires a special 3-phase timer with dead-band register to ensure that the high-side and low-side power switching devices are never turned on at the same time, a situation that otherwise might cause a melt down. The sine wave modulation scheme is known to reduce noise levels in the compressor due to the way it smoothly creates current in the stator coils. When the coil currents have no ripples, the torque ripples are reduced and thus noise is decreased. However, a very important characteristic is lost with sinusoidal current drive; i.e., back-EMF signals are no longer available. Thus, a key design challenge is to find an effective, low-cost way to measure the coil currents.

Figure 7 shows that 180-degree sine wave modulation can provide performance improvements in noise and efficiency. One of our goals was to maximize the gains in these two criteria.

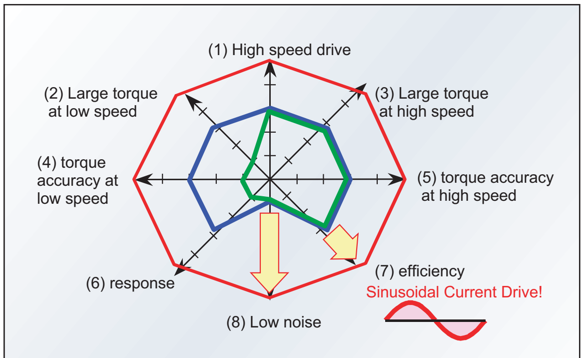


Figure 7. 180° sinusoidal modulation reduces noise and increases efficiency.

The second major feature of our Type A1 control method is that it uses a small resistor in low DC bus that can help measure the coil drive currents in the absence of back-EMF signals. Generally, for safety reasons such a resistor is always added into the hardware to detect over-current conditions. Our motor control method can measure the voltage across this shunt resistor to determine currents at a precise time during the pwm half-width. That allows us to obtain and resolve correct current measurements in the u and w coils. By measuring these currents with shunt resistors, we eliminate the need for the current sensors or transducers (marked as DCCT in figure 2a) on the high side and reduce the system BOM cost.

Once the currents in two coils are measured during the pwm time, we can use any suitable closed-loop control algorithm to handle speed accuracy and torque. The speed and position of the rotor of the BLDC motor can be estimated from two current measurements, plus the voltages applied during that pwm cycle. The accuracy required from this estimate generally dictates the best algorithm to use. If the speed of the motor can be controlled with low accuracy, then it is OK to execute a speed regulator algorithm and not worry much about torque accuracy. Speed estimates that are highly accurate enable very refined position estimates. With very accurate speed estimates, the i_d and i_q current estimates are also at a level where one can implement a vector control scheme to control the motor torque and the flux in the coils. In sum, the overall performance requirements of the application dictate the estimation algorithm required. Of course, the algorithm chosen is a major factor in determining the computing capability the microcontroller must deliver.

With these two features in mind — sine wave modulation and the use of a small resistor to measure drive current — we first want to describe the timer features necessary for implementing both features and discuss how to measure two currents correctly. Subsequently, we will describe the design issues of such implementations. Later, in the next section, we will review our test results.

To generate proper sinusoidal modulation, the timer peripheral must be able to create three independent sine waves. As shown in figure 8a, our SuperH RISC series microcontrollers allow channels 3 and 4 of a Multi-functional Timer Unit (MTU, one of the device's on-chip peripheral functions) to be used to create six pwm outputs. These six outputs enable three proper sine waves to be generated for driving three stator coils. Carrier cycle counts are loaded in the TGR3A register; voltage command values are loaded in the TGR3B, TGR4A and TGR4B registers. The MTU has a dead-time register for creating a complimentary pwm output pair that incorporates a dead time in the lower and upper outputs. This permits the lower IGBT or power MOSFET to be turned OFF before the upper or high side IGBT/power MOSFET is turned ON.

Each channel has a buffer register that holds the next pwm value the microcontroller has computed using the firmware algorithm. Whenever the counter starts counting up, that buffer value is also automatically loaded into the register that performs the comparison and generates the output. During count-up cycle, the high side is turned ON; during count-down cycle, the high side is turned OFF. Because the pwm values are based on a sine table, a proper sine wave is implemented. A sine table with 360 entries is generally used to achieve one-degree resolution. The table can be lengthened to 600 entries to avoid index computations due to rollover of the angle. A carrier frequency in the range of 12-20 kHz is used, depending on the computation time required for interrupt processing. For example, the total interrupt processing time available at 12 kHz frequency is 83μs, while at 20 kHz frequency it is 50μs. The optimum carrier frequency allows sufficient bandwidth for handling interrupts and other system control tasks. Note that the value loaded into the dead-time register depends on the characteristics of the power MOSFET or IGBT driving the motor coils. Generally, the dead time ranges between 2 and 3μs.

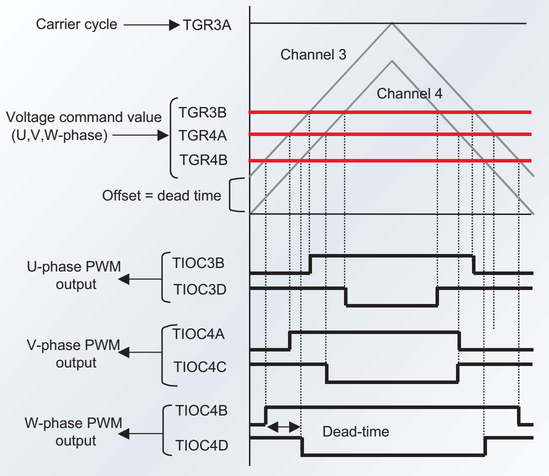


Figure 8a. MTU channels 3 and 4 create six independent pwm signals that can be used to generate three sine waves with dead time.

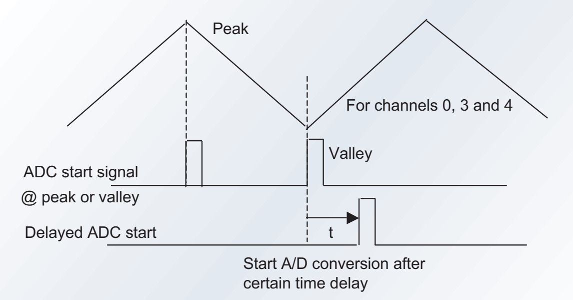


Figure 8b. MTU channels 0, 3 and 4 can issue ADC start triggers at peak or valley or on a delayed count.

A key feature of the MTU in SuperH devices is that it allows analog-to-digital (A/D or ADC) conversions to be triggered at the peak or the valley during the counting process for channels 3 and 4. This is shown in figure 8b. In a traditional BLDC controller implementation with two current transducers mounted on the high side, currents are measured at the peak in the pwm cycle. Thus, two A/D conversions are triggered during the complimentary pwm generation by channels 3 and 4.

The MTU also allows triggering of delayed A/D conversions for channels 0, 3 and 4. The delayed counts are loaded into a register for each channel. This is the capability that enabled us to create our method of One-Shunt Current Detection (OSCD). Using the MTU, it is possible to measure two independent currents in a given pwm cycle. In figure 8c, we show how the two special values for delayed triggering necessary for current measurements are determined. Processing performed during the interrupt calculates three pwm values, u_{pwm}, v_{pwm} and w_{pwm}.

If we assume that these three values are as shown in the figure 8c, then u_{pwm} is smallest value, w_{pwm} is largest value, and v_{pwm} is a middle value. When Δt1 is set between w_{pwm} and v_{pwm}, ADC1 will measure the current passing through the high side of the w coil, since that is the only high-side IGBT that is ON. When Δt2 is set between u_{pwm}, and v_{pwm} , ADC2 will measure high-side currents in the v and w coils. Because the sum of all high-side currents is zero, measurements of the v and w currents yield the value of the u current. Thus, two distinct coil drive currents are measured by this method.

During both conversions, the low-side resistor is used to measure the currents in the stator coils. Because the currents are measured at precise times using the known pwm values for the u, v and w coils, distinct current values are captured. From this data, the firmware must reconstruct the currents properly and then apply their values in a closed-loop control program.

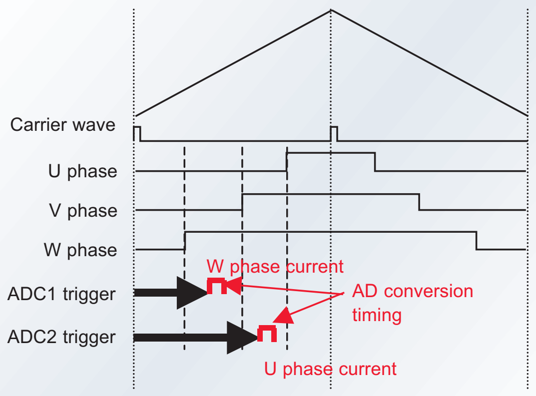


Figure 8c. Δt1 and Δt2 are set so that ADC1 measures w current and ADC2 measures u current.

We want to point out here several design issues that apply to the coil drive current measurements made using this method.

1. Each A/D channel must have its own sample-and-hold circuit. Otherwise, two conversions cannot be performed in a short enough time.
2. The difference between two pwm counts must be sufficiently large. As figure 9 shows, when the u and w phases are far apart, there is sufficient time to do a current measurement. However, when the u and w pwm values are close together, there isn't. We call the condition in which there is not enough time, the “Undetectable Zone.” Observe that as the pwm values change, this zone also changes. During the Undetectable Zone, current measurements are not accurate. Therefore no measurements are made; i.e., they are dropped. This is one of the reasons why the currents must be reconstructed properly. To emphasize, during one sine wave, current measurements have to be dropped whenever there isn't sufficient time to perform a complete, clean current measurement.

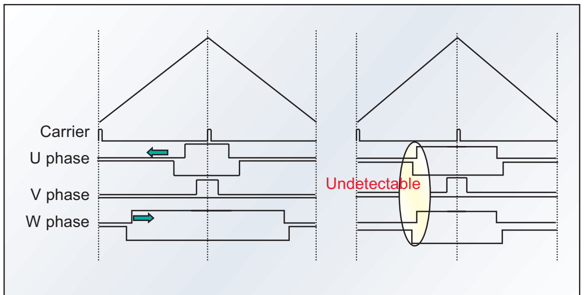


Figure 9. Detectable and undetectable zones for one shunt.

3. The number of measurements that must be dropped depends on the carrier frequency. If that frequency is high — say 20 kHz — then many measurements are dropped. If the carrier frequency is low (about 10 kHz), then fewer measurements have to be dropped. A carrier frequency of about 4 kHz seems to limit the dropouts to an acceptable number, allowing adequate reconstruction of the coil currents.
4. The algorithm that sets the Δt1 and Δt2 times could be complicated if a d-q frame to u, v, w frame transformation is used to compute pwm values. If pure sinusoidal modulation is implemented, then the symmetry of the six space-vector regions can be used to reduce the necessary computations. For example, when the angle is between 30 and 90 degrees, u_{pwm} has the largest count, v_{pwm} has the middle value, and w_{pwm} has the smallest count. So, it is easier to set six case statements to set Δt1 and Δt2 values.
5. Finally, external hardware circuits and internal software filters may be needed before any current measurements can be used in closed-loop algorithms.

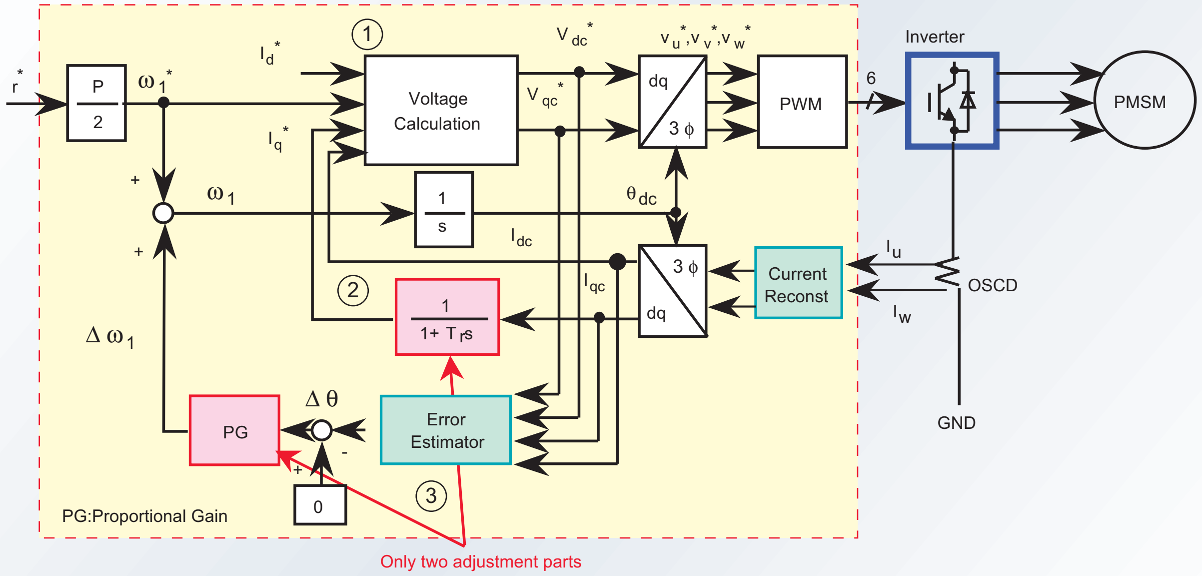


Figure 10. Type A1 closed-loop BLDC motor controller.

Figure 10 illustrates the design we implemented: a closed-loop control algorithm that uses two current measurements performed via the one-shunt current detection method. Two current measurements are transformed into the d-q frame. Using these i_d and i_q currents and the last u, v and w pwm values, this method estimates the error in the speed of the BLDC motor. After applying proportional gain (PG), the estimated error is added into the reference speed, which is integrated to get the angle value.

The voltage calculations are based on the measured i_q current and given i_d^* and i_q^* currents from the speed set-up value. Voltage commands along the d and q axes are output from the voltage calculation module. Using the angle value and sine and cosine tables, the d-q voltages are transformed into the u, v, w reference frame. Finally, the pwm values are computed from these three u, v and w voltages. We have implemented this algorithm for diverse appliance compressor applications.

Our control algorithm differs from the vector-control algorithm in many ways. In the vector control method, three regulators are used: one speed regulator and two current regulators. Because the 180-degree sine wave modulation approach doesn't have position-sensor inputs, we must generate an estimate of the rotor position based on the currents measured via the OSCD method. Instead of regulators, we use a simple method of voltage calculations and a much simpler method of integrating the angle. These differences enable our control method to achieve shorter computation times and use a much higher carrier frequency than traditional methods.

4.0 RESULTS

Tests of our Type A1 controller in refrigerator and compressor applications have been very successful. As shown in figure 11, our control approach exceeds or highly satisfies five of our eight performance criteria. Results for the other three criteria need further investigation.

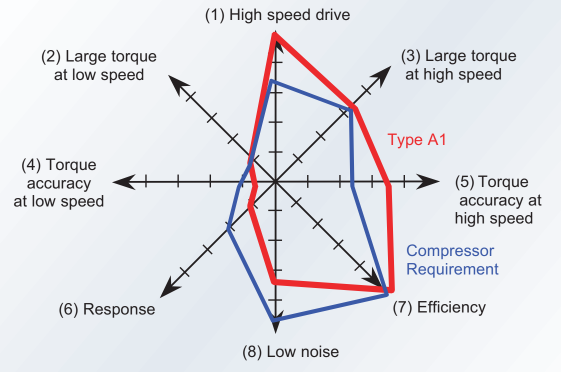


Figure 11. Performance of type A1 controller vs. the compressor requirements.

For high-speed drive (criterion 1) and torque accuracy at high speeds (criterion 5), our BLDC controller exceeds the performance requirements of home appliance compressor applications. For large torque at low speed (criteria 2), large torque at high speed (criteria 3), and efficiency (criteria 7), our controller meets the requirements. For the other criteria, the performance is less than the requirements. The torque accuracy at low speed (criteria 4) is not very important for compressors, so the reduced performance is acceptable. There is a greater shortfall in meeting the response requirement (criterion 6), yet the overall response needed is only 40 percent of that of the vector control method. Therefore, the response performance obtained is still acceptable. However, the requirement for low noise (criterion 8) is very important for home appliances and our controller design is somewhat too noisy. We are now investigating ways to get better noise performance. Overall, though, it is our opinion that our Type A1 controller satisfies most of the requirements for compressor applications.

It is very instructive to compare the performance of our 180-degree sensorless control method with that of the 120-degree sensorless control approach typically used today in cost-sensitive markets for white goods and home appliances. As shown in figure 12, the Type A1 controller improves in all areas except one. In particular, our 180-degree approach offers more perform-

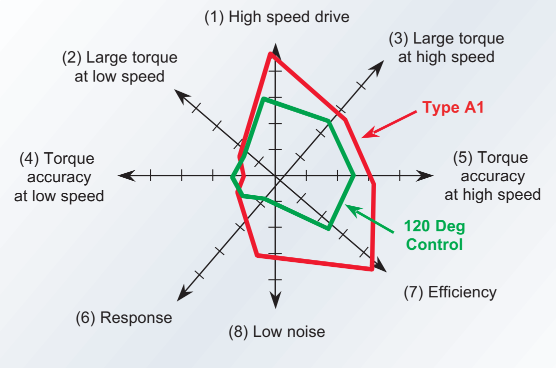


Figure 12. Type A1 control method improves performance in all criteria except one: torque accuracy at low speeds. This criterion has very low importance for compressors.

ance for criteria 1, 3, 5, 7 and 8. For the criteria of efficiency, low noise and high-speed drive, the improvement is significant and noticeable. For torque accuracy at low speeds, the Type A1 BLDC motor controller provides less performance than a 120-degree design. However, compressor applications don't require much torque accuracy at low speed and the performance of the 120-degree method is also so small that this deficiency is acceptable. Simply put, compressors generally do not run at slow speeds, so there isn't much need for good low-speed torque accuracy.

In Table 1, we have compared our 180-degree Type A1 motor controller with its performance requirements and also with the performance of the 120-degree control method. Notice that we have been successful in our objective of making gains in the areas of efficiency and low noise.

5.0 SUMMARY & FUTURE ACTIVITY

We have developed a technique for current measurements with a low-side DC bus shunt resistor. This technique is very cost effective and reduces the overall BOM for implementing BLDC motor controllers for compressors for home appliances. In our development work, we experimented with several carrier frequencies, found the undetectable zones, and discovered how to properly reconstruct the current measurements.

As a result, we have created a new Type A1 motor controller that uses two current measurements and an estimation of motor speed. This control method uses one-shunt current detection and performs speed control efficiently. Our 180-degree sensorless control method satisfies or improves the

Table 1. Comparison of Type A1 with 120 Deg control and performance requirements

Criteria	RQMTS	Type A1 control	Comments	120 deg control	Comments for A1
High-speed drive	3.5	5	Exceeds	3	Better
Large torque at low speed	1	1	Meets	1	Same
Large torque at high speed	3.5	3.5	Meets	3	Better
Torque accuracy at low speed	1	0.5	<	1	Less
Torque accuracy at high speed	2.5	3.5	Exceeds	3	Better
Response	2	1	<	1	Same
Efficiency	5	5	Meets	3	Better
Low noise	4.5	3	<	1	Better

performance required for appliance compressors. It achieves better performance in five areas than designs that use the 120-degree sensorless control method. Our objectives of obtaining improved efficiency and greater high speed torque have been achieved. Moreover, the superiority of our Type A1 control can be attained with implementations that meet tight cost targets for competitive consumer markets.

Two future activities are planned. We will investigate enhancements to the OSCD method and explore ways to further reduce the noise of compressor operation.

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