Application Note
Sensorless-FOC for PMSM With Single DC-Link Shunt

TEXAS INSTRUMENTS

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ABSTRACT

The three-phase current sensing with only one dc link shunt resistor can be used for cost sensitive applications. However, special efforts need to reconstruct three-phase current from a dc link current. Moreover, phase current cannot be correctly measured from the single shunt when the active vector duration is less than the minimum measurement time. In order to get dc link current in unmeasurable vector area, a special algorithm for PWM compensation is required. This application report describes how to reconstruct three phase currents with a single current sensor in the inverter dc link. This solution is verified through InstaSPIN™-FOC with MotorControl SDK software platform.

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1 Introduction

A Brushless Permanent Magnet Synchronous Motor (PMSM) has been widely applied to industrial and automotive applications due to lots of advantage over other motors. For control side, Field Oriented Control (FOC) and Pulse Width Modulation (PWM) have become a general control method in variable-speed ac motor drivers applications with PMSM. For most of applications power rating is lower than a couple of kW, three shunt resistors located in low side of power switches are generally used to measure three-phase motor currents for FOC. However, a single-shunt feedback located in dc link return side is also widely used for cost sensitive applications like digital appliance. This application report shows how to reconstruct three-phase currents with a single dc link current by using InstaSPIN-FOC solution with MotorControl SDK.

2 Fundamental Theories of FOC and Current Measurement

2.1 Basic Theory of FOC

The torque in the synchronous machine is vector cross product of the stator field or current vector and rotor magnetic field vector as following.

$$
\begin{aligned}
T_e &= K\lambda_{rotor} \times I_{stator} \\
\left|T_e\right| &= K\left|\vec{\lambda_r}\right|\left|\vec{I_s}\right|\sin\theta
\end{aligned}
$$

(1)

The K is constant and the amplitude of torque is proportion to the amplitude of rotor flux vector, the amplitude of stator current vector and sinθ which is angle between rotor flux and stator current vector. This expression shows that stator current vector and rotor magnetic field vector should be orthogonal to get maximum torque with given stator current. To keep the angle at 90 degrees, we have to know the rotor position. This can be achieved with a position sensor like encoder or resolver. Also, rotor position can be estimated by using sensorless technologies like InstaSPIN-FOC without these kinds of position sensors.

In brief, the goal of FOC is to control stator current vector based on rotor flux vector. For best performance, FOC algorithm aligns the stator current vector to 90° of the rotor flux vector, such that, orthogonal to the rotor flux vector. To do this, a three-phase stator current is measured by shunts or in-line magnetic based current sensors. A three sensors measurement can get the best performance in the most of applications. In particular area, a single sensor measurement can be used for a BOM cost saving and an easy pcb layout. If a single sensor is used for current measurement, a special algorithm is need for three phase current reconstruction. These current measurements feed into the Clarke transformation module. The outputs of this projection designated i_α and i_β are the inputs of the Park transformation that gives the current in the d,q rotating reference frame. The i_d and i_q components are compared to the references i_{d_ref} (the flux reference) and i_{q_ref} (the torque reference). For controlling a non-saliency PMSM, i_{d_ref} will be set to zero except flux-weakening control mode. The torque command i_{q_ref} could be the output of the speed regulator when using a speed controller. The outputs of the current regulators are V_{d_ref} and V_{q_ref}; they are applied to the inverse Park transformation. The outputs of this projection are V_{α_ref} and V_{β_ref}, which are the components of the stator vector voltage in the (α,β) stationary orthogonal reference frame. These are the inputs of the Space Vector PWM (SVM). The outputs of this SVM block are the signals that drive the inverter. For single-shunt measurement, the switching pattern of SVPWM is modified to reconstruct the phase current in the unmeasurable area. Note that both Park and inverse Park transformations need the rotor flux position. So, knowledge of the rotor flux position is the core of the FOC.
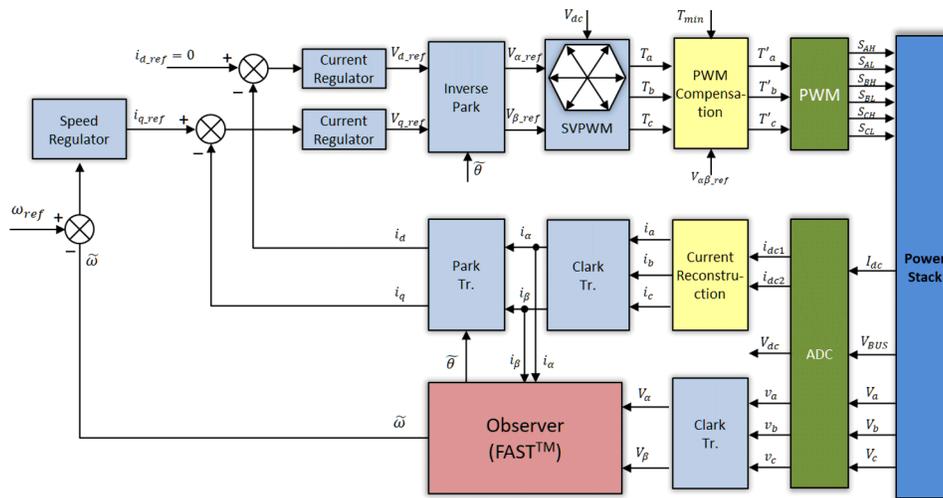
Figure 2-1. Block Diagram of Sensorless FOC With Single Current Sensor at DC Link

2.2 Current Sensing Technique

Fast and precise current sensing is required in motor control applications to have the minimum torque ripple and thus minimum audible noise. Accurate current sensing is important to have the best dynamic motor control. The delay in current sensing path can leads to incorrect current estimates and hence distorted current waveform in motor. The motor drive applications in major appliances such as a compressor motor control in air conditioners and refrigerators require accurate torque control to have best dynamic performance and lower acoustics. An inaccurate current sensing lead to distorted current waveform in the motor winding and thus produces torque ripple, which, in turn, results in inefficient and noisy performance.

Control the inverter system requires knowing the motor current information. For a three phase motor, the designer must know all the phase currents to be able to control the motor torque. The motor- phase winding current can be sensed by using different methods, for which the commonly- used methods are:

- Inline current sensing
- Inverter leg current sensing
- DC bus current sensing using a single-shunt

Figure 2-2 shows the placement of current sensor in the previously mentioned sensing methods.
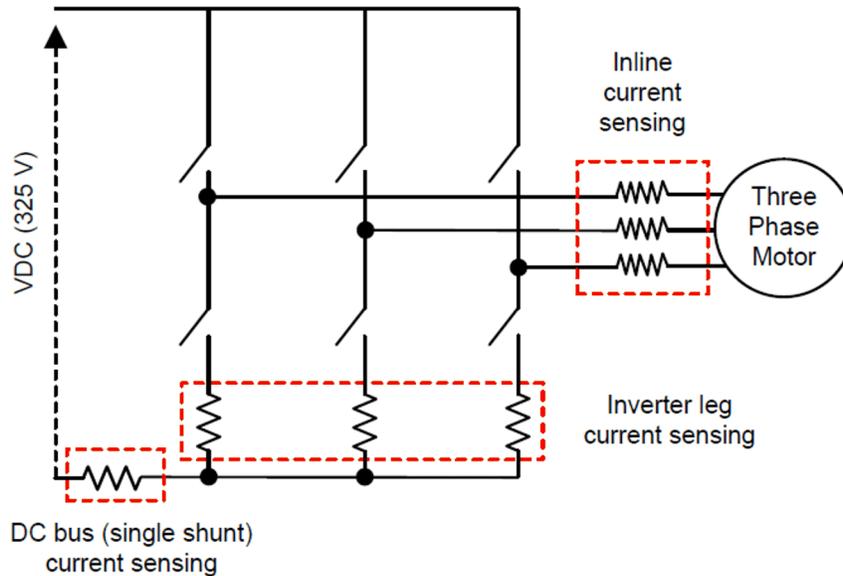

Figure 2-2. Different Current Sensing Method Used in Three-Phase Inverter

The simplest method of obtaining motor winding current is by measuring each of phase current directly at the phase node by placing a current sensor in line with the phase connection. Depending on the motor winding connections, this measurement requires at least two sensors to be applied directly to the individual motor phases. The common mode voltage existing in the inline sensing is equal to the DC bus voltage, which makes non-isolated shunt based sensing difficult. Isolated sensors are normally used in these lines and are usually sophisticated and expensive. Use of a non-isolated shunt-based solution is preferred in applications where the common-mode voltage is typically less than 100 V.

Another method is to measure the inverter leg currents as Figure 2-2. In this case, the common-mode voltage is close to zero and a low-cost shunt and an operational amplifier (op amp) can be used to sense the inverter current. The current sampling has to be done when the low-side switch is ON and the current sampling point must be synchronized with the pulse-width modulation (PWM). The ideal method is to use three-leg inverter current sensing. Two-leg inverter current sensing must be performed at the minimum to obtain accurate information on each of the three winding currents.

Another method, which is more complex, is to measure only the DC line current and then identify each of the three-phase currents sequentially in the different inverter switching states. Because the switching state of the inverter is controlled by the micro controller unit (MCU) or digital signal processor (DSP), the designer can determine the exact electrical route taken by the input current through the inverter, which allows the designer to directly relate the DC bus current to the motor phase current. The obtained phase currents are the result of a real measurement of the current and are not the result of an estimation that requires a model of the circuit. This method is broadly being used in the home appliance and automotive applications because of BOM cost saving.

Section 2.2.1 provides a detailed analysis of the different low side current sensing performed.

2.2.1 Low-Side Current Measurement

The low side current sensing topologies use a resistor located at the base of the phase or at the DC bus return path to measure current that is flowing through a phase. Regardless of the resistor configuration used (one-, two-, or three-shunt), current can only be measured when a lower switch is ON. The current signal must be clean to properly sample the current. A clean current signal or representation of the current signal must have no ringing or noise. The following subsections detail different current measurement techniques for resistor shunts that are used in the field.

2.2.1.1 Three-Shunt Current Sensing

Figure 2-3 shows three-shunt inverter leg current sensing. Three-shunt current sensing has some advantages. Contrary to the three-shunt technique, the use of single- or two-shunt circuit proves difficult to achieve over-

modulation. Additionally, the use of a low-bandwidth op amp is sufficient for current sensing. The three shunt technique can bounce sampling between current signals, selecting two out of three phases each period, which allows for long times for the current signals to settle. If large current measurement windows are possible, then much slower and cheaper op-amps can be used. For example, Figure 2-3 shows three PWM switching signals and what shunt resistor will be sampled. As Figure 2-4 shows, the current signal has plenty of time to stabilize.
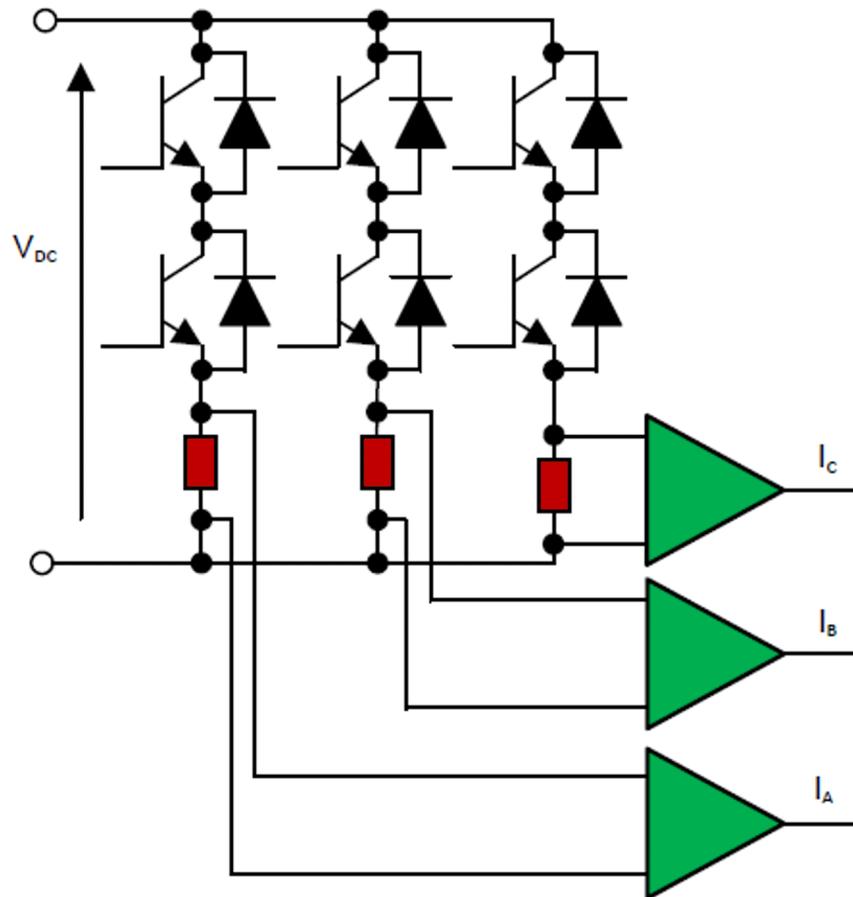

**Figure 2-3. Three-Shunt Current Measurement Circuit With Inverter**
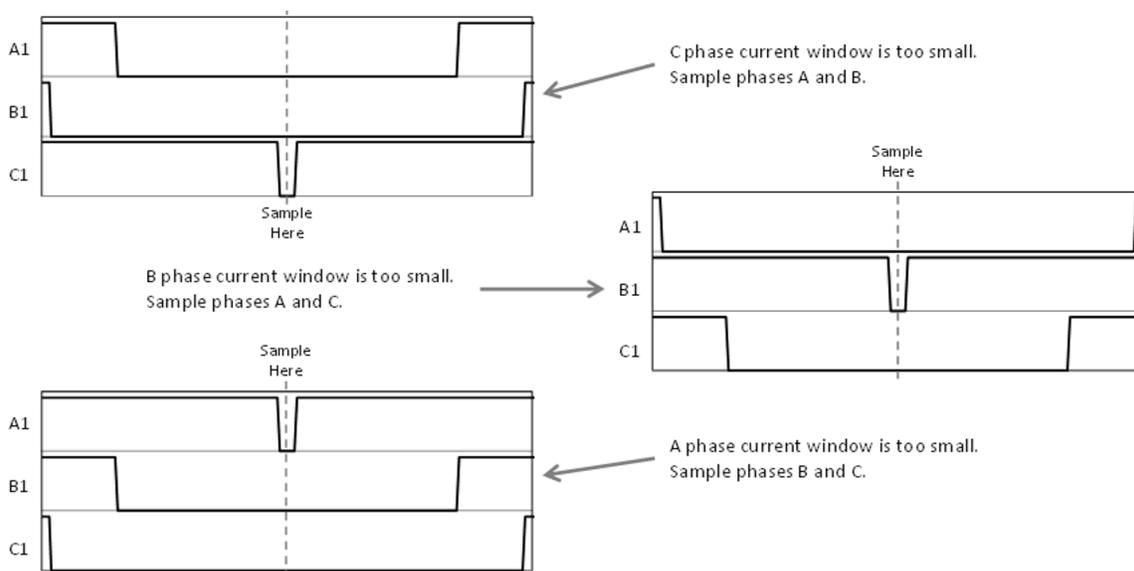
Figure 2-4. Using Three-Shunt Current Sampling Technique

2.2.1.2 Dual-Shunt Current Sensing

The two-shunt current measurement technique uses the principle of Kirchhoff's Current Law (KCL), which is that the sum of the currents into a single node equals zero. By measuring only two-phase currents, the third is calculated with KCL. Figure 2-5 shows a circuit for the two-shunt current measurement technique.
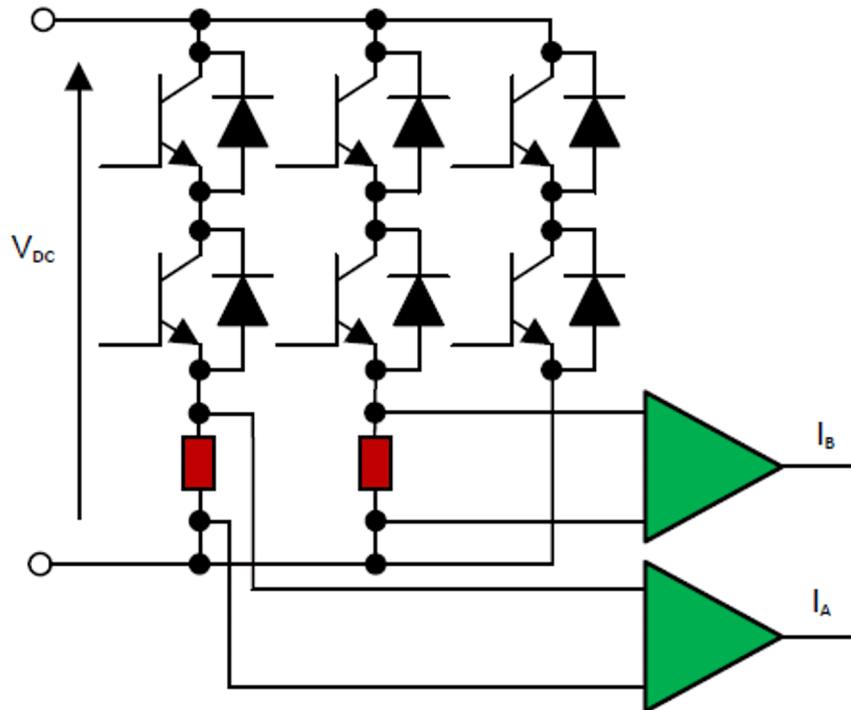

Figure 2-5. Dual-Shunt Measurement Circuit With Inverter

The two- and three-shunt measurement circuit has an advantage over the single-shunt circuit in that it can see circulating currents. Figure 2-6 shows an example of a switching waveform and where the analog-to-digital converter (ADC) samples the current. The PWM duty cycle for I_A is almost 100% in this example, which causes the I_A current to rise. The PWM for I_B is about 50% duty cycle and its current stays at approximately 0 A for this period. Phase current can only be measured when the lower switch of that particular phase is conducting. In the example, I_A is measureable for a very short time while I_B has a long time to measure. The inherent problem of using two-shunt technique is when the measured phase is operating at PWMs near 100%. For example, when sampling I_A, the measured current signal has not yet stabilized, which gives an incorrect representation of the current signal.
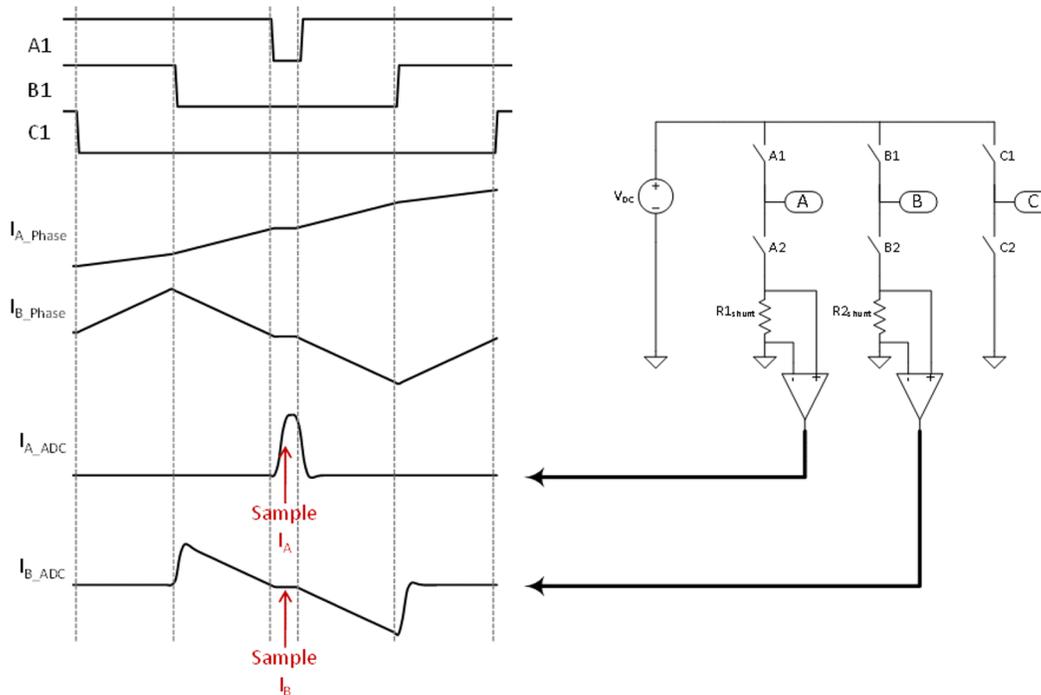

Figure 2-6. Sampling Current When Using Two-Shunt Measurement Technique

As the duty cycle increases, the time to measure voltage across the shunt resistor for the phase decreases and the current measurement must be quicker. As the duty cycle increases even more, the slew rate of op amps must be increased to properly capture the signal. Although the two-shunt current measurement technique lessens the speed requirement of the op amp as compared to the single-shunt measurement, there is a duty cycle where the slew rate has to be very large, but still less than the requirement for a single-shunt.

For two- and three-shunt techniques, the current being measured is bipolar. So, 0 A is now represented as half of the ADC full scale and the quantization step size doubles.

2.2.1.3 Single-Shunt Current Sensing

The single-shunt current measurement technique measures the dc link current and, with knowledge of the switching states, recreates each of the three phase currents of the motor. Figure 2-7 shows the single-shunt location in the inverter circuit.
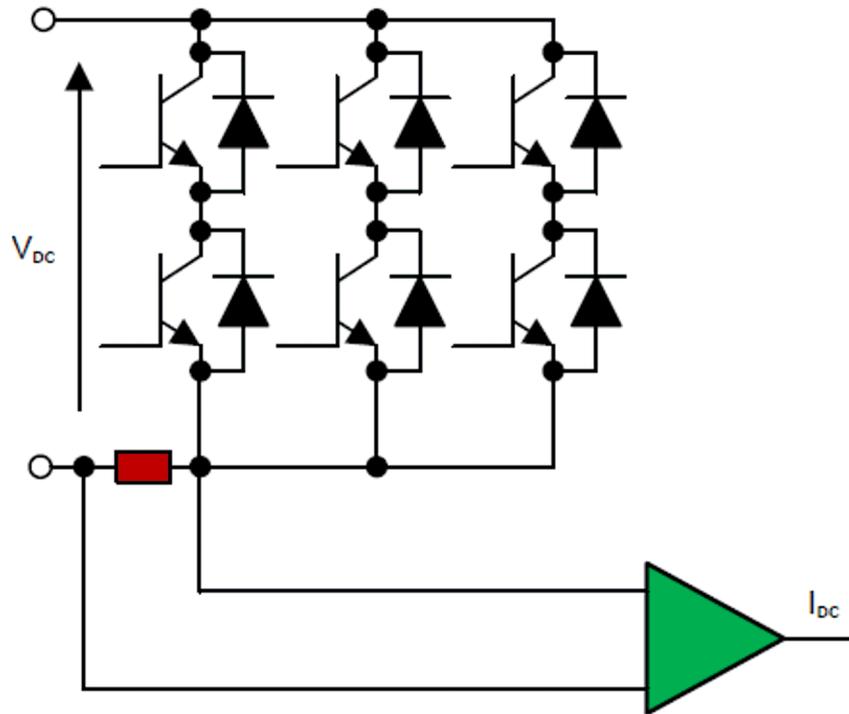

Figure 2-7. Single-Shunt Current Measurement Circuit With Inverter

For a better understanding of the measurement process and to represent the switching state of the inverter, this application note defines a switching function *Sa* for phase A as follows: *Sa = 1* when the upper transistor of phase A is ON, and *Sa = 0* when the lower transistor of phase A is ON. Similar definitions can be made for phases B and C.

The explanation of the process is based on the assumption that the inverter is fed in complementary mode. The signals in this mode, which control the lower transistors, are the opposite of *Sa*, *Sb*, *Sc*, which controls the upper transistors.

As previously stated, the measurement method in single-shunt current sensing depends on the switching states of the inverter switches. An example case is explained In Figure 2-8 and Figure 2-9. In Figure 2-8, the top-side switch of phase A is conducting and bottom-side switches of phase B and C are conducting. In this switching state, the DC bus current measurement gives the phase A current and is positive ($+I_A$). The direction of current in phase A is towards the motor winding (see Figure 2-8).
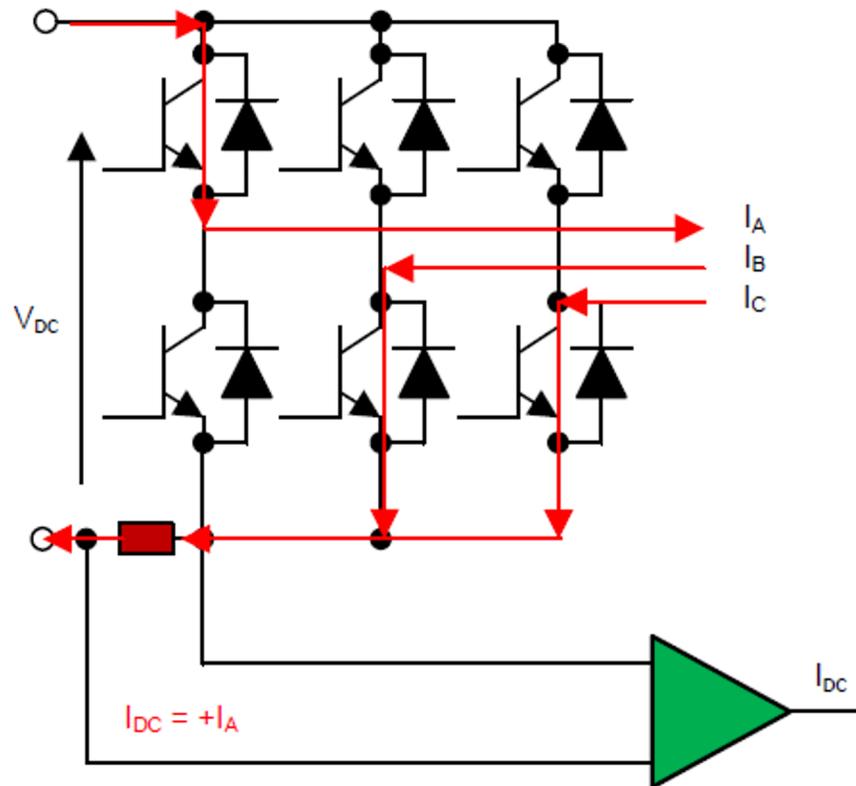

Figure 2-8. Switching Sate Sa, Sb, Sc: 100

In Figure 2-9, the top-side switches of phase A and phase B are conducting and the bottom-side switch of phase C is conducting. In this switching state, the DC bus current measurement gives the phase-C current and is negative ($-I_C$). The direction of current in phase C is towards the inverter from the motor winding (see Figure 2-9).
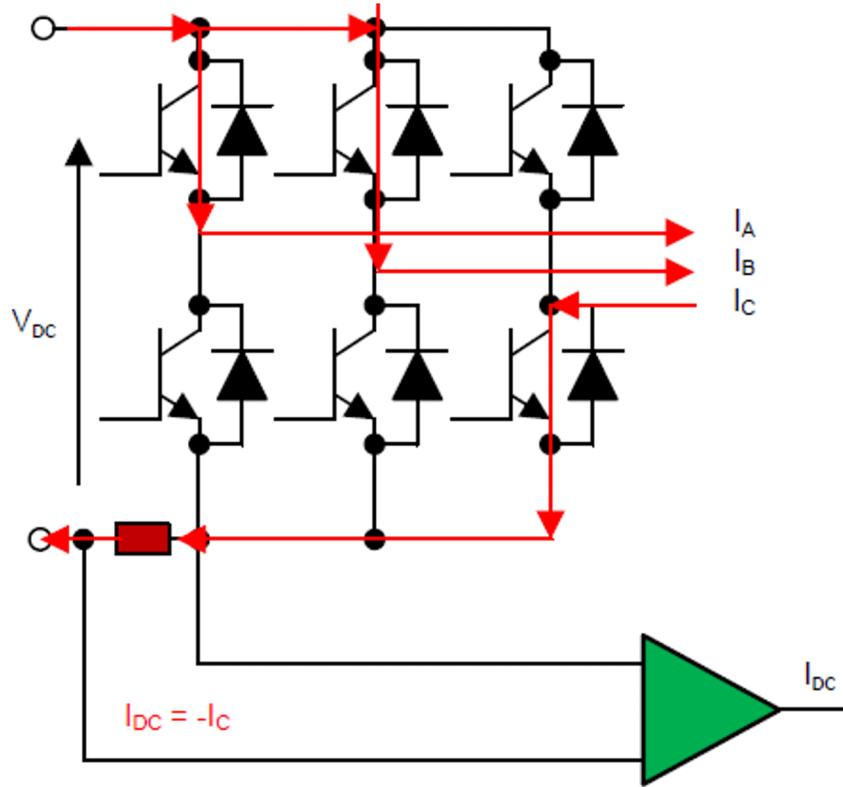

Figure 2-9. Switching Sate Sa, Sb, Sc: 110

Similar to the preceding explanation, there are eight different switch options in SVM PWM. Table 2-1 explains each one and shows the direction of the voltage space vector and what current can be measured in that state. With the switches in states 0 and 7 only circulating current is present and there is no possibility to measure current with the single-shunt technique. The six switching states from 1 to 6 are called as active vector or active voltage vector. The current measurement and switching state must both be properly considered to measure current with the single-shunt technique.

Table 2-1. The Space Vector Modulation Switching States

Switch State	AH	BH	CH	Vector	Measure
0	0	0	0	•	offsets
1	1	0	0	→	I_A
2	1	1	0	↗	$-I_C$
3	0	1	0	↖	I_B
4	0	1	1	←	$-I_A$
5	0	0	1	↙	I_C
6	1	0	1	↘	$-I_B$
7	1	1	1	•	offsets

[Figure 2-10](#) shows a SVM PWM waveform and the DC bus current measurement signal that resulted from the applied switching state. In this case the current conduction times for each switching state are on long enough so that the slew rate of the op-amp and settling time of the whole measurement system have enough time to go to steady state so that the ADC can have enough time to sample the current.
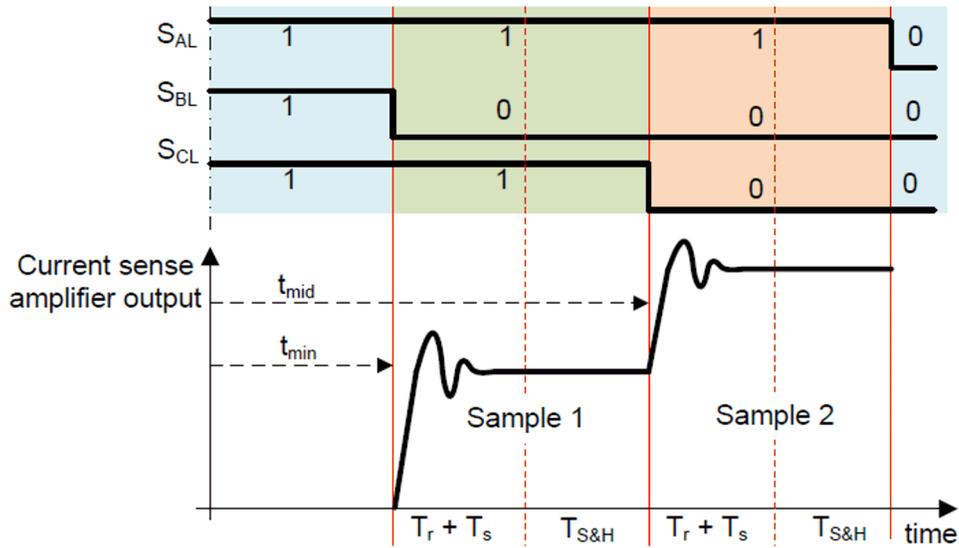

Figure 2-10. Single-Shunt Current Measurement When Sampling Times are Sufficient

When using the single-shunt technique, it is mandatory to be able to measure current in the smallest time possible. This requirement highlights the importance of ensuring that the minimum pulse width (minimum active vector duration) and pulse transition period needs to be maintained for a valid sample. To understand the minimum vector duration required, understanding the delays in the measurement is necessary. The [Figure 2-11](#) shows the delay components in the measurement path.
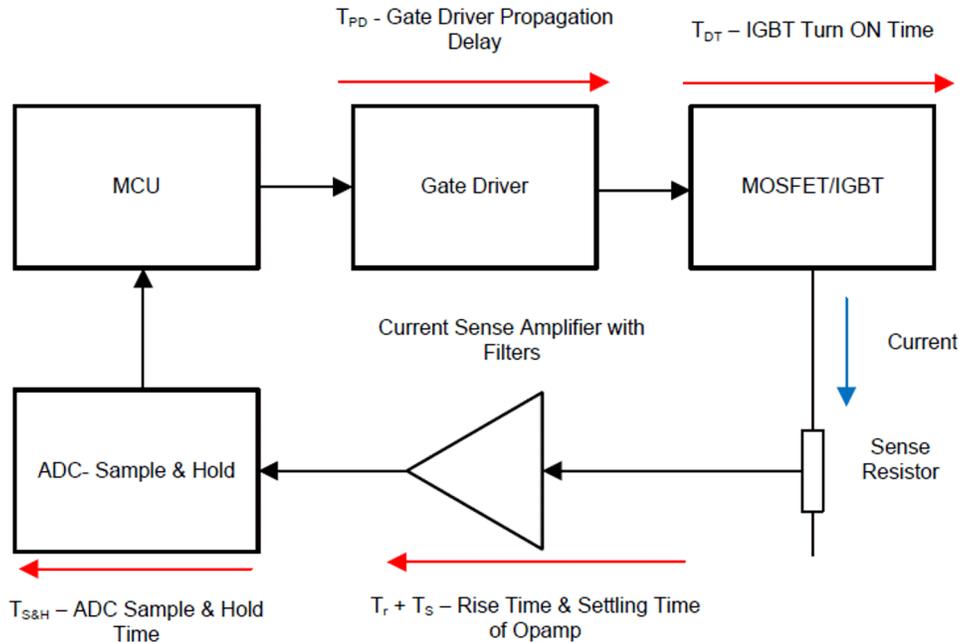


Figure 2-11. Delay in the Current Sensing Loop
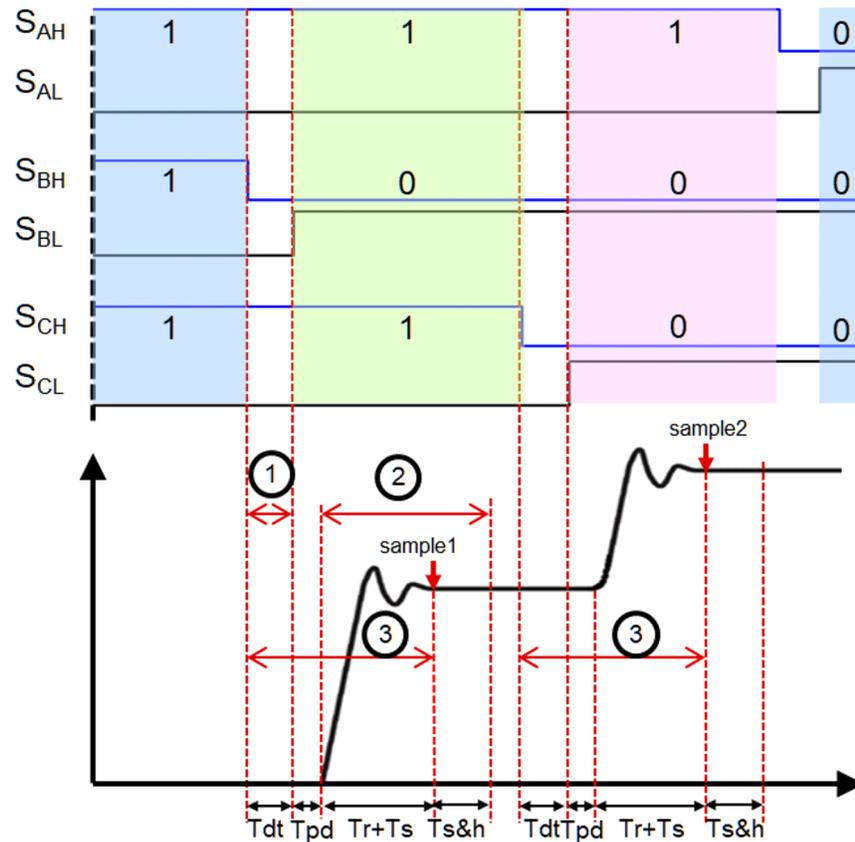
Figure 2-12. Single-Shunt Current Measurement Timing

The minimum active vector duration must be more than the total delay except gate driver propagation delay in the current sensing path. The gate driver propagation delay (Tpd) only influences the calculation of sampling point. Figure 2-12 shows one of switching pattern in SVM and current wave form at the output of OpAmp. Equation 2 can be used to determine the minimum active vector duration to derive a valid current sample.

$$T_{min\_dur} > \text{①} + \text{②} = T_r + T_s + T_{S\&H} + T_{DT} \tag{2}$$

where:

- T_r = Rise time of amplifier including power switches(MOSFET/IGBT) turn on time (dependent on the amplifier slew rate and gate charging time of power switches)
- T_s = Settling time of amplifier (dependent on amplifier GBW, gain, accuracy, sensing circuit filters)
- $T_{S\&H}$ = ADC Sample and Hold time
- T_{DT} = Dead-time between top and bottom switch

If the duration of active vector is less than the minimum time T_{min_dur} in Equation 2, it is impossible to get three-phase current from the shunt resistor.

As previously mentioned, phase currents can be sampled at zero vector state for two or three-shunt current measurement. But single-shunt currents should be sampled on each switching states of the inverter switches. So, ADC sampling point should be properly considered. From Figure 2-12, Equation 3 can be used for the sampling point calculation.

$$T_{sample\_delay} = ③ = T_{DT} + T_{PD} + T_r + T_s \qquad (3)$$

where:

- T_{DT} = Dead-time between top and bottom switc
- T_{PD} = Gate driver propagation delay
- T_r = Rise time of amplifier including power switches(MOSFET/IGBT) turn on time (dependent on the amplifier slew rate and gate charging time of power switches)
- T_s = Settling time of amplifier (dependent on amplifier GBW, gain, accuracy, sensing circuit filters)

Ideally, to have an undistorted current in the motor winding, the minimum active vector duration would be zero. Having the minimum active vector duration of zero is practically impossible because of the sensing and loop delay. A non-zero, minimum vector duration creates distortion in the current waveform unless it is properly compensated in the software algorithm (which is very complex and difficult to achieve). Figure 2-13 shows the space vector hexagon. As the space vector points toward the corners of the hexagon, the time window for sampling current completely disappears. There are zones located at 0°, 60°, 120°, 180°, 240°, and 300° where only one current can be measured and the other two currents must be found in another fashion. In low modulation index which is called as star area, any phase current cannot be sampled form the shunt resistor because the duration of the two active vectors applied in switching cycle are short than the minimum active duration time T_{min_dur}
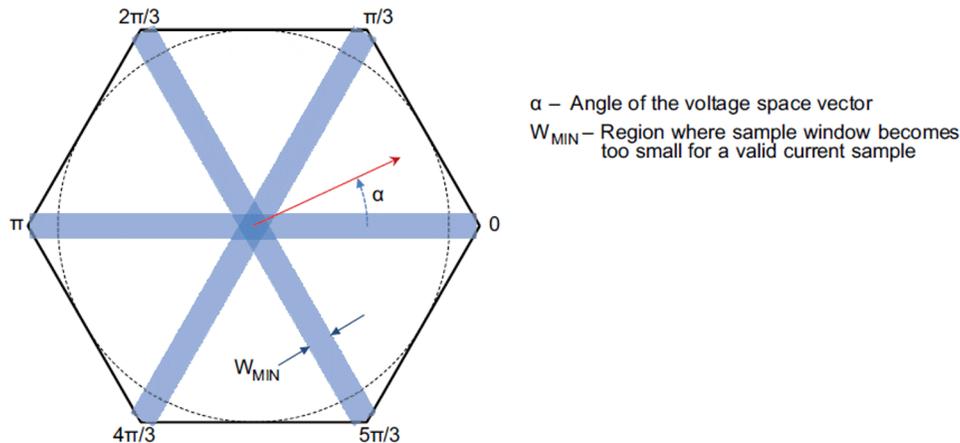

Figure 2-13. SVM and Regions Where Current Measurement is Not Allowed

Figure 2-14 and Figure 2-15 show the active vector durations (U1 and U2) during zero crossing and 60° sector changes. In Figure 2-14, the sector duration U1 is too small to have a valid sample. In Figure 2-15, the sector durations of U1 and U2 are too small to have a valid sample of current.
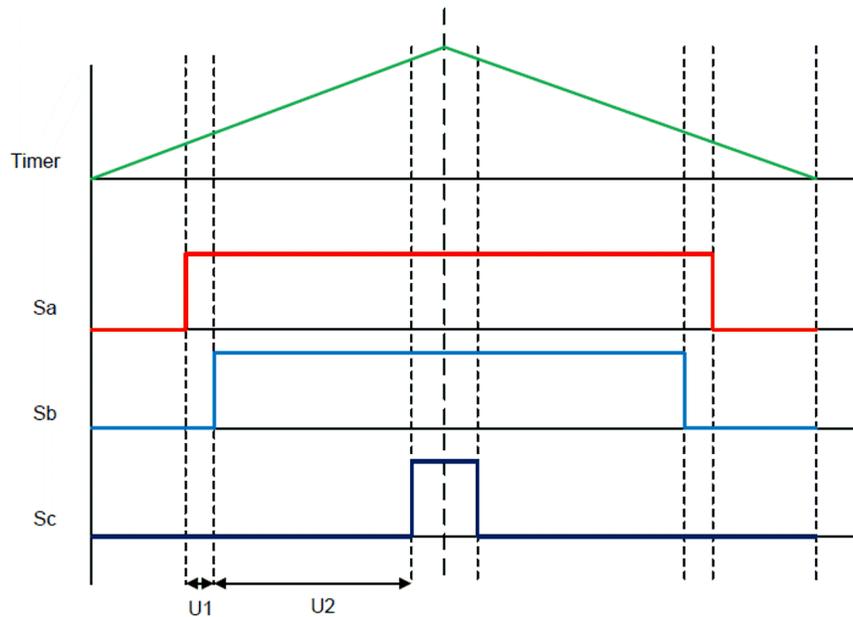

**Figure 2-14. Active Vector Durations During 60° Sector Changes**
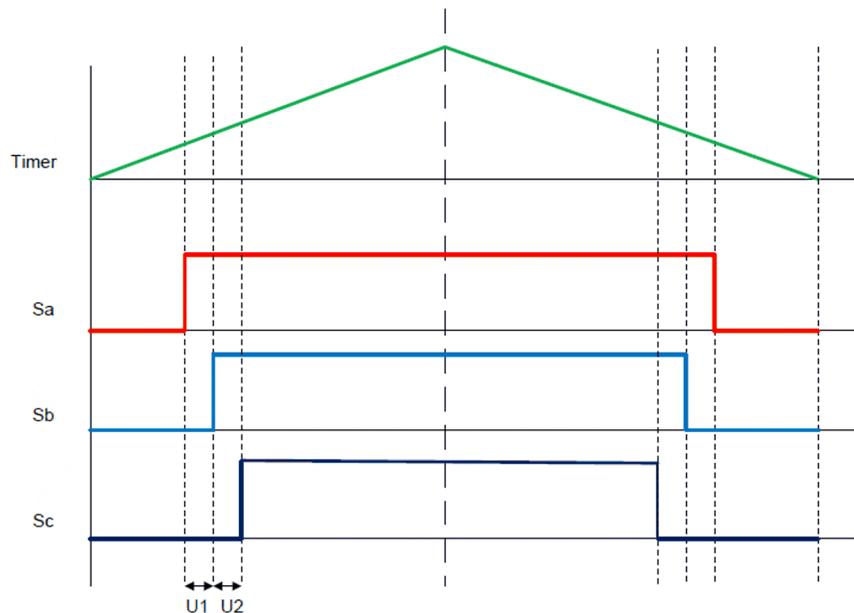
Figure 2-15. Active Vector Durations During Zero Crossing and Low Modulation Index

Designers ideally prefer to have an accurate and fast-settling current sensing to enable the very minimum active vector duration, which offers the following advantages.

- Reduces the current sensing complexity and hence reduces actual current distortion at zero-crossing, low modulation index and sector changes (every 60° interval)
- Reduces the software overhead in determining the winding currents during the lower active vector duration; the software algorithm may use mathematical prediction or PWM phase advancing or delaying in such scenarios.

To achieve very minimum vector duration requires reducing the overall delay in the current sensing path. This task can be achieved by using a fast current sensing (using a fast amplifier with high slew rate), using a fast ADC with minimum sample & hold time, and by optimizing the dead time.

3 Implementation of Single-Shunt Phase Current Reconstruction

As previously mentioned, the active voltage vectors must be long enough to reliably measure the dc link current during every PWM switching interval. In case the active vector duration is less than the minimum duration in Equation 2, PWM duty should be modified to ensure measurement time. This application report describes two methods for PWM compensation:

- The first solution is duty cycle compensation which keeps a symmetric PWM.
- The second solution is phase shift compensation that keeps average output voltage.

3.1 Duty Cycle Compensation

This method is relatively simple and can be used with same ePWM settings for symmetric SVPWM. After finding maximum and minimum duty cycle, the maximum duty cycle is extended up to minimum active duration if the V1 vector between maximum and middle duty cycle is less than the minimum active duration get in Equation 2. Also, the minimum duty cycle should be shortened up to minimum active duration if the V2 vector between middle and minimum duty cycle is less than the minimum active duration. The PWM channel with midrange duty cycle remains unchanged.

In this method, the distortion of the phase current is relatively large because average output voltage is not same with the original output voltage command.
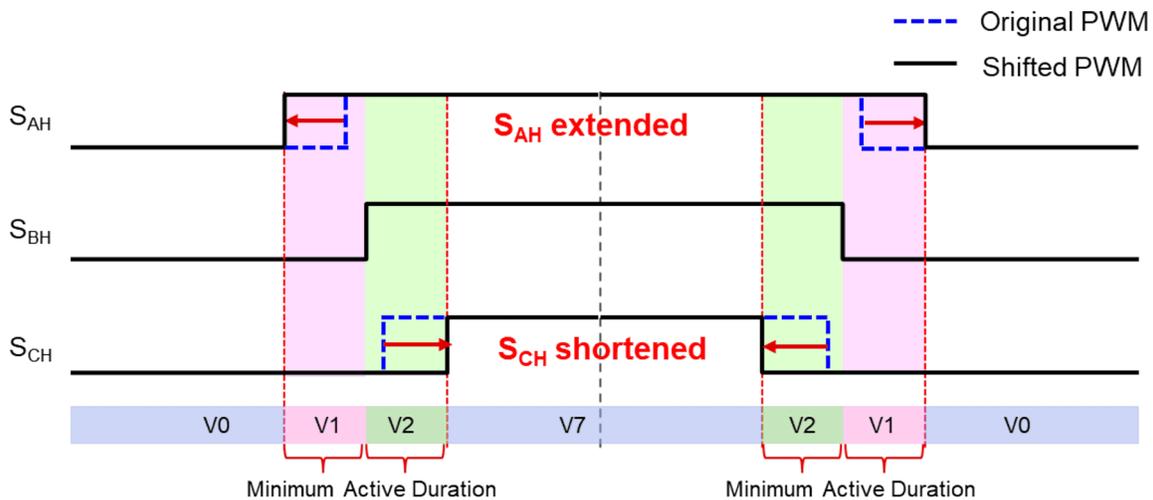

Figure 3-1. PWM Duty Cycle Compensation

If the phase currents should be sampled at every control cycle, V1 and V2 should always have sufficiently large active voltage duration. However, if the current control is performed once every multiple PWM periods, this duty cycle compensation method can be a good solution for single-shunt current measurement because phase current distortion happens just one time for multiple PWM periods. The *Synchronization Diagram of the Control* image in the *Measurement Process* section of *Three phase current measurements using a single line resistor on the TMS320F240* (BPRA077) shows this example that the current control is performed once every five PWM periods. Then only two dc link current measurements are required to get the phase currents every five PWM periods.

This method is available to the applications that do not need high current bandwidth. On the contrary, for the high current bandwidth, another PWM compensation method explained next chapter will be good solution.
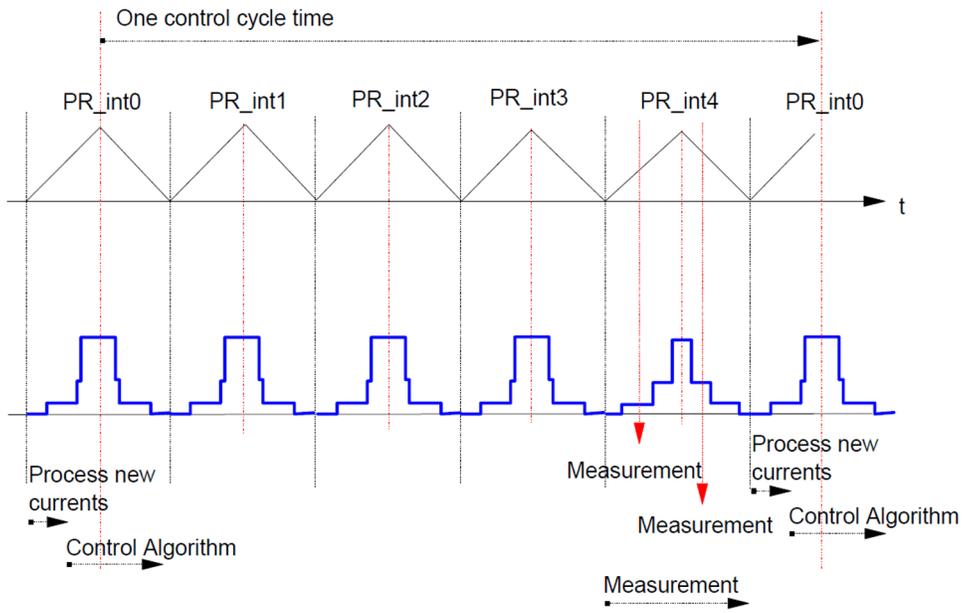
Figure 3-2. Advanced Duty Cycle Compensation

3.2 PWM Phase Shift Compensation

This method is more complex than the duty cycle compensation because it is implemented with asymmetric PWM. It means that both CMPA and CMPB values in ePWM module should be updated with different value depending on the value to be shifted. This method has some advantage such as same output voltage with original output voltage command. Also, it can be widely used in many applications because it doesn't rely on any motor and system parameters, even though it has some disadvantage such as high THD and acoustic noise than the two- or three-shunt solution.

If dc link currents are sampled at PWM down count such as Figure 2-12, V1 and V2 vector duration on right side of SVPWM should have enough large than minimum active duration. To do this, first, find maximum and minimum duty cycle. The maximum duty cycle is shifted to the right direction to get a minimum active duration if the V1 vector between maximum and middle duty cycle is less than the minimum active duration get in Equation 2. Also, the minimum duty cycle is shifted to the left direction to get a minimum active duration if the V2 vector between middle and minimum duty cycle is less than the minimum active duration. The PWM channel with midrange duty cycle remains unchanged. Figure 3-3 shows the PWM phase shift compensation method explained above.
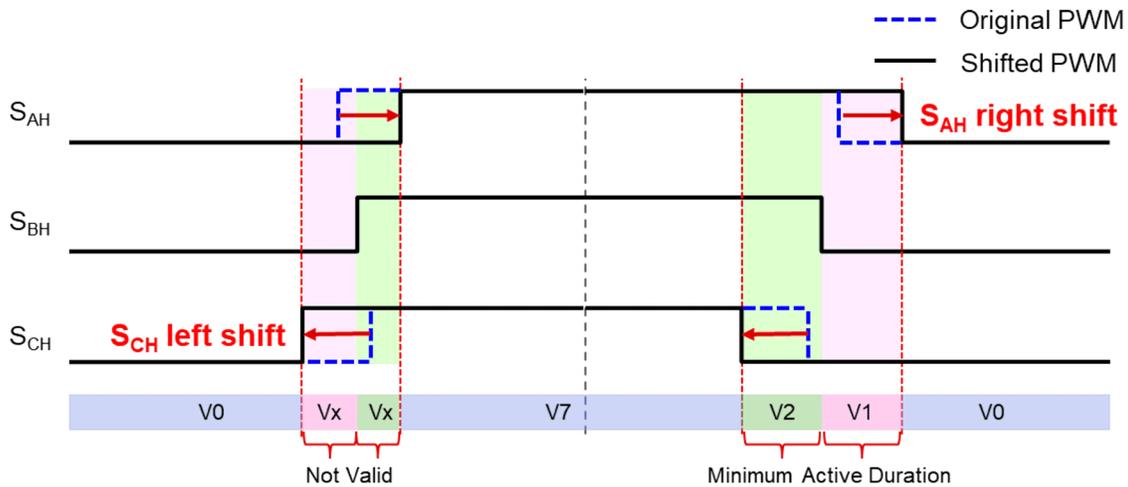
Figure 3-3. PWM Phase Shift Compensation

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Implementation of Single-Shunt Phase Current Reconstruction

Figure 3-4 shows the software flowchart of this method including ADC sampling point calculation. The CMPA and CMPB in EPWMx are newly calculated to have minimum active duration. It is necessary to know which sector the voltage reference output is in to determine which PWM channel have to be updated. Equation 4 shows the equation that was introduced in *Space-Vector PWM with TMS320C24x/F24x Using Hardware and Software Determined Switching Patterns* to determine the sector.

$$V_{ref1} = V_{\beta\_ref}$$

$$V_{ref2} = \sin 60 \times V_{a\_ref} - \sin 30 \times V_{\beta\_ref}$$

$$V_{ref3} = -\sin 60 \times V_{a\_ref} - \sin 30 \times V_{\beta\_ref}$$

$$N = \text{sign}(V_{ref1}) + 2 \times \text{sign}(V_{ref2}) + 4 \times \text{sign}(V_{ref3})$$

where,

$$\text{sign}(V_{refx}) = \begin{cases} 1 : \text{if}(\text{sign}(V_{refx})) > 0 \\ 0 : \text{if}(\text{sign}(V_{refx})) \leq 0 \end{cases}$$

(4)

N	1	2	3	4	5	6
Sector	2	6	1	4	3	5
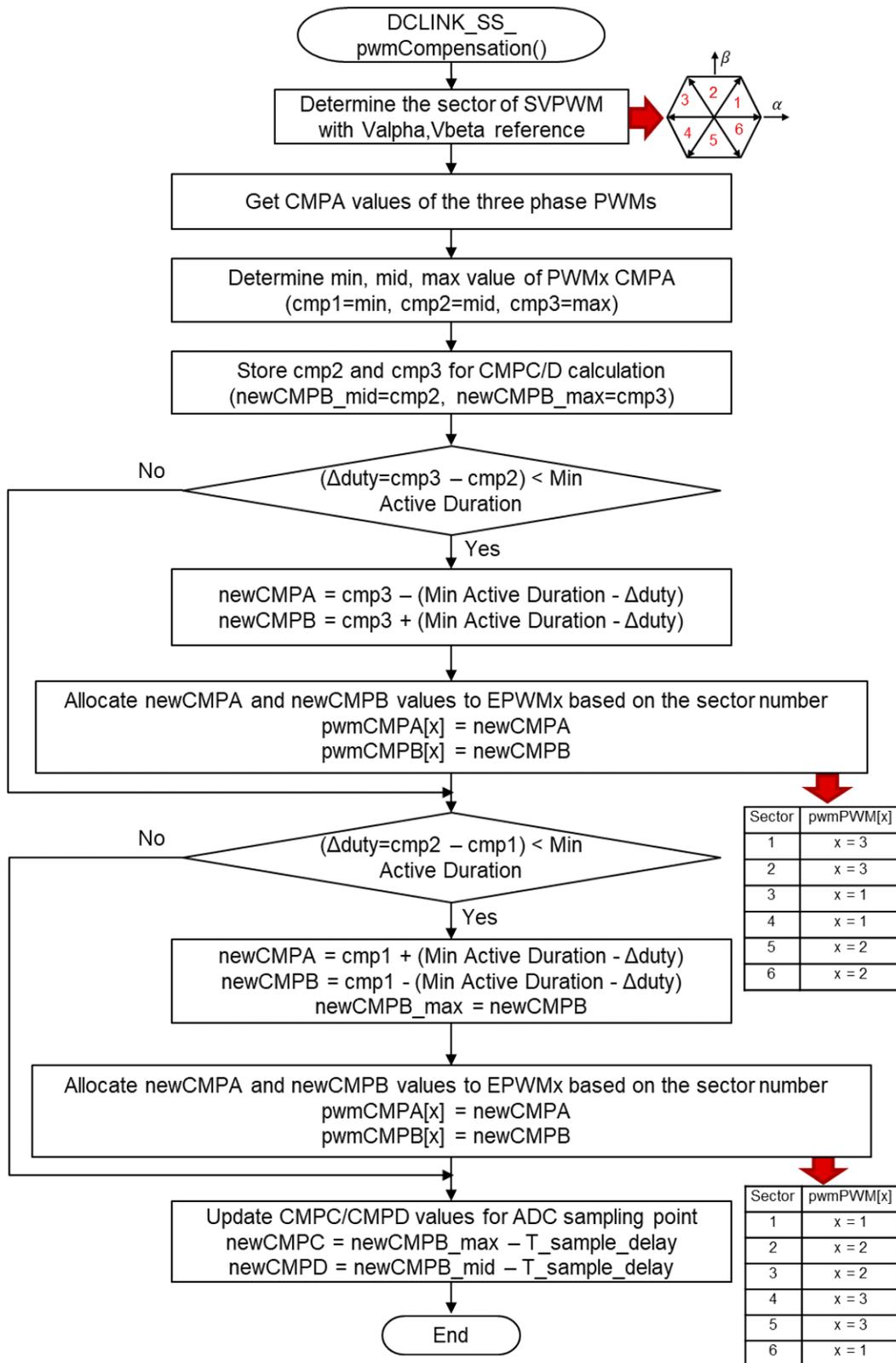
Figure 3-4. Flowchart of PWM Phase Shift Compensation

3.3 Current Reconstruction

The sampled dc link currents based on the timing diagram on Figure 2-12 can be reconstructed to three-phase currents by using the information in Table 3-1. The sector number calculated in Equation 4 is used here. The first

sampled dc link current ($I_{dc\_sample1}$) is measured at the first active vector duration during EPWMx down counter. And, the second dc link current ($I_{dc\_sample2}$) is measured at the second active vector duration during the same EPWMx down counter. The last one that was not directly measured from shunt can be calculated by using the principle of Kirchhoff's Current Law (KCL) that the sum of the currents into a single node equals zero.

Table 3-1. Phase Current Reconstruction Based on Sector Number

Sector	Phase Current (Ia, Ib, Ic)
1	$I_c = -I_{dc\_sample1}$, $I_a = I_{dc\_sample2}$, $I_b = -(I_a + I_c)$
2	$I_c = -I_{dc\_sample1}$, $I_b = I_{dc\_sample2}$, $I_a = -(I_b + I_c)$
3	$I_a = -I_{dc\_sample1}$, $I_b = I_{dc\_sample2}$, $I_c = -(I_a + I_b)$
4	$I_a = -I_{dc\_sample1}$, $I_c = I_{dc\_sample2}$, $I_b = -(I_a + I_c)$
5	$I_b = -I_{dc\_sample1}$, $I_c = I_{dc\_sample2}$, $I_a = -(I_b + I_c)$
6	$I_b = -I_{dc\_sample1}$, $I_a = I_{dc\_sample2}$, $I_c = -(I_a + I_b)$

Figure 3-5 shows the flowchart of three phase current reconstruction with two sampled dc link currents and sector information. This function is called right after reading the ADC data in main control loop (mainISR).
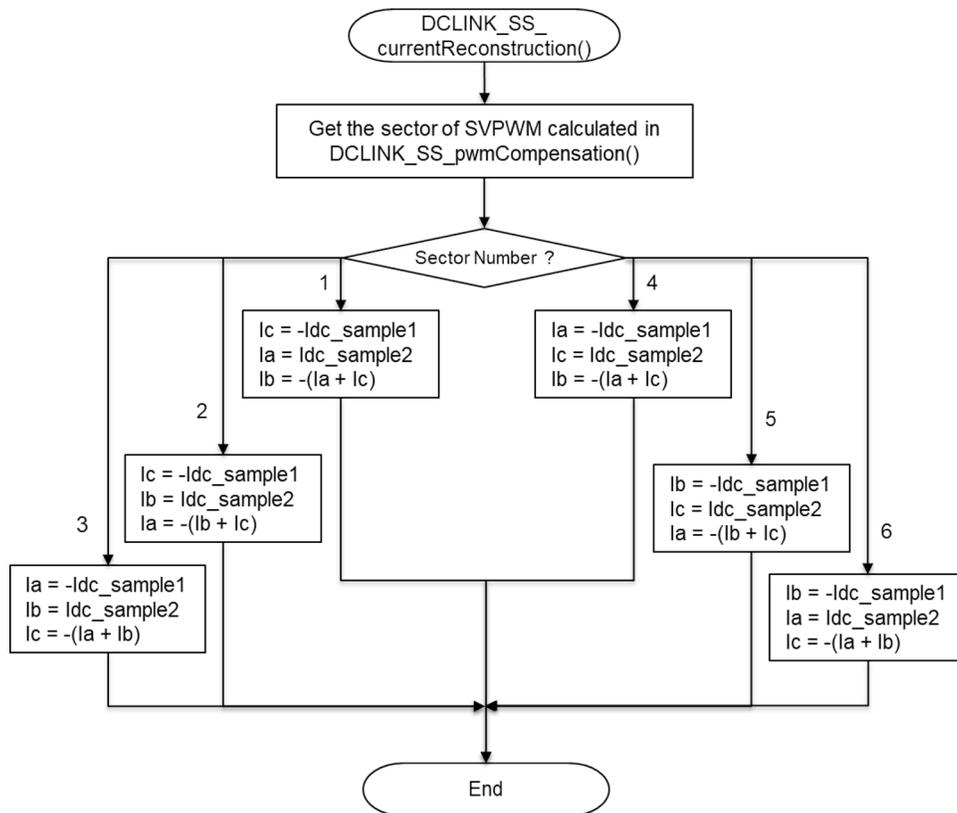
Figure 3-5. Flowchart of Phase Current Reconstruction

4 Sensorless FOC With Single-Shunt Measurement

The sensorless observer, which is called as FAST™, integrated in F28004xC and F28002xC was upgraded to version 2.0 with MotorControl SDK. The new version of FAST was implemented with floating point. It improves the accuracy of parameter estimation and the sensorless performance at low speed.

The current reconstruction algorithm and PWM phase shift compensation for single-shunt measurement was implemented and verified with MotorControl SDK. As shown in Figure 4-1, two new modules have been added. The first one is the module for three-phase current reconstruction from sampled dc link current by using space vector's sector information. The second one is the module for PWM compensation to get high enough active vector duration in unmeasurable area. In this module, CMPC and CMPD in ePWM type-4 were selected as ADC SOC trigger sources for sampling dc link current.
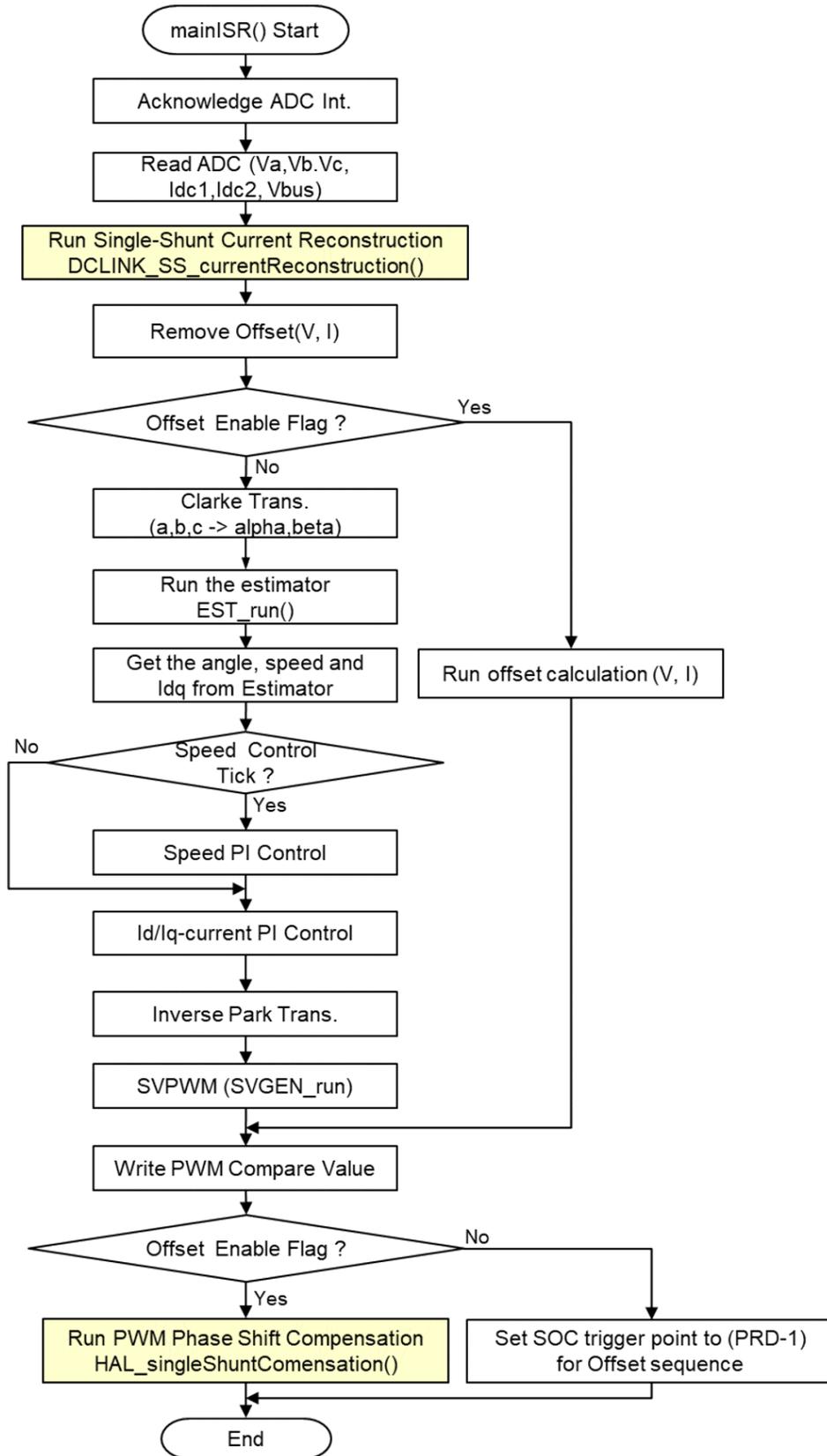
Figure 4-1. Flowchart of Main Control Loop With Single-Shunt for Sensorless-FOC

Figure 4-2 shows the function of PWM compensation, which is called from main control loop shown in Figure 4-1, for single shunt by using C2000™ device drivers in C2000Ware. This function calls PWM Phase Shift Compensation (DCLINK_SS_pwmCompensation) function as shown in Figure 3-4.
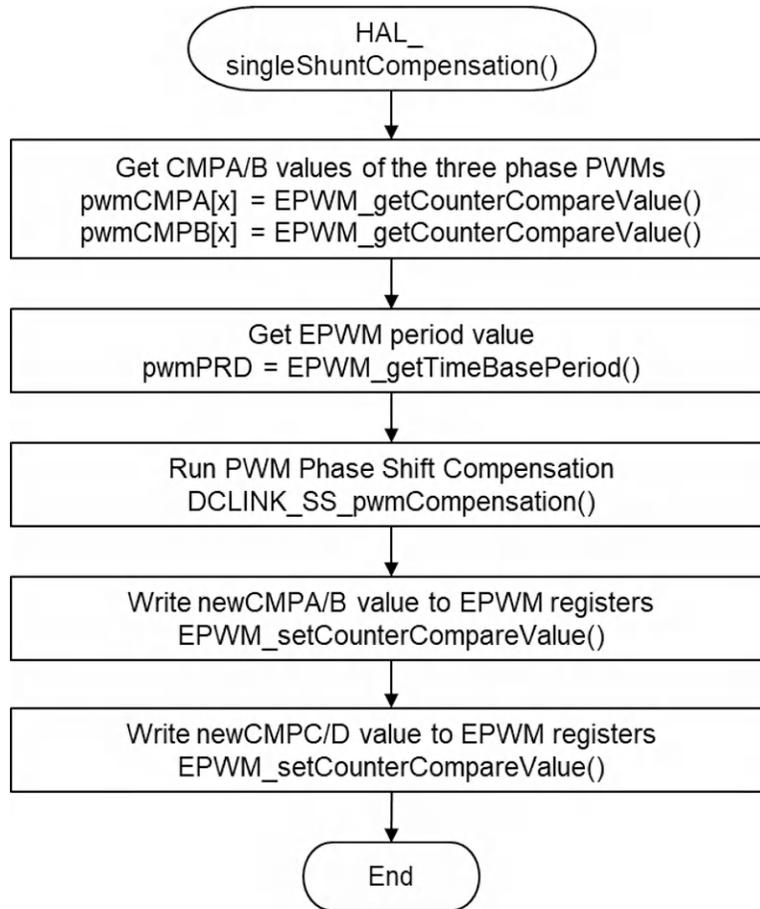
Figure 4-2. Flowchart of HAL_singleShuntCompensation Function

Figure 4-3 shows the timing diagram for ADC sampling and ADC interrupt. CMPC and CMPD in ePWM type-4 were selected as ADC SOC trigger sources for sampling dc link current. So, CMPC and CMPD values are updated every cycle based on shifted PWM CMPB value. Because InstaSPIN-FOC solution needs phase voltage measurement, phase output voltages (Va, Vb, Vc) and dc link voltage are sampled at ePWM1 zero counter. The interrupt service routine (ISR) is triggered by the end of conversion (EOC) of the ADC. In the ISR, the current information measured on the PWM down counter prior to one cycle is used for current control.
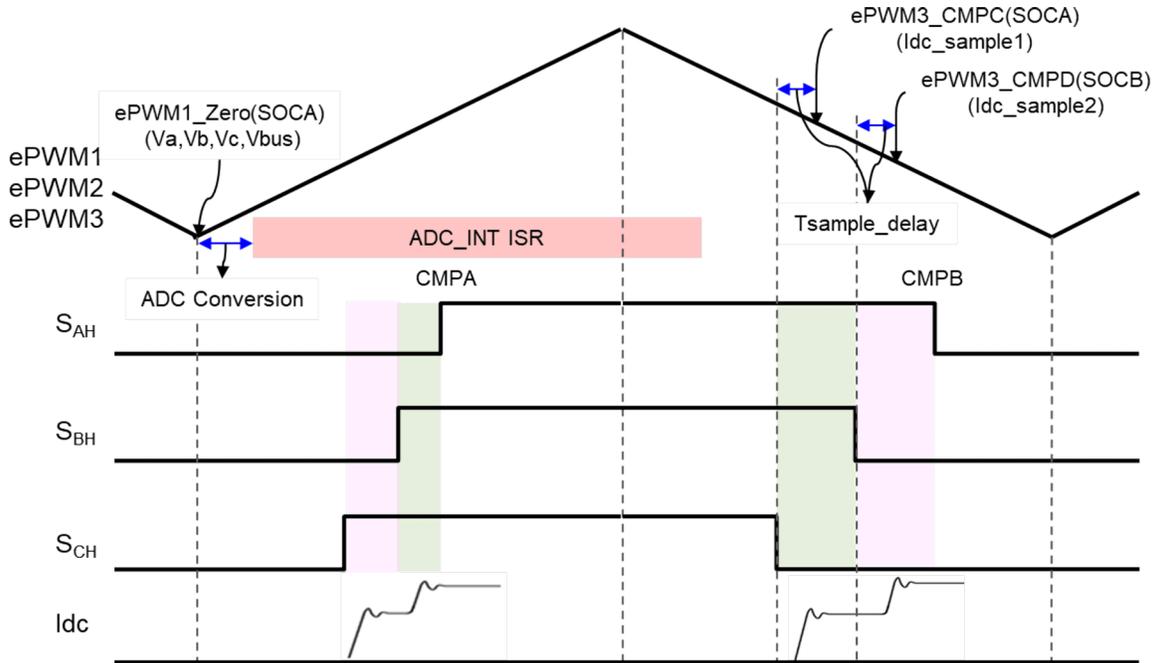
Figure 4-3. Timing Diagram of ADC Sampling and ADC Interrupt

5 Hardware Consideration for Single-Shunt Current Sensing

There are two things to be considered in the current sensing hardware. One is, as mentioned in Section 2.2, the single-shunt current measurement technique requires an OP-AMP that has a relatively higher slew ratio than the two or three shunt current measurement. The other is a sensing circuit with differential amplifier configuration plus offset voltage.

5.1 Slew Rate

A rising time of operational amplifier directly affect the current sensing delay as shown in Figure 2-11. So, when using the single-shunt technique, the slew rate parameter of op amp should be carefully considered. If the settling time of feedback signal and ADC sampling time are fixed parameters, the op-amp slew rate is important parameter to minimize duty cycle to be phase shifted. Generally, a slew rate of 10V/µs or more is recommended for single-shunt measurement.

F28004x, which is one of C2000 Generation 3 MCU in entry to middle performance portfolio, has Programmable Gain Amplifier (PGA) for amplifying an input voltage. The integrated PGA helps to reduce cost and design effort for many control applications that require external, standalone amplifier. Table 5-1 shows that the slew rate of the integrated PGA in F28004x is high enough for single-shunt measurement under all gain setting conditions.

Table 5-1. F28004x PGA Slew Rate

Parameter	Test Conditions	Typical Value
Slew Rate	Gain = 3	20 V/us
	Gain = 6	37 V/us
	Gain = 12	73 V/us
	Gain = 24	98 V/us

5.2 Current Sensing Circuit

In order to minimize common mode noise, a differential amplifier circuit is good solution for single-shunt feedback. Also, offset voltage circuit needs to avoid operation in the noise area near the zero voltage even though the current being measured is unipolar during motoring mode. When using F28004x with built-in op-amp, sensing circuit can be configured only by using external R, C passive components like Figure 5-1. The output voltage of PGA can be calculated by using Equation 5.

$$V_{PGA\_OUT} = \frac{R_{fbk} \times (I_{dc} \times R_{shunt} - V_{offset})}{R_{in} + R_{fbk}} \times PGA\_GAIN$$

For example,

$I_{dc} = 50 \text{ A}$

$R_{shunt} = 2 \text{ m}\Omega$

$R_{fbk} = 20 \text{ K}\Omega$

$R_{in} = 1 \text{ K}\Omega$

$V_{offset} = 0.5 \text{ V}$

$PGA\_GAIN = 24$

$$V_{PGA\_OUT} = \frac{20 \times ((50 \times 0.002) - 0.5)}{20 + 1} \times 24 = 2.857 \text{ V}$$

$$USER\_ADC\_FULL\_SCALE\_CURRENT\_A = \frac{R_{in} + R_{fbk}}{R_{fbk} \times R_{shunt} \times 24} \times 3.3 = 72.1875$$

(5)
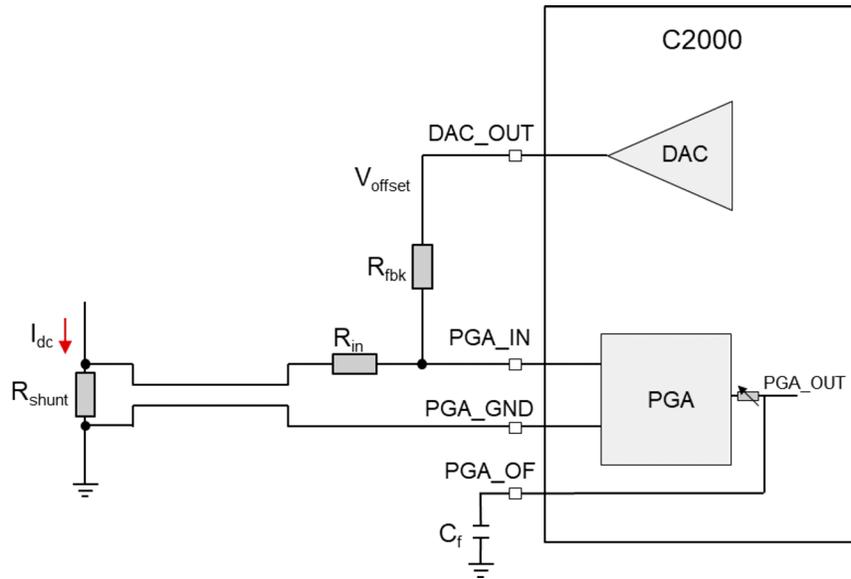
Figure 5-1. Current Sensing Circuit for F28004x With Internal Op-Amp

Figure 5-2 shows a typical current sensing circuit that uses an external differential amplifier that has an offset reference voltage by resistor divider and voltage follower. Voffset and Vout can be calculated by using Equation 6 and Equation 7, respectively.

$$V_{offset} = \frac{R_2}{R_1 + R_2} \times 3.3$$

(6)

$$V_{out} = (I_{dc} \times R_{shunt}) \times \frac{R_{fbk}}{R_{in}} + V_{offset}$$

$$USER\_ADC\_FULL\_SCALE\_CURRENT\_A = \frac{R_{in}}{R_{fbk} \times R_{shunt}} \times 3.3$$

(7)
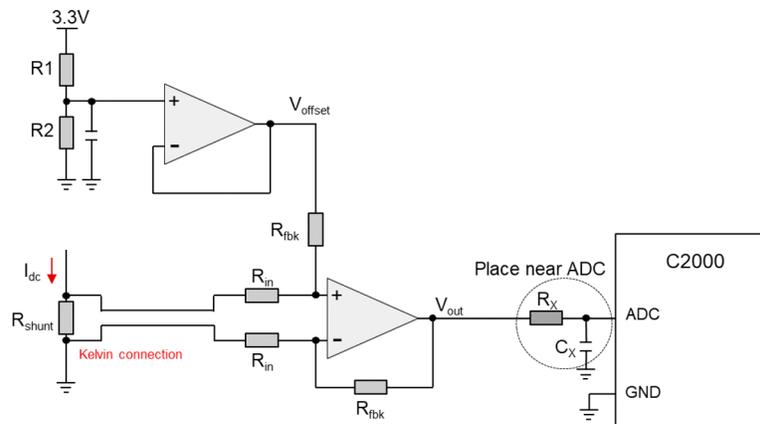
Figure 5-2. Current Sensing Circuit for F28002x With External Op-Amp

6 Test Results

Figure 6-1 shows the motor test setup used for verifying single-shunt solution. The inverter board used for this testing is DRV8312EVM_revD that has a shunt resistor in the inverter dc-link side as well as thee shunt resistors in FET low side. Also, F280049C controlCARD and TMDSADAP180TO100 adapter card was used for this test.
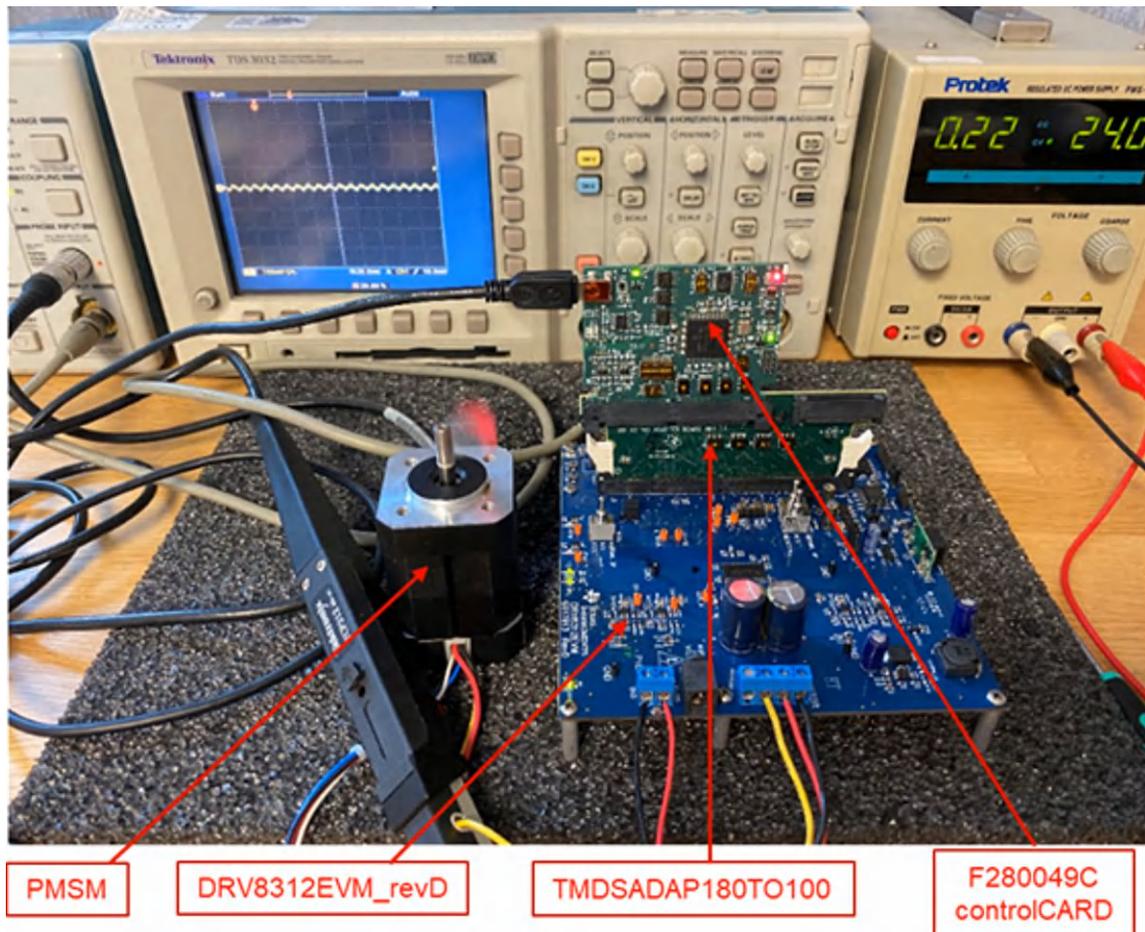

Figure 6-1. Motor Test Setup

In other to verify the proposed solution in this application report, firstly open-loop control which is called V/F without current control was carried out.

The delay time in current sensing loop for the inverter board used in this test is as following

- T_r = 100 ns (Rise time of amplifier including power switches(MOSFET/IGBT) turn on time)
- T_s = 100 ns (Settling time of amplifier)
- $T_{S\&H}$ = 170 ns (ADC Sample and Hold time, 1 + (14) + 2 = 17 SYSCLK)
- T_{DT} = 10 ns (Dead-time between top and bottom switch)
- T_{PD} = 38 ns (Gate driver propagation delay)

From Equation 2 and Equation 3, the two critical parameters for dc-link current sampling can be calculated as following.

T_MinAVDuration	$= T_{DT} + T_r + T_s + T_{S\&H}$
	$= 10 + 100 + 100 + 170 = 380$ ns => 38 SYSCLK cycles (@100 MHz)
T_SampleDelay	$= T_{DT} + T_{PD} + T_r + T_s$
	$= 10 + 38 + 100 + 100 = 248$ ns => 25 SYSCLK cycles (@100 MHz)

Figure 6-2 shows dc-link current measured at the voltage vector of sector 1. Because the T_SampleDelay is set as 25 SYSCLK (250 nsec), the first ADC SOC is triggered after 250 nsec based on the falling edge of PWMC_TOP (S_{CH}). It was confirmed that a clean signal can be sampled and converted by ADC without switching noise at the sensing point.
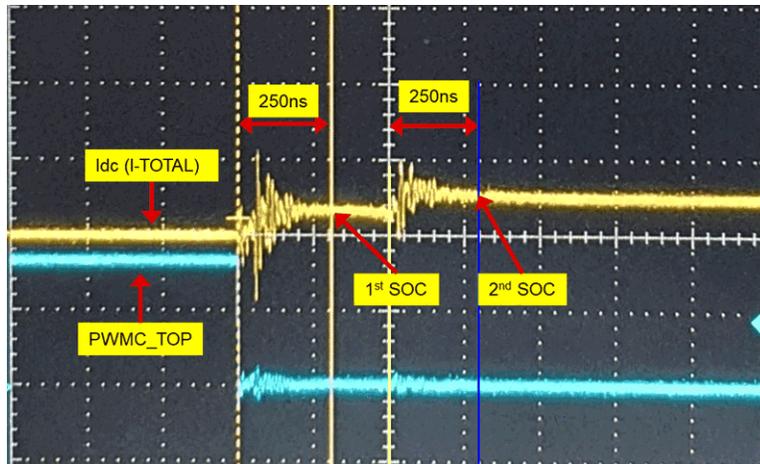
Figure 6-2. DC-Link Current (@ sector 1, Vdref = 1 V, Vqref = 0 V), 200 ns/div

Figure 6-3 and Figure 6-4 show before and after applying the PWM compensation, respectively. Figure 6-3 shows the reconstructed phase current from dc link current without PWM compensation. This waveform has lots of distortion because the current are not properly measured at the output vector that has a small active duration less than a minimum active duration.
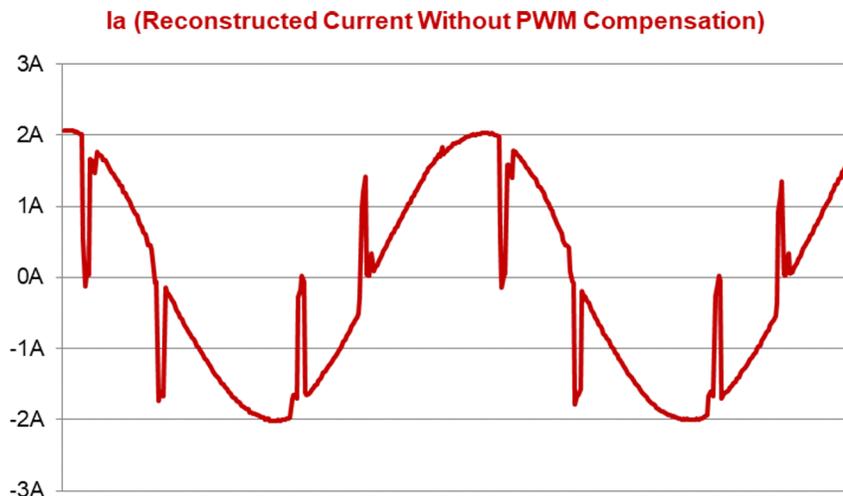

Figure 6-3. Reconstructed Phase Current Without PWM Compensation During Open-Loop V/F Operation (1.4V/20Hz)

On the contrary, Figure 6-4 shows the reconstructed phase motor current with PWM phase shift compensation described in Section 3.2. It shows that the phase current is reconstructed without any current distortion.
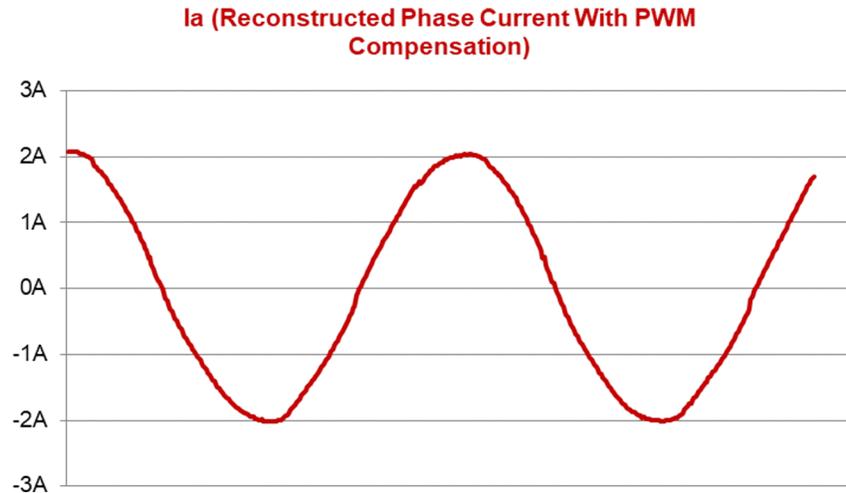
Figure 6-4. Reconstructed Phase Current With PWM Phase Shift Compensation During Open-Loop V/F Operation (1.4V/20Hz)

Figure 6-5 shows a measured oscilloscope waveform of phase-A current while running at 30Hz with closed-loop current and speed PI regulator. Since no load current of the motor used in this test is too small to determine whether PWM compensation and current reconstruction algorithm work well, it was measured by applying some loads to the motor shaft by hand.
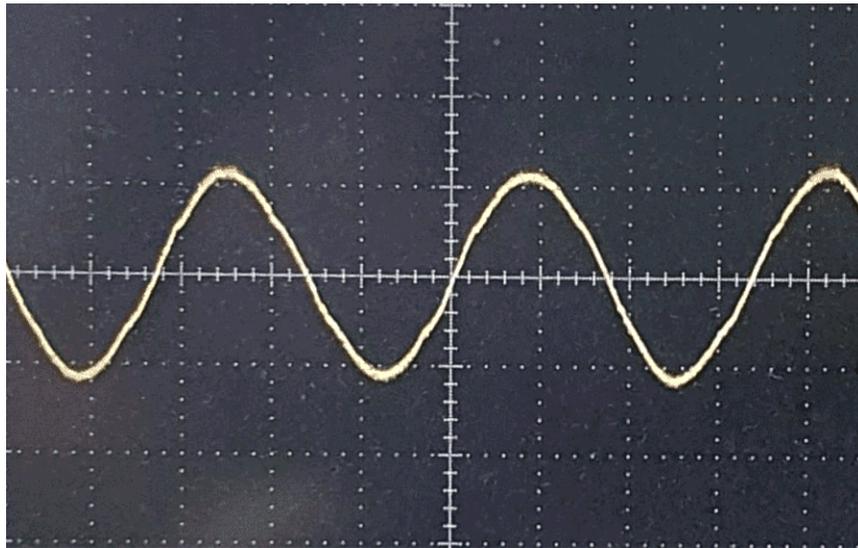
Figure 6-5. Measured Current in Phase A During Steady-State Operation at 30Hz (10ms/div, 1A/div)

Figure 6-6 shows reconstructed phase current captured from MCU during operation at 30Hz same as Figure 6-5. The Figure 6-5 and Figure 6-6 are almost identical waveform. It means that the PWM compensation and current reconstruction algorithm in this application report work well in load condition.
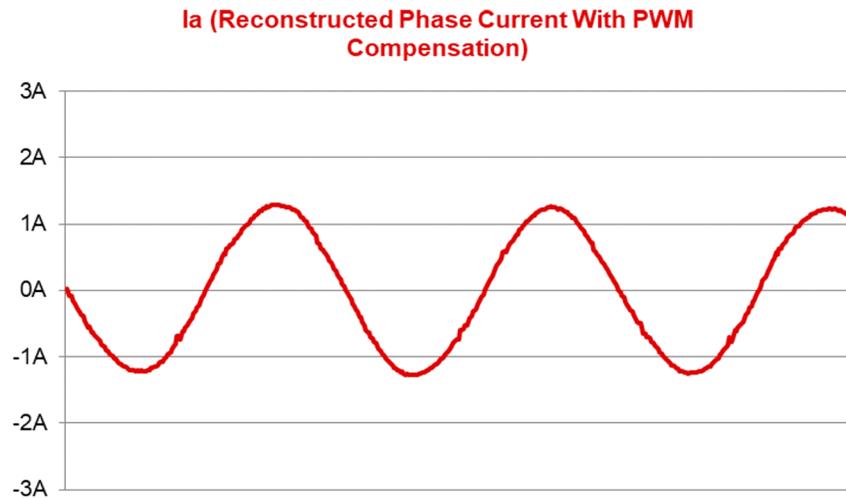
Figure 6-6. Reconstructed Current in Phase A During Steady-State Operation at 30Hz

7 Summary

This application report discussed Sensorless Field Oriented Control of a Permanent Magnet Synchronous Motor with a single-shunt dc link current measurement. The single-shunt measurement technique is suitable for cost-sensitive or PCB space-sensitive applications. This document showed the PWM compensation method and current reconstruction technique to get three-phase motor current with a single dc-link current sensor.

It was also verified that the PWM phase shift compensation method that causes minimum distortion on the output voltage matches well with InstaSPIN-FOC that requires output phase voltage to be measured by ADC. This solution also can be applicable to other sensorless FOC such as TI's eSMO solution. This solution was implemented and verified with F28004x and DRV8312EVM based on MotorControl SDK. Since the reference code was implemented with floating-point, other C2000 Generation 3 MCUs such as F28002x can be also well matched.

8 References

- Texas Instruments, Current Sensing With <1-us Settling for 1-,2-, and 3-Shunt FOC Inverter Reference Design
- Texas Instruments: *Three phase current measurements using a single line resistor on the TMS320F240* (BPRA077)
- Texas Instruments: *Space-Vector PWM with TMS320C24x/F24x Using Hardware and Software Determined Switching Patterns*
- Texas Instruments: *InstaSPIN-FOC and InstaSPIN-MOTION User's Guide*
- MotorControl Software Development Kit (SDK) for C2000 MCU (C2000WARE-MOTORCONTROL-SDK)
- Texas Instruments: *Sensorless-FOC with Flux-Weakening and MTPA for IPMSM Motor Drives*
- Texas Instruments: *TMS320F28004x Microcontrollers Data Manual*
- F280049C controlCARD Evaluation Module
- Three Phase BLDC Motor Kit with DRV8312

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