FM3 Microcontroller, Field Weakening Control On Wash Machine

This Application Note describes wash machine's field weaken control algorithm. This solution is either adapted for PMSM or BLDC.

Contents

1 Introduction

1.1 Purpose

This application note describes wash machine's field weaken control algorithm.

This solution is either adapted for PMSM or BLDC.

1.2 Definitions, Acronyms and Abbreviations

PMSM: Permanent Magnet Synchronous Motor

BLDC: Brush less DC Motor

V_{DC}: DC bus voltage

Vsq: Voltage on q axis of d/q coordinates in FOC algorithm

Vsd: Voltage on d axis of d/q coordinates in FOC algorithm

Isq: Current on q axis of d/q coordinates in FOC algorithm

Isd: Current on d axis of d/q coordinates in FOC algorithm

N: Rotor rotation speed

i_{dref}: d-axis reference current

i_{qref}: q-axis reference current

I_{sMAX}: Max limit of current scalar

V_{sMAX}: Max limit of voltage scalar

DD: Direct drive

λ_f: Flux link-age

ω_r: Rotor electrical angular velocity

1.3 Document Overview

The rest of document is organized as the following:

Chapter 2 explains the principle of field weakens.

Chapter 3 describe the field weaken algorithm besides on FOC.

Chapter 4 Verification the weaken algorithm on DD wash machine

1.4 Reference Documents

Lajos Hanzo, Editor in Chief, “Control of Electrical Drive Systems”. IEEE Press Editional Board. NO. 5. pp.246 – 269,1979.

2 Field Weakening Control

This chapter introduces the Flux weakening control beside on vector control

2.1 Overview

The torque and speed of the variable-speed drive system controlled by a PWM inverter is limited by current and voltage rating of the inverter and electrical machine. In this section the optimal flux weakening method, which lets the electrical machine generate maximum torque under the given current and voltage constraints, is described for an AC machine driven by a three-phrase PWM inverter.

2.2 Constraints of Voltage and Current to AC Machine

The inverter, which provides variable-voltage and variable-frequency electrical power to an AC machine, has limited voltage and current ratings because of the components of the inverter itself and input voltage to the inverter. Also, even if the inverter has large enough voltage and current ratings, that AC machine have constraints in current and voltage ratings because of insulation, magnetic saturation, and thermal limit. Because the thermal time constant of an AC machine is usually much larger than that of the inverter, several hundred percentage of rated current can flow into AC machine for a short time. Thus, the torque at a constant torque region, where the torque of the AC machine is only limited by the current constraints, can be increased by several times of the rated torque. Usually, the voltage ratting of the inverter is set to equal to the ratted voltage of the AC machine. However, the current ratting of the inverter is sometimes set as serial times that of the AC machine to get higher acceleration and deceleration torque, especially in PMSM or BLDC driving application.

2.2.1 Voltage Constraints

Figure 1. VVVF Inverter with Pulse Width Modulation (PWM).

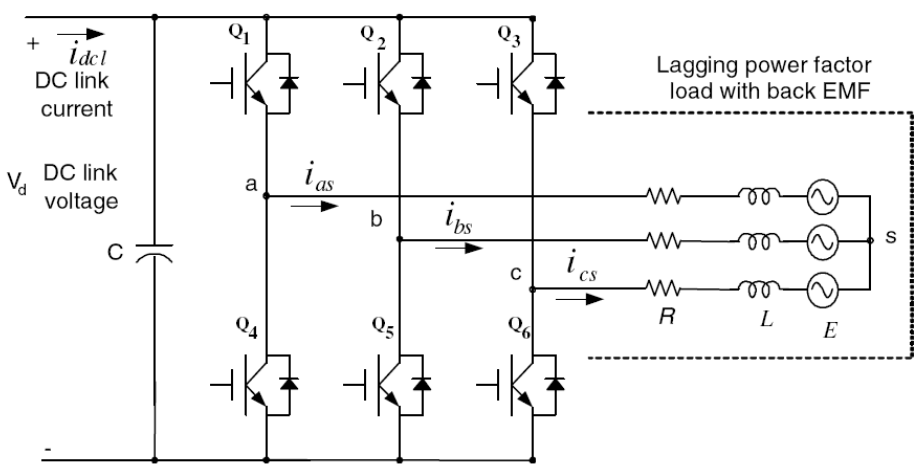


Figure 1 is a circuit of topology of a three phrase PWM inverter. The inverter takes DC voltage as an input and transforms it to AC voltage and output to AC load. From Electrical and Electronic Mathematic, the maximum phrase voltage, V_{sMAX}, is decided by DC link voltage, V_{DC}, of a PWM inverter and the PWM method. If the space vector PWM (SVPWM) method is used, V_{sMAX} obtained in the linear control range is $V_{DC}/\sqrt{3}$. With the consideration of some

margins because of the dead time of the inverter and the control voltage for the current regulation, the maximum phrase voltage, V_{sMAX} can be set as equation (2-1), where η can be 0.9-0.95.

$$V_{sMAX} = \frac{V_{DC}}{\sqrt{3}} \cdot \eta \qquad (2\text{-}1)$$

If the maximum phrase, V_{sMAX}, is decided by the inverter, then in the d/q axis stator voltage should satisfy equation (2-2) regardless of the reference frame.

$$V_{ds}^2 + V_{qs}^2 \le V_{sMAX}^2 \qquad (2\text{-}2)$$

2.2.2 Current Constraints

The maximum current to an AC machine, I_{sMAX}, is usually decided by the therml limit of the inverter or the AC machine itself. If the constraint is decided by the inverter, then the limitation condition of the current is set by the heat dissipation of switching and conduction losses of the switching power semiconductor. If the constraint is decided by the motor itself, then the current is decided by the motor's ratting current. In generally, to prevent the motor's iron and copper too heat, the maximum is always under the motor's ratting current. After I_{sMAX} is decided, the reference current should satisfy the equation (2-3) regardless of the reference frame.

$$i_{ds}^2 + i_{qs}^2 \le I_{sMAX}^2 \qquad (2\text{-}3)$$

2.3 Operating Region of Permanent Magnet AC Machine in Current Plane at Rotor Reference Frame

2.3.1 Operating Region Under Current and Voltage Constraints

The voltage and current constraint in equation (2-2) and (2-3) wash expressed in the d/q reference frame, but the constraints are presented in different planes, where one is voltage plane and the other is current plane. To communicate these two constraints, it can use the voltage equation of an AC machine. In this case, the voltage constraint can be represented in terms of the current by using the stator voltage equation of the permanent magnet AC machine in equation (2-4) and (2-5).

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_d \qquad (2\text{-}4)$$

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + \omega_r \lambda_f \qquad (2\text{-}5)$$

From equation (2-2), (2-4) and (2-5), the voltage constraint can be expressed in terms of the currents under the assumption of the steady-state operation or slow enough variation of the currents. Like as equation (2-6).

$$Z_{ds}^2 (i_d + \frac{\omega_r^2 L_q \lambda_f}{R_s^2 + \omega_r^2 L_d L_q})^2 + Z_{qs}^2 (i_q + \frac{\omega_r R_s \lambda_f}{R_s^2 + \omega_r^2 L_d L_q})^2$$

$$+2\omega_r R_s (L_d - L_q) \left(i_d + \frac{\omega_r^2 L_q}{R_s^2 + \omega_r^2 L_d L_q}\right)\left(i_q + \frac{\omega_r R_s}{R_s^2 + \omega_r^2 L_d L_q}\right) \le V_{sMAX}^2 \qquad (2\text{-}6)$$

Where Z_{ds} and Z_{qs} are defined as equation (2-7).

$$Z_{ds} = \sqrt{R_s^2 + (\omega_r L_d)^2} \qquad Z_{qs} = \sqrt{R_s^2 + (\omega_r L_q)^2} \qquad (2\text{-}7)$$

In the case of a surface-mounted PMSM (SMPMSM), because $L_d = L_q = L_s$, equation (2-6) can be forward simplified as equation (2-8).

$$(i_d + \frac{\omega_r^2 L_q}{R_s^2 + \omega_r^2 L_d L_q})^2 + (i_q + \frac{\omega_r R_s}{R_s^2 + \omega_r^2 L_d L_q})^2 \le \frac{V_{sMAX}^2}{R_s^2 + (\omega_r L_s)^2} \qquad (2\text{-}8)$$

From above equation, if the$L_d \neq L_q$, the area satisfied is the interior of the dotted ellipse as shown in Figure (2-2); if$L_d = L_q$, the area satisfied is the interior of the dotted cycle as shown in Figure (2-3). And for the system state, only at the public zoom of the current limit curve and voltage limit curve.

Figure 2. Phrase Voltage and Current Limit on the Station of L_d 〖≠L〗_q

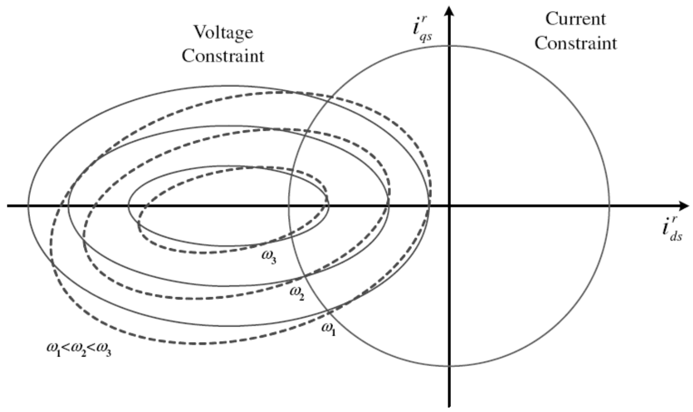
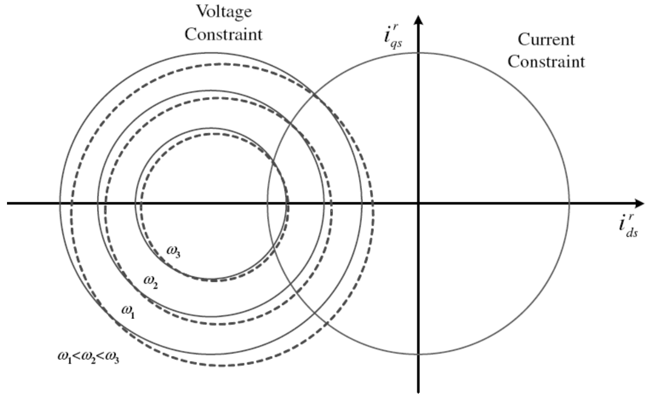


Figure 3. Phrase Voltage and Current Limit on the Station of L_d 〖=L〗_q



As mentioned before, the current constraint is expressed as the inner part of a circle, whose centre is the origin of the current plane. The voltage constraint is expressed as the inner part of an ellipse. If the voltage drop in the stator resistance is neglected, the major axis of the ellipse lies on the d axis of the current plane. And its centre is constant regardless of the operating speed of the permanent magnet machine. However, the length of major and minor axes of the ellipse decrease as the operation speed increases. If the voltage drop in the stator resistance is considered, the major axis has an offset angle with the d axis, and the centre of the ellipse also varies according to the speed. Under the given constraints, the possible operating area in the current plane is the common inner part of the interior of both ellipse and circle. As the operating speed increases, the area by the voltage constraint shrinks and the common area also shrinks. Above a certain speed, there is no common inner area, and the operation of the electric machine at that speed is impossible, satisfying both current and voltage constraints.

2.3.2 Operating Region According to the Parameters of the Permanent Magnet AC Machine

The output characteristics of a permanent magnet synchronous machine are decided by the relative location of the center of the ellipse by the voltage constraint to the circle by the current constraint. The center is set by the parameters of the electric machine. So the permanent magnet motor driving system can be classified as a finite-speed drive system and an infinite-speed system. As shown in Figure (2-4).

Figure 4. Operating Regions according to the Parameters of the Permanent Magnet AC machines.

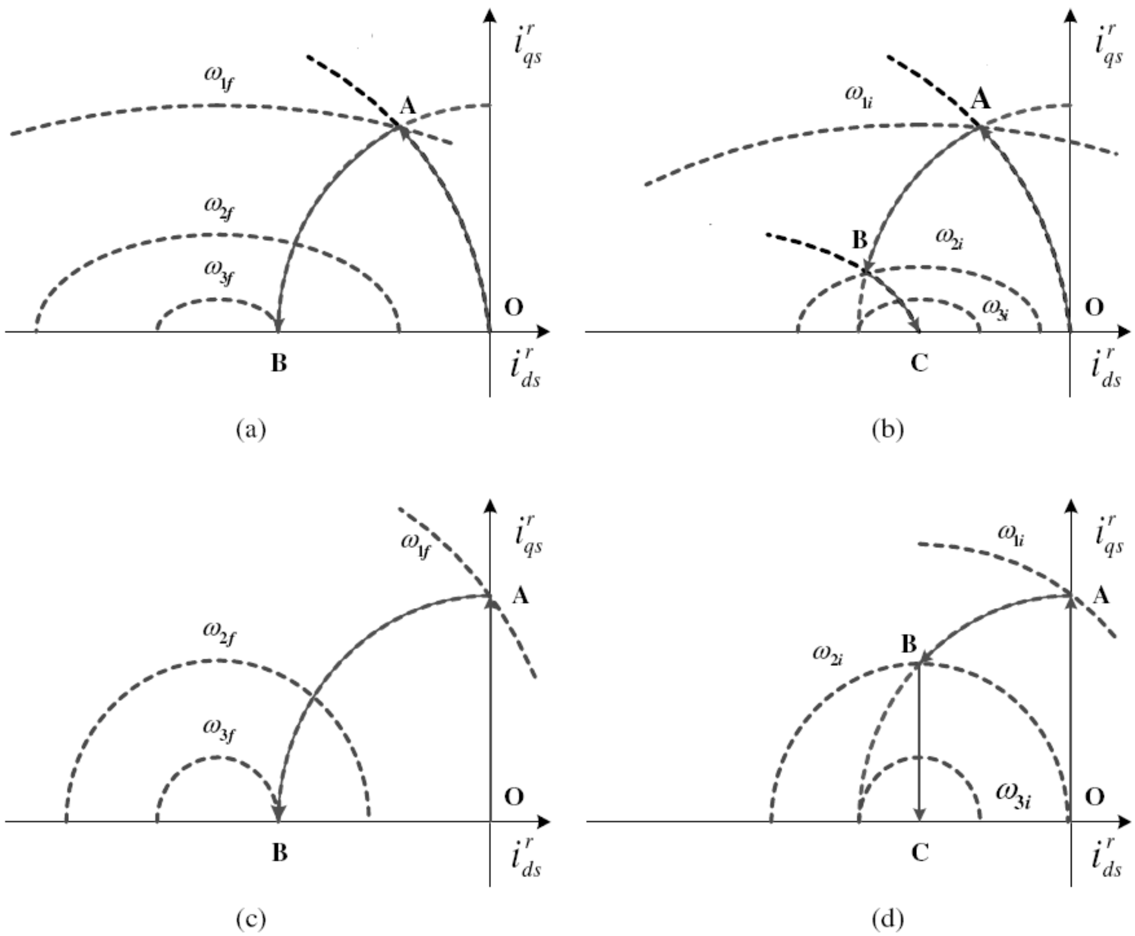


Figure 4, is the trajectory of the current operation in IPMSM. When speed run out of ω_{3f}, the system can not be control. It is a finite speed driving system that satisfy $\lambda_f \geq L_d I_{sm}$.

Figure 4b, is the trajectory of the current operation in IPMSM. In the figure, the center of the ellipse is inside of the circle and the maximum speed is not limited by electrical constraints. It is a infinite speed driving system. When speed running at ω_{1i}, the current moves on the curve by 'OA'. When speed up to ω_{2i}, the current moves on the bundary of current constraints circle, which is the curve "AB". However, above ω_{2i} the current moves not on the boundary of the current constraint circle but on the curve for maximum torque per voltage operation. It satisfy $\lambda_f \leq L_d I_{sm}$.

Figure (2-4)c, is the trajectory of the current operation in SMPMSM. When speed run out of ω_{3f}, the system can not be control. It satisfy $\lambda_f \geq L_d I_{sm}$.

Figure (2-4)d, is the trajectory of the current operation in SMPMSM. Analyzing it can be as Figure (2-4)b. It satisfy $\lambda_f \geq L_d I_{sm}$.

2.3.3 Ensure the Base Speed and Maximum Speed.

The speed up to which the machine is operated in the most torque mode is called the base speed, vb. In Figure 4 it is represented as ω_{1f} and ω_{1i} . Up to the base speed, the speed region is called the constant torque region, and above the base speed the region is called the flux weakening region. In the infinite-speed drive system, the speed where only voltage constraint limits the operating speed is called the critical speed, ω_c.

In particular, the IPMSM motor is seldom used in industry, because of it's difficulty control and madden material. So, this section's talk only focuses on the SMPMSM of infinite system. After neglecting the stator resistance voltage drop, the maximum possible operating speed can be derived for an SMPMSM as (2-9).

$$\omega_{c,SMPMSM} = \frac{V_{Smax}}{\sqrt{(L_S I_{Smax})^2 - \lambda_f^2}} \qquad (2\text{-}9)$$

From above talking, driving system's constraints has been ensured.

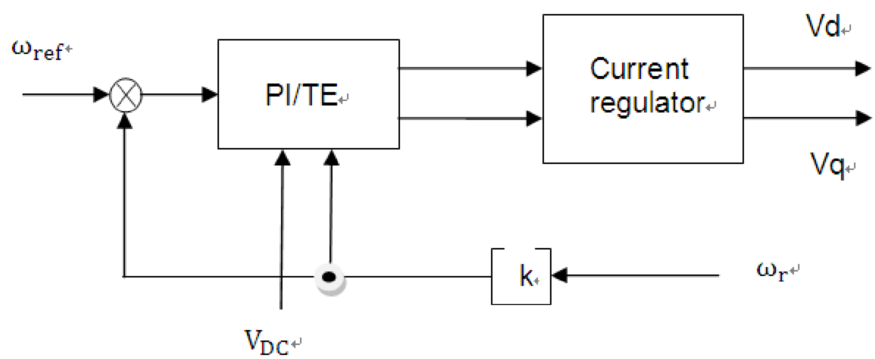
2.4 Field Weakening Control of PMSM

2.4.1 Overview

If the current reference is outside of the possible operation area shown in Figure (2-3), then actual current cannot follow the current reference. Hence, the drive system is out of control. By a proper flux weakening control method, the current reference can be set to achieve maximum available torque under the voltage and current constraints. This chapter will give available control method according 2.3's talk.

2.4.2 Field Weakening Control with Feed-Forward Compensation

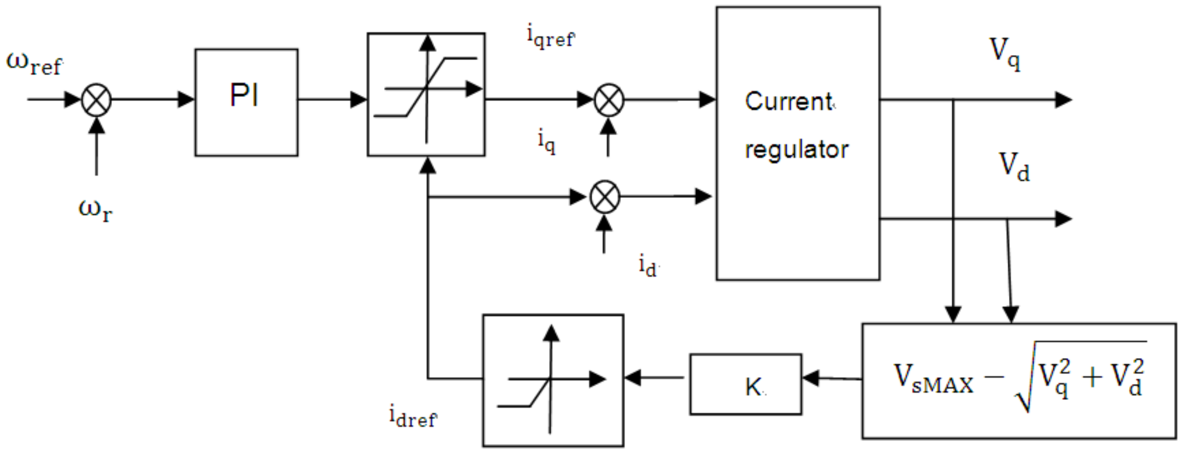
Figure 5. Flux Weakening Method Using Feed-Forward Compensation



The feed-forward compensation technique can be implemented based on the steady-state voltage equation of the machine. The torque command is limited within the available maximum value at that operating speed. With the limited torque command, the optimal current reference in the rotor reference d–q frame is calculated considering voltage and current constraints from the steady-state voltage equations in (2-4) and (2-5). In this method, because the voltage is decided under the steady-state operating condition, the voltage margin for the regulation of the current should be considered. The method can be easily implemented with the nominal machine parameters, and it is simple because of no gains to set for the flux weakening control. But the performance would be degraded with the variation of the parameters because the compensation is done in the open loop manner. Also, if the speed and torque varies rapidly and if the current varies suddenly, then the performance would be poor because of the deficiency of the voltage margin for the current regulation.

2.4.3 Field Weakening Control with Feed-Back compensation

Figure 6. Flux Weakening Method Using Feed-Back Compensation

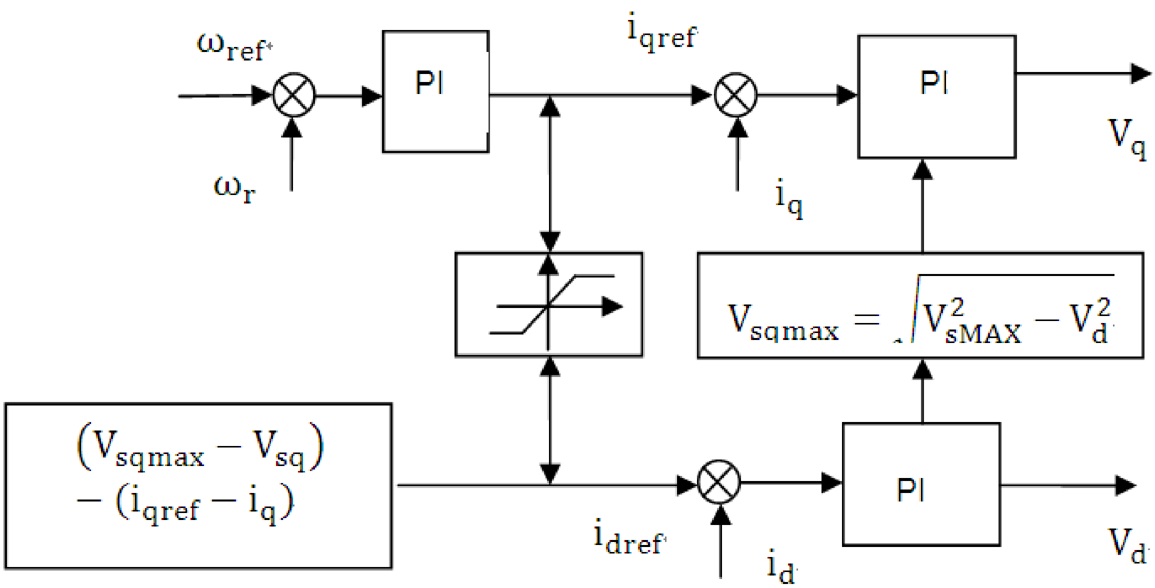


As shown in Figure 6 this flux weakening method is keeping the output voltage of the current regulator within the voltage constraint by feedback of the output voltage to the flux weakening regulator.

The input to the field weakening regulator is the difference between the output of the current regulator and the available maximum voltage, V_{sMAX}. The output of the flux weakening regulator is d-axis current to adjust the flux level of the electric machine. Because of the feedback of the output voltage of the current regulator, this method is robust to the variation of the parameters according to the operating conditions. However, because the output of the current regulator includes not only the term to cancel the current error but also the term to decouple the back EMF and the cross-coupling voltage in rotor reference frame, the parameter variations affect the performance of the current regulator, which is a part of the field weakening control. Also, the performance of the flux weakening regulator is affected by the parameter variations through the current regulator. Moreover, the PI gain setting of the flux weakening controller, is not straightforward and the gains should be set by trial and error. The bandwidth of the flux weakening control loop should be low enough to prevent the interference with the current control loop. Hence, if the speed varies rapidly, the performance of flux weakening control is degraded severely, and the current of the machine, especially the d-axis current, may reveal oscillatory responses.

2.4.4 Field Weakening with Nonlinear Modulation Region

Figure 7. Field Weakening with Nonlinear Modulation



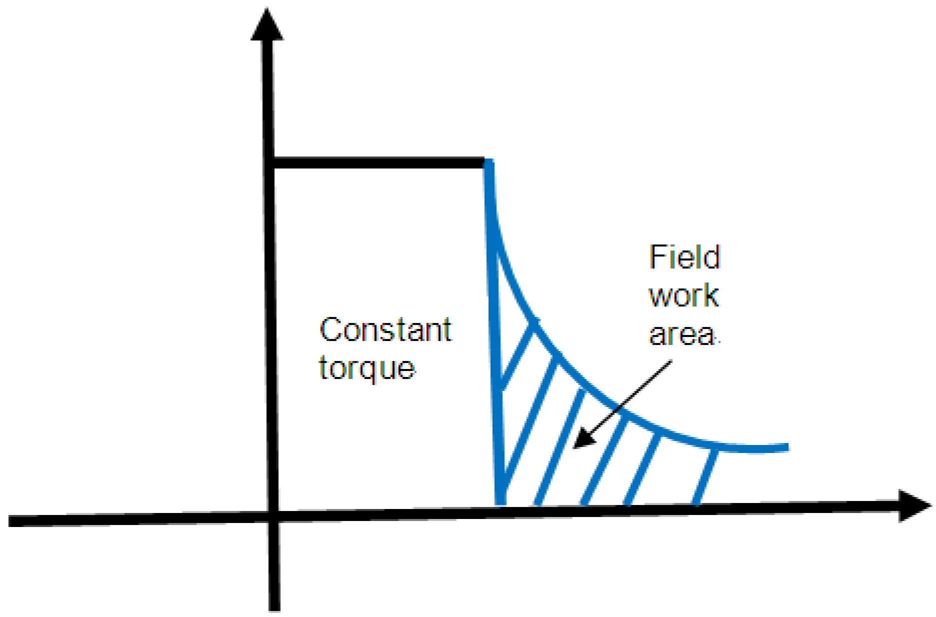
The above two flux weakening methods are formulated under the assumption that the output of the current regulator can be synthesized exactly by a PWM inverter. Therefore, the voltages are limited in the inscribed circle of a hexagon of voltage plane, which is $V_{DC}/\sqrt{3}$ in the case of space vector PWM as described at part 2.1. Actually, the voltage is

furthermore limited to consider the control margin of the current and the dead time effect of the inverter. In some application field such as electric/hybrid vehicle, center air-condition, the torque of the electric machine should be maximized to get maximum acceleration under varying DC link voltage from the battery. In this case, over modulation is inevitable and PWM is extended to nonlinear modulation region, where the output voltage includes low-order harmonics. The fundamental component of output voltage in the nonlinear modulation region can be maximized at the cost of low-order harmonic currents, and the available maximum torque increases. But in this region the flux weakening control method is complicated due to the nonlinearity. However, throw amount of test on SMPMSM motor, it's control structure can be simplified as Figure 7 By this method, the inverter's efficiency can rise 10%.

2.5 Field Weakening Control on Wash Machine

Wash machine's work module can be defined as two modules. One is the normal washing working module. The other is the spin module. When in normal washing status, the controller is in the constant regulation. When in the spin module, the controlling inverter works in field weakening area. Washing machine's work property can be shown in Figure 8

Figure 8. Wash Machine Work Module



From Figure 8, it can be seen that wash machine has a width regulating area.

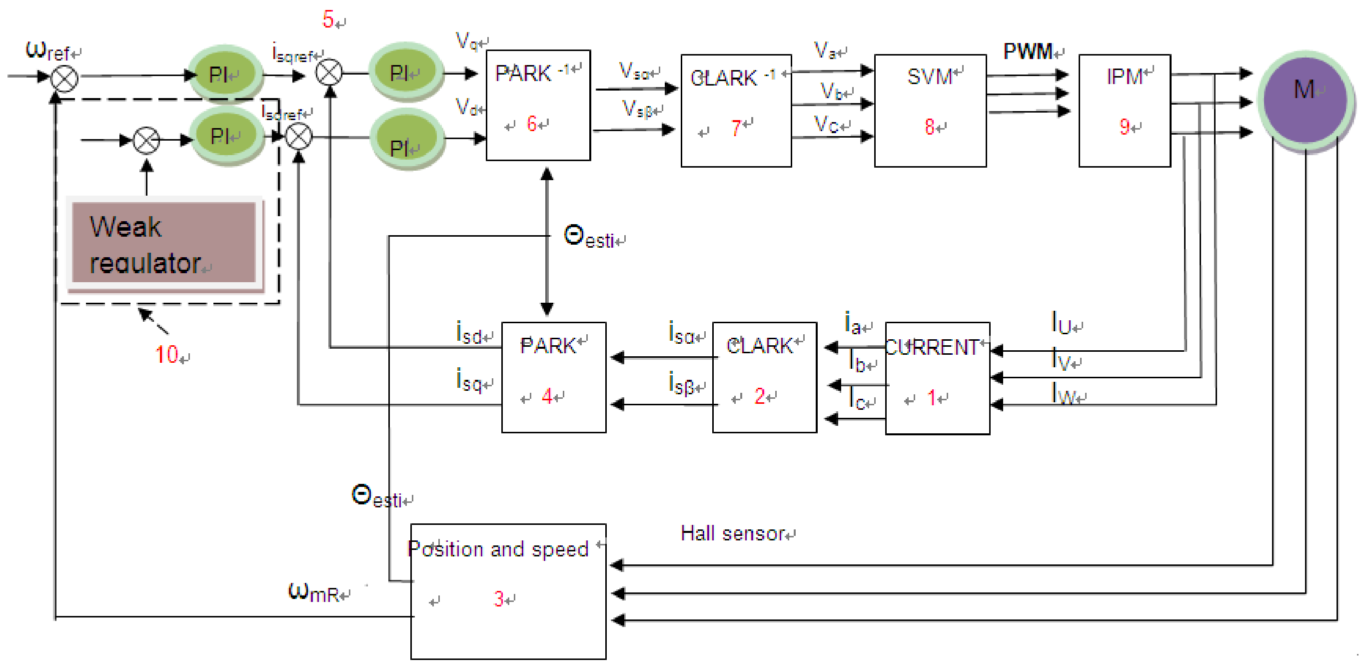
The main frequency may arrange from 5HZ to 600HZ. So it requires a strong weakening controller, and making the best of motor's field area. In real working status, the motor's parameter may change each other, which taking difficult to build a pure math equation and controlling transforming function. To realize the field weakening controlling, using FOC algorithm can easily solve the problem. What's more, throwing this Field control, it can ignore any parameter and outside bad factor. The controlling structure can be seen as Figure 7 or 8 These two field weakening method all satisfy the wash machine.

3 Field Weakening Implementation

This chapter introduces the Field weakening control algorithm

3.1 Control Structure

Figure 9. Block Diagram of FOC Control with Field Weakening



Each module is simply described as flows:

1. Current module: AD converter for Current sensor input signal. And scale the I_U I_V I_W to i_a, i_b, i_c
2. Clark module : Clarke transform
3. Estimate module : estimate the speed and the position of the rotor
4. Park module : park transform
5. Pi module : pi regulator for speed ,i_q ,i_d and field weakening
6. Park inverse module : park inverse transform
7. Clark inverse module : Clarke inverse transform
8. SVM module :generate the SVPWM signal to IPM
9. IPM module
10. Field weakening module

The weak regulator is shown as Figure 6 or 7. As mentioned before, these two methods can satisfy the wash machine, but the nonlinear modulation's PI parameter is difficult to set than Feed-Back compensation when in field weakening control.

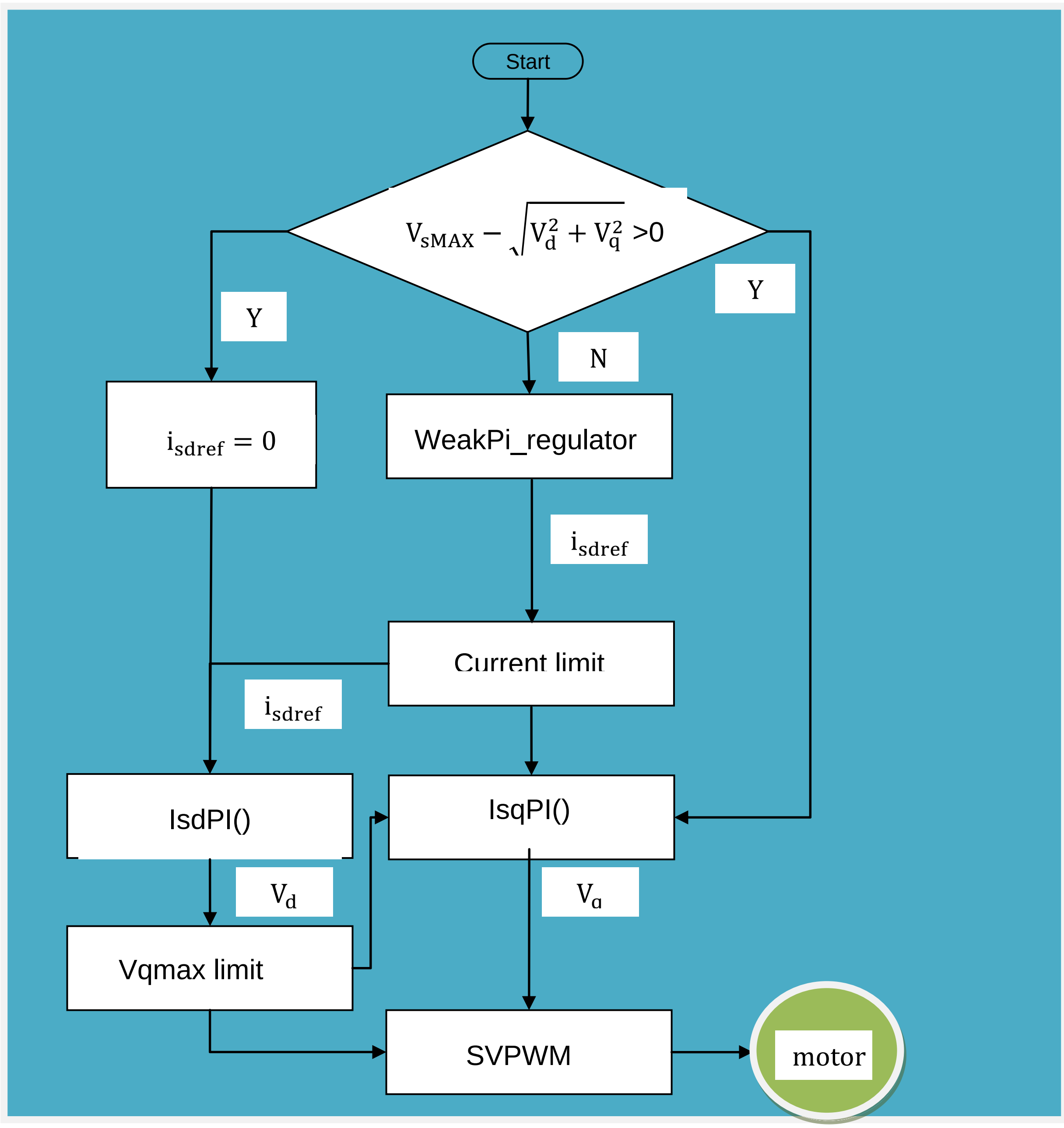
3.2 Field Weakening Control Algorithm

The chapter 2 has talked the field weakening control Algorithm. The Feed-compensation field controls include below steps.

1. Calculate the error of V_{sMAX} and $\sqrt{V_d^2 + V_q^2}$. If the error smaller than zero, then begin weak field control as step 2. If the error larger than zero, then keep the $i_{sdref} = 0$ as a constant control.
2. Throw PI regulator, getting the i_{sdref}.
3. Limit the current reference by I_{sMAX} and get virtual i_{sdref}
4. Throw PI regulator, getting the i_{qref}.
5. Limit the max voltage of q axis by V_{sMAX}.

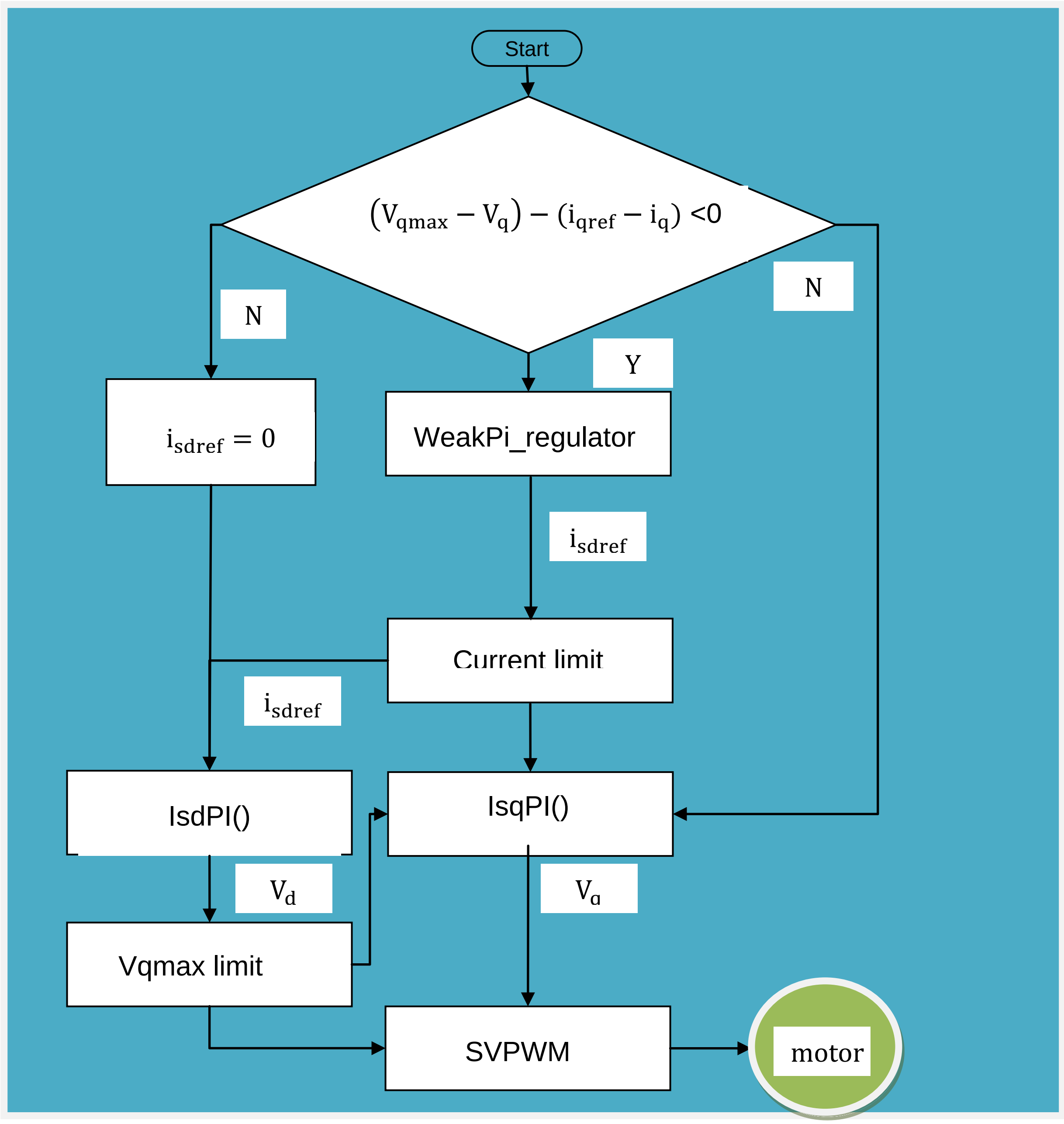
This step can be seen as Figure 10.

Figure 10. Flow Chart of SMPMSM Drive with Feed-Back Compensation Control



The Nonlinear modulation field control's steps seem easier than the Feed-Back compensation control. Its step can be seen as Figure 11.

Figure 11. Flow Chart of SMPMSM Drive with Nonlinear Modulation Control



This method is different from the before, the main different as below.

1. The weakening PI regulator's error change as the error of $(V_{qmax} - V_q) - (i_{qref} - i_q)$.
2. The original Vsqmax come to be $\frac{2}{\pi}V_{dc}$, not the $V_{dc}/\sqrt{3}$.
3. The PI parameter must be very little. The weakening regulator's cycle time must be longer. If cannot stand by the condition, system may be oscillation.

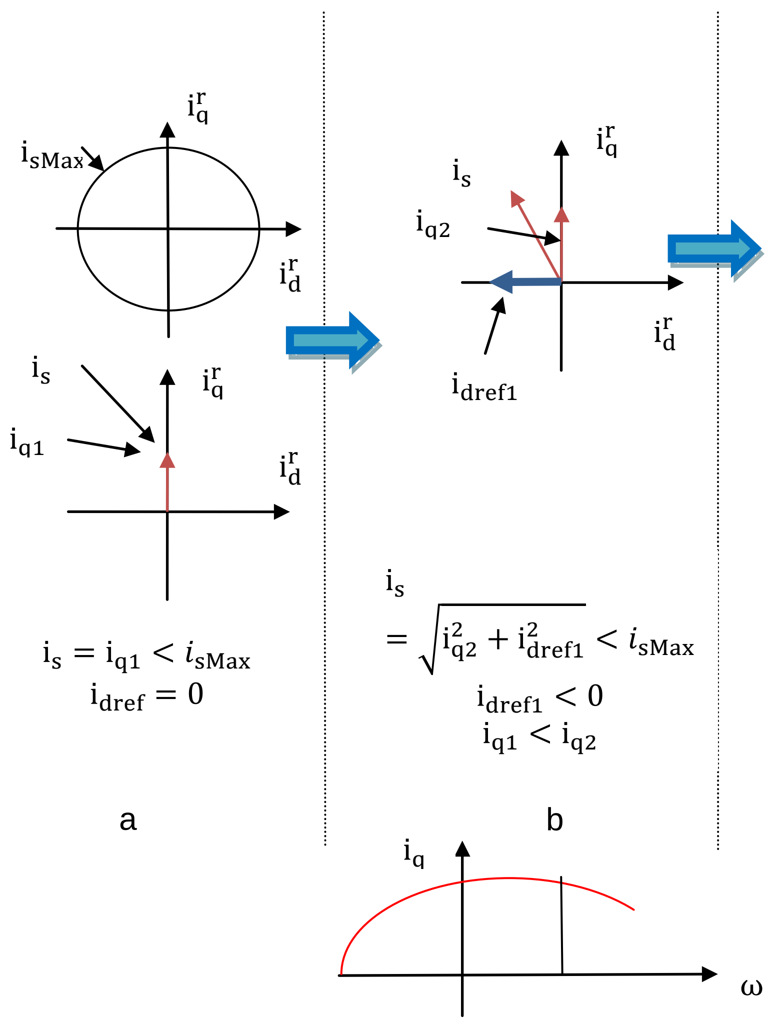
Use this method; the inverter can give out most maximum torque and power. But it need long times to regulator the PI parameter.

3.3 Notes On Field Weakening Control

As weakening Field control is at the status of the high speed, if the control system failed, there will be dangerous. So there is some useful experience notes on the regulation of field weaken.

1. Acknowledge the motor's special proper. Especially the Back-EMF at high speed. Weakening regulator must follow the Back-EMF and regulator it slowly.
2. Outside Weak regulator's operation cycle time may at 20ms to 30ms. Don't set it too fast, or the speed will exceed. But the inner current regulator's operation cycle should be fast, which arrange from 50us to 200us.
3. When testing the weakening regulator, the parameter should from small to large.
4. Having a large filter at the DC voltage of inverter, speed estimator and d/q current.
5. Weakening PI parameter should be regulated as the input error.
6. Have a knowledge on the dealing of the limit of V_{qMAX}. In some application, the inverter's output voltage has been limit, because of the motor's ratting constraints. However, the current is not reached the motor's ratting number, which is also one function of inverter. At this field condition, the d/q's current will larger than the base current. When d/q's current meet the maximum complex current ratting, then inverter will keep the power in constant, where regulation in the constant power area, shown in Figure 12.

Figure 12. Current on q Axis Changes at the Field Area.



4 Verification

This section provides experiment on PMSM wash machine

4.1 Overview

To validate the field weakening algorithm, this chapter try some experience on wash machine.

Testing motor: 12 pole pairs; rated current 7.5 A; PMSM module; three hall sensor; sin wave BACK-EMF.

Testing hardware; FUJITSU_WM-0.1.2

Testing software; FUJITSU_WM-FW0.1.2

Washing machine type: Roll-type washing machine

4.2 Field Weakening Test

Testing regular performance without load: speed at 400r/min and 1000r/min.

Figure 13. Phrase Current Wave at 400r/min without Load

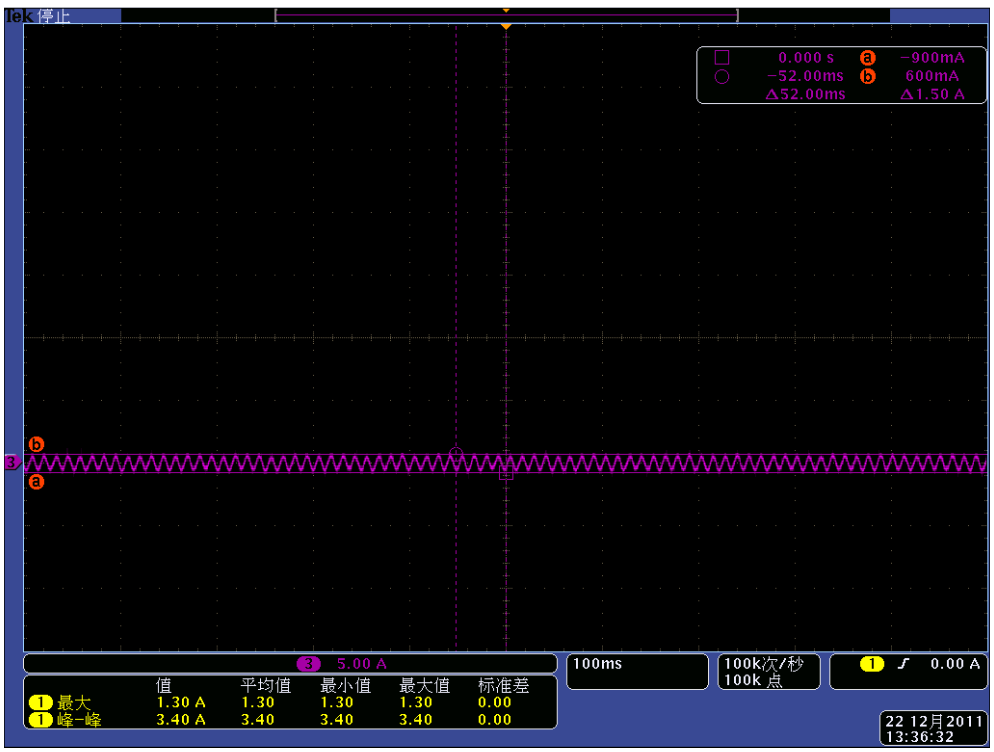
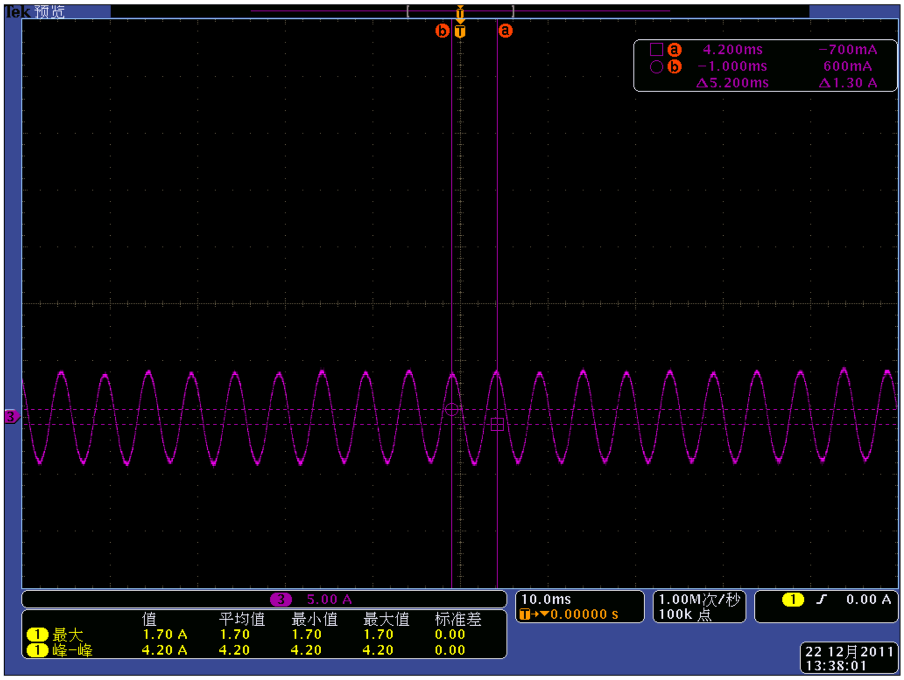


Figure 14. Phrase Current Wave at 1000r/min without Load



Testing regular performance with 700g OOB: speed at 400r/min and 1100r/min.

Figure 15. Phrase Current Wave at 400r/min with 700g OOB

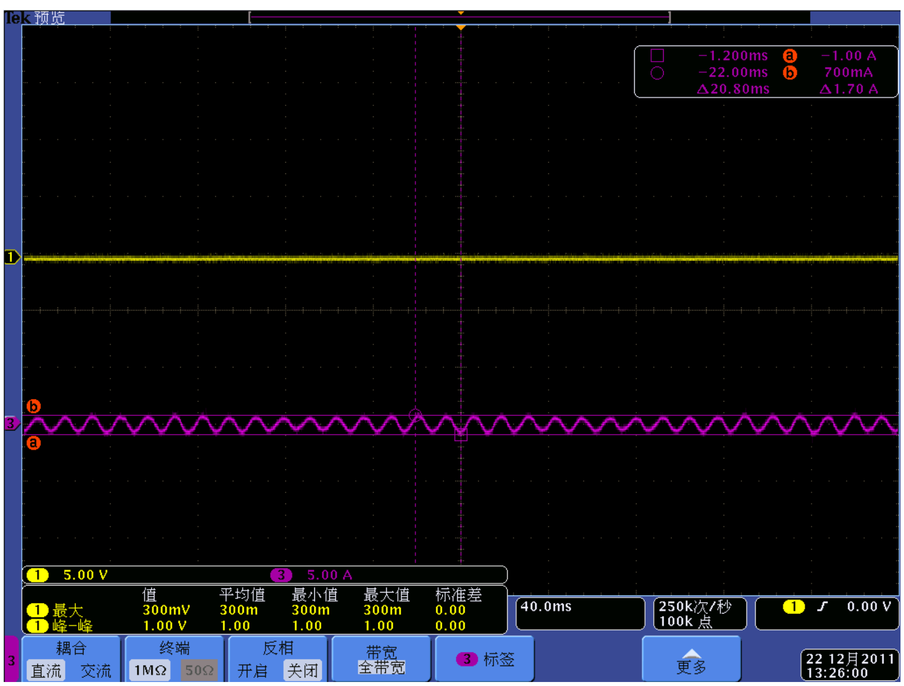
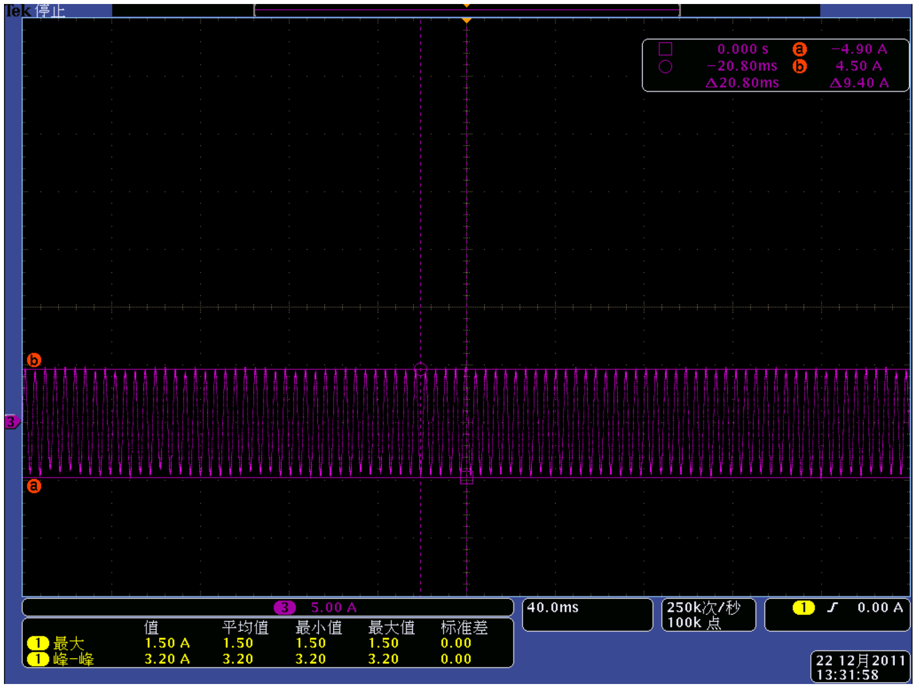
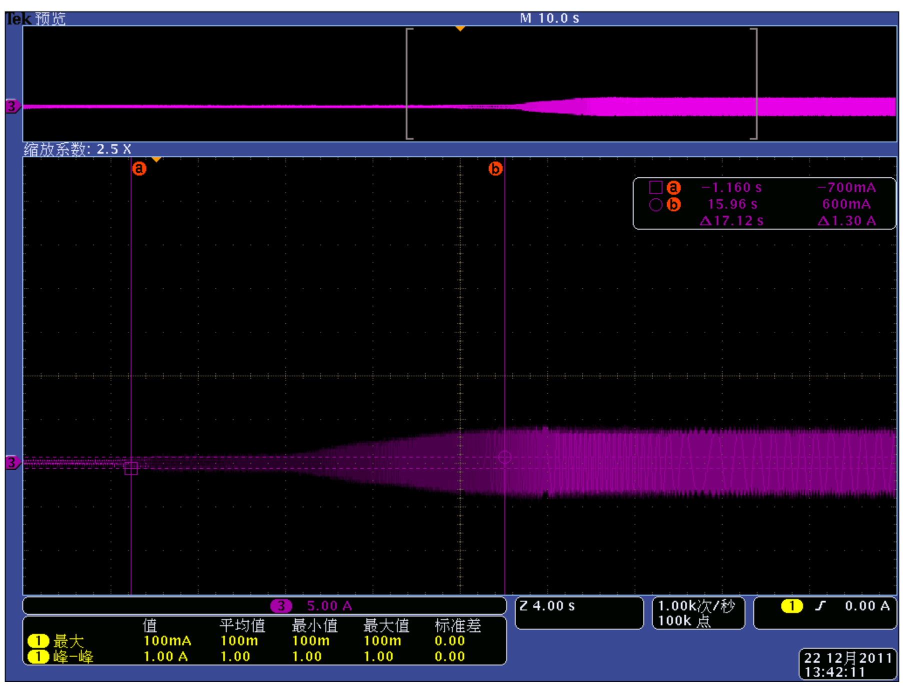


Figure 16. Phrase Current Wave at 1100r/min with 700g OOB



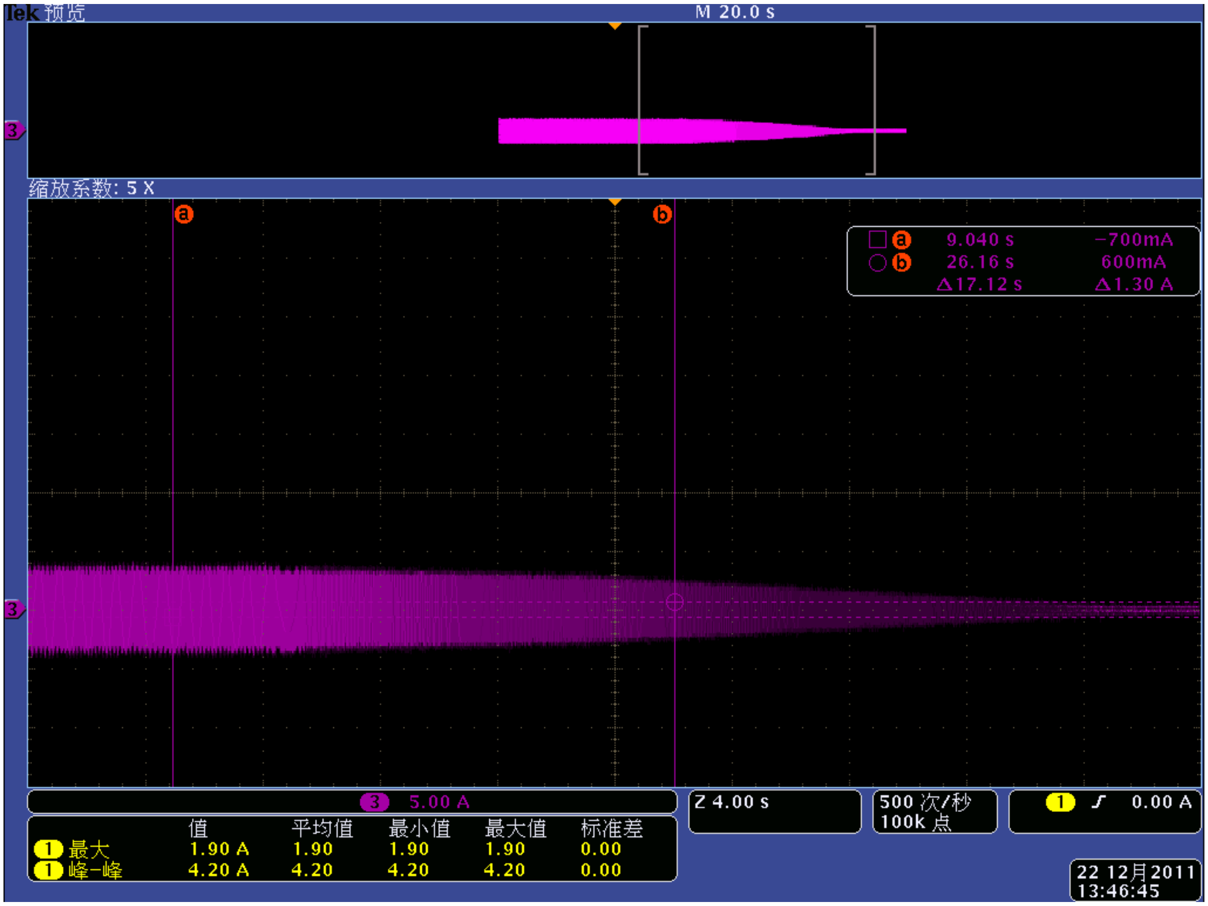
Testing regular performance without load: speed from 50r/min to 1000r/min

Figure 17. Phrase Current Wave at the Processing of Rising Speed



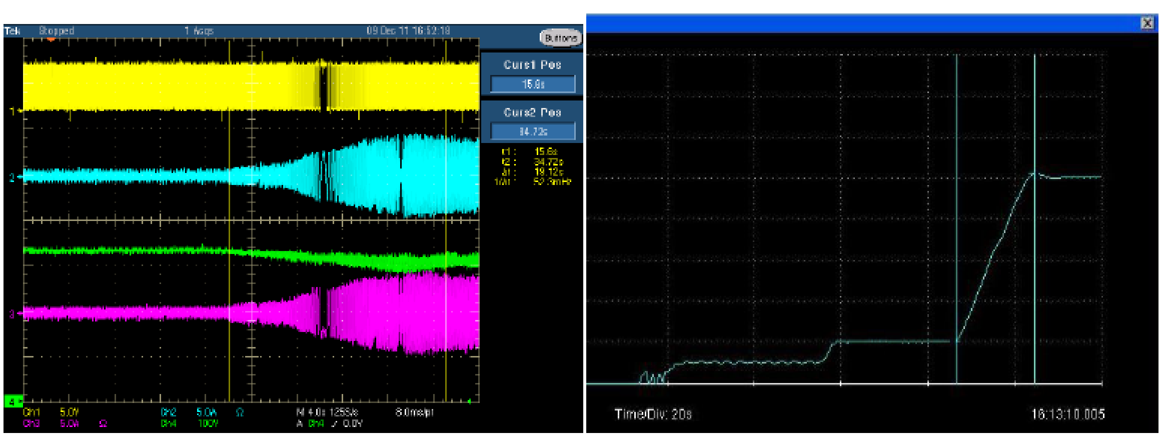
Testing regular performance without load: speed from 1000r/min to 600r/min

Figure 18. Phrase Current Wave at the Processing of Down Speed



Testing regular performance with 700g OOB: speed from 50r/min to 1000r/min

Figure 19. Phrase Current Wave at the Processing of Rising Speed with 700g OOB



phrase current wave and DC voltage wave

speed wave

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**	–	DOHE	09/31/2011	Initial release
*A	5043382	DOHE	12/09/2015	Converted Spansion Application Note “MCU-AN-510116-E-10” to Cypress format
*B	5799165	AESATP12	07/05/2017	Updated logo and copyright.

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