AN205350

# FM3 MB9BFXXXX/MB9AFXXXX Series MTPA

**Associated Part Family: MB9BFXXXX/MB9AFXXXX Series**

This application note describes the maximum torque per ampere (MTPA) implementation in MB9Bxxxx/MB9Axxxx Series.

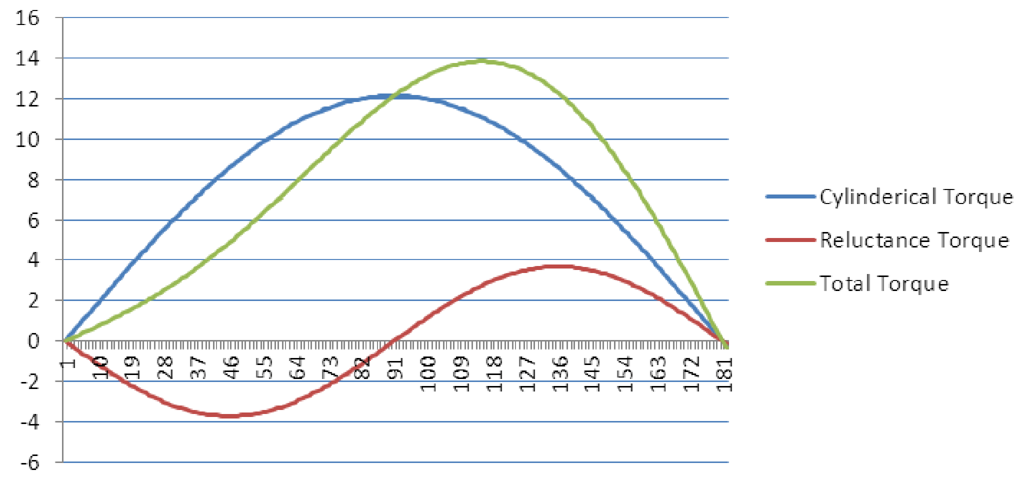
## Contents



# 1 Introduction

This application note describes the maximum torque per ampere (MTPA) implementation in - MB9Bxxxx/MB9Axxxx Series. Salient-pole synchronous motors are widely used in variable speed drive applications due to their high efficiency. It is important not only to accurately detect rotor positions but also to control current at optimum phases for high efficiency and wide range operations such as maximum torque control and flux weakening control. Although rotor positions can be detected precisely with position sensors, mechanical position sensors have several problems such as cost and low reliability. Therefore, many sensorless control methods have been proposed. This document have also proposed sensor less control techniques with observers based on PLL observe model. In position sensorless controls, it is known that position estimation errors are sensitive to q-axis inductance set in the observers. Such parameter errors affect both position estimation and current vector phase accuracy. Position estimation errors caused by inductance errors have been analyzed. One of the typical trajectories in a current phase control is the maximum torque per ampere (MTPA) control, which is also called maximum torque control. It is important for high efficiency drives, because the reluctance torque can be used effectively the most and the copper losses are minimized. The conventional methods are that d-axis current commands for the current control loop are set to negative values at maximum torque per ampere trajectory. It can be obtained by solving an external problem that the motor torque is maximized with respect to the current phase angle at constant current amplitude. By utilizing these relations, unified methods for position estimation and current phase control with inductance setting have been reported. The inductance setting which is set so as to associate the current vector with a quasi-optimal trajectory is presented in. For example, the trajectory is located between unity power factor trajectory and minimum copper loss trajectory. According to theory as our known, the maximum torque control is realized with inductance setting in a modified control model. The robustness against magnetic saturation has been experimentally pointed out. However, this approach is based on a particular observe model constructed on maximum torque control frame. Therefore considerable knowledge on observe model must be reconsidered. Based on these concepts, this paper presents maximum torque control with inductance setting of normal PLL observers. In case of normal PLL observer, the relations between position estimation errors and parameter errors have been derived analytically in steady state. In addition, a phase angle of the maximum torque control frame which is equal to a current phase angle under the maximum torque control has also been derived. In the proposed method, the inductance is set so as to make the estimated position error equal to the phase angle of the maximum torque control frame. Also the proposed method is simply constructed and robust against magnetic saturation. Based on this approach, the validity of the proposed method can be explained in the conventional frame work.

Figure 1. Salient-pole Synchronous Motors of Torque

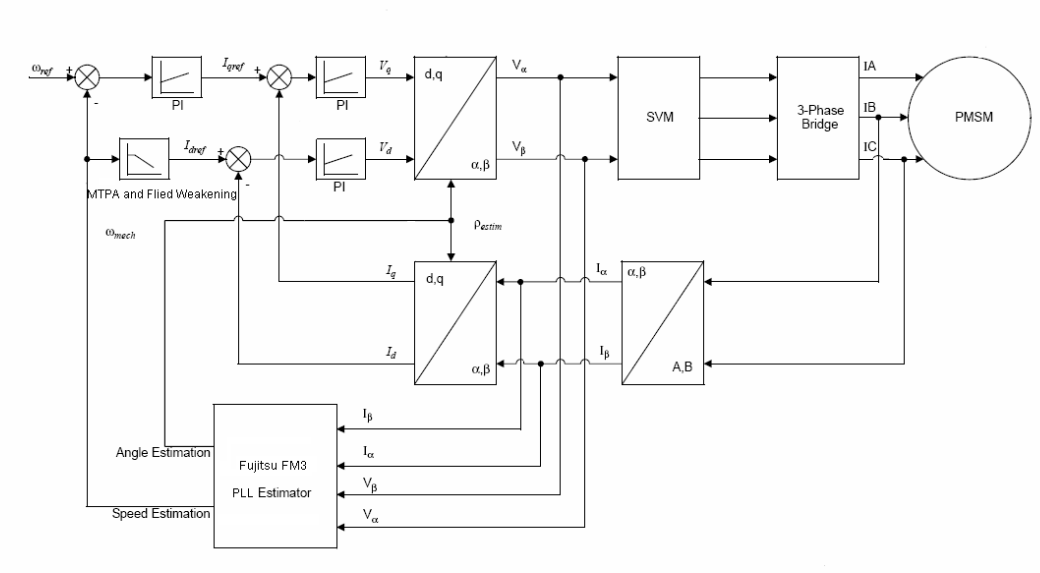



# 2 MTPA Principle

## 2.1 Motor Control Theory

Motor control structure as below figure show:

Figure 2. Motor Control Structure



The structure including the content:

1. Permanent Magnet Synchronous Motor.
2. 3-Phase Bridge – rectifier, inverter and acquisition and protection circuitry.
3. Clarke forward transform block.
4. Park forward and inverse transform block.
5. Angle and speed estimator block.
6. Proportional integral controller block.
7. MTPA and Field weakening block.
8. Space vector modulation block.

In the structure of upper if Ld equal to Lq and no flied weakening that Idref is equal to zero, The particularity of the FOC in the case of PMSM is that the stator's d-axis current reference Idref (corresponding to the armature reaction flux on d-axis) is set to zero. The rotor's magnets produce the rotor flux linkage, ΨPM, unlike ACIM, which needs a constant reference value Idref for the magnetizing current, thereby producing the rotor flux linkage. The air gap flux is equal to the sum of the rotor's flux linkage, which is generated by the permanent magnets plus the armature reaction flux linkage generated by the stator current. For the constant torque mode in FOC, the d-axis air gap flux is solely equal to ΨPM, and the d-axis armature reaction flux is zero. On the contrary, in constant power operation, the flux generating component of the stator current, Id, is used for air gap field weakening to achieve higher speed. In sensorless control, where no position or speed sensors are needed, the challenge is to implement a robust speed estimator that is able to reject perturbations such as temperature, electromagnetic noise and so on. Sensorless control is usually required when applications are very cost sensitive, where moving parts are not allowed such as position sensors or when the motor is operated in an electrically hostile environment. However, requests for precision control, especially at low speeds, should not be considered a critical matter for the given application. The position and speed estimation is based on the mathematical model of the motor. Therefore, the closer the model is to the real hardware, the better the estimator will perform. The PMSM mathematical modeling depends on its topology, differentiating mainly two types: surface-mounted and interior permanent magnet. Each type has its own advantages and disadvantages with respect to the application needs. The proposed control scheme has been developed around an interior permanent magnet synchronous motor, because we need to realize the maximum torque per ampere function. Because the surface-mounted permanent magnet which has the advantage of low torque ripple and lower price in comparison with other types of PMSMs. The air gap flux for the motor type considered is smooth so that the stator's inductance value, Ld equal to Lq and the Back Electromagnetic Force (BEMF) is sinusoidal. The fact that the air gap is large (it includes the surface mounted magnets, being placed between the stator teeth and the rotor core), implies a smaller inductance for this kind of PMSM with respect to the other types of motors with the same dimension and nominal power values. These motor characteristics enable some simplification of the mathematical model used in the speed and position estimator, while at the same time enabling the efficient use of FOC. The FOC maximum torque per ampere is obtained by uninterruptedly keeping the motor's rotor flux linkage situated at 90 degrees behind the armature generated flux linkage. But the interior permanent magnet motor need to special function control of MTPA, because the maximum torque per ampere of the motor's rotor flux linkage situated don't at 90 degrees position. So this document to explain how to realize this function and how to obtain the Idref negative value.

## 2.2 Motor Torque Formulary

The motor torque formulary as equation as below:

$$\mathrm{Te} = \frac{3}{2}\mathrm{Pn}(\Psi\mathrm{m} * \mathrm{Iq} + (\mathrm{Ld} - \mathrm{Lq}) * \mathrm{Iq} * \mathrm{Id}) \quad (1)$$

Where,

$P_n$ is the number of poles

$\Psi_m$ is the permanent magnet linked flux

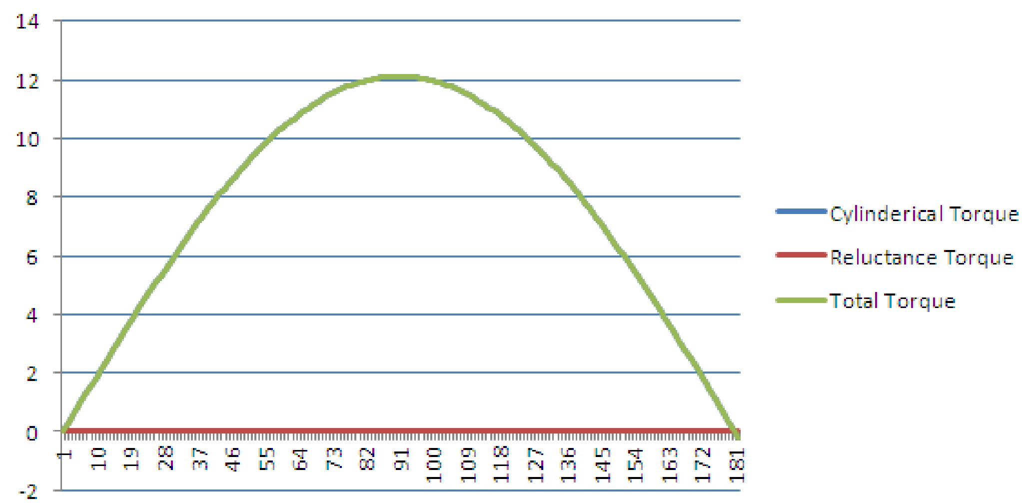
Ld and Lq are the direct and quadrature axis inductances

As this total torque $T_e$ includes tow part of torque: one is cylindrical torque ($\Psi_m$*Iq) and the other is the angle advance curve torque ((Ld-Lq)*Iq*Id).

### 2.2.1 SPM Motor Module

The SPM synchronous motor parameters Ld equal to Lq, the angle advance curve torque is zero, there is zero saliency and Idref is set to zero for maximum efficiency at 90 degrees position. The IPM motor torque curve as bellow:

Figure 3. SPM Motor Torque Structure

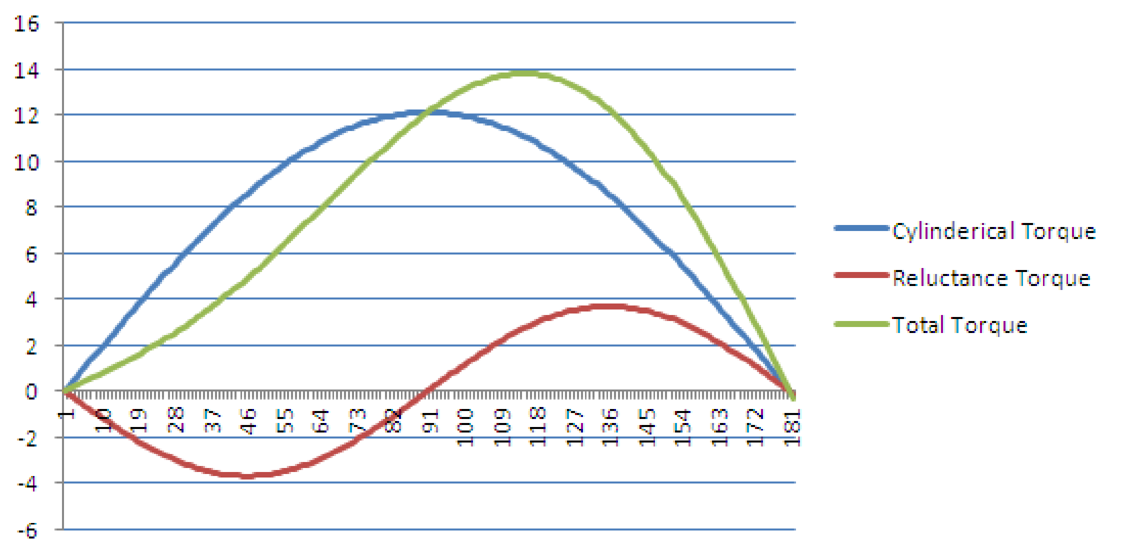



From above figure, we can obtain the episteme that total torque as the same as the cylindrical torque. The reluctance torque is equal to zero.

### 2.2.2 IPM Motor Module

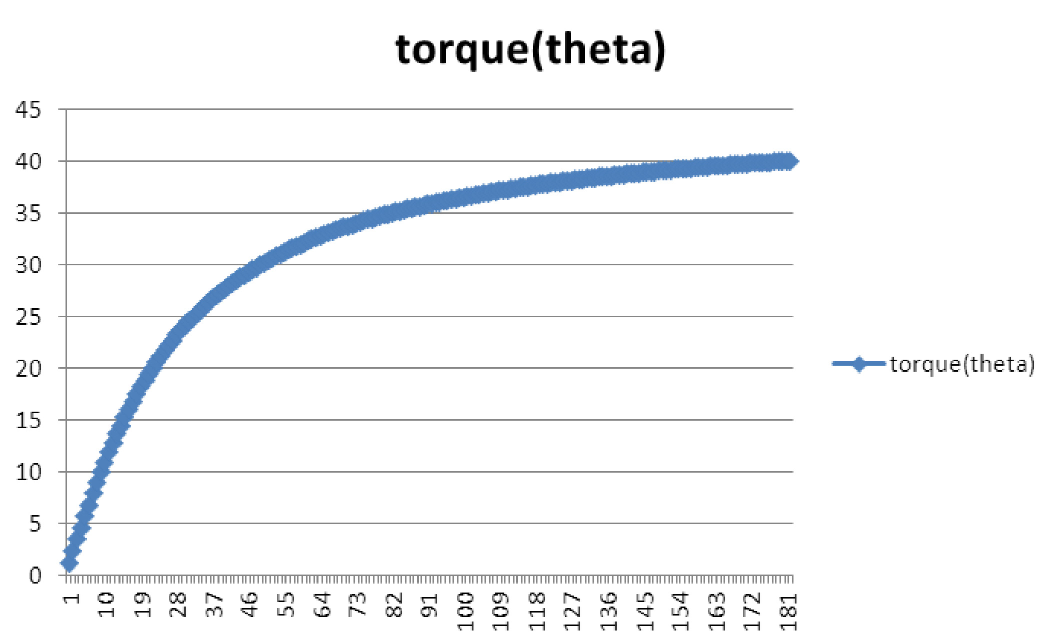
The IPM synchronous motor parameters Ld not equal to Lq, the angle advance curve torque is nonzero value, there is saliency and Idref is set to nonzero value for maximum efficiency at maximum 90 degrees position The IPM motor torque curve as below:

Figure 4. IPM Motor Torque Structure



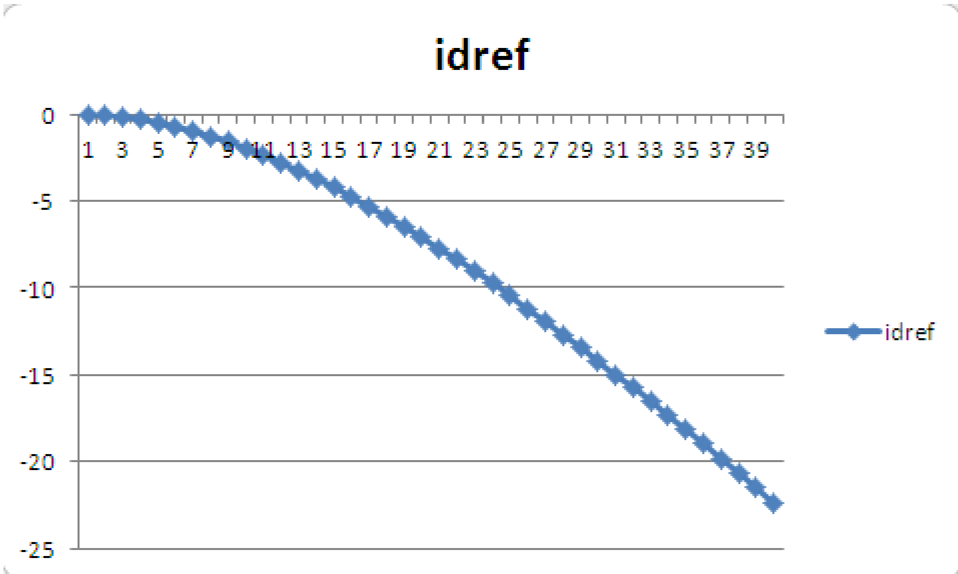

From above figure, we can obtain the episteme that total torque as the same as the cylindrical torque add to reluctance torque. The maximum torque position is maximum 90 degrees position.

Figure 5. IPM Motor Torque Theta



The Idref value curve as below figure, they have different position at different current and different motor parameters. At below document we will to analyses the relator parameters and what it is influent this value.

Figure 6. IPM Motor at Different Current Id Reference




## 2.3 IPM MTPA Control Theory

### 2.3.1 Discursion the Torque Theory

From above the explain and the follow torque formulary,

$$Te = 3/2Pn(\Psi m * Iq + (Ld - Lq) * Iq * Id) \quad (2)$$

When driving a surface magnet motor, there is zero saliency (Ld = Lq) and Id is set to zero for maximum efficiency. In the case of IPM motor which has saliency (Ld < Lq) a negative Id will produce positive reluctance torque. The most efficient operating point is when the total torque is maximized for a given current magnitude. This is found by transforming Equation 1 into a form with current magnitude (Im) and phase advance (β) terms by substituting Id with Im.cos(β) and Iq with Im.sin(β). So the torque formulary will instead of bellow:

$$Te = 3/2Pn(\Psi m * Im * \sin(\beta) + (Ld - Lq) * (Im)2 * \sin(\beta) * \cos(\beta)) \quad (3)$$

So we can use the sin function Equation to express the torque formulary.

$$Te = 3/2Pn(\Psi m * Im * \sin(\beta) + (Ld - Lq) * (Im)2 * \sin(2\beta)/2) \quad (4)$$

From above equation we can realize the maximum torque when β and other parameters were confirmed.

### 2.3.2 Distribute the Current Realize the MTPA

If we can obtain the max value of $T_e$ the β degree, we can make sure the Id and Iq reference value from the total current $I_m$. So now we consequence the equation for below:

Differential the equation,

$$Te = 3/2Pn(\Psi m * Im * \sin(\beta) + (Ld - Lq) * (Im)2 * \sin(2\beta)/2) \quad (5)$$

The equation change to,

$$Te' = 3/2Pn(\Psi m * Im * \cos(\beta) + (Ld - Lq) * (Im)2 * \cos(2\beta)) \quad (6)$$

When Te' = 0, the Te has maximum value at [0,180] degree region. So above equation will change to,

$$3/2Pn(\Psi m * Im * \cos(\beta) + (Ld - Lq) * (Im)2 * \cos(2\beta)) = 0 \quad (7)$$

Or,

$$\Psi m * \cos(\beta) + (Ld - Lq) * Im * \cos(2\beta) = 0 \quad (8)$$

Perform mathematical trigonometric function calculations,

$$\cos(\beta) = \frac{-\Psi m + \sqrt{\Psi m^2 + 8 * (Ld - Lq)^2 * (Im)^2}}{4 * (Ld - Lq) * Im} \quad (9)$$

using ,

$$Id = Im * \cos(\beta) \quad (10)$$

Obtain ,

$$Id = \frac{-\Psi m + \sqrt{\Psi m^2 + 8 * (Ld - Lq)^2 * (Im)^2}}{4 * (Ld - Lq)} \quad (11)$$

Using Iq express Id,

$$Id = \frac{-\Psi m + \sqrt{\Psi m^2 + 4 * (Ld - Lq)^2 * (Iq)^2}}{2 * (Ld - Lq)} \quad (12)$$

Because Ψm, Ld, Lq are the motor parameters, Iq is the control signal so we can obtain the Id value from above equation.

## 2.4 Simulator the MTPA Theory

When IPM motor parameters:

| |
|---|
| Ld = 10.4 mh |
| Lq = 18.6 mh |
| Ψm = 0.404 Wb |
| Iq = 8 A |

The simulator figure as below,

Figure 7. Salient-pole Synchronous Motors Of Torque

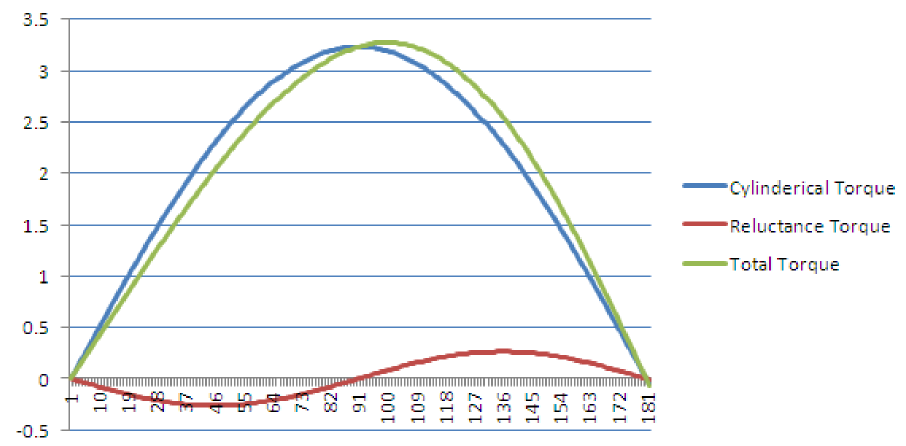



Figure 8. Salient-pole Synchronous Motors of Id Reference

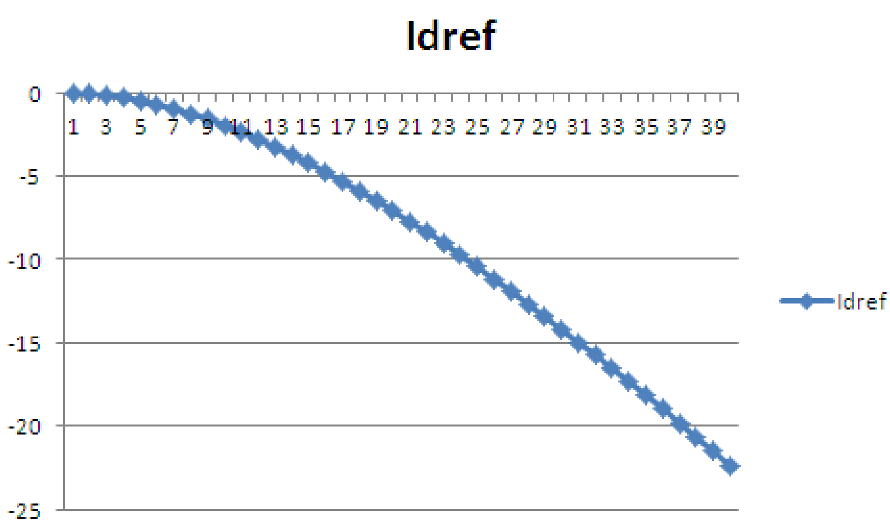
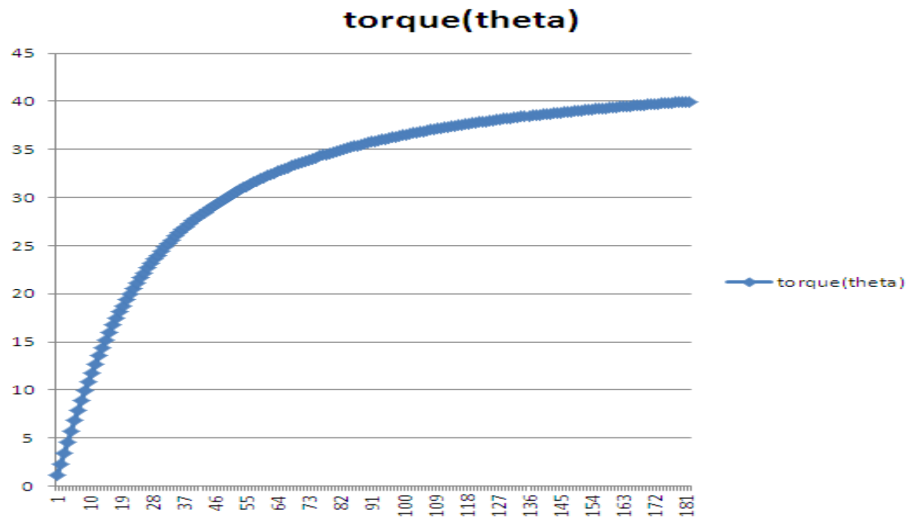


Figure 9. Salient-pole synchronous motors of torque theta




When other IPM motor parameters:

| |
|---|
| Ld = 5.4mh |
| Lq = 15.6mh |
| Ψm = 0.204Wb |
| Iq = 20A |

The simulator figure as below,

Figure 10. Salient-pole Synchronous Motors of Torque

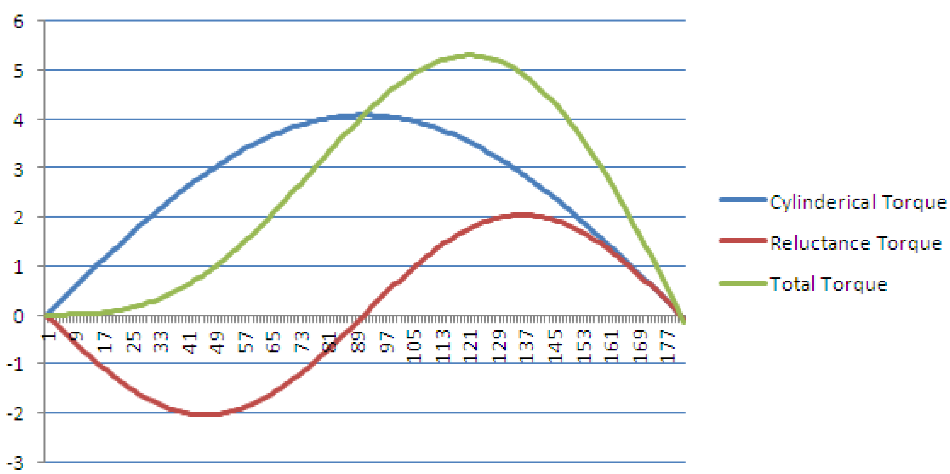


Figure 11. Salient-pole Synchronous Motors of Id Reference

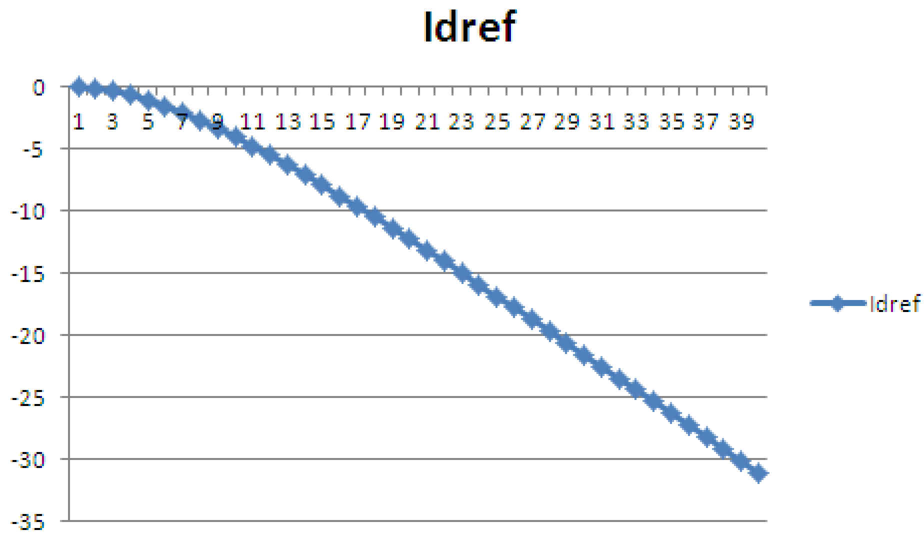
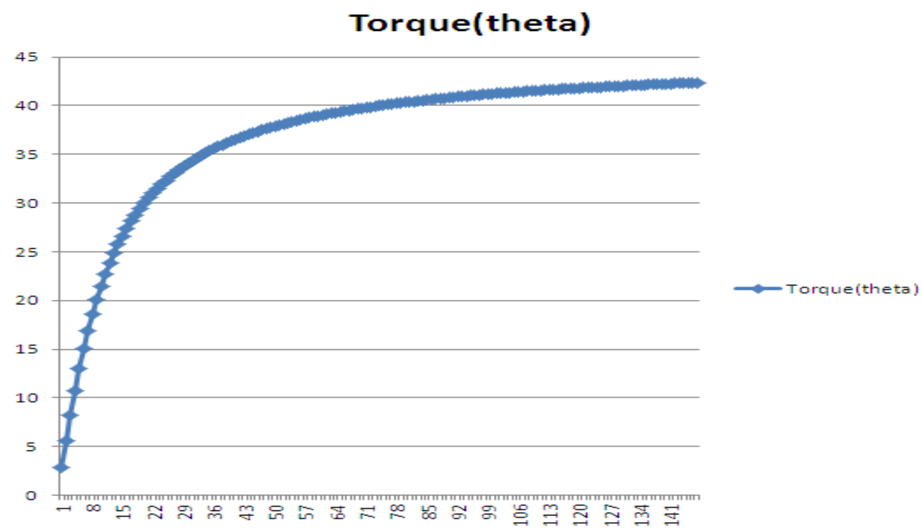



Figure 12. Salient-pole Synchronous Motors of Torque Theta



When other surface-mounted motor parameters:

| |
|---|
| Ld = 8.4mh |
| Lq = 8.4mh |
| Ψm = 0.204Wb |
| Iq = 20A |

The simulator figure as below,

Figure 13. Surface-mounted Motor of Torque

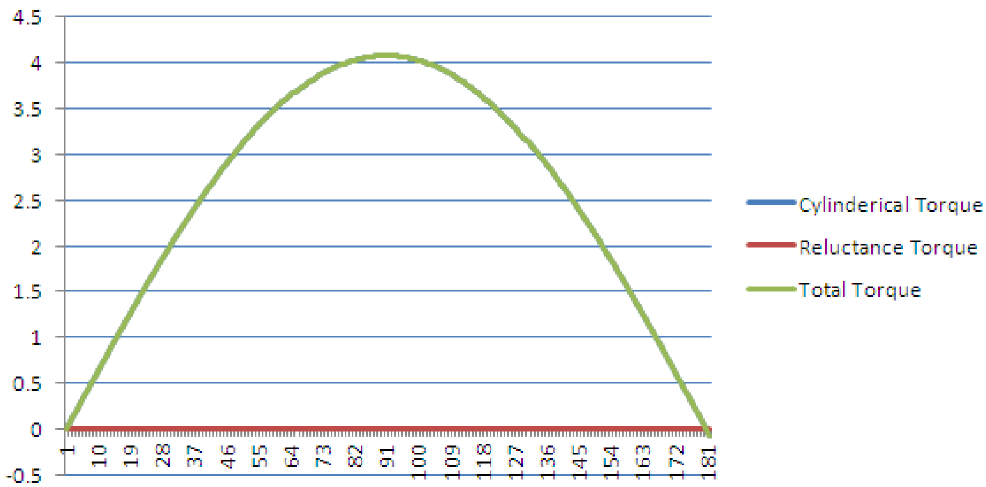



Figure 14. Surface-mounted Motor of Id Reference

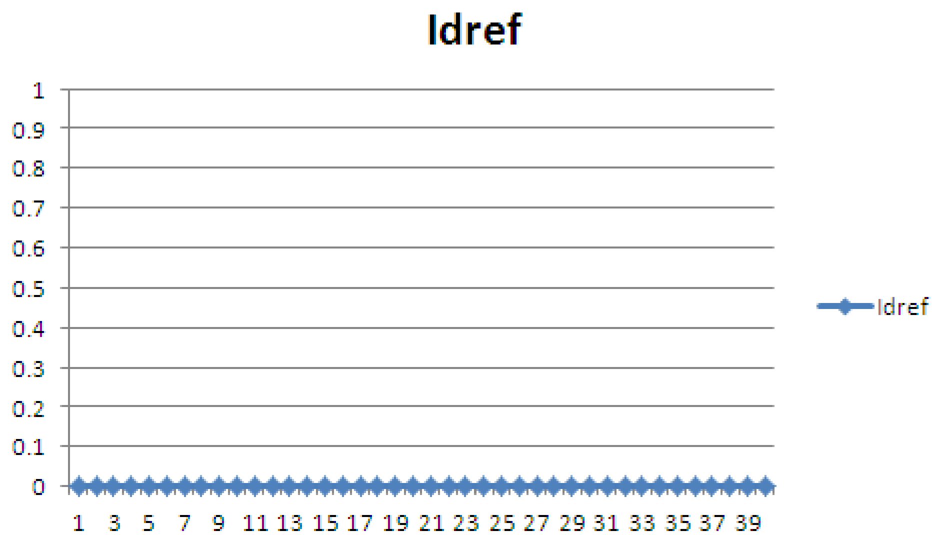
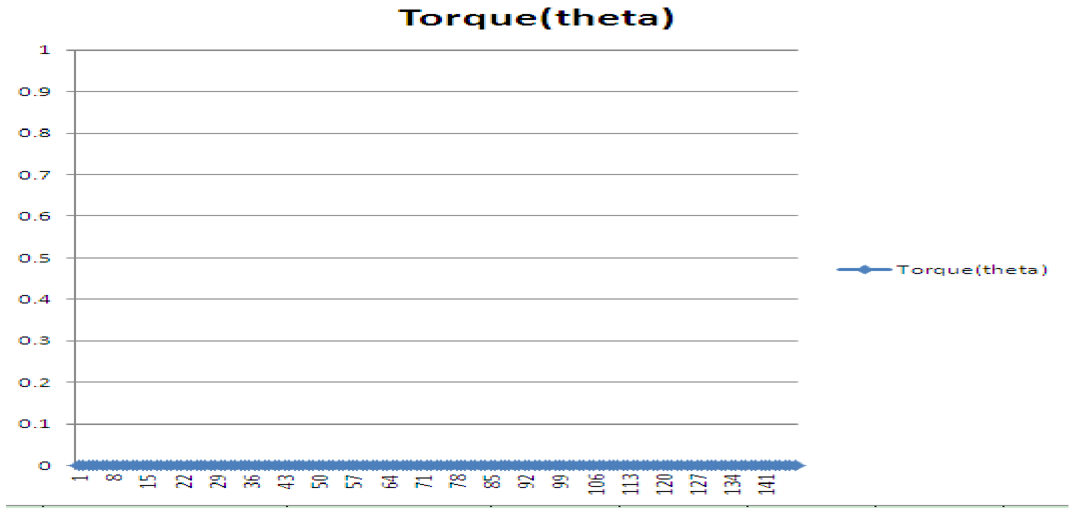


Figure 15. Surface-mounted Motor of Torque Theta




From above simulator figure, our theory of the maximum torque per ampere is impactful.

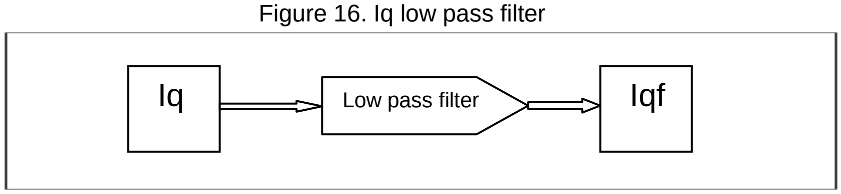
# 3 MTPA Implementation

## 3.1 Obtain the Current of Id

### 3.1.1 Obtain the steady Iq current

In AD and PI control system has some disturb, in order to obtain the data cleanly, we will add the low pass filter. The Iq input and Iqf will output. So the high frequency yawp will be filtered. And the flow chart as below:

Figure 16. Iq low pass filter




Using the below equation to catch the Idref value. Idref value added the low pass filter if some system control need. The equation as below:

Figure 17. MTPA equation

$$\mathrm{Idref} = \frac{-\Psi m+\sqrt{\Psi m^2+4*(Ld-Lq)^2*(Iqf)^2}}{2*(Ld-Lq)} \qquad (13)$$

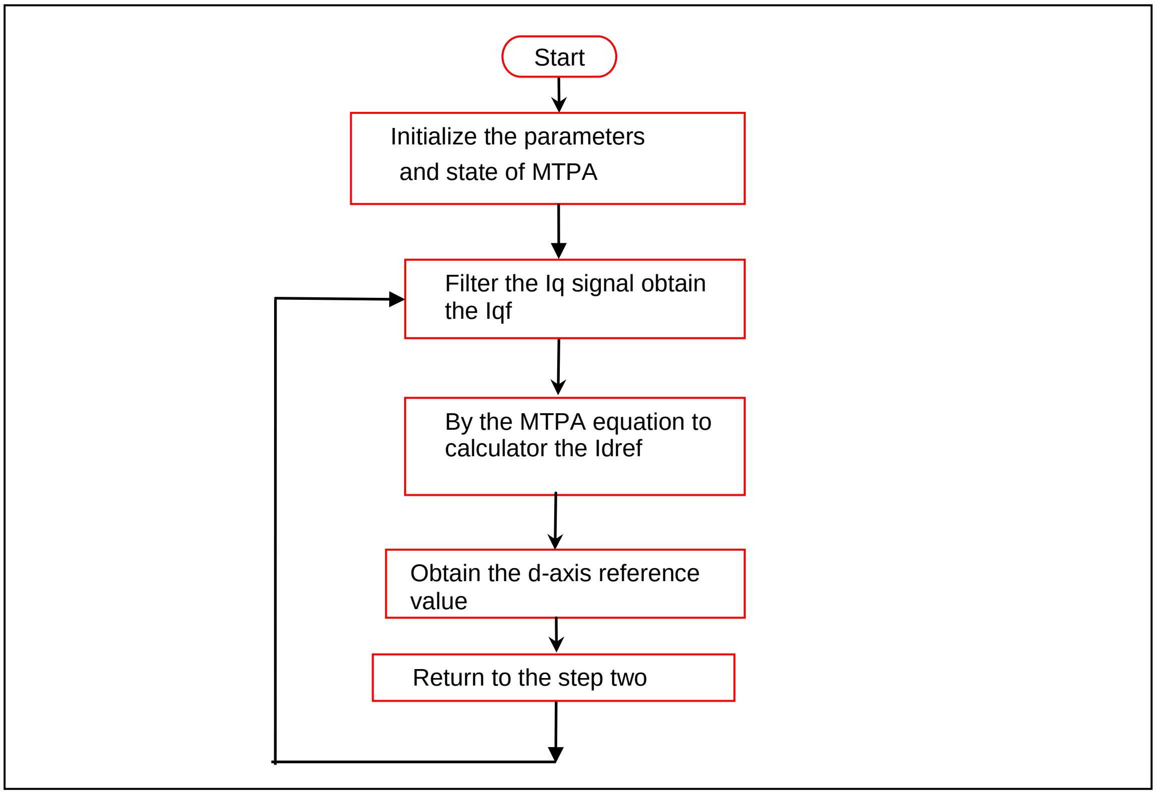
By the current Idref from the equation was calculated. We can add the d-axis to control motor to realize the maximum torque per ampere function.

## 3.2 MTPA Software Implementation

### 3.2.1 Software Flowchart

By up explain to write the flow chart as below.

Figure 18. Dead Time Compensation Software Flowchart




Algorithm flow explanation:

1. Initialize the parameters and state of MTPA.
2. Filter the Iq signal to obtain Iqf.
3. Using filter signal obtain the d-axis current reference;
4. Return to the step two.

### 3.2.2 Software Code Implement

```
/*****************************************************
Function name:    MTPA
Description: realize the maximum torque per ampere
Input: none
Output: none
*****************************************************/
void MTPA(void)
{
//to realize the MTPA function
        NAME MTPA

        #define SHT_PROGBITS 0x1

        EXTERN Ld
        EXTERN Lq
        EXTERN PLL_LPF
        EXTERN __aeabi_d2uiz
        EXTERN __aeabi_f2uiz
        EXTERN __aeabi_fdiv
        EXTERN __aeabi_fmul
        EXTERN __aeabi_fsub
        EXTERN __aeabi_ui2d
        EXTERN isq_tempf
        EXTERN pmsm_isdref
        EXTERN sqrt

        PUBLIC MTPA_Function
        PUBLIC MTPA_initialize
        PUBLIC MTPA_isdref
        PUBLIC MTPA_isdreff
        PUBLIC MTPA_lpf
        PUBLIC Q0_Inv_DetaL
        PUBLIC Q12_Flux
        PUBLIC Q16_DetaL
        PUBLIC Q24_Square_DetaL
        PUBLIC Q24_Square_Flux
        PUBLIC motor_Flux
```

```
        SECTION `.data`:DATA:REORDER:NOROOT(2)
MTPA_initialize:
        DATA
        DC8 0
        DC8 0, 0, 0
motor_Flux:
        DC32 3EA6E979H
Q16_DetaL:
        DC8 0, 0, 0, 0
Q24_Square_DetaL:
        DC8 0, 0, 0, 0
Q0_Inv_DetaL:
        DC8 0, 0, 0, 0
Q12_Flux:
        DC8 0, 0, 0, 0
Q24_Square_Flux:
        DC8 0, 0, 0, 0
MTPA_isdref:
        DC8 0, 0, 0, 0
MTPA_isdreff:
        DC8 0, 0, 0, 0
MTPA_lpf:
        DC16 50

        SECTION `.text`:CODE:NOROOT(2)
        THUMB
MTPA_Function:
        PUSH     {R4-R6,LR}
        LDR.N    R4,??MTPA_Function_0
        LDRB     R0,[R4, #+0]
        CBNZ.N   R0,??MTPA_Function_1
        MOVS     R0,#+1
        STRB     R0,[R4, #+0]
        LDR.N    R0,??MTPA_Function_0+0x4
        LDR      R0,[R0, #+0]
        LDR.N    R1,??MTPA_Function_0+0x8
        LDR      R1,[R1, #+0]
        BL       __aeabi_fsub
```

```
    MOV     R5,R0
    LDR.N   R6,??MTPA_Function_0+0xC  ;; 0x447a0000
    MOV     R1,R6
    BL      __aeabi_fdiv
    LDR.N   R1,??MTPA_Function_0+0x10  ;; 0x477fff00
    BL      __aeabi_fmul
    BL      __aeabi_f2uiz
    STR     R0,[R4, #+8]
    LSRS    R0,R0,#+4
    MULS    R0,R0,R0
    STR     R0,[R4, #+12]
    MOV     R0,R6
    MOV     R1,R5
    BL      __aeabi_fdiv
    BL      __aeabi_f2uiz
    STR     R0,[R4, #+16]
    LDR     R1,[R4, #+4]
    LDR.N   R0,??MTPA_Function_0+0x14  ;; 0x457ff000
    BL      __aeabi_fmul
    BL      __aeabi_f2uiz
    STR     R0,[R4, #+20]
    MULS    R0,R0,R0
    STR     R0,[R4, #+24]
    POP     {R4-R6,PC}
??MTPA_Function_1:
    LDR.N   R5,??MTPA_Function_0+0x18
    LDR     R0,[R4, #+8]
    CMP     R0,#+0
    BEQ.N   ??MTPA_Function_2
    LDR.N   R0,??MTPA_Function_0+0x1C
    LDR     R1,[R0, #+0]
    LDR     R0,[R0, #+0]
    LDR     R6,[R4, #+20]
    LDR     R2,[R4, #+24]
    LDR     R3,[R4, #+12]
    ASRS    R1,R1,#+4
    MULS    R1,R1,R3
    ASRS    R0,R0,#+4
```

```
        MULS    R0,R0,R1
        ADD     R0,R2,R0, LSR #+6
        BL      __aeabi_ui2d
        BL      sqrt
        BL      __aeabi_d2uiz
        SUBS    R0,R6,R0
        LDR     R1,[R4, #+16]
        MULS    R0,R0,R1
        ASRS    R0,R0,#+5
        STR     R0,[R4, #+28]
        ADD     R2,R4,#+36
        ADD     R1,R4,#+32
        BL      PLL_LPF
        LDR     R0,[R4, #+32]
        B.N     ??MTPA_Function_3
??MTPA_Function_2:
        STR     R0,[R4, #+28]
??MTPA_Function_3:
        STRH    R0,[R5, #+0]
        POP     {R4-R6,PC}      ;; return
        Nop
        DATA
??MTPA_Function_0:
        DC32    MTPA_initialize
        DC32    Lq
        DC32    Ld
        DC32    0x447a0000
        DC32    0x477fff00
        DC32    0x457ff000
        DC32    pmsm_isdref
        DC32    isq_tempf

        SECTION `.iar_vfe_header`:DATA:REORDER:NOALLOC:NOROOT(2)
        SECTION_TYPE SHT_PROGBITS, 0
        DATA
        DC32 0
```

```
    SECTION __DLIB_PERTHREAD:DATA:REORDER:NOROOT(0)
    SECTION_TYPE SHT_PROGBITS, 0

    SECTION __DLIB_PERTHREAD_init:DATA:REORDER:NOROOT(0)
    SECTION_TYPE SHT_PROGBITS, 0

    END
}
```

# 4 MTPA Function Performance

## 4.1 Basic Verification

### 4.1.1 Test waveform of run motor

By the theory of the up expound, realize the algorithm and obtain the perfect performance, as show as below figure added MTPA function and no-added MTPA function waveform:

Figure 19. Added the MTPA Function

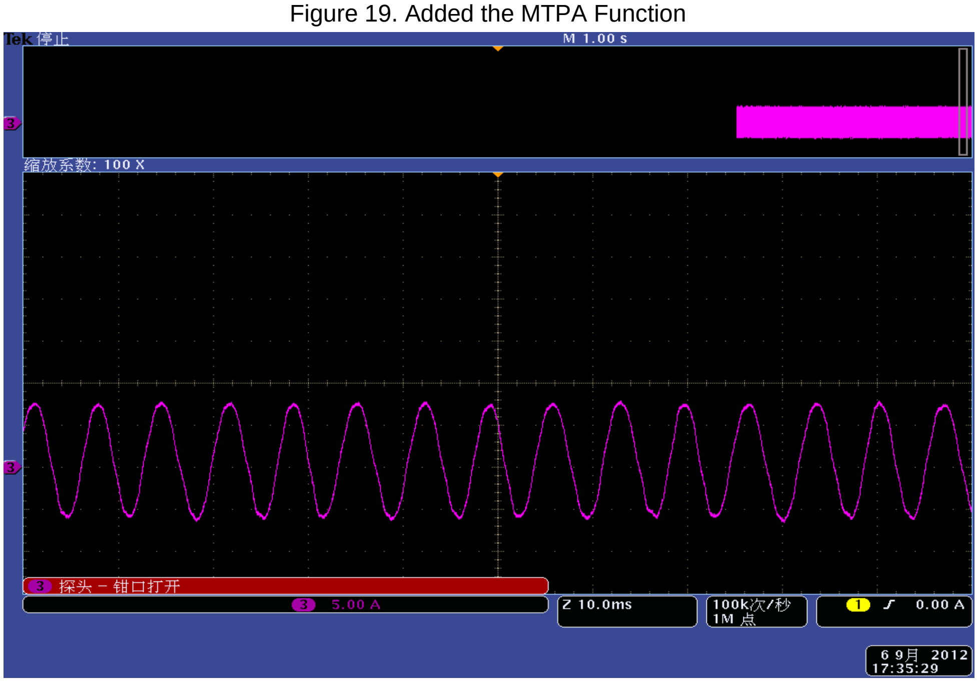
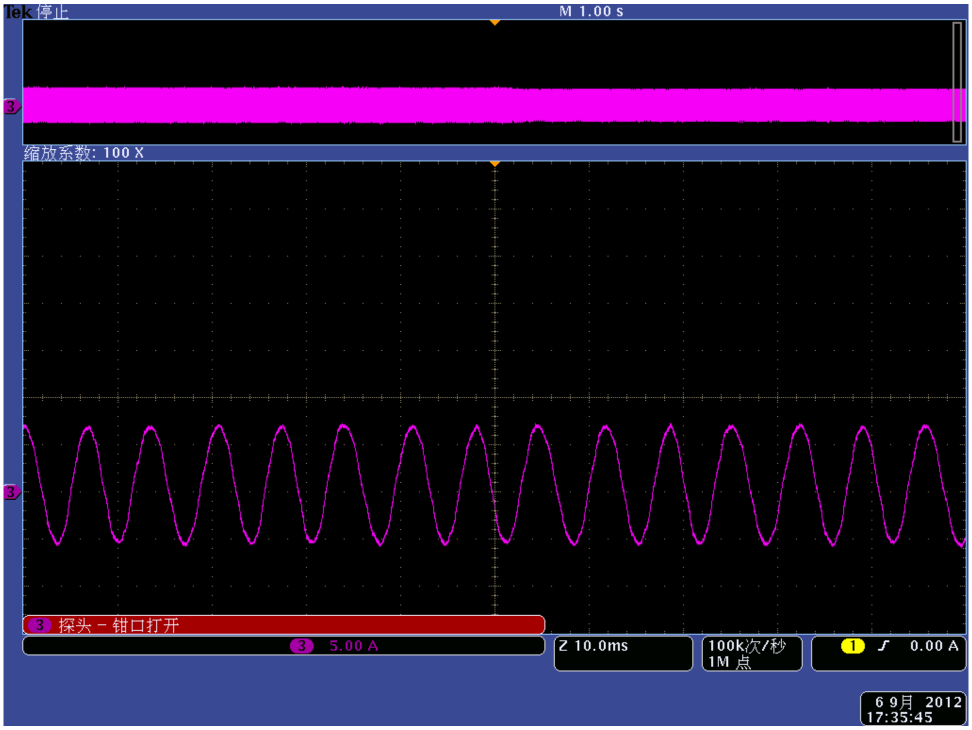


Figure 20. No-added the MTPA Function




From above, maximum torque per ampere function performance is very well. From the test motors purpose, also decrease the power waste and pyrotoxin. So the MTPA theory can carry into execution.

# 5 Conclusion

This paper presented maximum torque control only with PLL observers and general current control systems. In the proposed method, the d-axis current in the PLL observer for the sensorless control are set to the different values from the motor one so as to make the estimated reference frame equal to maximum torque control frame. The proposed system give explicitly have maximum torque controller, and the calculation is not complicated. Moreover, the proposed control is easy applying other motor and control system. The effectiveness of the proposed method has been confirmed by experimental results.

# Document History

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Document Number: 002-05350

| Revision | ECN | Orig. of Change | Submission Date | Description of Change |
|---|---|---|---|---|
| ** | - | FCZH | 09/05/2012 | Initial release |
| *A | 5262192 | FCZH | 05/10/2016 | Migrated Spansion Application Note MCU-AN-510111-E-11 to Cypress format. |
| *B | 5843225 | AESATMP9 | 08/03/2017 | Updated logo and copyright. |

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