Sensorless FOC tuning guide for BPA motor control workbench

Application note

About this document

Scope and purpose

This document describes the control loop tuning procedure for sensorless field-oriented control (FOC) implemented in the EVAL_6EDL7141_FOC_3SH and EVAL_IMD700A_FOC_3SH evaluation boards under the battery powered applications (BPA) motor control workbench of Infineon Developer Center.

Intended audience

This document provides basic guidance on using the proportional-integral-derivative (PID) tuning tool in the MOTIX™ BPA motor control workbench to tune the FOC motor control loop under the VQ motor control scheme and speed motor control scheme.

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1 Introduction

The sensorless FOC motor control example project consists of shunt field-oriented control algorithm software which targets end applications such as power drills and gardening tools. The example project is downloaded to the evaluation board via the MOTIX™ BPA motor control workbench from the Infineon developer center.

Furthermore, the sensorless FOC example project also provides a VQ and speed control scheme for different target applications. This document provides general guidelines on tuning the two control schemes with the help of the “PID tuning tool” in the MOTIX™ BPA motor control workbench.

Sensorless FOC depends on the three shunt resistors to sense the inverter leg current. So, the choice of the three shunt resistors on the evaluation board also affects the functioning of the sensorless FOC example algorithm.

1.1 Installation of MOTIX™ BPA motor control workbench

To follow this motor control tuning guide, the following software must be installed:

- MOTIX™ BPA Motor Control Workbench
  - The GUI tool comes from the Infineon Developer Center launcher. Open the Infineon Developer Center launcher and log in with the “myInfineon” account, find the “MOTIX™ BPA Motor Control Workbench”, and click “Start” to install the tool.

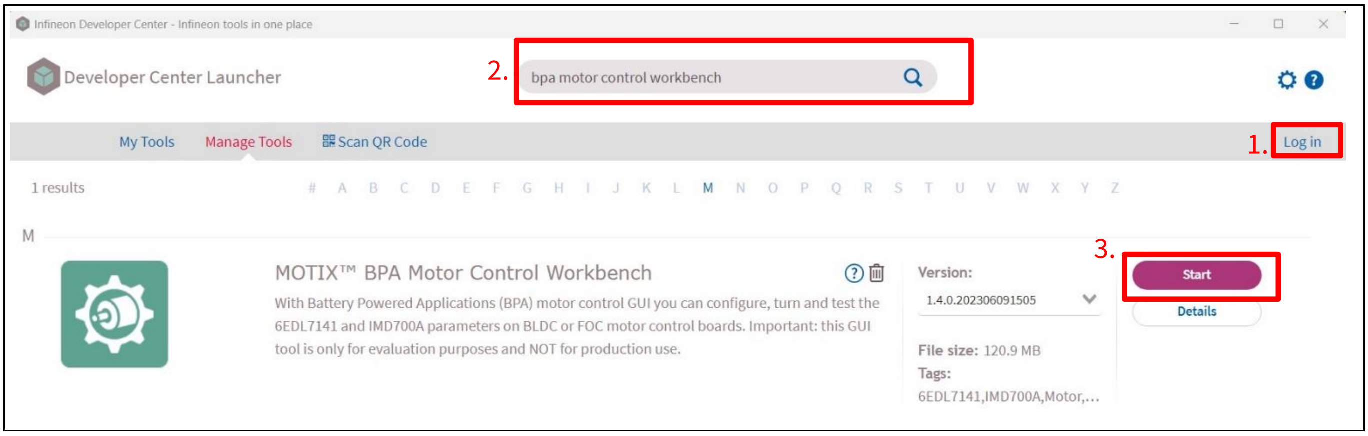

Figure 1 Infineon Developer Centre

  - To get started with the MOTIX™ BPA Motor Control Workbench, please refer to the “Help” document provided on the start page.

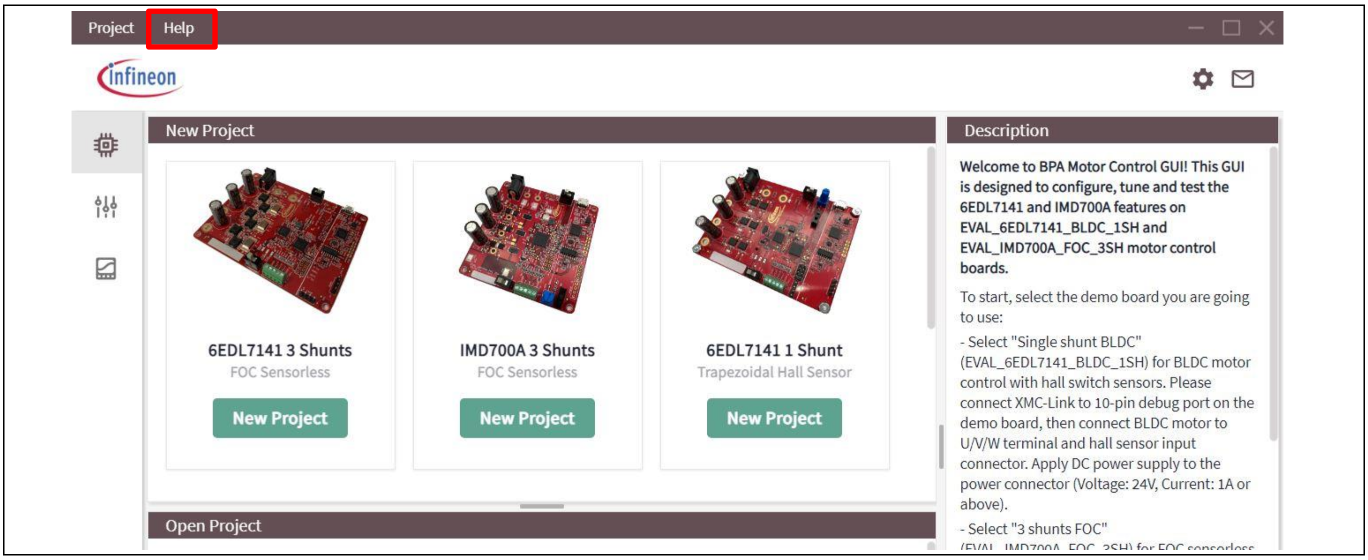

Figure 2 **Start page of MOTIX™ BPA motor control workbench**

- The GUI provides easy configurations to quickly get your motor running. The PID tuning and oscilloscope tools help the user tune the control loop in VQ and speed control mode.
- Use the knob to select VQ or speed control mode when the motor has stopped.

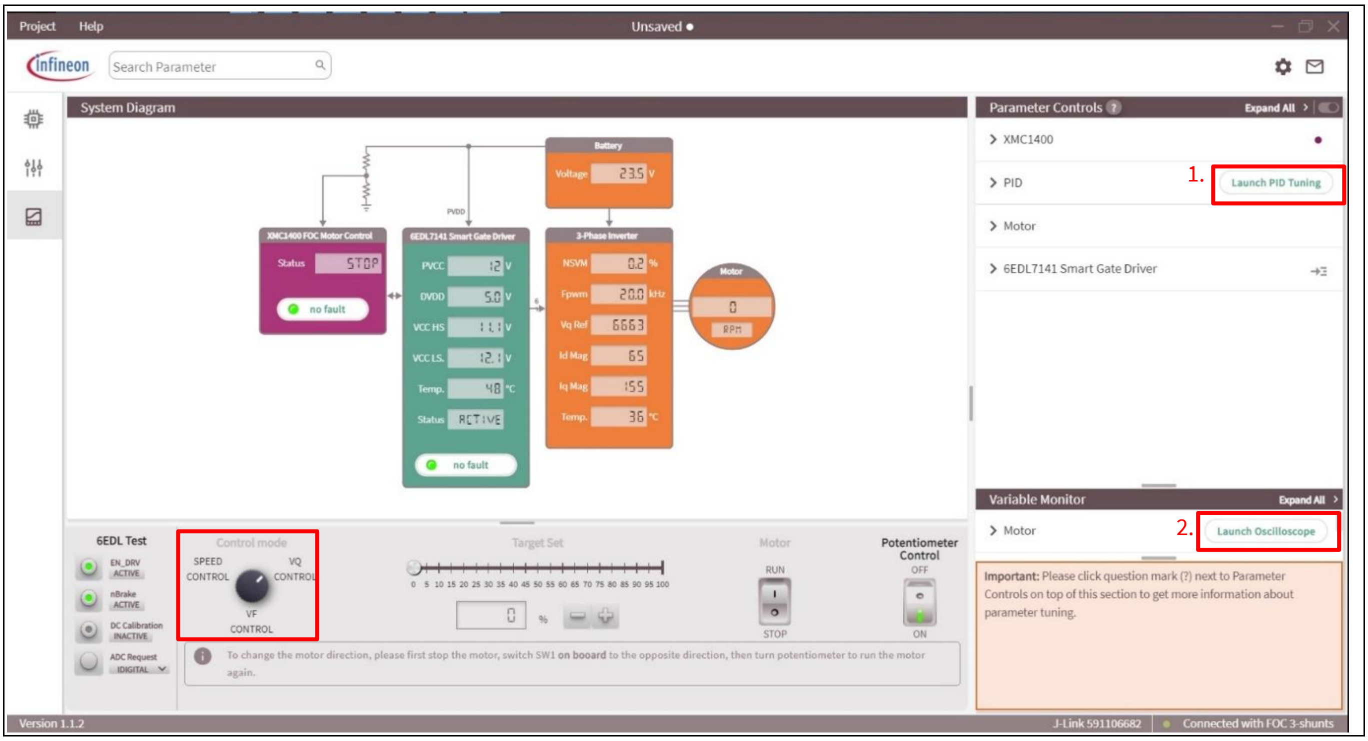

Figure 3 **MOTIX™ BPA motor control workbench**

2 Step-by-step guide on tuning process

2.1 Selecting current sensing resistor

A high current sense resistance value increases the power loss in the sensing resistors. But a too-low sense resistance value will cause the sensorless FOC algorithm to malfunction, as the noise floor voltage will mask the sense current. So, the selected current sense resistor R_{sense} should produce a clean voltage at the analog-to-digital converter (ADC) from the phase current when operating the motor. Furthermore, the maximum overcurrent protection (OCP) threshold of MOTIX™ 6EDL7141 is 300 mV. So, if the maximum peak phase current is 10 A, then each shunt resistance should be about (120 mV/10) mΩ to provide sufficient current sensing information to the ADC.

2.2 Set 6EDL7141's OCP current threshold value

To protect the MOSFET from high current during the tuning process, set 6EDL7141's overcurrent threshold to about 120% of the motor's rated current level. Then, we can set the OCP positive and negative threshold to 1.2* $I_{motor's\ rated\ current}$ * shunt resistance. For example, if the motor-rated current is 1.8 A shunt resistance is 10 mΩ, then the OCP threshold voltage is 1.2*1.8*0.01 = 0.0216 V. The OCP threshold voltage should be set to 20 mV. Next, set the Dead time rising and falling value to 840 ns to minimize high-side and low-side MOSFET's shoot through during the tuning process.

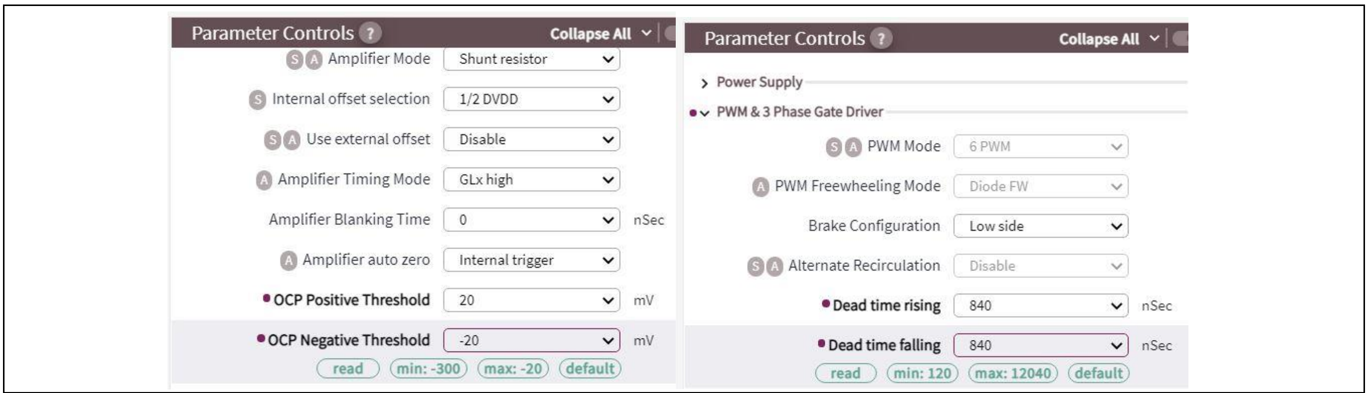

Figure 4 OCP threshold and dead time setting in MOTIX™ BPA motor control workbench

2.3 Motor parameters measurement

Find and set motor parameters (e.g., inductance per phase, resistance per phase, motor's pole pair, motor maximum speed) from the motor's datasheet. We assume the motor used is a Y-connected motor, and the phase resistance refers to the phase-to-neutral resistance in a Y-connected motor. Similarly, phase inductance refers to the phase of neutral inductance in a Y-connected motor. Hence, if the motor is delta connected, then a delta-to-Y conversion must be done to set the resistance value. For example, if the delta-connected motor value's resistance per phase is 3 Ω in the datasheet, the equivalent Y resistance per phase value is R(Y) = R(delta)/3 = 1 Ω. Similarly, if the delta-connected motor's per-phase inductance is 30 µH, the equivalent Y connected per-phase inductance is L(Y) = L(delta)/3 = 10 µH.

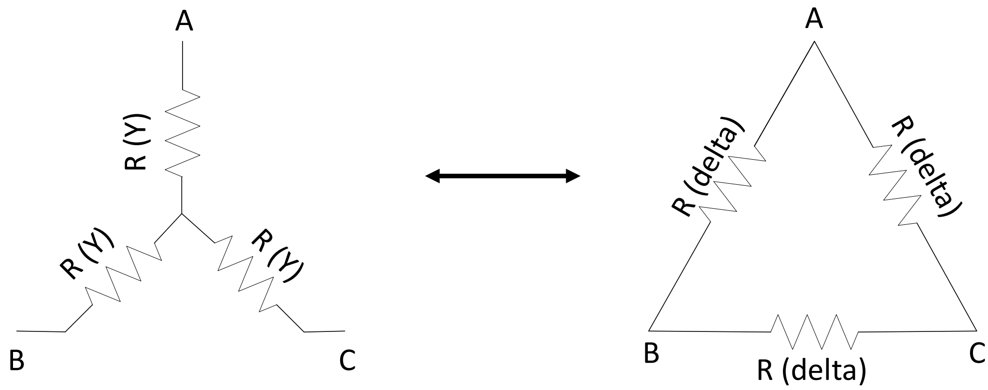

Figure 5 **Conversion of delta motor's resistance to equivalent Y motor's resistance**

If the motor's datasheet is unavailable, the motor resistance per phase could be measured with a multimeter, and motor inductance per phase could be measured with an LCR meter. If the motor inductance is low (in order of 10 uH), please use a precision RCL meter (e.g., Instek LCR-6100) to measure the motor per phase inductance. The inductance measurement is important as the PLL observer uses the motor's per-phase inductance for angle estimation.

If IPMSM (Interior Permanent Magnet Synchronous Motor) is used, one motor phase's q-axis inductance (Lq) should be used. For example, Lab is the phase-phase inductance measured by an LCR meter at 1 kHz while moving the motor to different angles of a mechanical revolution. Take the highest inductance measurement and divide it by two to get the per-phase inductance of the motor.

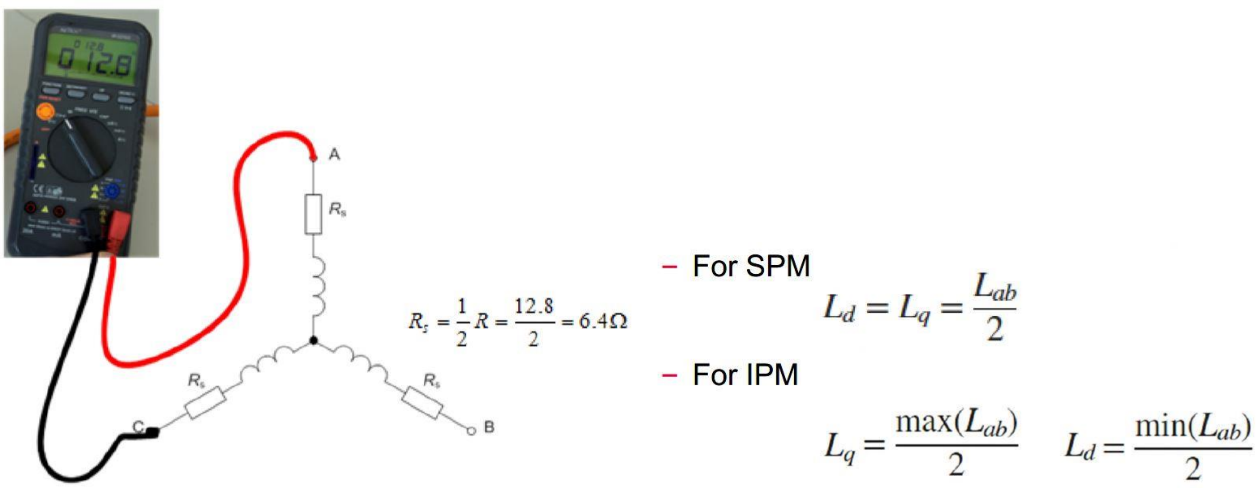

Figure 6 **Motor's per phase resistance and inductance measurement**

2.4 Update motor parameter to MOTIX™ BPA motor control workbench

Set the motors's minimum speed to about 5% of the motor's maximum speed and input the measured motor's resistance and inductance per phase.

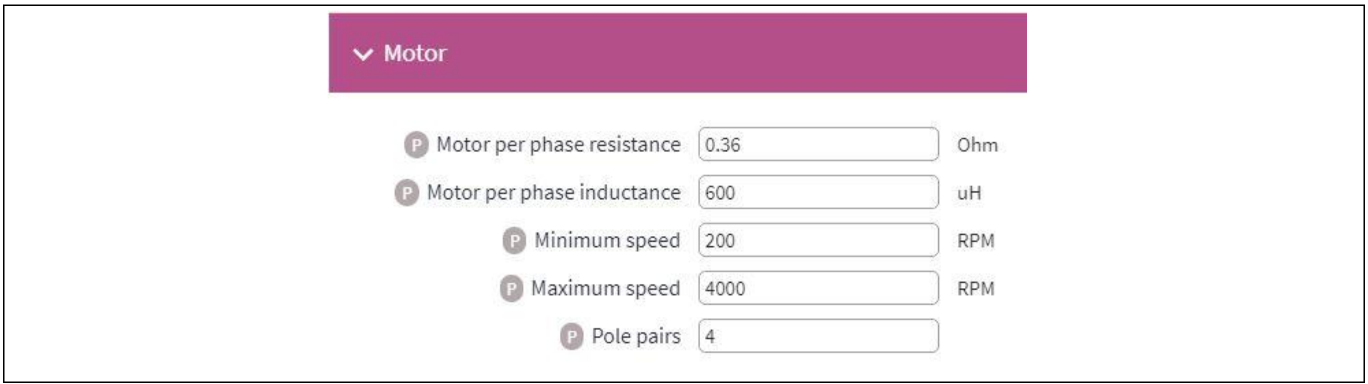

Figure 7 MOTIX™ BPA motor control workbench's motor parameters input

2.5 VQ ramp rate and speed ramp rate

Adjust VQ or Speed ramp rate according to motor and load conditions. The VQ ramp rate has to adjust in the firmware source code, while the speed ramp rate can be adjusted using the MOTIX™ BPA motor control workbench.

The slew rate configuration shown in Figure 9 determine how many PWM frequency's period has passed, before perform the ramp-up or down step. For example, if the slew rate is set to three, it means every three PWM period, the ramp-up or down step will be updated until the reference VQ voltage has reached. If the user wants to ramp up the VQ voltage faster, increase the USER_VQ_RAMPUP_STEP and decrease USER_VQ_RAMP_SLEWRATE. If the user wants to reduce the VQ ramp-up, reduce the USER_VQ_RAMPUP_STEP and increase the USER_VQ_RAMP_SLEWRATE. This is illustrated in Figure 10.

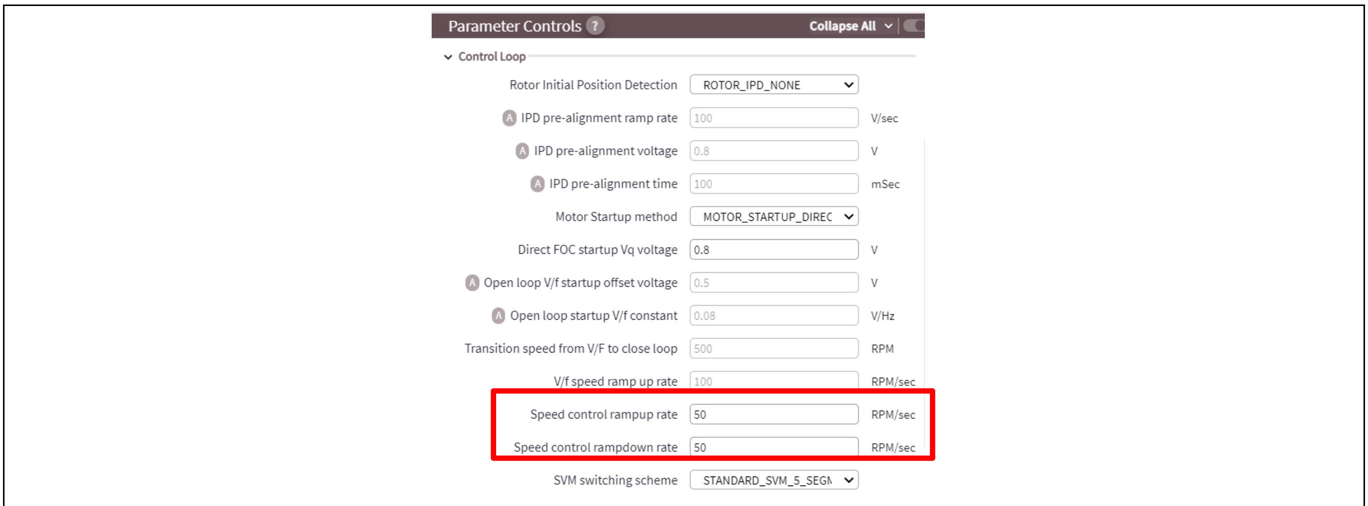

Figure 8 MOTIX™ BPA motor control workbench's speed ramp input

```
pmsm_foc_user_input_config.h
#define USER_VQ_RAMPUP_STEP                     (1U)
#define USER_VQ_RAMPDOWN_STEP                   (1U)
#define USER_VQ_RAMP_SLEWRATE                   (3U)
```

Figure 9 Configure VQ ramp rate and slew rate in pmsm_foc_user_input _configure.h file

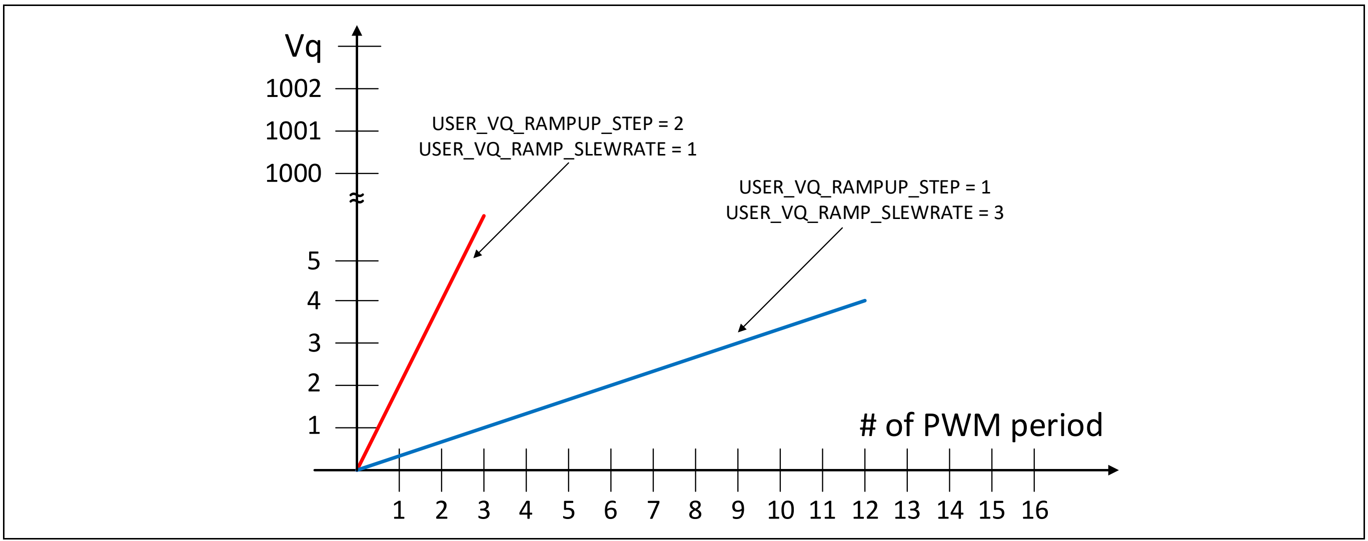

Figure 10 **Changing VQ ramp rate using ramp-up step and slew rate parameters**

2.6 Pre-alignment mode

If rotor pre-alignment mode is enabled, set the pre-alignment time longer first, then progressively reduce it.

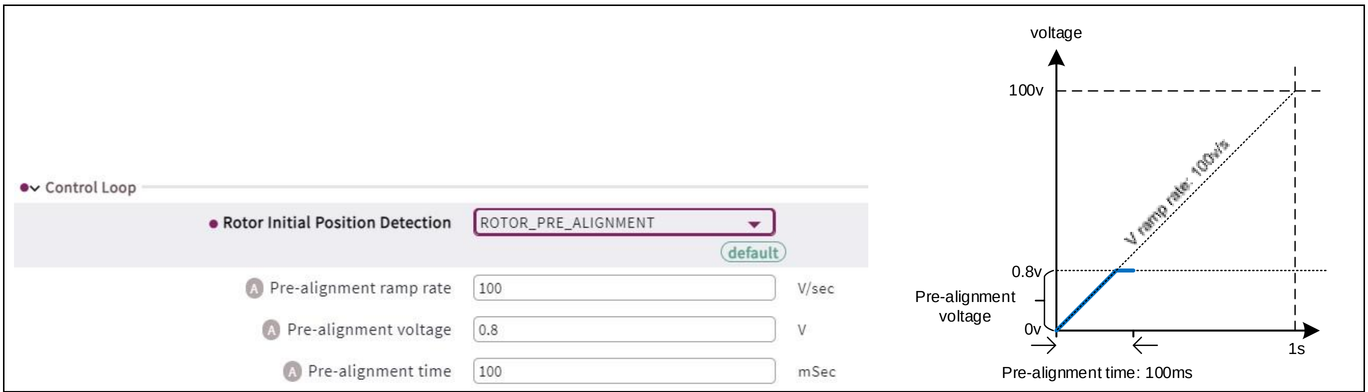

Figure 11 **Pre-alignment setting**

2.7 V/f start-up mode

If V/f start-up mode is enabled, set a suitable V/f offset voltage to move the rotor's inertia. Set transition speed close to motor minimum speed to enable the quick transition from open loop to close loop to reduce time interval in open loop, which consumes high current.

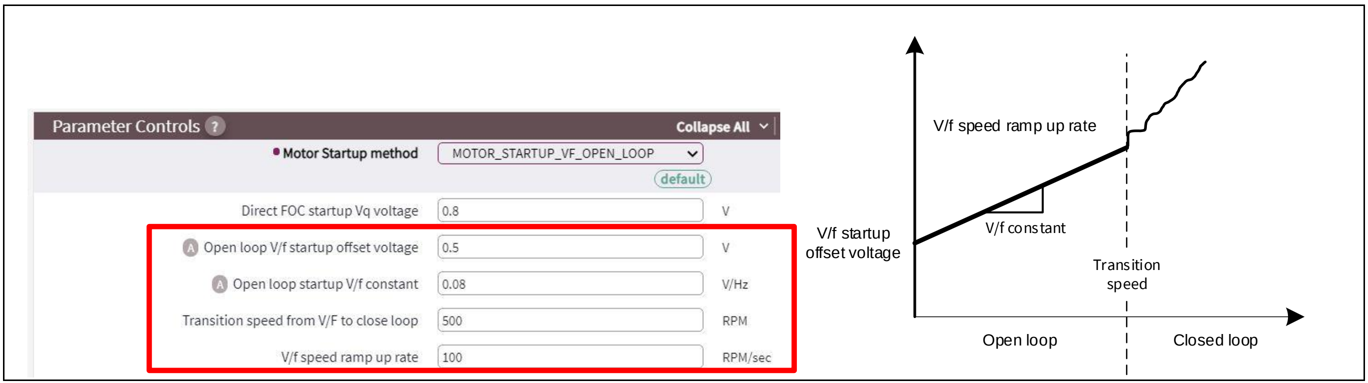

Figure 12 V/f startup method input in MOTIX™ BPA motor control workbench

2.8 Direct FOC start-up

If direct FOC start-up mode is enabled, set a suitable direct FOC start-up VQ voltage to run the motor to reach the minimum motor speed first, then ramp up to reach the target VQ voltage or target speed. If the user uses VQ control mode, then the user should adjust the VQ ramp rate in pmsm_foc_user_input_config.h file. However, if the user is using speed control mode, then the user can change the speed ramp rate in the MOTIX™ BPA motor control workbench. Users can test with direct FOC start-up to run the motor under test first, as it does not need a pre-alignment setting and V/f setting.

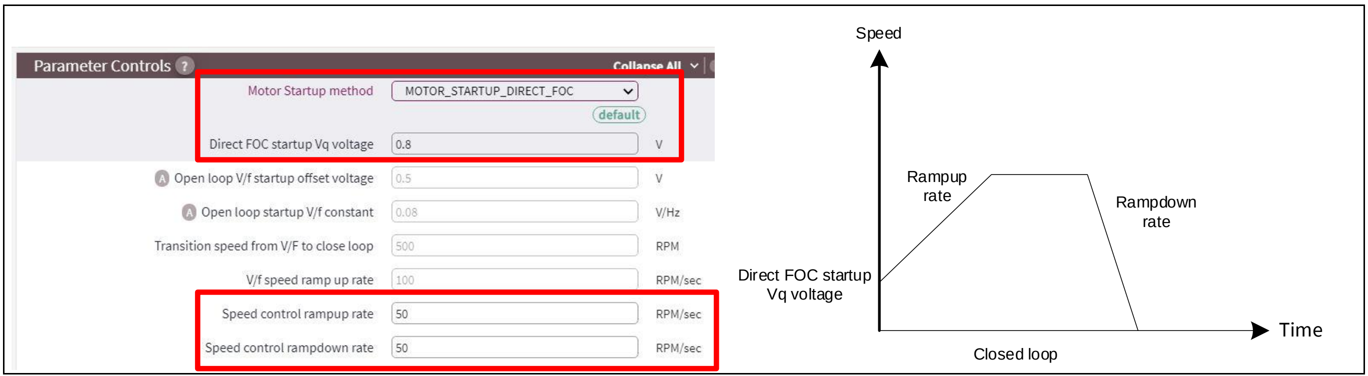

Figure 13 MOTIX™ BPA motor control workbench's direct FOC start-up inputs

2.9 Motor control schemes

After setting the pre-alignment parameter, followed by V/f start-up or direct FOC start-up, tune the Kp and Ki values of the control loops running the motor in a close loop. In the MOTIX™ BPA motor control workbench, three motor control schemes are provided: V/f open loop mode, VQ control mode, and Speed control mode. The V/f open loop is not used for running the motor but for testing the current sensing circuitry on the evaluation board. VQ and speed control mode are the two options for users to run their motor.

2.9.1 V/f open loop mode

In an open loop voltage control, a reference voltage (V_{ref}) is used to cause the power inverter to generate a given voltage at the motor. The mechanical load influences the speed and the current of the PMSM motor.

In the MOTIX™ BPA motor control workbench, this mode is used for debugging purposes. It is used to test the current sensing circuitry on the board, and the motor should run under no-load conditions so it can spin smoothly. If the current sensing works fine, the oscilloscope tool should display a somewhat sinusoidal waveform for IU, IV, and IW signals (Figure 15). By comparing the phase U current captured using a current probe in Figure 16, we can see that the current sensing circuit on the evaluation board works fine, as both Figure 15 and Figure 16 are similar. Under the condition that the motor is heavy and it is not spinning when operating in V/f open loop mode, we can increase the VF_OFFSET value to overcome the motor's inertia.

In the example project, the V_{ref} is also restricted to a low voltage to prevent a large current being drawn when running the motor under V/f open loop mode. So, the user might be able to change the potentiometer on the MOTIX™ BPA motor control workbench, but the motor speed will not increase further.

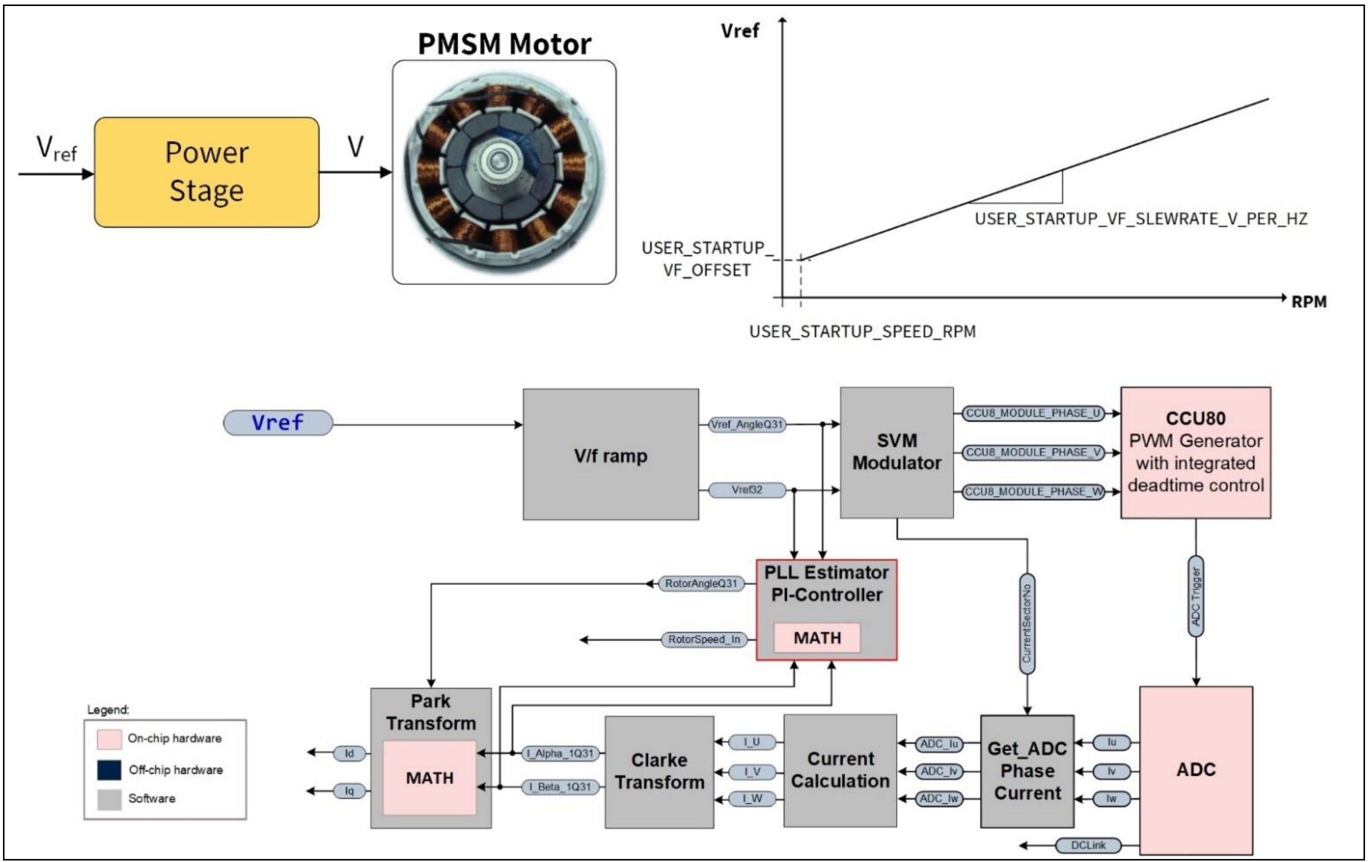

Figure 14 **Open loop V/f voltage control**

Figure 15 V/f open loop IU, IV, and IW current waveforms captured by the GUI's oscilloscope

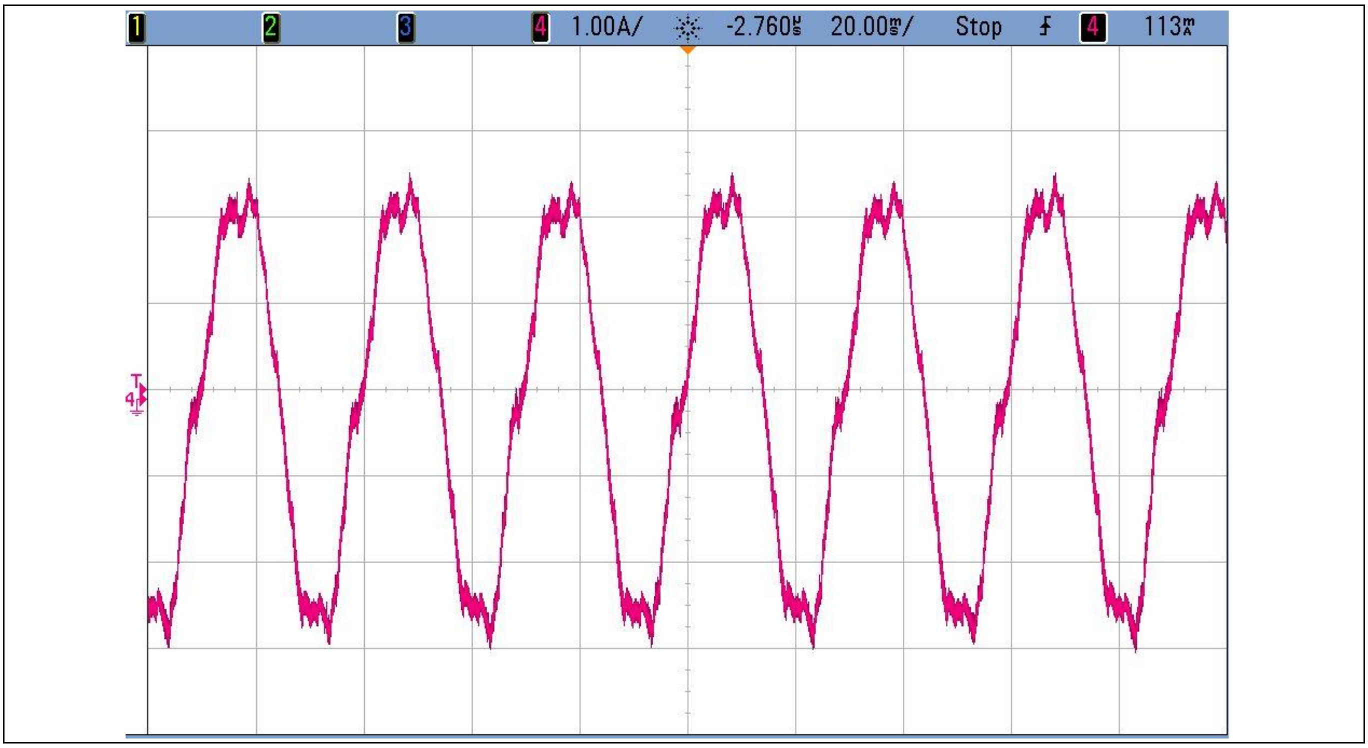

Figure 16 V/f open loop IU current waveform captured by the current probe

2.9.2 VQ control direct start-up

The VQ control is used when a fast response is required, and varying speeds are not a concern.

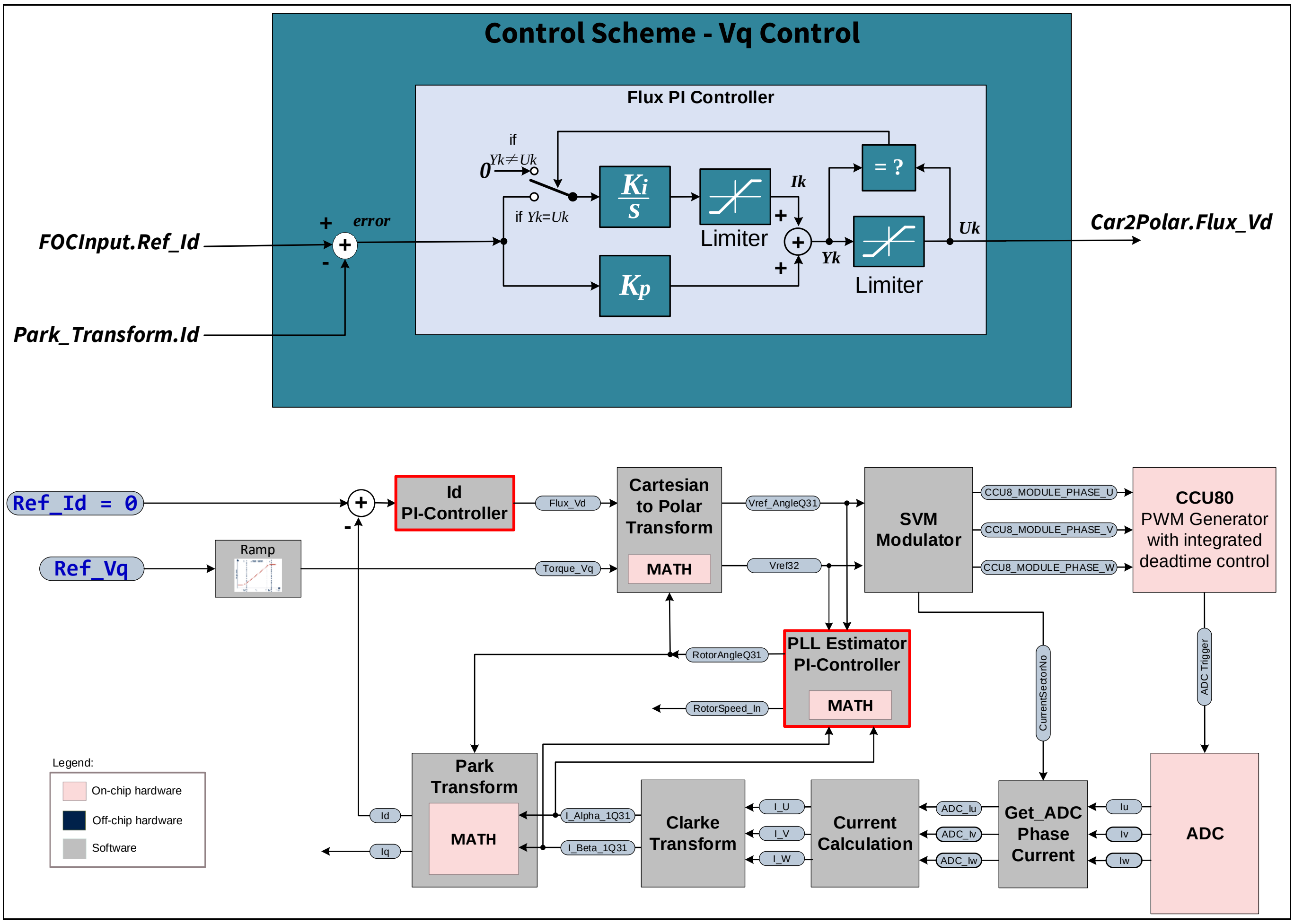

Figure 17 Control scheme - VQ control scheme

2.9.2.1 Determination of flux (Id) and torque (Iq) current PI gains

The PI gains are calculated using the pole-zero cancellation technique, as illustrated in Figure 18 . By having $K_P/K_I = L/R$, the controller zero will cancel the motor pole. With this, the transfer function of the control loop is a first-order LPF with time constant, T_c. In addition, the proportional gain calculation is based on motor inductance, and the integral gain is on the motor resistance.

At constant motor speed the Back-EMF of the motor is near constant. Therefore it is negligible in the frequency domain. Figure 18 shows the simplified diagram after pole-zero cancellation.

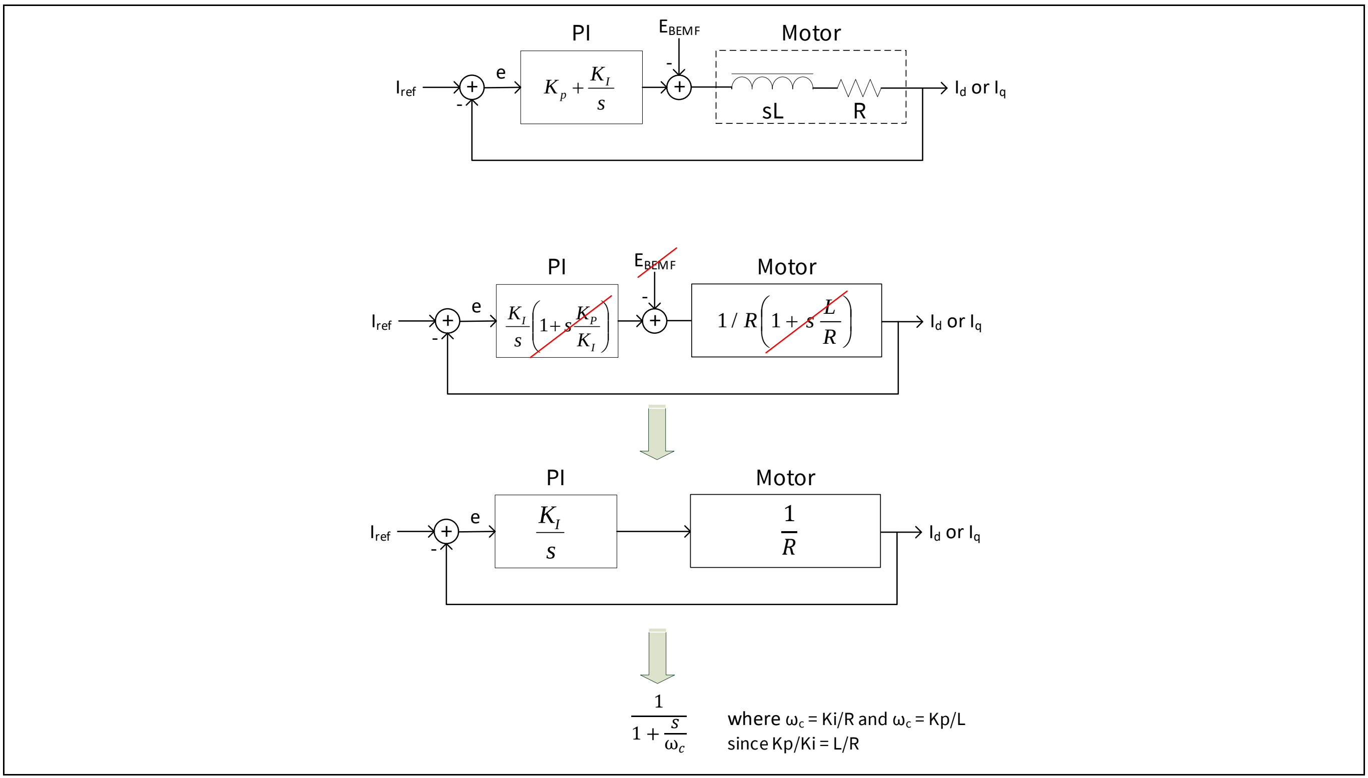

Figure 18 **Simplified current control loop due to pole-zero cancellation**

As $K_P/L = K_I/R = \omega_C$, the PI controller gains are:

Proportional gain $K_P = \omega_C L$

Integral gain $K_I = \omega_C R$

Where:

- ω_C is the cut-off frequency of the first-order LPF.
- L is the motor inductance.
- R is the motor resistance.

In the digital controller implementation, the integral part is a digital accumulator. Therefore the K_I gain has to include a scaling factor for the sampling time T_S, which is the PWM frequency.

Revised formula:

Proportional gain $K_P = \omega_C L \times A$

Integral gain $K_I = \omega_C R \times T_S = RT_S K_P/L$

Where:

- A is the XMC hard ware optimize scaling factor.

Based on the past experience, set the cut-off frequency to three times of the maximum electrical motor speed to obtain a good trade-off dynamic response and sensitivity to the measurement noise.

2.9.2.2 VQ control loop tuning

Figure 17 shows that only Id or Flux PI control and PLL PI control (for the IP-restricted PLL estimator) must be tuned for VQ control. The purpose of tuning the control loop is to enable the smooth running of the motor with a sinusoidal phase current waveform even when the motor encounters load changes.

Figure 19 show that for each control loop, there is Kp, Ki, and scale for the user to input. Adjusting those values will affect output response to the error detected at the input of the control loop. Their relationships are as follows:

$K_{proportional\ gain} = Kp/2^{Scale}$ and $K_{integral\ gain} = Ki/2^{Scale}$ where, Kp, Ki, and scale are integer values represented in the source code for proportional gain, integral gain, and scale calculation, respectively.

Regarding the block diagram of Figure 17, we are monitoring the feedback (park_transform.flux_id) and output (uk) of the flux PI control loop in Figure 19. We also monitor the PLL PI control loop's input error (error) and output (uk). For VQ control, we want to minimize the flux PI control's park_transform.flux_id peak-to-peak value and PLL PI control's error by adjusting their Kp, Ki ,and scale value under the motor operation condition.

If motor is unable to run when startup, increase scale value of PLL PI control loop first and decrease the PLL control loop Kp and Ki value. If still unable to get it running, do it the opposite way by reducing the scale value of the PLL control loop and increase the PLL control Kp and Ki value instead. When tuning the PLL PI control loop, check that the PMSM_FOC_PLL_PI.uk (red line of PLL PI control) of Figure 19 is not saturated to a constant value.

When tuning the Kp, Ki and Scale value of flux PI control loop, the main objective is to minimize the peak-to-peak value of PMSM_FOC_OUTPUT.park_transform.flux_id (red line of flux PI control) at zero value. However, Kp, Ki, and scale value for flux (Id) and torque (Iq) control loop can be calculated by MOTIX™ BPA motor control workbench by clicking on 'Get calculated values' in the PID tuning page of MOTIX™ BPA motor control workbench. The flux and torque control gains are calculated based on the pole-zero cancellation method illustrated in Figure 18.

In general, decreasing the scale of the PLL PI control loop or increasing Kp of the PLL control loop will reduce the peak-to-peak value of PMSM_FOC_OUTPUT.park_transform.flux_id (red line of Flux PI control). While tuning the gain of the PLL PI control loop, observed the phase current using a current probe. The phase current profile should be sinusoidal, and its RMS value should be low when tuning of the gain at flux and PLL PI control loop is optimum. Adjusting the Ki of the PLL PI control loop may also help to shape the phase current to be more sinusoidal.

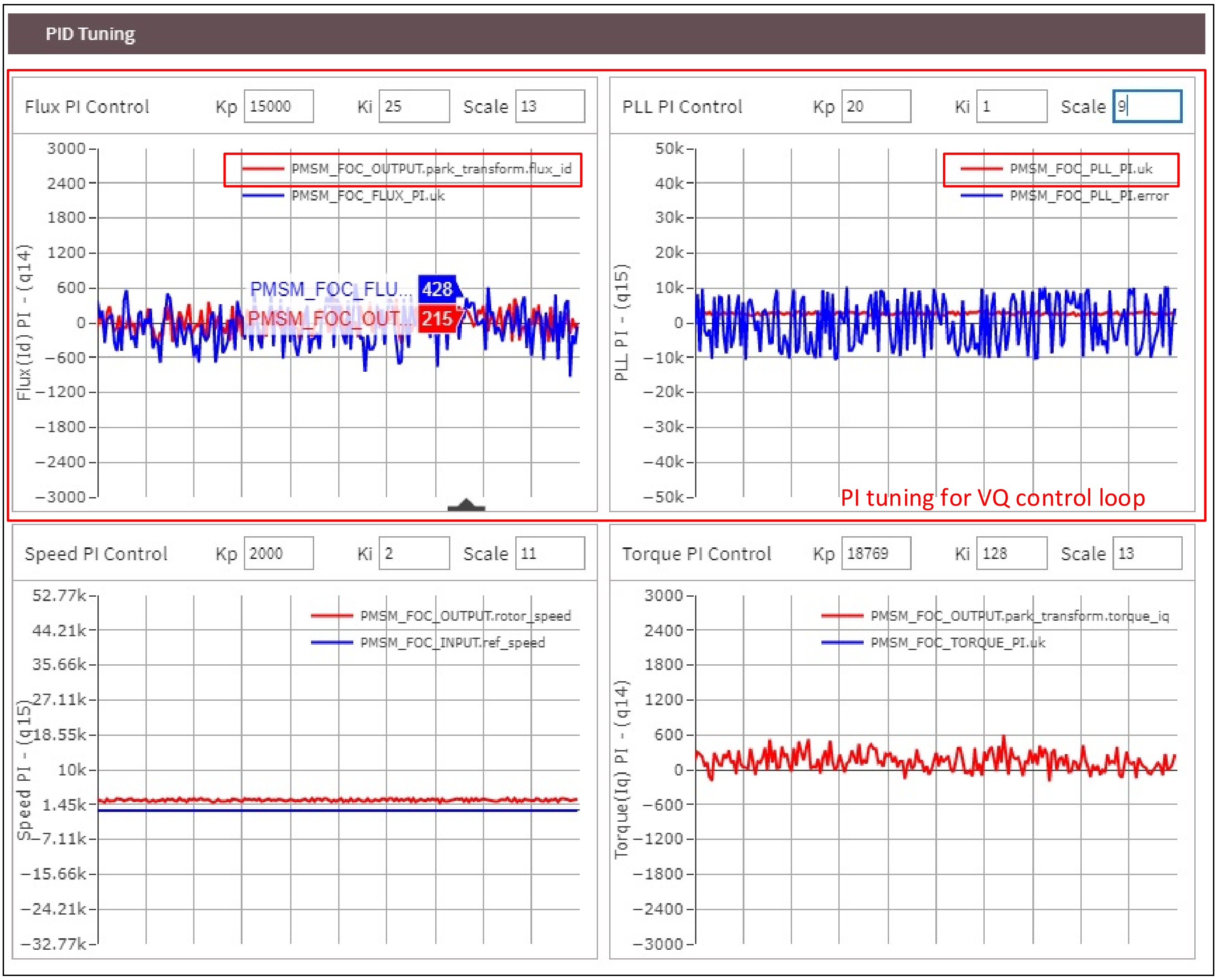

Figure 19 **PID tuning page in MOTIX™ BPA motor control workbench**

2.9.2.3 Effects of adjusting $K_{proportional\ gain}$, $K_{integral\ gain}$ of a PI control loop

To increase both the $K_{proportional\ gain}$ and $K_{integral\ gain\ by}$ by one time, reduce the scale value by one. To reduce both $K_{proportional\ gain}$ and $K_{integral\ gain}$ values to half, increase the scale value by one. Generally, try to increase or decrease the value of the scale and check whether the current waveforms of IU, IVt, and IW become more sinusoidal. In other words, the 'Scale' of Figure 19 acts as a coarse adjustment to $K_{proportional\ gain}$ and $K_{integral\ gain}$ value. The phase current waveforms of IU, IV and IW can be monitored by using the MOTIX™ BPA motor control workbench's oscilloscope function, illustrated in Figure 21.

To further fine-tune the phase current waveform by individually adjusting the value of Kp and Ki to make a fine adjustment to the $K_{proportional\ gain}$ an $K_{integral\ gain}$ value of the PI control loop.

The effects of increasing the $K_{proportional\ gain}$ or $K_{integral\ gain}$ of the PI controller independently are illustrated in Table 1, with reference to Figure 20:

Table 1 Effects of increasing the proportional gain Kp or integral gain Ki of the PI controller

Gain change	Effect on step response characteristics			
	Rise time	**Overshoot**	**Settling time**	**Steady-state error**
$K_{proportional\ gain}$ increase, $K_{integral\ gain}$ unchanged	Decrease	Increase	Minor change	Decrease
$K_{integral\ gain}$ increase, $K_{proportional\ gain}$ unchanged	Decrease	Increase	Increase	Eliminate

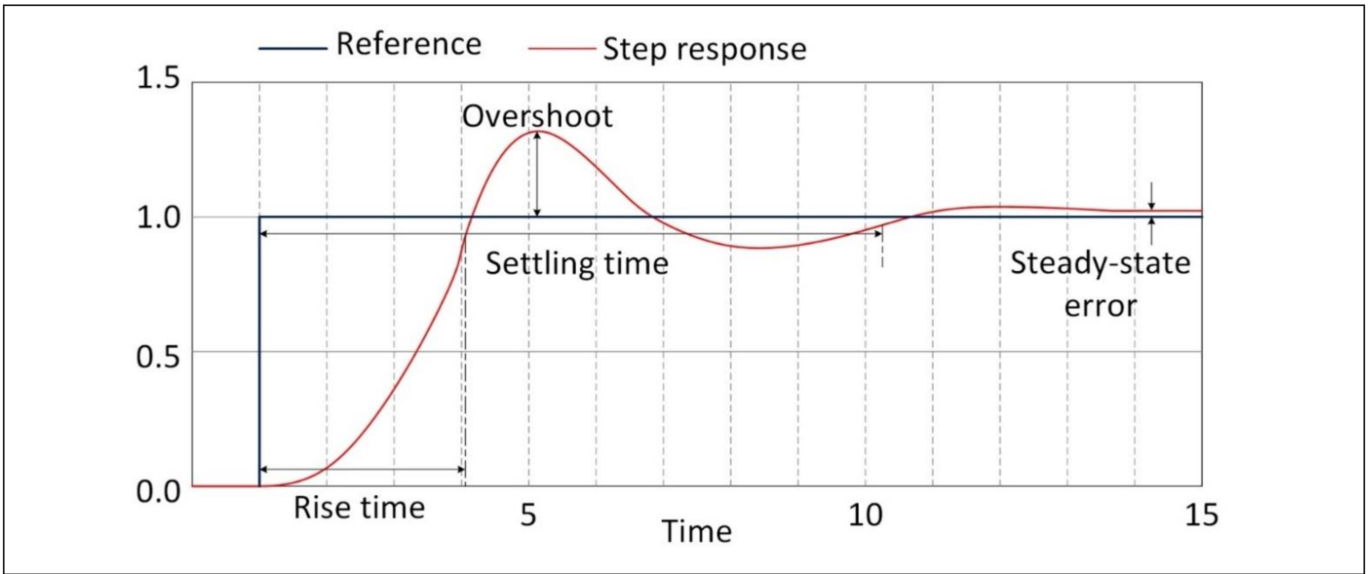

Figure 20 Step response of a control system

Figure 21 Oscilloscope monitoring IU, IV, IW in MOTIX™ BPA motor control workbench

2.9.3 Speed control

A speed control scheme is a closed-loop control. For the speed control scheme, a cascaded speed and current control structure is used. This is because the change response requirement for speed control loop is much slower than the one for current loop.

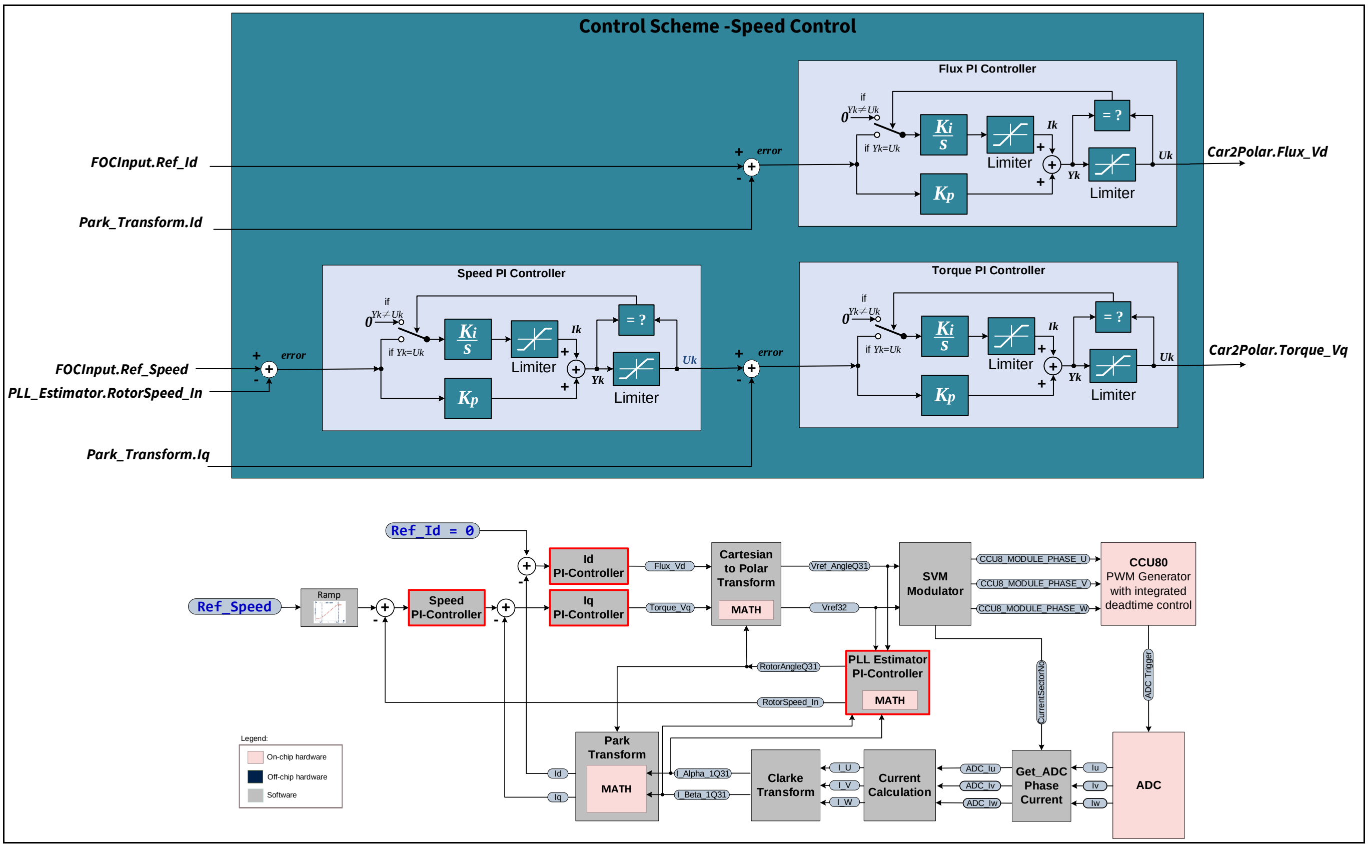

Figure 22 Control scheme - speed control

Direct FOC start-up and V/f start-up are supported in speed control. The speed PI controller supports integral anti-windup. The integral output is held stable when either PI output or integral output reaches its limit. The output of the speed PI is used as the reference for the torque PI controller.

2.9.3.1 Speed control loop tuning

Figure 22 shows four control loops: PLL PI control, flux PI control, torque PI control, and speed PI control. It is difficult to tune these control loops at the same time. Tune the motor using VQ mode, considering only flux and PLL PI control loop tuning. After the motor can run in VQ control mode, switch to speed mode control. Usually, we can use the tuned Kp, Ki, and scale values (obtained from VQ control mode) for the PLL PI control, flux PI control, and torque PI control when we start to tune the speed PI control to get sinusoidal phase current waveforms under different load conditions and at a steady speed. The Kp, Ki, and scale values for flux should be used for the torque PI control loop's Kp, Ki, and scale value.

Furthermore, when the motor transit from V/f open loop start-up or direct FOC start-up to speed control mode, it will proceed to VQ control mode until the motor speed reaches four times the motor minimum speed setting. The default value of four times the motor minimum speed setting can be reconfigured in the source code, as shown in Figure 23. This feature enables the user to run the motor in speed control mode more easily because VQ mode provides the initial torque to overcome the motor's inertia. Users could also decide the speed to change to speed control by modifying the source code set.

```
pmsm_foc_scl_systick_isr.c

    if (PMSM_FOC_INPUT.user_ctrl_scheme == SPEED_INNER_CURRENT_CTRL_SCHEME)
    {
        if ((PMSM_FOC_CTRL.msm_state == PMSM_FOC_MSM_CLOSED_LOOP)
          && (PMSM_FOC_CTRL.transition_status == PMSM_FOC_MOTOR_STATUS_TRANSITION))
        {
          PMSM_FOC_SPEED_PI.uk_limit_max = PMSM_FOC_INPUT.limit_max_iq;

          /* During startup Vq voltage control is used and then it will switch to the speed current control */
          /**********************************************************************************************/
          if (PMSM_FOC_PLL_ESTIMATOR.rotor_speed > (4 * MotorParam.ELECTRICAL_SPEED_LOW_LIMIT_TS))
          {
            PMSM_FOC_CTRL.transition_status = PMSM_FOC_MOTOR_STATUS_STABLE;
            PMSM_FOC_SPEED_PI.ik = PMSM_FOC_OUTPUT.park_transform.torque_iq << PMSM_FOC_SPEED_PI.scale_kp_ki;
            PMSM_FOC_TORQUE_PI.ik = PMSM_FOC_OUTPUT.torque_vq << PMSM_FOC_TORQUE_PI.scale_kp_ki;
            PMSM_FOC_CTRL.ctrl_scheme_fun_ptr = &PMSM_FOC_SpeedCurrentCtrl;
          }
        }
    }
```

Figure 23 Speed control mode will run with VQ control first when transit from startup to close loop

Similarly, as shown in Figure 24, the PID tuning and oscilloscope tools are available to help in PI control loop tuning.

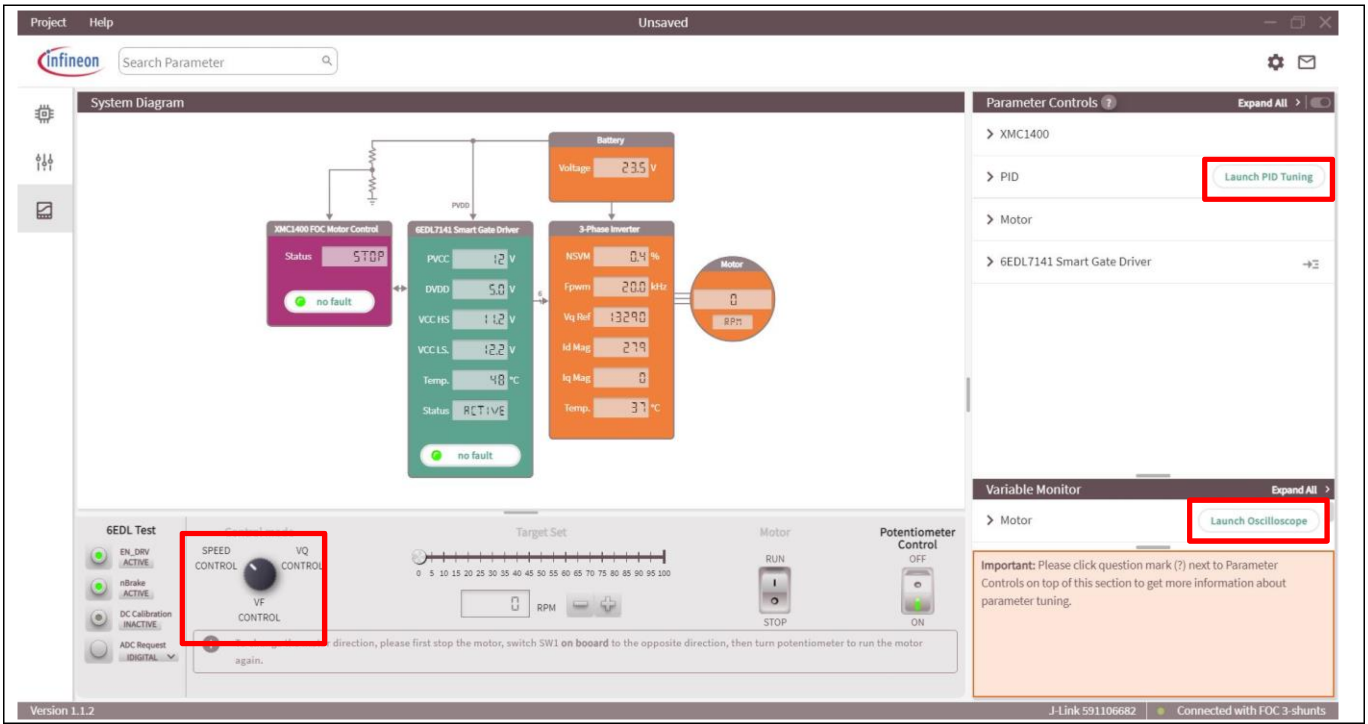

Figure 24 MOTIX™ BPA motor control workbench test bench view

The Kp, Ki of the flux, torque, and speed PI control chart of Figure 25 correspond to the PI controller block diagram of Figure 22. The PLL PI control block diagram is not shown in Figure 22, as PLL estimator is IP restricted. To understand the relationship between Kp, Ki, and scale of the control loop and the effect of adjusting those value, please refer to Chapter 2.9.2.2 and Chapter 2.9.2.3.

If the speed changes too much when the load changes, increase the speed PI control loop's Kp value. With low Kp of the speed PI control loop will have better stability at a steady state but slower startup. Low Ki of the speed PI control loop will lead to instability at high speed but will have a better startup.

If, by adjusting the scale value of the speed PI control, the phase current waveform is not sinusoidal, we might need to adjust the scale value of the flux and torque PI control to check their effect on the phase current. One thing to note is that the Kp, Ki, and scale values for both flux and torque PI control should be the same when tuning the speed control of the motor.

In general, a high Kp of flux and torque PI control loop will tend to start the motor very fast and cause significant speed overshoot during startup, while a low Kp of flux and torque PI control loop will not allow full speed full load operation. However, a low Ki for flux and torque PI control loop will lead to steady-state instability. However, usually, we could use Kp, Ki, and scale value for flux (Id) and torque (Iq) control loop calculated by MOTIX™ BPA motor control workbench by clicking on 'Get calculated values' on the PID tuning page. The flux and torque control gain are calculated based on the pole-zero cancellation method illustrated in Figure 18.

If the motor cannot run during startup, increase the scale value of the PLL PI control loop first and decrease the PLL control loop Kp and Ki value. If still unable to get it running, do it the opposite way by decreasing the scale value of the PLL control loop and increasing the PLL control Kp and Ki values instead. If we encounter a high current in a motor startup, we could lower the speed ramp-up rate using MOTIX™ BPA motor control workbench's setting or change the VQ ramp-up rate by changing the setting in the example code described in Chapter 2.5.

While tuning the gain of the PLL PI control loop, observed the phase current using a current probe. The phase current profile should be sinusoidal, and its RMS value should be low when tuning of the gain at flux and PLL PI control loop is optimum. Adjusting the Ki of the PLL PI control loop may also help to shape the phase current to be more sinusoidal. Decreasing the scale of the PLL PI control loop or increasing Kp of the PLL control loop will reduce the peak-to-peak value of PMSM_FOC_OUTPUT.park_transform.flux_id (red line of flux PI control).

If the rotor_speed (red line) cannot reach the ref_speed (blue line) in the speed PI control chart, the scale of torque PI control needs to decrease while its Kp and Ki need to increase to get a higher output (uk) at the torque PI control loop. With higher output at the torque PI control loop, it should help to increase the rotor_speed at the speed PI control loop in Figure 25.

By adjusting the Kp, Ki, and scale value of the four control loops in speed control, the motor should be able to run at target speed under its operating condition and achieve sinusoidal phase current waveform of IU, IV, and IW as shown in Figure 26.

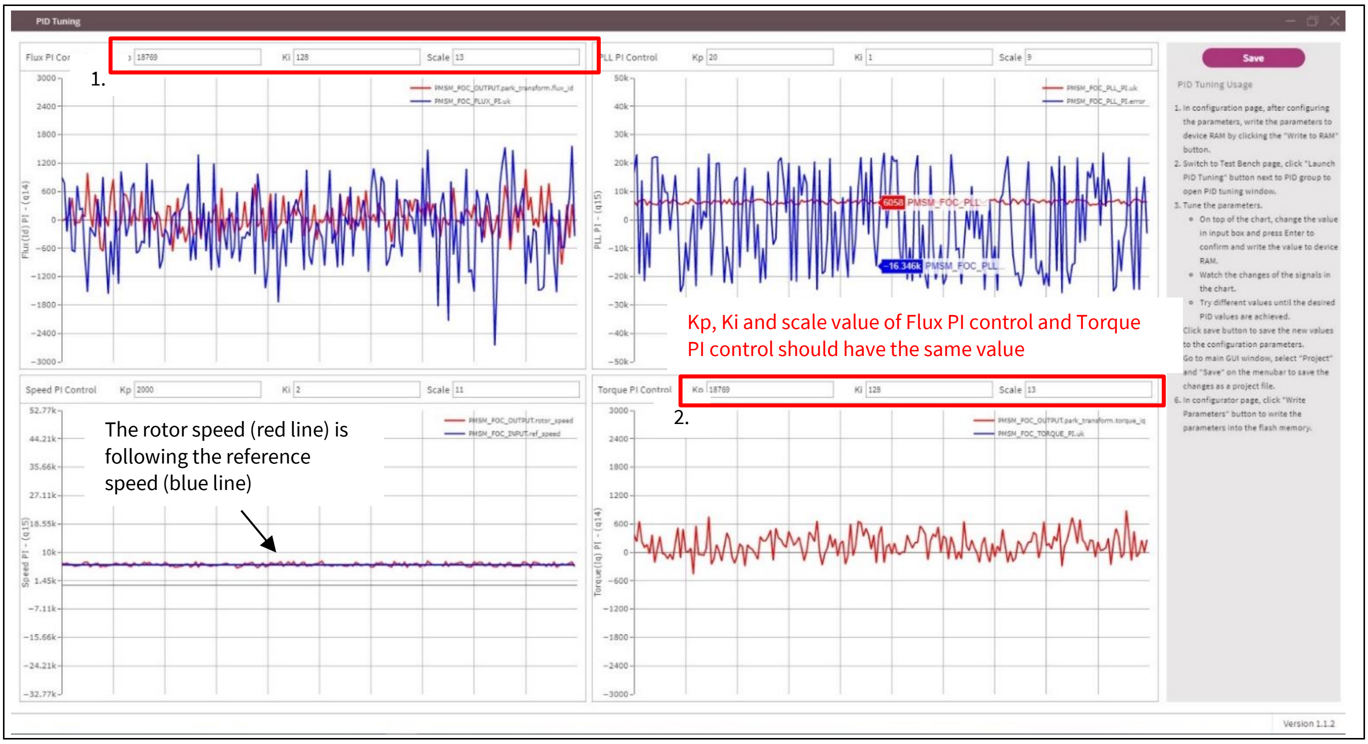

Figure 25 PID tuning page in speed control

Figure 26 Oscilloscope view for speed control, showing IU (green), IV (pink), and IW (blue) waveforms

3 Case study of PI tuning in ceiling fan and power drill applications

Here we provide some of the considerations that we made when running the ceiling fan and power drill using sensorless FOC motor control with MOTIX™ BPA motor control workbench and EVAL_6EDL7141_FOC_3SH 1kW evaluation board.

3.1 PI tuning in ceiling fan application

3.1.1 Getting the ceiling fan motor parameter

Table 2 Ceiling motor parameters

Motor inductance per phase (Y connection)	Motor resistance per phase (Y connection)	Pole pair	Max. speed	Motor-rated current
4400 µH	1 Ω	5	300 rpm	4 A

3.1.2 Checking the current and thermal capability of EVAL_6EDL7141_FOC_3SH 1 kW evaluation board

The EVAL_6EDL7141_FOC_3SH 1kW evaluation board's user manual shows that the board is able to withstand input power of approximately 1000 W, with V_{rms} and I_{rms} values of 36 V and 29 A, respectively. Therefore, the board input current rating is far higher than the motor current rating of about 4 A peak. As for the thermal capability, it is recommended that the board temperature be constrained to 100°C.

3.1.3 Setting the overcurrent threshold to protect the ceiling fan motor

As the maximum peak current of the ceiling fan is 4 A, three larger shunt resistors of 0.12 V/4 A = 0.033 Ω replace the original 1 mΩ shunt resistors on the 6EDL7141 3SH evaluation board. The OCP threshold of 125 mV is selected.

3.1.4 Select the motor startup method and PI tuning

After testing with the 'Direct FOC' and 'V/f' startup, it was found that the V/f startup method is better in moving the heavy inertia of ceiling fan for the startup phase. Hence, pre-alignment setting and V/f startup parameters are adjusted to get a good startup behavior.

Adjusting V/f startup voltage and ramp rate RPM/sec help to reduce or limit the current spike in the startup phase. The trade-off is that if too low V/f offset voltage or V/f ramp rate, the motor may not be able to overcome the ceiling fan inertia in the startup phase. The V/f offset voltage is approximated by phase current * motor's resistance per phase which is 2 A * 1 Ω = 2 V.

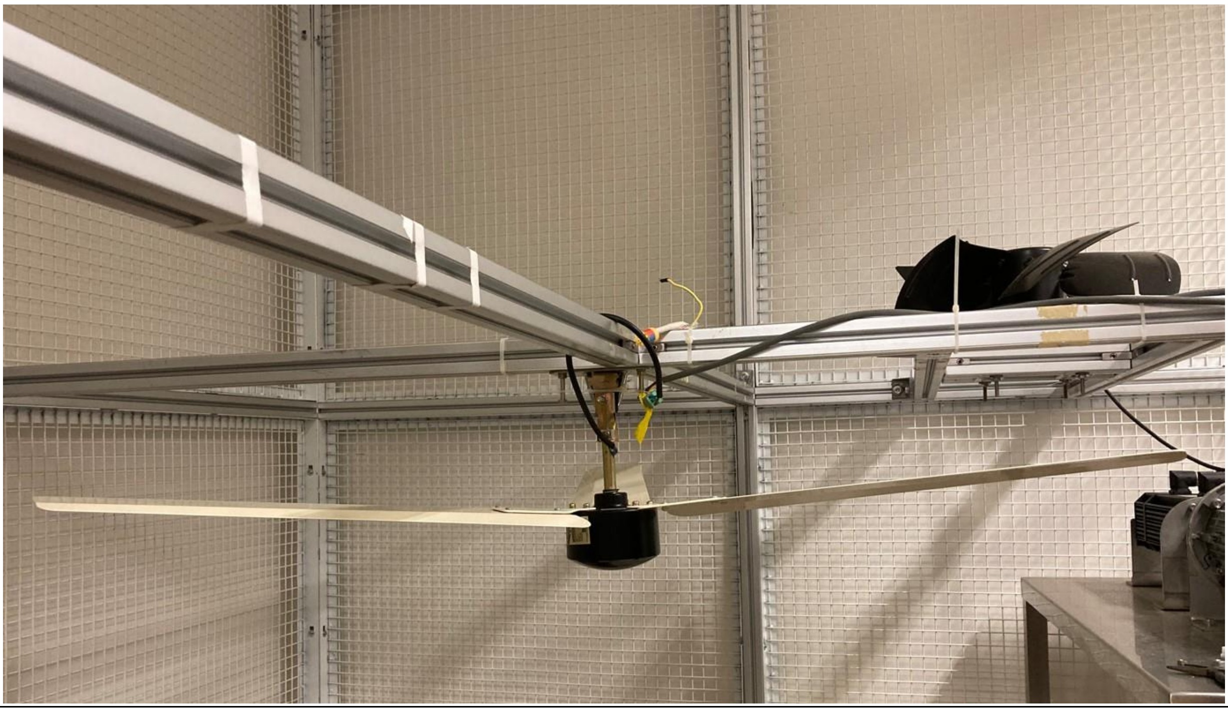

Figure 27 Setup for the ceiling fan

When open-loop V/f control is not able to transit to closed-loop FOC smoothly, reduce the PLL control loop gain by increasing the scale and decreasing the Kp and Ki setting of PLL control loop. If still unable to transition to closed loop, increase the PLL control loop gain.

During the motor startup, the motor is briefly stuck before running properly again; increasing the Ki value of PLL control loop help. When the motor speed is unstable, decrease the Kp of the PLL control loop.

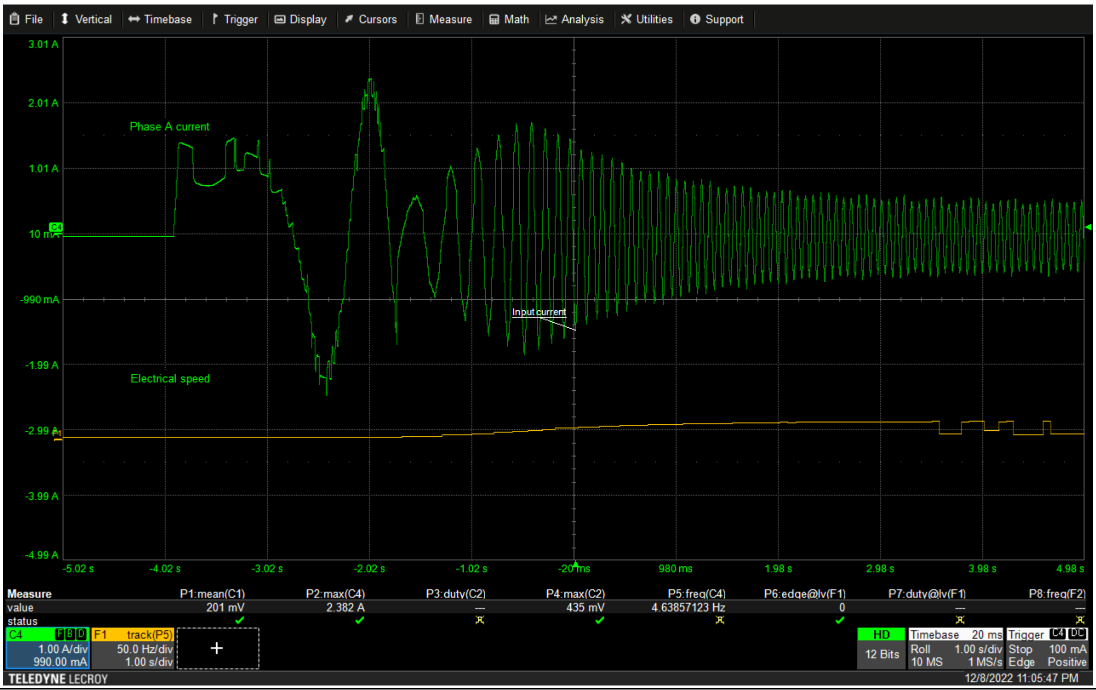

Figure 28 Phase current startup profile when transit from V/f to VQ control

When tuning the flux PI control loop, adjust the scale, Kp, and Ki to ensure flux_id stays approximately zero value.

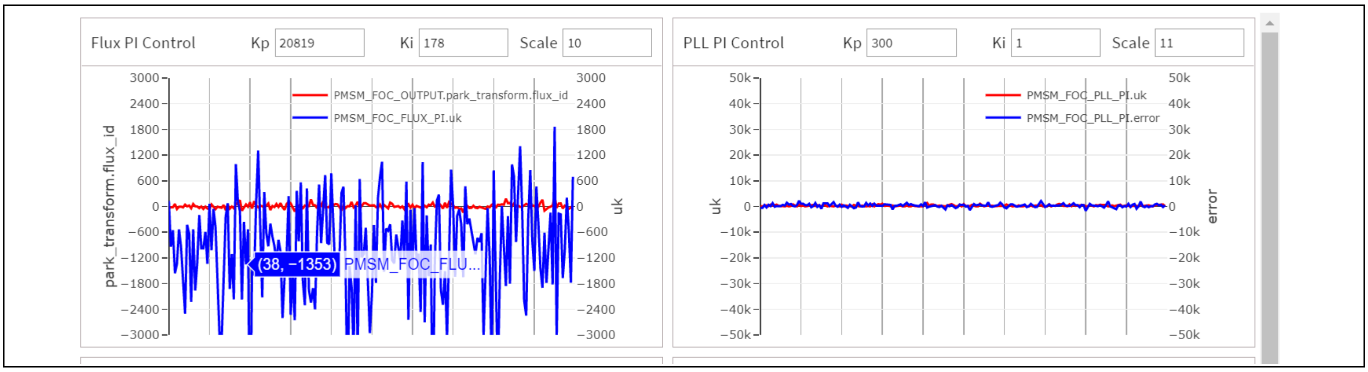

Figure 29 PI tuning for PLL and flux PI control loop for ceiling fan application

3.2 PI tuning in power drill application

3.2.1 Getting the power drill motor parameter

Table 3 Power drill motor parameters

Motor inductance per phase (Y connection)	Motor resistance per phase (Y connection)	Pole pair	Max. speed	Motor-rated current
12 uH	0.0066 Ω	2	30000 rpm	180 A

3.2.2 Checking the current and thermal capability of EVAL_6EDL7141_FOC_3SH 1 kW evaluation board

The EVAL_6EDL7141_FOC_3SH 1 kW evaluation board's user manual shows that the board can deliver an output power of approximately 1000 W (with supplied heatsink), with a nominal input voltage of 36 V and maximum output phase current of 282 A. Therefore, the board output current rating can take the power drill's peak motor current rating of 180 A. As for the thermal capability, it is recommended that the board temperature be constrained to 100°C.

3.2.3 Setting the overcurrent threshold to protect the power drill motor

As the maximum peak current of the power drill is 180 A and the shunt resistors mounted on EVAL_6EDL7141_FOC_3SH 1 kW evaluation board are 1 mΩ, the OCP threshold of 175 mV is selected. The power supply's output is set at 18 V and 80 A threshold to limit the power output to power drill at 1.44 kW.

3.2.4 Select the motor startup method and PI tuning

Direct FOC startup can drive the power drill directly. VQ control is chosen as it directly drives the torque output and is well-suited for power drill applications.

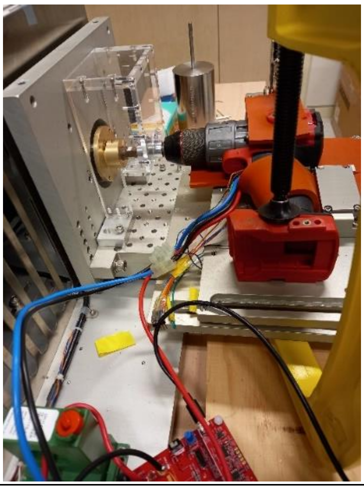

Figure 30 The power drill is connected to a dynamometer to capture the performance

By clicking the 'Get calculated value' button on the PID tuning page, the calculated Kp, Ki, and scale value for the flux and torque PI control loop are updated on the PID tuning page. With those PI parameters, the power drill can run with a load applied by the dynamometer.

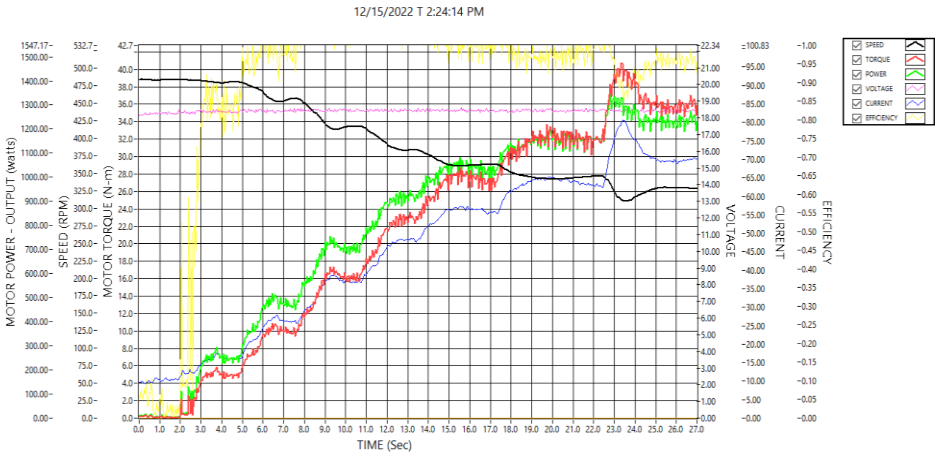

Figure 31 With the power drill running at maximum speed, apply incremental torque at 5 Nm step

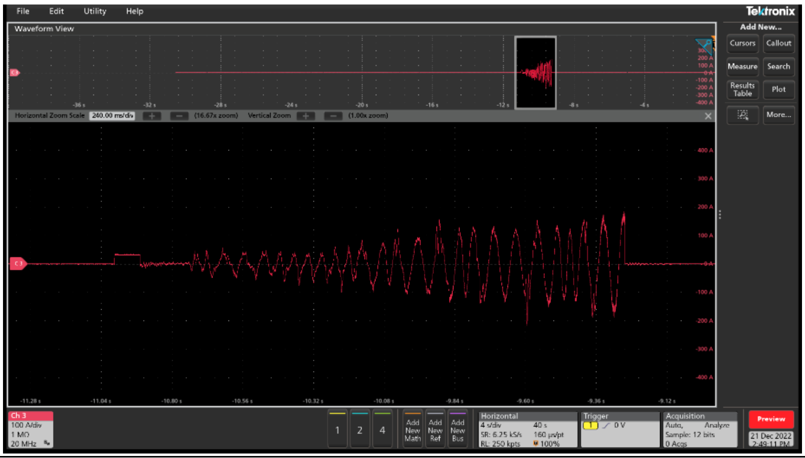

Figure 32 Phase current at startup with maximum load of 30 Nm applied

4 Summary

First, choose a suitable shunt resistor for the application required. Next, choose direct FOC startup. Then, select VQ control mode first and tune the PLL PI's gain values only as flux PI's gain value and torque PI's gain value can be calculated by MOTIX™ BPA motor control workbench using pole-zero cancellation method. The effect of adjusting the PID tuning page's Kp, Ki, and scale value is described in Chapter 2.9.2.2.

We can proceed to speed control mode after using the VQ control mode to find the optimum PLL PI's gain values to achieve a sinusoidal phase current waveform. In speed control mode, it consists of PLL, flux, torque, and speed control loop. The PLL, flux, and torque PI control loop gain values, are available from VQ control mode PI tuning. So, we only need to tune the speed control loop's gain values to achieve the required speed profile.

Figure 33 illustrates the startup behavior using pre-alignment followed by V/f startup, compared to that of using direct FOC startup. With direct FOC startup, it provides a much smaller startup current and fewer parameters to set compared to V/f startup. However, only some motor control applications can use direct FOC startup, so users must test out both startup methods to choose the suitable one.

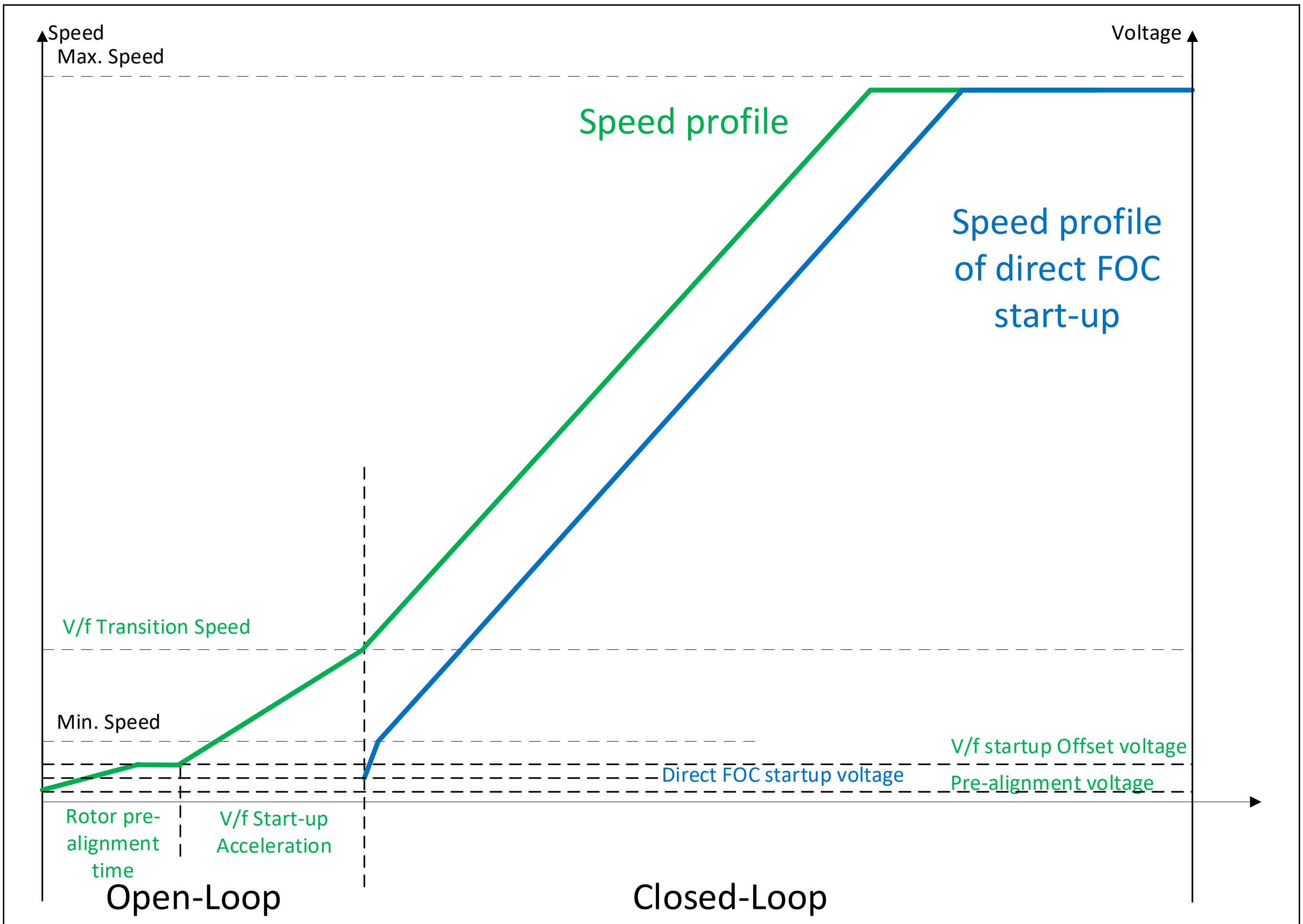

Figure 33 Startup behavior

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Revision history

Document version	Date of release	Description of changes
V 1.0	2022-05-04	Initial release
V 2.0	2023-09-15	Provided additional description in the PI tuning procedure and gave two PI tuning case studies

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