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Variable PWM Frequency Manual

Revision 0.4

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1. Introduction

The Gen 5 and CMxxx inverters support variable Pulse Width Modulation (PWM) frequency. PWM frequency is the rate at which the inverter switches the DC bus voltage to produce AC voltage waveforms for the motor. It can be advantageous to adjust the PWM frequency depending on motor characteristics and/or inverter operating characteristics.

This document describes setup and operation of variable PWM frequency for the Gen 5 and CMxxx inverters. The variable PWM frequency features described in this manual are only applicable to inverters that have either the GEN5 control board or the CMxxx inverters. These inverters run a firmware version with a release version of 65XX.

Variable PWM frequency features include the ability to change PWM over CAN during operation, and automatic PWM rate changes during operation.

Other features of the Gen 5 / CMxxx inverters are covered in either specific manuals or in common manuals that cover both the Gen 3 and Gen 5 inverters.

Note: 65XX series firmware should only be used with a PMxxx-G5 controller with the GEN5 control board or a CMxxx inverter. Do not try and install this firmware on a Gen 3 inverter.

1.1 CAN PWM Frequency Override

The PWM frequency can be set over CAN using the CAN Parameter Message. Refer to the CAN Protocol Manual for more information on the CAN Parameter Message.

Address	R/W Bit	Data
21	1	0, 2 to 24

A write to the CAN Parameter Message with the above information will over-ride the current PWM frequency and set the PWM frequency based on the value in the Data field (in kHz). Valid ranges of PWM frequency are 2 to 24kHz. If the Data field is set to 0 then the over-ride will be turned off and the PWM frequency will revert to being controlled by the EEPROM parameters.

The PWM frequency can be changed when the inverter is enabled or disabled.

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Care must be taken when changing the PWM frequency. There are some PWM frequencies that might not be compatible with either the motor or the inverter. Too low of a PWM frequency can result in excess current ripple in the motor that leads to excessive motor heating. Too high of a PWM frequency can lead to excess losses in the inverter that could lead to damage.

Motor speed must also be taken into consideration when selecting a PWM frequency. As a rule of thumb there should be at least 10 switching events per electrical cycle, or the switching frequency must be at least 10x the motor electrical frequency. The electrical frequency of the motor is the physical frequency at which the shaft is spinning multiplied by the number of motor poles divided by 2. This can be calculated as such:

$$Motor\ Speed_{Electrical\ Hz} = Motor\ Speed_{Mechanical\ RPM} * \left(\frac{1}{60}\right) * \left(\frac{Motor\ Poles}{2}\right)$$

For Example: If the desired switching frequency of a 10 pole motor is 6 kHz then the maximum mechanical speed at which 6 kHz should be used is 600 Hz electrical frequency or 600*60/(10/2) = 7200 rpm mechanical speed.

Below is a recommended range of PWM frequency based solely on inverter capability. The recommended range may not be applicable to all motor types and subject to the consideration of operating speed stated above.

Inverter Model	Recommended PWM Frequency Range	
	Minimum	Maximum
PM100DX/R	6	16
PM100DZ	6	24
PM150DX/R	6	16
PM150DZ	6	24
PM250DX	6	12
PM250DZ/R	6	16
CM200DX	2	24
CM200DZ	2	24
CM350DZ	2	24

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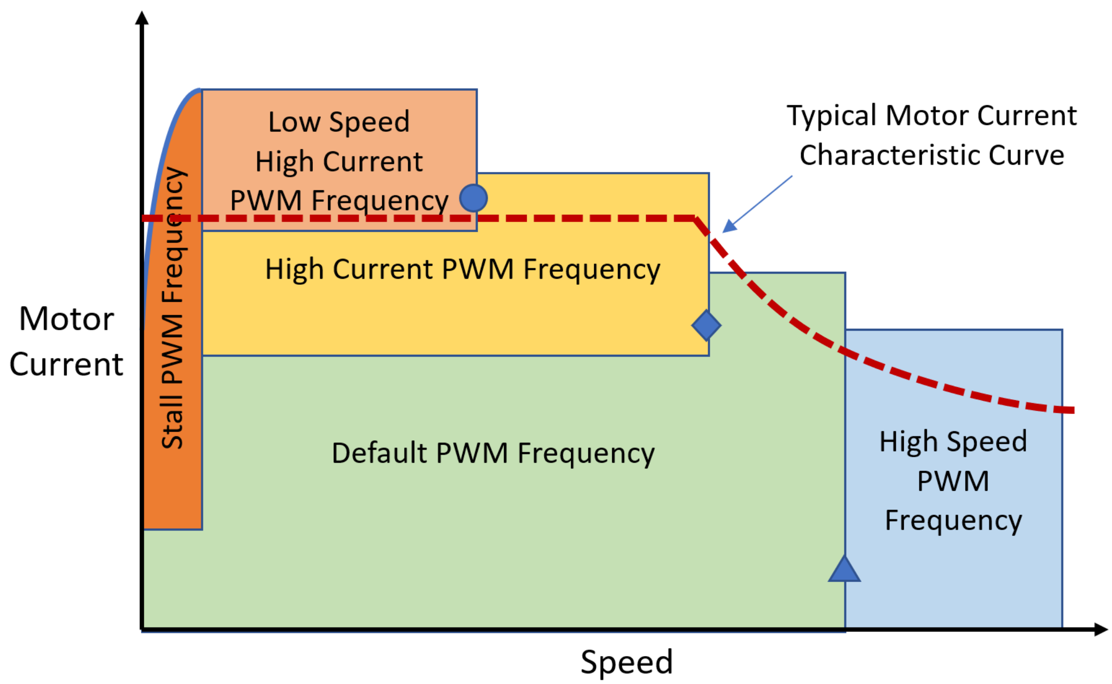
1.2 Automatic Variable PWM Frequency

The inverter can be setup to automatically change the PWM frequency during operation. The purpose of this is to automatically transition to appropriate PWM frequency based on factors of current level and speed. In general, lower PWM frequencies have a higher current limit at the cost of lower available speed and a more distorted excitation waveform. While higher PWM frequencies offer smoother excitation waveforms at higher speeds at the cost of lower max available current.

The transition of states is based on the inverter output current (motor current) and the motor speed. An overview of the possible switching (PWM) states is outlined in the graph below, along with a typical motor current characteristic curve for reference.



The justification for these various switching regions and their intended use are outlined in the table on the next page. Users can select the speeds at which the PWM transitions (within a fundamental limit), but the current will transition automatically based on the peak available current at the given PWM. This ensures maximum performance out of a PWM region and it updates accordingly for temperature based on the internal peak current calculations.

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PWM Region	Description
Override PWM	PWM frequency is set over CAN and overrides all other PWM states.
Stall PWM	This region directly specifies a PWM frequency for stall, or near stall, operation (<30 Hz Electrical Frequency). At or very near stall the current capabilities of the inverter are limited due to the DC current running through the power module. Significantly lowering the PWM frequency at stall allows for increased current capability. Typically, this can be as low as 2 kHz. Recommended to set this the same as Low Speed High Current PWM.
Low Speed High Current PWM	This region is used for peak torque operations at low speed. At low speeds and high current, the capability of the inverter can be extended by lowering the switching frequency without incurring issues of motor control given the low electrical frequency of the motor. This region would typically be used to achieve the max current capability of the inverter and is usually set anywhere from 2-6 kHz. Recommended to set this the same as Stall PWM.
High Current PWM	This is another region of high current and low speed operation. This region acts as an extension to the High Current Low Speed PWM region, but usually uses a slightly higher PWM frequency in order to extend the speed range of the higher current capability. Typically, this region would use a PWM frequency between 6-8 kHz.
Default PWM	This is the PWM state when not in the other PWM states. Typically, this PWM frequency is set around 8-12 kHz.
High Speed PWM	This state is used for high-speed operation. At high speeds a higher PWM frequency is needed to maintain control of the motor given the higher electrical frequency. At high speeds, due to field weakening, the current capability of the motor is limited and thus there is no loss of capability going to a higher switching frequency. Typically, this PWM frequency is set around 10-16 kHz.

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The following EEPROM settings are used to setup the Stall, Low Speed High Current, High Current PWM, Default PWM, and High Speed PWM regions in the RMS GUI.

RMS GUI Parameter	GUI Address	CAN Address	Value Range	Description
PWM_Frequency_EEPROM_(kHz)	0x0150	241	2 – 24	This parameter sets the default PWM frequency in kHz. The typical setting is 12 for 12 kHz. Default PWM is one of six total PWM states. If none of the conditions are met for the other PWM states, then the default PWM state is used.
High_Speed_PWM_Frequency_EEPROM_(kHz)	0x0179	250	2 – 24	This parameter sets the high speed PWM frequency in kHz. For example: a value of 16 sets it to 16 kHz. Typically, it is set to 10 – 16 kHz. High Speed PWM state is one of the six total PWM states and is used for high-speed operation. The transition to this region is based on a motor speed transition defined by: **PWM_High_Speed_Limit_EEPROM_(RPM)**
High_Current_PWM_Frequency_EEPROM_(kHz)	0x017A	244	2 – 24	This parameter sets the high current PWM frequency in kHz. For example: a value of 6 sets it to 6 kHz. Typically, it is set to 6 – 8 kHz. High Current PWM state is one of the six total PWM states and is used for low speed high current operation above the Default PWM but below the Low Speed High Current PWM in terms of current magnitude. The transition to this region is based on motor speed and motor current defined by: **PWM_High_Current_Spd_Limit_EEPROM_(RPM)** **PWM_High_Current_Limit_EEPROM_(Amps_x_10)**

RMS GUI Parameter	GUI Address	CAN Address	Value Range	Description
Low_Speed_High_Current_PWM_Frequency_EEPROM_(kHz)	0x01BF	247	2 – 24	This parameter sets the low speed high current PWM frequency in kHz. For example: a value of 4 sets it to 4 kHz. Typically, it is set to 2 – 6 kHz. Low Speed High Current PWM state is one of the six total PWM states and is used for lower speed high current operation above the High Current PWM in terms of current magnitude. The transition to this region is based on motor speed and motor current defined by: **PWM_Low_Speed_High_Current_Spd_Limit_EEPROM_(RPM)** **PWM_Low_Speed_High_Current_Limit_EEPROM_(Amps_x_10)**
Stall_PWM_Frequency_EEPROM_(kHz)	0x01C0	248	2 – 24	This parameter sets the stall PWM frequency in kHz. For example: a value of 2 sets it to 2 kHz. Typically, it is set to 2 – 4 kHz. Stall PWM state is one of the six total PWM states and is used for stall operation. The current level and speed at which the region is entered are inherent to the code for safety and are not user configurable.
PWM_High_Speed_Limit_EEPROM_(RPM)	0x0176	249	0 – 30000 RPM	This parameter sets the speed for entering High Speed PWM state in RPM. When motor speed exceeds this PWM high speed limit, the PWM state will change to the High Speed PWM state.

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RMS GUI Parameter	GUI Address	CAN Address	Value Range	Description
PWM_High_Current_Spd_Limit_EEPROM_(RPM)	0x0175	243	0 – 30000 RPM	This parameter sets the maximum speed limit for entering High Current PWM state in RPM. When motor speed is below PWM High Current Speed Limit, the PWM state can change to High Current PWM state. Current also needs to be higher than PWM High Current Limit to enter High Current PWM state.
PWM_Low_Speed_High_Current_Spd_Limit_EEPROM_(RPM)	0x01BE	246	0 – 30000 RPM	This parameter sets the maximum speed limit for entering Low Speed High Current PWM state in RPM. When motor speed is below PWM Low Speed High Current Speed Limit, the PWM state can change to Low Speed High Current PWM state. Current also needs to be higher than PWM Low Speed High Current Limit to enter Low Speed High Current PWM state.

Previous firmware releases included EEPROM settings for the current transition points. In the latest firmware release these values are calculated automatically and require no user configuration. In the latest firmware (6522 and forward) the current transition point is calculated at 90% of the peak current for the given PWM frequency. This ensures that the inverter stays in the given PWM region as long as possible to improve control/dynamic response while not compromising on peak current. This also allows for dynamic limit changing with temperature. The temperature derate is described later in the document. This increases the performance of the inverter and ensures the user is getting the most capability of a given PWM region.

Alongside the EEPROM settings listed above, it is highly recommended to limit the torque ramp rate of the system (via EEPROM Torque_Rate_Limit_EEPROM_(Nm)_x_10) to no more than 70 Nm/3ms or a setting of 700. This corresponds to a torque ramp rate of ~ 23,000 Nm/s and rates faster than this may cause stability issues.

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The flowchart for moving between these various PWM regions is presented below.

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1.3 PWM Safety Settings

To ensure safety of operation when setting the transition limits for the automatic variable PWM there are some built in safety features.

1. The PWM switching frequency must be equal or increasing following the order: Stall PWM →Low Speed High Current PWM →High Current PWM →
   Default PWM → High Speed PWM

   For example: a respective setting of 2 kHz, 4 kHz, 6 kHz, 8 kHz, 10 kHz or 6 kHz, 6 kHz, 6 kHz, 6 kHz, 6 kHz is acceptable but a setting of 6 kHz, 2 kHz, 4 kHz, 8 kHz, 10 kHz is not

   When a PWM frequency is selected that does not abide by this equal or greater than order, the selected PWM frequency that violates this condition will be set equal to its lower counterpart.

   For example: if a respective setting of 6 kHz, 2 kHz, 4 kHz, 8 kHz, 10 kHz is chosen, the software will correct this to 6 kHz, 6 kHz, 6 kHz, 8 kHz, 10 kHz.

2. When selecting speed transition points a 20% buffer is installed to avoid logic oscillation between PWM states. This is enforced in the software such that:
   PWM_Low_Speed_High_Current_Spd_Limit_EEPROM_(RPM)
   < 0.8* PWM_High_Current_Spd_Limit_EEPROM_(RPM)
   < 0.8* PWM_High_Speed_Limit_EEPROM_(RPM)

   For example: a respective speed transition point selection of 1000 rpm, 4000 rpm, and 8000 rpm is acceptable but a selection of 4000 rpm, 4500 rpm, and 9000 rpm is not.

   When speed transition points are selected that do not abide by this logic, the selected speed that violates this condition will be set to 80% of its upper counterpart.

   For example: if a respective setting of 4000 rpm, 4500 rpm, and 9000 rpm is chosen the software will correct this to 3600 rpm, 4500 rpm, and 9000 rpm.

3. The speed transition settings are also checked/limited further to ensure that for the given PWM frequency selected the maximum speed for that region does not violate the previously mentioned 10 switching events per electrical cycle.

For example: a Low_Speed_High_Current_PWM_Frequency_EEPROM_(kHz) setting of 2 kHz with a 10 pole motor can have a maximum PWM_Low_Speed_High_Current_Spd_Limit_EEPROM_(RPM) setting of 2400 rpm.

When a speed transition level is selected that violates this rule the value will be set to allows 10 switching events per electrical cycle.

For example: if a Low_Speed_High_Current_PWM_Frequency_EEPROM_(kHz) setting of 2 kHz with a 10 pole motor selects a PWM_Low_Speed_High_Current_Spd_Limit_EEPROM_(RPM) setting of 3000 rpm, the software will set the PWM_Low_Speed_High_Current_Spd_Limit_EEPROM_(RPM) setting to 2400 rpm.

1.4 Maximum Current Limiting

The current capability of the inverter depends on several factors:

- Current rating of the power module
- PWM Frequency, higher frequency will reduce maximum current
- DC Bus Voltage, higher DC bus voltage will reduce current
- Motoring vs Regeneration may affect current rating
- Inverter Coolant Temperature, higher temperature will reduce current

The Gen 5 software will adjust the current limit based on these factors.

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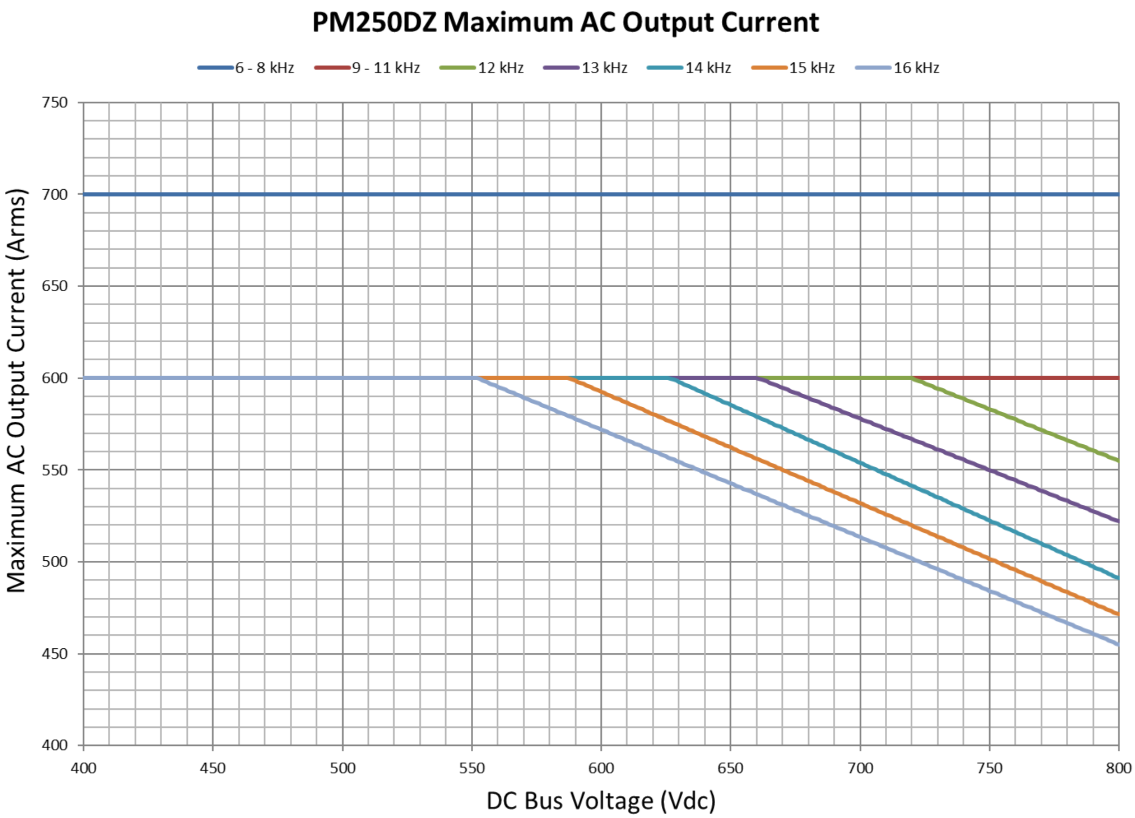
1.5 PWM Frequency and DC Bus Voltage Effects

The current rating of the inverter is dependent on the PWM frequency that it is operating at. The inverter will change the maximum current of the inverter based on what PWM frequency the inverter is currently operating at.

The current rating of the inverter will also change as the DC bus voltage applied to the inverter changes.

Below is one example of the rating of an inverter versus PWM frequency and DC bus voltage.



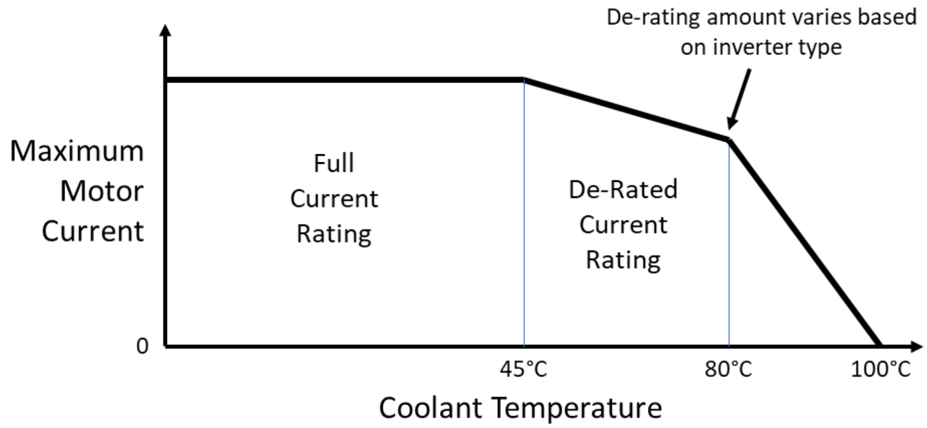
Cascadia Motion can provide additional information on current limits for other inverters.

1.6 Maximum Current Derating with Coolant Temperature

The Gen 5 software now has an added estimation (or measurement) of coolant temperature. The estimated coolant temperature will impact the maximum current rating of the inverter.

Most inverters do not have a coolant temperature sensor. The coolant temperature is estimated based on the power module temperature measurement.

The Coolant Temperature Estimate is included CAN broadcast message. See the CAN Protocol Manual for details.



The above graph shows the current limit of the inverter is adjusted as the temperature of the coolant is increased.

Revision History

Version	Description of Versions / Changes	Responsible Party	Date
0.1	Initial version.	Andrew Louie Chris Brune	2/12/2021
0.2	Revision for added PWM regions	Christian Tigges	12/6/2021
0.3	Clarified PWM regions with colored shapes. Fixed the coolant temperature rating graph. Corrected formatting issues.	Chris Brune	1/24/2022
0.4	Removed current level definitions as the code now does this automatically	Andrew Louie Christian Tigges	7/16/2022