Resolution, Accuracy and Limits

Last updated: 11/11/2020

Resolution

Frequency
If the frequency is defined by writing the reference directly to a parameter (e.g. *Preset Reference 1* (01.021)) then the standard resolution is 0.1Hz. This can be improved to 0.001Hz if the precision reference is used (i.e. *Precision Reference Coarse* (01.018) and *Precision Reference Fine* (01.019)).

Speed
If the speed is defined by writing the reference directly to a parameter (e.g. *Preset Reference 1* (01.021)) then the standard resolution is 0.1rpm. This can be improved to 0.001rpm if the precision reference is used (i.e. *Precision Reference Coarse* (01.018) and *Precision Reference Fine* (01.019)).

Torque
If the motor is operated in torque control in RFC-A or RFC-S mode the torque reference can be specified using *Torque Reference* (04.008) with a resolution of 0.01% of the motor rated torque.

If an analogue input is used to control the frequency, speed or torque the resolution may be reduced due to the resolution of the input.

Accuracy

Frequency and Speed
If the reference is written directly to a parameter then the accuracy is defined by the accuracy of the clock used in the drive control system. Provided the drive is not synchronised to an external network via an option module the accuracy is 0.03% of the reference level.

Torque
The torque produced by a motor varies as the motor parameters change, particularly with temperature and load. The torque accuracy depends on the accuracy of the motor parameters helf by the drive.

Frequency Limits

The maximum frequency limits are either imposed by the drive or are advisory. If the advisory limits are exceeded, then either the control system may not function correctly or the PWM switching will produce excessive current sub-harmonic components (i.e. current components below the required fundamental output frequency). Sub-harmonic components, which can become significant when the ratio between the switching frequency (f_{sw}) and the output frequency is less than 12, can cause low frequency motor speed oscillations and contribute to the overall current level. The table below shows the imposed and advisory frequency limits.

Mode	Advisory Limit	Standard Drive Imposed Limit	HS Drive Imposed Limit
Open-loop	$f_{sw}/12^{+}$	599Hz	3000Hz
RFC-A with feedback	1000Hz or $f_{sw}/12$ whichever is lower	550Hz	*
RFC-A without feedback	400Hz or $f_{sw}/12$ whichever is lower	550Hz	*
RFC-S with feedback	1000Hz or $f_{sw}/12$ whichever is lower	550Hz	*
RFC-S without feedback	400Hz for low saliency motors, 200Hz for high saliency motors or $f_{sw}/12$ whichever is lower	550Hz	*
Regen	150Hz	200Hz	200Hz

$^{+}$ In Open-loop mode it is possible for the drive to change to an alternative quasi-square wave switching strategy when the output voltage reaches its maximum limit. This is selected by setting *Quasi-square Enable* (05.020) to 1. This switching method prevents sub-harmonic components but produces significant odd multiple harmonics of the output frequency (i.e. 5th, 7^{th}, etc.). The low frequency instability caused by sub-harmonics will not occur, but the additional current distortion caused by the inverter switching is much higher than with normal PWM. This gives increased acoustic noise, an increase in the peak current and additional motor heating.

* The maximum motor speed is limited to 50000rpm which limits the frequency to (50000/60) x Motor pole pairs. The maximum speed is also limited so that the encoder feedback frequency for incremental and SINCOS encoders is limited to 500kHz.

Current Limits

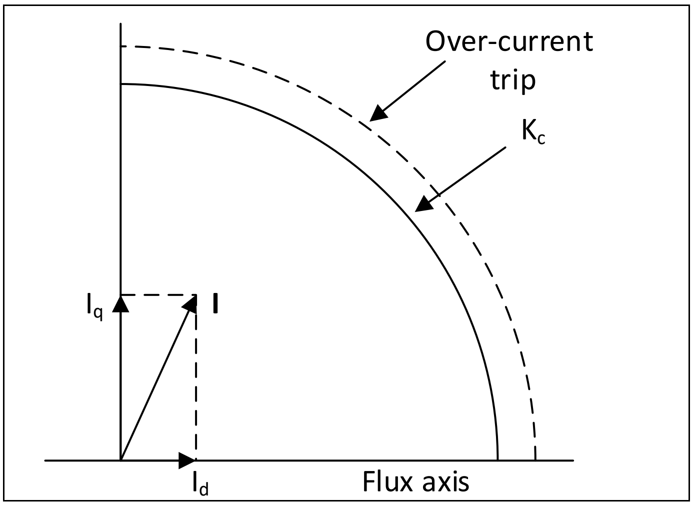
Each drive size has an instantaneous over-current trip level, as given in the “Current Ratings” section of the parameter reference guide, which protects the power circuit. This trip is initiated if the drive output current exceeds its limit for a few microseconds. To avoid spurious over-current trips the maximum instantaneous current should be kept below the trip level with some margin. In each operating mode the drive current control system will attempt to limit the output current to a level that will prevent an over-current trip. However, the additional effects given in the table below can increase the instantaneous current level and cause a trip even though the drive control system is operating correctly.

Additional Effect	Description
Pulse width modulation (PWM) switching	Ideally the drive would produce a sinusoidal output current, but the high frequency switching within the drive output power circuit causes additional high frequency components. The additional current is reduced if the drive switching frequency and/or motor inductance are increased.
Current controller overshoot	When a sudden change of current reference occurs, the actual current may overshoot the required level depending on the gains used for the current controllers.

Drive to motor cable charging currents	Each time a device in the drive output power stage switches it causes a short pulse of cable charging current. Some filtering is provided in the drive current feedback to reduce this effect, but it cannot be removed completely.

The additional current produced by each of these effects should be summed and then added to the maximum expected drive output current to give the maximum instantaneous output current. If the calculated current exceeds the over-current trip level, then it is possible that the drive will initiate an over-current trip under normal operation. The systems that the drive uses in each mode to limit the output current are describe and should allow the maximum expected current to be calculated. Methods are then given to estimate the current produced by the additional effects, which should allow the maximum instantaneous current to be calculated.

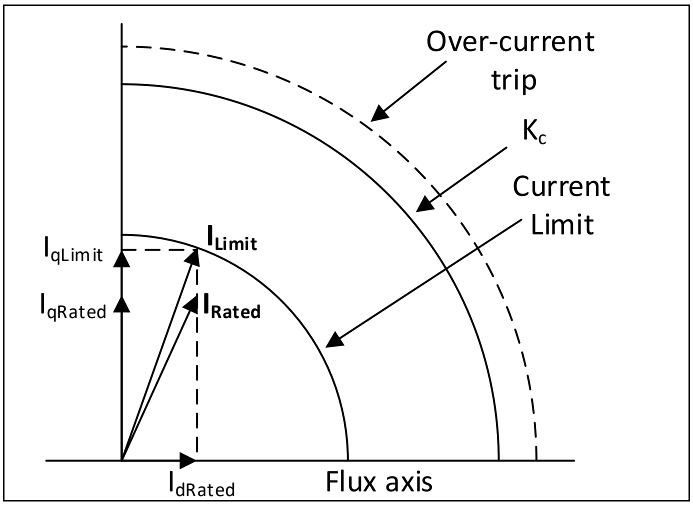
The three phase drive output currents can be represented as a phasor which can be split into flux and torque producing current, I_d and I_q respectively, as shown below. By convention for forward rotation phasors rotate anti-clockwise, and so the diagram shows one quadrant for an induction motor that has a motoring load and is rotating in the forwards direction.



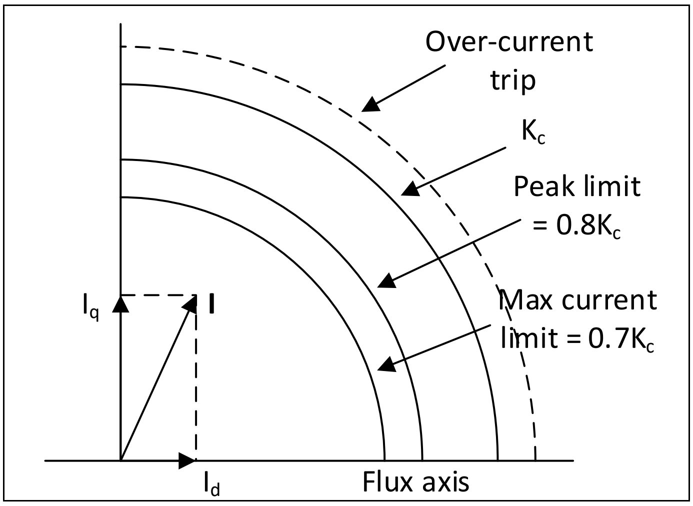
K_c is the full-scale current for the drive which is the maximum measurable and controllable current. This is given as an r.m.s. value in *Full Scale Current Kc* (11.061). The over-current trip level, which is also shown, is either at or beyond this level. See the "Current Ratings" table included in this parameter reference guide for the level of K_c and the over-current trip level for each drive size.

The following sections all relate to Motor Map 1, but also apply to Motor Map 2. Where appropriate the parameters and variable minimum/maximums are duplicated for Motor Map 2 and they should be used if Motor Map 2 is selected.

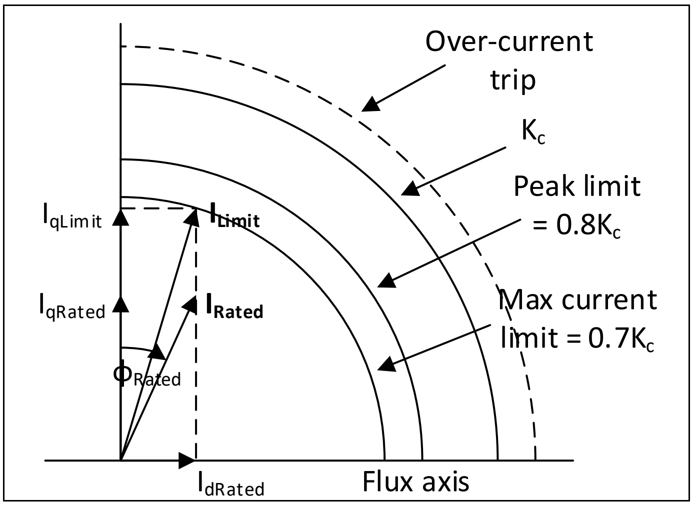
Current control: Open-loop Mode
In Open-loop mode the current limit modifies the output frequency of the inverter to control the torque producing current (I_q), which in turn controls maximum torque produced by the motor. If a motoring load is applied, I_q will increase and the speed will reduce due to slip. I_q increases and the speed falls until I_q reaches the current limit. The drive will then reduce its output frequency which reduces the motor slip and controls the load on the motor and limits I_q to the current limit. If the load is not removed the motor will slow down and eventually stall. The diagram below shows the current phasors for a motor operating under two conditions: rated load and at current limit. The magnetising current (I_d) is shown to be constant, however there is a slight increase in I_d with load unless the motor reaches rated voltage when flux weakening will become active, at which point I_d is reduced.



This current limit system is effective if the current disturbances caused by loads applied to the motor or frequency changes controlled by the drive ramp rates are relatively slow. If a fast load disturbance is applied, then this system alone would not prevent an over-current trip. To maintain control of the motor and prevent tripping an additional faster "peak limit" system is used with a threshold at a higher current level. The peak limit is fixed at $0.8K_c$ and provided the drive is operating in heavy duty mode the current limit level can be increased up to $0.7K_c$ as shown below.



The current limit user parameters are limited by variable maximum VM_MOTOR1_CURRENT_LIMIT. If heavy duty mode is active the value of this variable maximum depends on the ratio between K_c and the *Rated Current* (05.007), and *Rated Power Factor* (05.010) which is equal to $\cos(\varphi_{Rated})$. The diagram below shows the motor operating under rated conditions and under the conditions where the current is at the maximum current limit.



From the diagram

$$I_{Limit}{}^2 = I_{dRated}{}^2 + I_{qLimit}{}^2 = (I_{Rated} sin(\varphi_{Rated}))^2 + I_{qLimit}{}^2$$

Rearranging gives

$$I_{qLimit} = \sqrt{I_{Limit}{}^2 - (I_{Rated} sin(\varphi_{Rated}))^2} = \sqrt{(0.7K_c)^2 - (I_{Rated} sin(\varphi_{Rated}))^2}$$

Also

$$I_{qRated} = I_{Rated} cos(\varphi_{Rated})$$

The maximum value of the current limit user parameter (VM_MOTOR1_CURRENT_LIMIT) is given as a percentage ratio of the maximum torque producing current and the rated current.

$$I_{LimitMax} = \frac{I_{qLimit}}{I_{qRated}} \times 100\% = \frac{\sqrt{(0.7K_c)^2 - (I_{Rated} sin(\varphi_{Rated}))^2}}{I_{Rated} cos(\varphi_{Rated})} \times 100\% = \frac{\sqrt{(0.7K_c/I_{Rated})^2 - sin^2(\varphi_{Rated})}}{cos(\varphi_{Rated})} \times 100\%$$

If the rated current is set to its default (the maximum for heavy duty mode), which for most smaller drive sizes is $0.45K_c$, and *Rated Power Factor* (05.010) is left at its default of 0.850, then,

$$I_{LimitMax} = \frac{\sqrt{(0.7/0.45)^2 - 0.527^2}}{0.85} \times 100\% = 172\%$$

If the rated current is increased above its maximum heavy duty rating the drive will operate in normal duty mode and the maximum current limit is reduced to 1.1 x *Maximum Rated Current* (11.060). The maximum value of the current limit user parameter is modified as follows.

$$I_{LimitMax} = \frac{\sqrt{((1.1 \times I_{MaxRated})/I_{Rated})^2 - sin^2(\varphi)}}{cos(\varphi)} \times 100\%$$

If the rated current is set to its maximum value and *Rated Power Factor* (05.010) is left at its default of 0.850, then

$$I_{LimitMax} = \frac{\sqrt{1.1^2 - 0.527^2}}{0.85} \times 100\% = 113\%$$

Some drive sizes have a no-overload rating. If this is the case then *Minimum No-overload Current* (11.059) is less than *Maximum Rated Current* (11.060). If the motor rated current is set to a value above *Minimum No-overload Current* (11.059) then the maximum current limit is reduced to *Maximum Rated Current* (11.060) and

$$I_{LimitMax} = \frac{\sqrt{(I_{MaxRated}/I_{Rated})^2 - sin^2(\varphi)}}{cos(\varphi)} \times 100\%$$

The following should be considered to determine the maximum expected current before adding the current due to the additional effects:

1. If the ramps rates are set to 0.0s/100Hz then it is likely that the maximum expected current could be up to the over-current trip level.
2. For applications with fast torque transients and/or fast ramp rates the peak limit may become active. Allowing for current overshoot by the peak limit system, the maximum expected current would be at or below $0.9K_c$. This should apply even if the current limit is reduced below its maximum possible level.
3. If there are no fast torque transients and moderate ramp rates are used it could be assumed that the peak limit does not become active, and so the maximum expected current would be at, or below, $0.8K_c$.
4. If there are no fast torque transients and moderate ramp rates are used and the current limit is reduced below its maximum level, then the following equation could be used to estimate the maximum expected current. Note this does not include the increase in the magnetising current with load, but it should give a reasonable approximation for the maximum expected current.

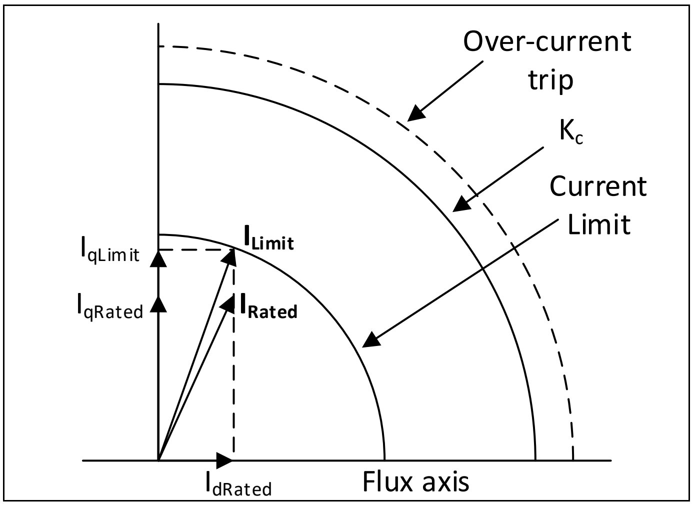
$$I_{Max} = \sqrt{I_{dRated}{}^2 + \left(I_{qRated} \times Current\ Limit/100\%\right)^2}$$

$$= \sqrt{I_{Rated}sin(\varphi_{Rated})^2 + (I_{Rated}cos(\varphi_{Rated}) \times Current\ Limit/100\%)^2}$$

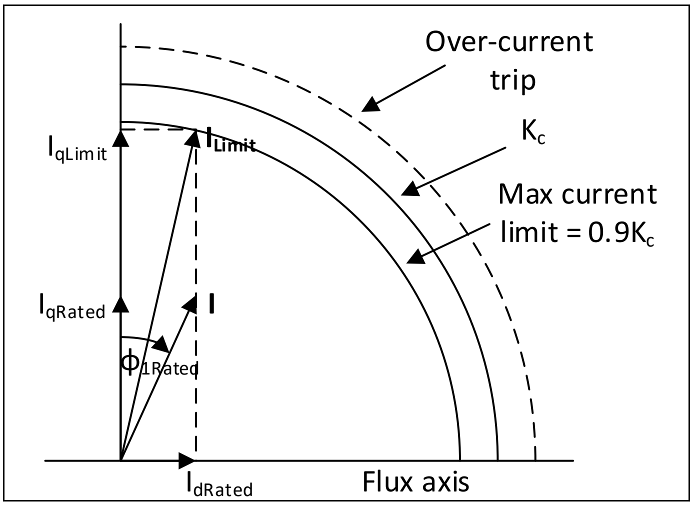
$$= I_{Rated}\sqrt{sin(\varphi_{Rated})^2 + (cos(\varphi_{Rated}) \times Current\ Limit/100\%)^2}$$

Current control: RFC-A Mode

Unlike Open-loop mode where the main current limit controls the output frequency with an additional faster peak limit which controls the current by modifying the output voltage, RFC-A mode has a single current limit which limits the d and q axis currents directly by modifying the d and q axis voltages. The diagram below shows the current phasors for a motor operating under two conditions: rated load and at current limit. The magnetising current (I_d) is constant in this operating mode unless the motor reaches rated voltage and flux weakening becomes active, at which point I_d is reduced.



The control system operates quickly to limit the current, and so no additional limit is needed, and a smaller margin is required between the maximum current limit and the over-current trip level. If heavy duty mode is active the current limit can be increased up to 0.9Kc as shown below.



The current limit user parameters are limited by variable maximum VM_MOTOR1_CURRENT_LIMIT. If heavy duty mode is active this depends on the ratio between K_c and the *Rated Current* (05.007), and the angle between the torque producing current axis and the motor current phasor under rated conditions (φ_{1Rated}). The diagram above shows the motor operating under rated conditions and under the conditions where the current is at the maximum current limit. The angle φ_{1Rated} is generally smaller than φ_{Rated} used in Open-loop mode, and is not derived directly from the power factor, but depends on a number of parameters. This is covered later. The maximum value of the current limit user parameter (VM_MOTOR1_CURRENT_LIMIT) can be derived in a similar way to Open-loop mode, but with φ_{Rated} replaced with φ_{1Rated} and with the maximum current limit increased to $0.9K_c$.

$$I_{LimitMax} = \frac{I_{qLimit}}{I_{qRated}} \times 100\% = \frac{\sqrt{(0.9K_c)^2 - (I_{Rated} sin(\varphi_{1Rated}))^2}}{I_{Rated} cos(\varphi_{1Rated})} \times 100\% = \frac{\sqrt{(0.9K_c/I_{Rated})^2 - sin^2(\varphi_{1Rated})}}{cos(\varphi_{1Rated})} \times 100\%$$

If the motor parameters are not provided (i.e. a rotating auto-tune is not carried out) then the drive uses $\cos^{-1}$(*Rated Power Factor* (05.010)) as an approximation for φ_{1Rated}. For best performance the motor parameters should be provided, but this approximation is used as an example. If the rated current is set to its default (the maximum for heavy duty mode), which for most smaller drive sizes is 0.45 x K_c, and $\cos(\varphi_{1Rated})$ = 0.850, then,

$$I_{LimitMax} = \frac{\sqrt{(0.9/0.45)^2 - 0.527^2}}{0.85} \times 100\% = 227\%$$

If the rated current is increased above its maximum heavy duty rating the drive will operate in normal duty mode and the maximum current limit is reduced to 1.1 x *Maximum Rated Current* (11.060). The maximum value of the current limit user parameter is modified as follows.

$$I_{LimitMax} = \frac{\sqrt{((1.1 \times I_{MaxRated})/I_{Rated})^2 - sin^2(\varphi_{1Rated})}}{cos(\varphi_{1Rated})} \times 100\%$$

If the rated current is set to its maximum value and $\cos(\varphi_1)$ = 0.850, then

$$I_{LimitMax} = \frac{\sqrt{1.1^2 - 0.527^2}}{0.85} \times 100\% = 113\%$$

Some drive sizes have a no-overload rating. If this is the case then *Minimum No-overload Current* (11.059) is less than *Maximum Rated Current* (11.060). If the motor rated current is set to a value above *Minimum No-overload Current* (11.059) then the maximum current limit is reduced to *Maximum Rated Current* (11.060) and

$$I_{LimitMax} = \frac{\sqrt{(I_{MaxRated}/I_{Rated})^2 - sin^2(\varphi_{1Rated})}}{cos(\varphi_{1Rated})} \times 100\%$$

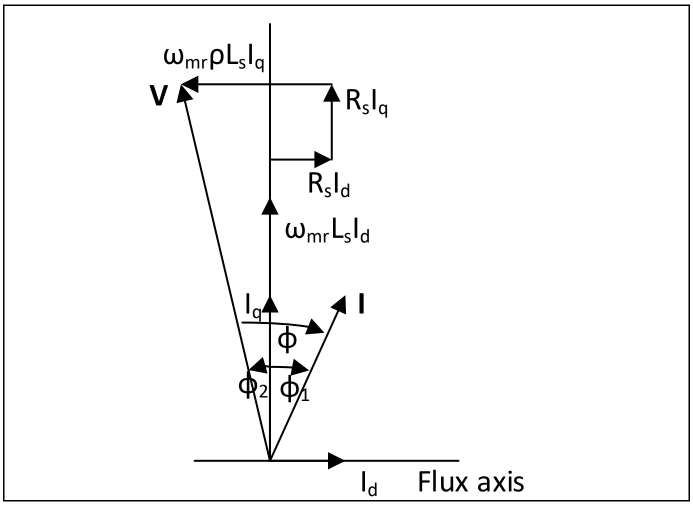
As mentioned previously φ_{1Rated} depends on a number of motor parameters. The required parameters given in the table below can be obtained from the motor nameplate and a rotating auto-tune (*Auto-tune* (05.012) = Improved).

Motor parameter	**User parameter**	**Obtained from…**
V_{Rated}	*Rated Voltage* (05.009)	Nameplate
I_{Rated}	*Rated Current* (05.007)	Nameplate
F_{Rated}	*Rated Frequency* (05.006)	Nameplate
Rs	*Stator Resistance* (05.017)	Basic (stationary) or Improved (rotating) auto-tune
ρLs	*Transient Inductance* (05.024)	Basic (stationary) or Improved (rotating) auto-tune
Ls	*Stator Inductance* (05.025)	Improved (rotating) auto-tune

The d and q voltage components that make up the terminal voltage are

$$v_d = R_s I_d - j\omega_{mr}\rho L_s I_q$$
$$v_q = R_s I_q + \omega_{mr} L_s I_d$$

In addition to the currents, the phasor diagram shows the voltage components that make up the terminal voltage in the steady state. The power factor is cos(φ) where φ is the sum of φ_1 and φ_2. φ_1 is the angle between the current phasor and the q axis, and φ_2 is the angle between the q axis and the terminal voltage.



An estimate can be made for the rated magnetising current (I_{dRated}) as the level that would give rated voltage at rated frequency under no-load conditions ignoring the stator resistance drop due to I_d.

$$I'_{dRated} = V_{Rated}/(\omega_{mrRated}L_s) = V_{Rated}/(2\pi F_{Rated}L_s)$$

This estimate can be used to give an estimate for φ_1 under rated conditions, which can then be used to give an estimate of the torque producing current (I_{qRated}) under rated conditions.

$$\varphi'_{1Rated} = sin^{-1}(I'_{dRated}/I_{Rated})$$

$$I'_{qRated} = I_{Rated}\cos(\varphi'_{1Rated})$$

The estimate of magnetising current gives an approximation of rated voltage at rated frequency with the motor operating with no-load. The stator resistance drop due to I_q dominates the change in terminal voltage between no-load and full-load, and so the magnetising current can be scaled down to give approximately rated terminal voltage under rated conditions as follows.

$$I_{dRated} = I'_{dRated} \times \left(V_{Rated} - R_s I'_{qRated}\right)/V_{Rated}$$

A more accurate estimate of φ_1 under rated conditions can now be calculated.

$$\varphi_{1Rated} = sin^{-1}(I_{dRated}/I_{Rated})$$

This can be used in the equations given previously to define the maximum current limit. This gives the best estimate of φ_1 under rated conditions and will give the best setting for the maximum current limit. However, if only a basic (stationary) auto-tune is performed then *Stator Inductance* (05.025) is not measured. But if *Rated Power Factor* (05.010), i.e. cos(φ_{Rated}), is provided from the nameplate the drive can calculate a less accurate value for φ_1 under rated conditions.

$$I''_{dRated} = I_{Rated}\sin(\varphi_{Rated})$$

$$I''_{qRated} = I_{Rated}\cos(\varphi_{Rated})$$

These estimated current components can be used to give φ_2 under rated conditions, which in turn can be used with *Rated Power Factor* (05.010) to give an estimate of φ_1 under rated conditions.

$$\varphi_{2Rated} = sin^{-1}\left(\left(\left(2\pi F_{Rated}\rho L_s I''_{qRated}\right) - R_s I''_{dRated}\right)/V_{Rated}\right)$$

$$\varphi_{1Rated} = \varphi_{Rated} - \varphi_{2Rated}$$

The following should be considered to determine the maximum expected current before adding the current due to the additional effects:

1. The drive will set up the magnetising current for the motor and the torque producing current scaling based on the motor parameter provided. If the Improved (rotating) auto-tune is carried out and the motor slip is set correctly the best motor performance is achieved and the torque will be scaled correctly so that 100% torque producing current will correspond to rated torque. Also, the value of variable maximum VM_MOTOR1_CURRENT_LIMIT will correspond to the maximum torque that can be produced.
2. If the current limit is set to its maximum level, then the maximum expected current is 0.9Kc.
3. If the current limit is reduced below its maximum level, then the following equation should be used to estimate the maximum expected current. Note that φ under rated conditions (cos^{-1}(*Rated Power Factor* (05.010)) is used instead of φ_1 because φ_1 is not available to the user. However, the calculated result will give an estimate of the maximum expected current.

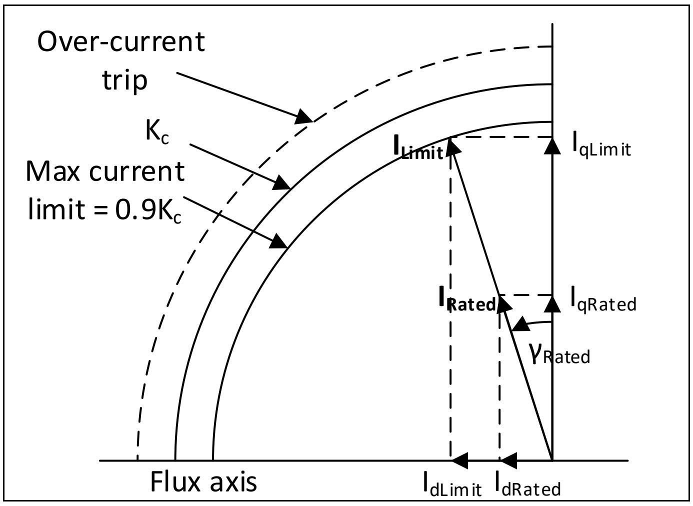
$$I_{Max} = I_{Rated}\sqrt{sin(\varphi_{Rated})^2 + (cos(\varphi_{Rated}) \times Current\ Limit/100\%)^2}$$

Current control: RFC-S Mode

The current controllers in RFC-S mode operate in the same way as RFC-A mode, and so RFC-S mode also has a single current limit which controls the d and q axis currents by modifying the d and q axis voltages. However, the current reference components are produced in a different way. The final output of the speed controller, or the torque reference, is used to define the current magnitude which is then split into d and q axis components depending on the *Rated Torque Angle* (05.060). If the motor voltage reaches its rated voltage level, then flux weakening becomes active and either

i_d or i_q are modified to limit the motor voltage. Otherwise if the rated torque angle is γ_{Rated} then the current components are defined by the following equations.

$$i_d = i\ sin(\gamma_{Rated})$$
$$i_q = i\ cos(\gamma_{Rated})$$



The current limit user parameters are limited by variable maximum VM_MOTOR1_CURRENT_LIMIT. If heavy duty mode is active this depends on the ratio between K_c and the *Rated Current* (05.007). The maximum value of the current limit user parameter (VM_MOTOR1_CURRENT_LIMIT) is given by the ratio of the maximum current and the rated current as a percentage.

$$I_{LimitMax} = \frac{I_{Limit}}{I_{Rated}} \times 100\% = \frac{0.9K_c}{I_{Rated}} \times 100\%$$

If the rated current is set to its default (the maximum for heavy duty mode), which for most smaller drive sizes is 0.45 x K_c.

$$I_{LimitMax} = \frac{0.9}{0.45} \times 100\% = 200\%$$

If the rated current is increased above its maximum heavy duty rating the drive will operate in normal duty mode and the maximum current limit is reduced to 1.1 x *Maximum Rated Current* (11.060). The maximum value of the current limit user parameter is modified as follows.

$$I_{LimitMax} = \frac{1.1\ \times I_{MaxRated}}{I_{MaxRated}} \times 100\% = 110\%$$

Some drive sizes have a no-overload rating. If this is the case then *Minimum No-overload Current* (11.059) is less than *Maximum Rated Current* (11.060). If the motor rated current is set to a value above *Minimum No-overload Current* (11.059) then the maximum current limit is reduced to *Maximum Rated Current* (11.060) and $I_{LimitMax}$ = 100%.

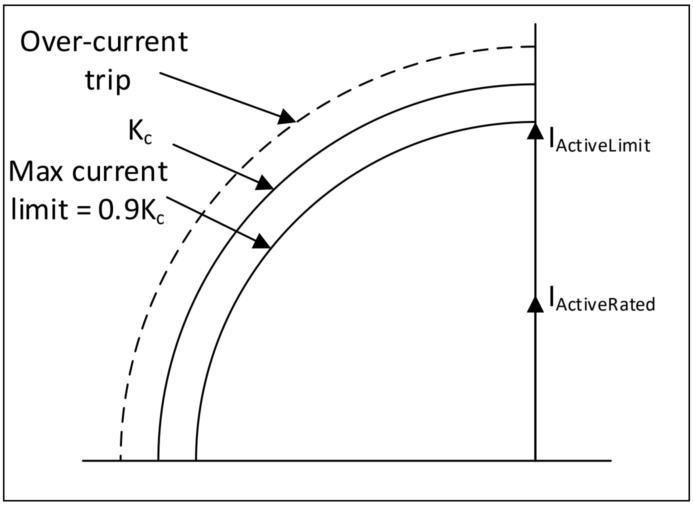
The following should be considered to determine the maximum expected current before adding the current due to the additional effects:

1. If the current limit is set to its maximum level, then the maximum expected current is 0.9Kc.
2. If the current limit is reduced below its maximum level, then the following equation should be used to estimate the maximum expected current.

$$I_{Max} = I_{Rated} \times Current\ Limit/100\%$$

Current control: Regen Mode

The active current is the current nominally in phase with the supply voltages in Regen Mode. This current is controlled in a similar way to RFC-S mode. The current limits are applied to the active current and the maximum current limit is $0.9K_c$ as shown below.



The current limit user parameter is limited by variable maximum VM_MOTOR1_CURRENT_LIMIT. If heavy duty mode is active this depends on the ratio between K_c and the *Rated Current* (05.007). The maximum value of the current limit user parameter (VM_MOTOR1_CURRENT_LIMIT) is given by the ratio of the maximum current and the rated current as a percentage.

$$I_{LimitMax} = \frac{I_{Limit}}{I_{Rated}} \times 100\% = \frac{0.9K_c}{I_{Rated}} \times 100\%$$

If the rated current is set to its default (the maximum for heavy duty mode), which for most smaller drive sizes is 0.45 x K_c.

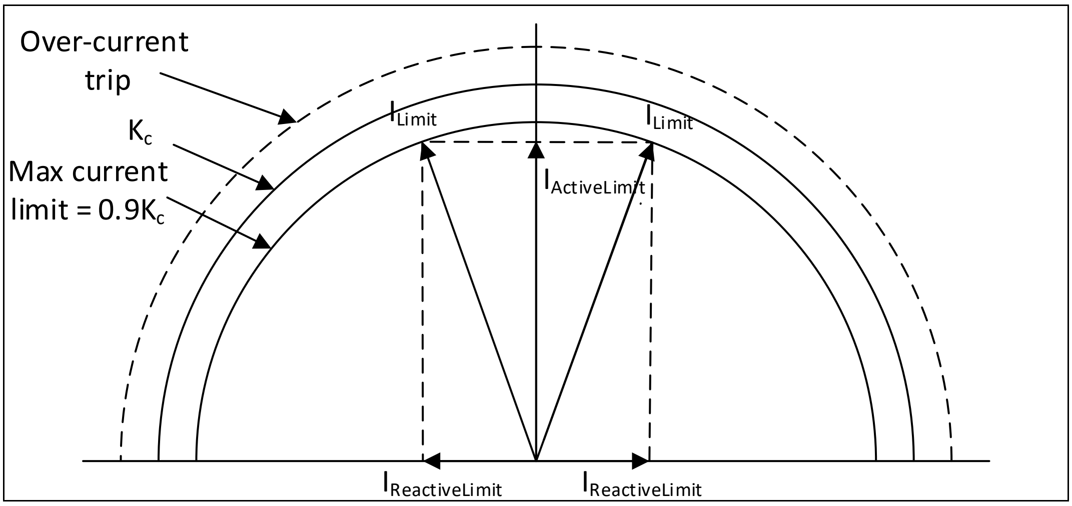
$$I_{LimitMax} = \frac{0.9}{0.45} \times 100\% = 200\%$$

If the rated current is increased above its maximum heavy duty rating the drive will operate in normal duty mode and the maximum current limit is reduced to 1.1 x *Maximum Rated Current* (11.060). The maximum value of the current limit user parameter is modified as follows.

$$I_{LimitMax} = \frac{1.1 \times I_{MaxRated}}{I_{MaxRated}} \times 100\% = 110\%$$

Some drive sizes have a no-overload rating. If this is the case then *Minimum No-overload Current* (11.059) is less than *Maximum Rated Current* (11.060). If the motor rated current is set to a value above *Minimum No-overload Current* (11.059) then the maximum current limit is reduced to *Maximum Rated Current* (11.060) and $I_{LimitMax}$ = 100%.

Although the diagram above only shows active current, it is possible to have either positive or negative reactive current as shown below.



The maximum reactive current is limited by the variable maximum VM_REGEN_REACTIVE which is defined by the following equation.

$$I_{ReactiveLimit} = \frac{\sqrt{(0.9K_c)^2 - {I_{Limit}}^2}}{I_{Rated}} \times 100\%$$

This ensures that the required combined active and reactive current does not exceed 0.9Kc. If *Island Detection Enable* (03.030) = 1, to enable islanding detection, an additional reactive current component is used for detection and VM_REGEN_REACTIVE is reduced by 5% with a minimum level of 0%.

The following should be considered to determine the maximum expected current before adding the current due to the additional effects:

1. If the current limit is set to its maximum level, then the maximum expected current is 0.9Kc.
2. If the current limit is reduced below its maximum level, then the following equation should be used to estimate the maximum expected current where $I_{Reactive}$ = *Reactive Current Reference* (04.008).

$$I_{Max} = \sqrt{{I_{Reative}}^2 + (I_{Rated} \times Current\ Limit/100\%)^2}$$

Additional Effect: PWM switching
The PWM switching produces harmonic current components with the following frequencies.

$$(2p+1)f_{sw} \pm 2qf_{out}\ and\ 2pf_{sw} \pm (2q+1)f_{out}$$

where

p = 0, 1, 2 …
q = 0, 1, 2 …
f_{sw} is the PWM switching frequency
f_{out} is the drive output frequency

The harmonics are side bands of the switching frequency (f_{sw}), of twice the switching frequency ($2f_{sw}$) etc. Almost all the harmonic current is contained in the frequency components around the switching frequency (f_{sw}), therefore all the harmonic distortion could be assumed to be at the switching frequency. The additional current due to PWM switching have been calculated using simulation under the following conditions:

d.c. link voltage	V_{dc}	600V
Inductance	L	10mH
Modulation depth	m	1.0
Switching frequency	f_{sw}	3000Hz

The peak of the additional current caused by the PWM under these conditions is 1.7A. This can be scaled to give the current for different conditions as follows.

$$I = 1.7 \times \left(\frac{V_{dc}}{600}\right) \times \left(\frac{10}{L}\right) \times \left(\frac{3000}{f_{sw}}\right) \times \left(\frac{m}{1.0}\right)$$

If the drive is connected to an a.c. supply, V_{dc} is given by the line to line supply voltage multiplied by √2. For example, with a line to line supply voltage of 400V, V_{dc} = 566V. If the drive is connected to a d.c. source, such as a drive operating in Regen mode then V_{dc} is defined by the d.c. source.

L is the inductance of the motor plus any additional inductance connected between the drive and the motor in mH, or the regen inductors when operating in Regen Mode. For an induction motor L is the transient inductance which is measured during auto-tuning and written to *Transient Inductance* (05.024). This can be calculated from the equivalent circuit as

$$L = \rho L_s = (L_{sl} + L_m) - \frac{{L_m}^2}{(L_{rl}+L_m)}$$

L_{sl} is the stator leakage inductance, L_{rl} is the rotor leakage inductance and L_m is the magnetising inductance.

For a permanent magnet motor the inductance can vary with load, however it is usually acceptable to use the d axis inductance. This is measured during auto-tuning and written to L_d (05.024).

The modulation depth is the ratio between the output voltage and the maximum output voltage that can be produced by a given d.c. link voltage, and so

$$m = \frac{v_{ll\ out}}{V_{dc}/\sqrt{2}}$$

Unless the drive is supplied with a d.c. source, such as a Regen drive, then the maximum modulation depth is normally close to unity. As the additional current is proportional to the modulation depth it is normally best to assume m = 1.

If the ratio between the PWM switching frequency and the fundamental drive output frequency is less than 12 the lower side bands of the switching frequency begin to approach zero frequency. The additional current distortion produced by the sub-harmonic components is beyond the scope of this document.

Additional Effect: Current controller overshoot
For Open-loop mode see the notes at the end of the "Open-loop Mode: Current Control" section. No further current needs to be added for current controller overshoot.

In RFC-A and RFC-S modes, after auto-tuning the current controller gains are set up depending on the measured stator resistance and the transient inductance for an induction motor, or Ld for a permanent magnet motor. With standard current control (Current Control Mode (04.030) = 0) or high performance mode (*Current Control Mode* (04.030) = 1) the gain settings (*Current Controller Kp Gain* (04.013) and *Current Controller Ki Gain* (04.014)) after auto-tuning give minimal current controller over-shoot. An additional 5% of the expected maximum current should be added to allow for this. Normally the proportional gain is not increased, but the integral gain is set to a conservative level and may be increased, particularly with high speed motors. If high performance current control is used (*Current Control Mode* (04.030) = 1) then increasing the integral gain does not significantly increase the over-shoot, and so the additional level only needs to be increased to 10% if the integral gain is increased. If standard current control is used (*Current Control Mode* (04.030) = 0) then increasing the integral gain has a significant effect on the over-shoot. It is difficult to give an exact value, but it is suggested that the additional expected current is increased to 10% if the auto-tuned integral gain is multiplied by a factor up to 5. If the gain is multiplied by more than 5 then the additional expected current should be increased by (m / 5) x 10%, where m is the multiplying factor.

In Regen mode the current controller over-shoot is dependent on the inductors and capacitors connected between the regen unit and the supply and also the characteristics of the supply, and so it is difficult to predict the additional expected current.

Additional Effect: Drive to motor cable charging currents
The worst case cable charging current occurs at zero output frequency and voltage because the devices in all three output phases switch at the same time. Even if the drive is operating under less than worst case conditions most of the time, this worst case condition must be used to ensure that spurious over-current trips do not occur when the drive output passes transiently through this condition. The example results for different drive sizes are given for this worst case condition using different lengths of $4mm^2$ SY cable. These can be used to give an approximate prediction of the contribution of cable charging currents to the maximum current seen by the over-current trip detector as follows:

1. Select the results for the required frame size and the required cable length. The contribution as a percentage of Kc is given for at least one drive in each frame size. To obtain the value for a different drive size within a frame size, the contribution must be scaled by multiplying by (Test drive Kc / Actual drive Kc).
2. The example results are given with a d.c. link voltage of 600V. The maximum possible d.c. link voltage for the application can be used to scale the example results by multiplying by (Maximum expected d.c. Link Voltage / 600). The highest d.c. link voltage occurs when braking. The table below gives the maximum expected d.c. link voltage under different braking conditions.

***Ramp Mode* (02.004)**	**Supply**	**Maximum expected d.c. link votage**
Fast (0)	a.c.	*Braking IGBT Upper Threshold* (06.074)
Fast (0)	d.c. from regen drive	*Voltage Set-point* (03.004) in the regen drive
Standard (1)	a.c.	*Standard Ramp Voltage* (02.008)
Std Boost (2)	a.c.	1.2 x *Standard Ramp Voltage* (02.008)

3. The results are given for SY cable. If screened or armoured cable are used, or the cables are in an earthed conduit then the cable charging currents are increased. It is suggested that the contribution from the cable charging currents is multiplied by 1.2 if these alternative arrangements are used.

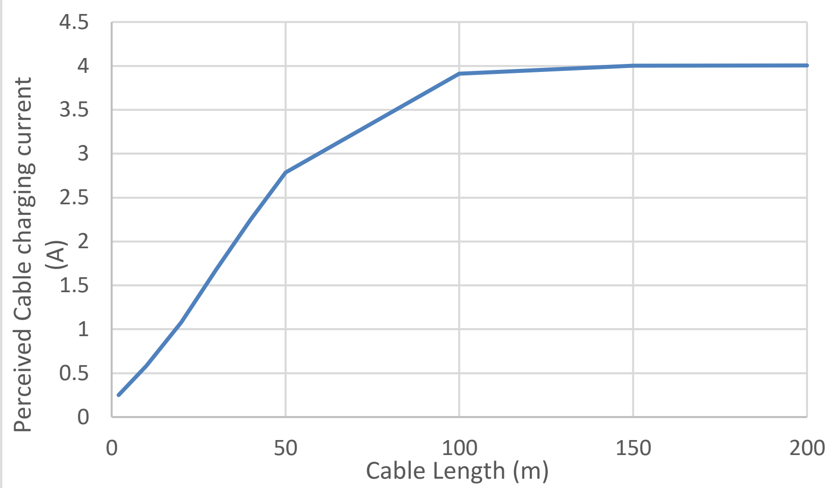
The required calculations are demonstrated by the following example:

03400062 drive (Kc = 13.778A) connected to an a.c. supply
Ramp Mode (02.004) = Fast (0)
Braking IGBT Upper Threshold (06.074) = 700V
Connection between the drive and the motor: 100m of SY cable

The results for 0300100 drive (Kc = 22.222A) and 100m of SY cable: 32.96%
Scaling for the drive current rating: 32.96% x Test drive Kc / Actual drive Kc = 32.96% x 22.222 / 13.778 = 53%
Scaling for braking method: 53% x Maximum expected d.c. Link Voltage / 600 = 53% x 700 / 600 = 62%

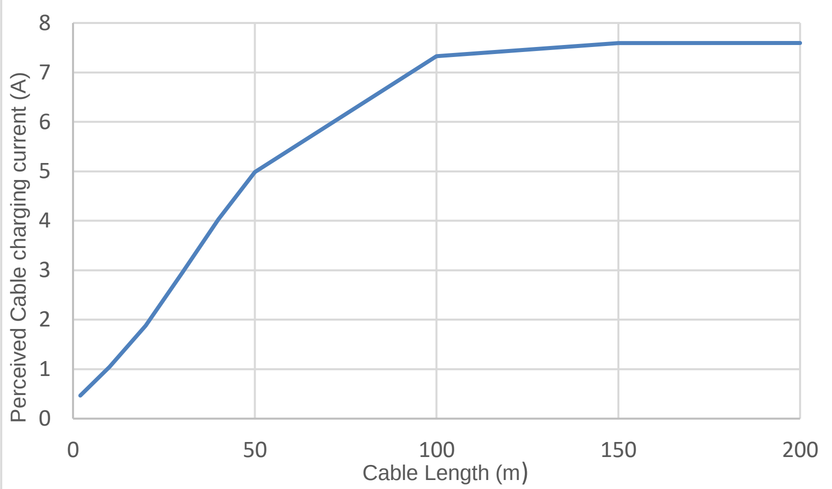
03400045

Length (m)	Perceived Cable Charging Current (A)	% Kc
2	0.25026	2.50%
10	0.58297	5.83%
20	1.07767	10.78%
30	1.6781	16.78%
40	2.25234	22.52%
50	2.78584	27.86%
100	3.91298	39.13%
150	4.00125	40.01%
200	4.00513	40.05%



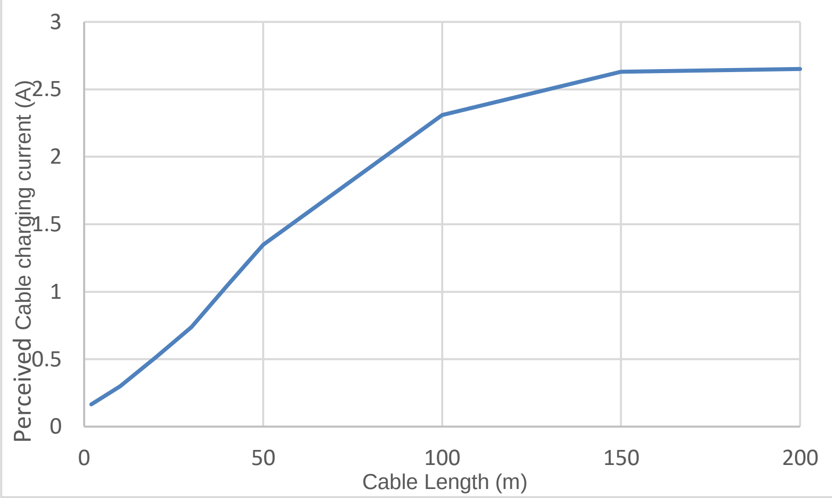
03400100

Length (m)	Perceived Cable Charging Current (A)	% Kc
2	0.467	2.10%
10	1.0476	4.71%
20	1.880	8.46%
30	2.948	13.27%
40	4.031	18.14%
50	4.984	22.43%
100	7.325	32.96%
150	7.593	34.17%
200	7.595	34.18%



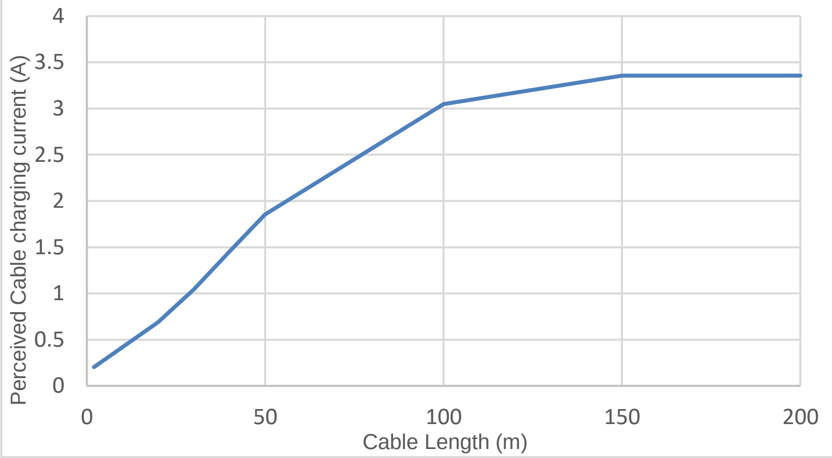
04400172

Length (m)	Perceived Cable Charging Current (A)	% Kc
2	0.165	0.43%
10	0.299	0.78%
20	0.514	1.34%
30	0.739	1.93%
40	1.046	2.74%
50	1.349	3.53%
100	2.310	6.04%
150	2.630	6.88%
200	2.651	6.94%



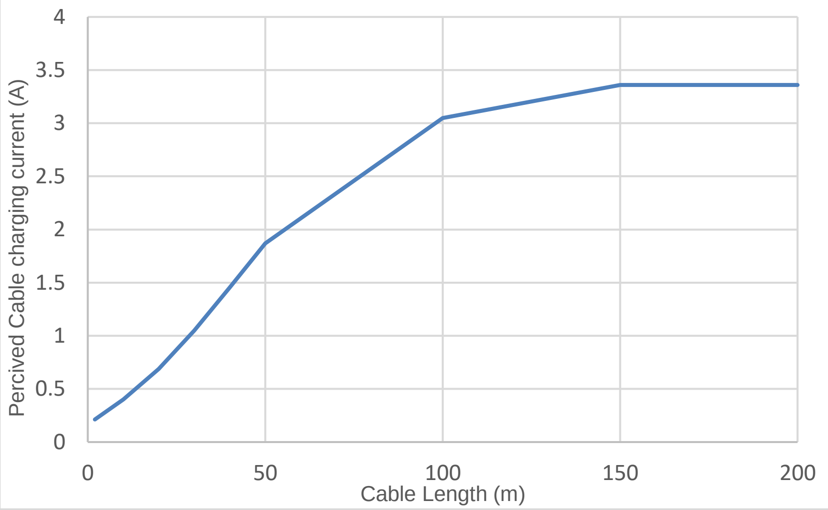
05400300

Length (m)	Perceived Cable Charging Current (A)	% Kc
2	0.203	0.30%
10	0.419	0.63%
20	0.688	1.03%
30	1.044	1.57%
40	1.455	2.18%
50	1.856	2.78%
100	3.049	4.57%
150	3.355	5.03%
200	3.356	5.03%



06400470

Length (m)	Perceived Cable Charging Current (A)	% Kc
2	0.213	0.20%
10	0.402	0.39%
20	0.687	0.66%
30	1.049	1.00%
40	1.455	1.39%
50	1.868	1.79%
100	3.050	2.92%
150	3.360	3.22%
200	3.360	3.22%



07401000 and Above

Length (m)	Perceived Cable Charging Current (A)	% Kc
2	0.2513776	0.11%
10	0.65358176	0.29%
20	1.2725991	0.57%
30	1.9481764	0.88%
40	2.5766204	1.16%
50	3.1265089	1.41%
100	4.1477304	1.87%
150	4.1791526	1.88%
200	4.1948637	1.89%
250	4.1948637	1.89%