

Introduction

A motor branch circuit, including a Variable Frequency Drive (VFD) and one or more Motor Protection Circuit Breakers (MPCBs), is a complex system and its performance depends on all components, devices, configuration and their interconnection.


In applications where an MPCB is to be used on the output (load side) of a VFD, several factors must be considered due to the influences of voltage pulses and current harmonics. Current harmonics and reflected voltage waves generated with long cables at the motor terminals can have a significant negative impact on the MPCB and switchgear performance if they are not taken into account appropriately.

This publication explains some considerations for the selection of MPCBs. European (IEC) nomenclature refers to MPCBs as Motor Protection Circuit Breakers. In North America, UL508 nomenclature refers to Bul. 140M devices as Self-Protected Combination Motor Controller, or a Type E Motor Controller applicable under NEC §430-52 C.6. These clarifications aside, the application issues for use with variable frequency drives do not change globally.

The information in this paper has been developed through known engineering principles and validated by thorough testing and simulation.

Typical Application

Bulletin 140M Motor Protection Circuit Breakers provide the functional control and protection requirements as specified by local electrical codes such as the National Electrical Code (NEC). Whether in single- or multi-motor installations, the 140M MPCB provides several key control and protection functions required for these types of installations. 140M controllers used as a Self-protected Manual Motor Controller can provide the individual motor circuit with following functionality:

- Disconnect function, providing approved isolation of motor circuits (IEC symbol )
- Manual motor controller, turning the individual motor circuit on and off
- Motor overload protection, protecting the motor from thermal overload
- Short circuit protection for the individual motor and the conductors

ATTENTION:



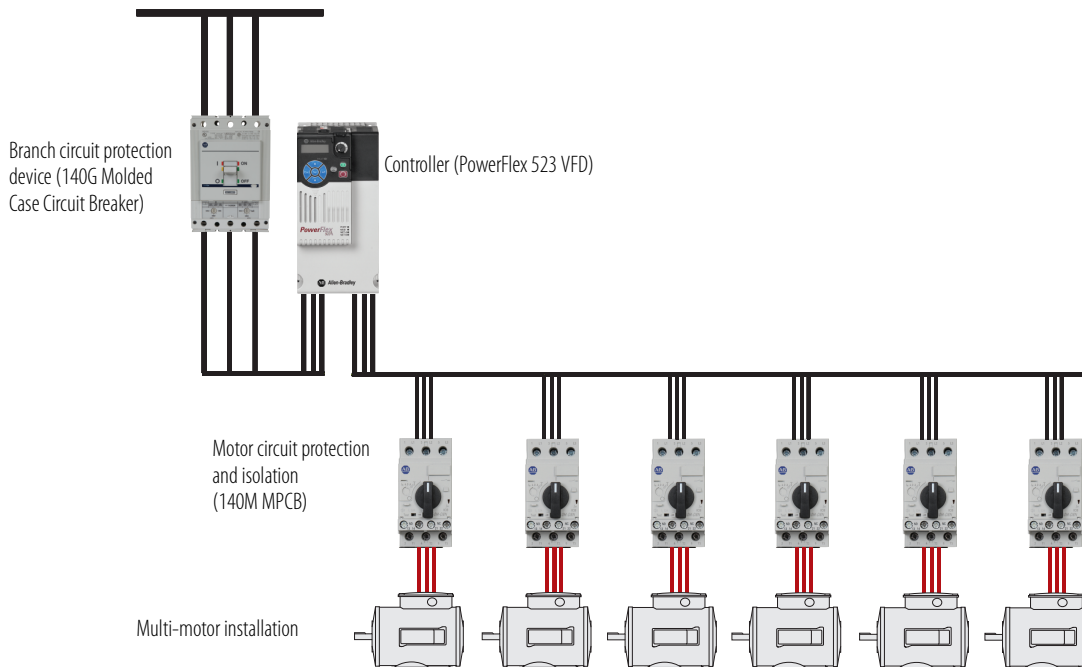
Not every circuit breaker or MPCB provides approved isolation / disconnect function (IEC symbol ). To cover a disconnect function, if needed, either circuit breakers or load switches suitable for use as disconnecting means (switch disconnector per IEC, symbol ) should be used.

Figure 1 - Typical Multi-motor Installation with VFD

General

MPCBs are designed to handle the operational frequency range up to 60 Hz. Since they include magnetic short circuit trip coils, the carrier frequency of the VFD should be selected as low as possible and must not exceed 4 kHz to avoid overheating. This is in agreement with recommendations given for line terminators and filters.

The actual motor operational current of the MPCBs (140M) should be as close as possible to the low end of their current (setting) range to keep the power loss at minimum.

When MPCBs, due to a partially loaded motor, operate at currents lower than the min. current setting, they are usually not able to trip thermally when additional heating in the magnetic trip coil occurs. The breaker, however, still is permanently experiencing the load of the voltage pulses as described below. Magnetic only versions (MCP) rated lower than 10 A with separate bimetallic overload-relays are also not suitable for these applications since the MCPs have no thermal trip capability for self protection. In addition, the separate bimetallic overload-relays rated 1 A and below would suffer from heating as well and probably not trip for self protection.

The user manual for each VFD drive lists the cable length limitations based on drive size and the quality of the insulation system in the chosen motor. See publication "[DRIVES-IN001: Wiring and Grounding Guidelines for Pulse Width Modulated \(PWM\) AC Drives](#)".

There are various options of filter solutions available to reduce voltage rise time or occurrences of reflected waves.

The application of filter solutions like line reactors (3R...) and reflected wave reactors (3RWR...) can be beneficial with regard to reduced voltage rise times.

To maintain the insulation coordination required for the entire drive system, the occurrence of reflected waves at the motor terminals must be limited to 1400 V_{pk} (IEC-Motors Category A), since the insulation voltage of the switchgear is only 690 V_{RMS}. The max. permissible operational voltage therefore is 500V AC for these applications.

As an optimal solution, sine wave filters would reduce the occurrence of reflected voltage waves.

Circuit Breakers on the “line side” of a VFD

NEC §430.52 and §430.53 resp. requires an MCCB (e.g. 140U-xx) or set of fuses for short-circuit protection on the line side of a VFD. An MPCB may be used in a single-motor-application provided it is tested and specified in the VFD's instruction.

The input current of VFDs is non sinusoidal, containing high peaks and harmonic currents. The peak values can be 1.5...4 times higher than the VFD output currents. The 140M circuit breaker used on the line side of the drives will provide branch circuit protection against short circuits and isolation of the complete VFD circuit through the disconnecting function.

When the motor operates at low speed (low frequency of the output current) the peak input current value can rise noticeably and tripping of the line side breaker may occur.

- To avoid nuisance tripping, the line side breaker must be selected according to the maximum input current to the VFD, not to the rated motor full load current.
- Since 140M is a Self-Protected Motor Controller and should be selected to match motor full load current, the thermal overload function will compete with the overload function of the VFD. This fact alone suggests an alternative approach may be useful. However, many have applied 140M-xxE and 140M-xxT successfully because peaks of VFDs are transient in nature.
- 140U, a UL 489 approved thermal-magnetic Molded Case Circuit Breaker, can be used on the line side of a VFD to provide short circuit protection per NEC §439-52 c.1. The selection of a thermal-magnetic breaker can be as large as 2.5 times full load current. The selection, combined with the 15 times fixed magnetic rating, allows for short circuit protection measured in milliseconds and avoids the problems of selecting a Self-Protected Motor Controller based on full load amps. This method avoids competing overloads tripping with VFD overload. 140U is available up to 30 amps (80% rated, maximum 24 amps continuous).
- Refer to the VFD User Manual for the listing of approved branch circuit protection devices and their sizing recommendations.

Circuit Breakers on the “load side” of a VFD

General

In multiple motor applications on the load side of the VFD it shall meet the group installation requirements per NEC §430.53. In those cases only individual overload protection is required.

When bypassing a VFD via paralleling, using a contactor for example, branch circuit protection is required for either path. The load side must include external overload protection for either the contactor or the VFD.

When circuit breakers are installed on the load side of a VFD, several aspects have to be considered to help ensure proper and reliable operation:

VFDs are limited to a max. output current. The fixed short circuit trip level of MPCBs on the other hand is approximately 13 times the max. current setting. Alternatively, 140M-xxT motor controllers are approximately 15 times the maximum setting. Since the cut off time of the VFD is in range of μ s whereas the reaction time of the trip unit is in the range of ms no short circuit protection function of an individual branch in a multi motor application is given through the MPCB. Even if the trip current value does not exceed the max. output current of the VFD, only a thermal trip might occur.

Due to the PWM voltage pulses and due to the surge impedance of the motor, reflections of the voltage pulses occur at the terminals of the motor. Their amplitude is dependent of the:

- system voltage
- voltage rise time t_{rise} of the VFD
- current rating of the MPCB (surge impedance)
- operational voltage (DC_{BUS} -voltage)
- location of the MPCB (close to the VFD output or close to the motor)
- cable type and length between MPCB and motor (surge impedance).

System voltages up to 240V AC need no specific consideration. To reduce the impact on the system components at higher operational voltages,

- the interconnection between VFD and motor should be as short as possible and not exceed manufacturers' recommendations.
- Location of the MPCB near the motor is the preferred solution.

The formula to determine the max. permissible ("critical") cable length l_{crit} at which reflected voltage phenomena are fully developed given by motor and drive manufacturers is a suitable estimation also for applications with MPCBs located near the VFD:

Equation 1

$$l_{crit} \approx \frac{v_{cable} * t_{rise}}{2}$$

- l_{crit} - critical length
- v_{cable} - propagation speed
- t_{rise} - rise time of VFD pulses

Typical pulse propagation speed on a cable is $v_{cable} \approx 150 \text{ m}/\mu\text{s}$. The voltage rise time t_{rise} is dependent on the drive semiconductor technology.

Semiconductor Technology	$t_{rise} [\mu\text{s}]$		$l_{crit} [\text{m}]$	
	$t_{rise min.}$	$t_{rise max.}$	$t_{rise min.}$	$t_{rise max.}$
BJT	0.2	2	15	150
GTO	2	4	150	300
IGBT	0.05	0.4	3.75	30

Example: Assuming a voltage rise time of 200 ns (example: for BJT) the critical length is 15 m.

If MPCBs are located near the output of the VFD, those devices rated 10 A and above are not significantly affected by these effects due to their constructional properties. The surge impedance of MPCBs < 10 A, however, does not match that of the cable sufficiently therefore reflected voltage waves originated at the motor terminals and returning to the MPCB cause high dielectric stress on the trip coils resulting in accelerated aging of the insulation and probably disabling of the instantaneous short circuit trip function.

For

- Standard MPCBs rated 10 A and higher the max. cable lengths of drive manuals apply.
- Standard MPCBs below 10 A the value according to "Equation 1" or the drive manual applies, whichever is lower.
- Alternatively specific MPCBs suitable for downstream VFD application shall be used (e.g. 140M-D8V-xxx).

Always take measurements of rise times on site to verify the real conditions.

Conclusion

Unless specifically stated as suitable for use like 140M-D8V-xx, switchgear selection in these applications should take into account the complexity of the system dynamics such as capacitive loads and reflected wave. There are several factors that must be considered in the installations where MPCBs are used at the output of VFD to minimize the influence of voltage pulse and current harmonics.

- The MPCB should be selected so that its current setting is close to the low end of the setting range. This reduces the basic temperature level at the trip coil and allows adjustments.
- For standard MPCBs rated 10 A and higher – The interconnection between the VFD and motor should be as short as possible and not exceed drives manufacturer recommendations.
- For standard MPCBs below 10 A – The maximum permissible (“critical”) cable length I_{crit} value according to [Equation 1](#) or the drive manual applies, whichever is lower. Using [Equation 1](#) to determine I_{crit} values given by motor and drive manufacturers, at which reflected voltage phenomena are fully developed, is also a suitable estimation for applications with MPCBs located near the VFD.
- The preferred location of MPCB installations is as close to the motor as possible, in order to reduce the cable length between the motor and MPCB.
- The chopping frequency of the VFD should be as low as possible and not exceed 4 kHz.
- Filter solutions, like line reactors and reflected wave reactors, can be applied to reduced voltage rise times. Application of sine wave filters would eliminate the occurrence of reflected voltage waves. These are suggested by drive manufacturers.
- Always take measurements of peak voltages to verify effectiveness of the measures.
- The surge impedance of electronic overload relays is also low in principle and unless specifically stated they are not suitable for this kind of application, since their current sensor technology may not be able to measure the load current and harmonics correctly when operating at frequencies outside their nominal sensing range.
- Main circuits of contactors and load switches are normally not affected as described above, due to their low surge impedance. However, depending on capacitive load through long cables or capacitor charging currents, contact welding might occur when switched under load, so consideration related to capacitive load shall be taken in account in selection of these devices to be used with drives.
- Consider the use of 140U on the line side of the VFD when continuous currents are less than 24 amps.