

# **Application of Multi-function Motor Protection Relays to Variable Frequency Drive Connected Motors**

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## **Abstract:**

This paper reviews the application of multi-function motor protection relays to motors that are connected by variable frequency drives (VFD). Typical VFD internal motor protection functions are reviewed to understand the required rolls of external motor protection relays. Applications discussed include protection requirements when the relay is located on the source side of the VFD and the motor side of the VFD. The impact of using a bypass switch around the VFD on protection requirements is also discussed.

## **Introduction:**

This paper discusses options for applying motor protection to installations which include variable frequency drives (VFD). In most cases, the VFD provides basic motor protection as an integral part of the drive control system so a separate motor protection relay may not be required. However, the presence of bypass switches and owners' standards may require the use of load side motor protection. This often leads to questions and confusion about the applicability of motor protection relays to variable frequency systems.

Several different arrangements are considered in this paper, including protection requirements of the VFD itself, the applicability of relays to the motor side of the VFD and the impact of bypass switches and shared VFDs. Figure 1 shows typical one-line diagrams for dedicated VFD (one for each motor) applications. Figure 1(b) includes a bypass switch. In some applications, the motor can start and run through the bypass switch without using the VFD. In other cases the motor can run through the bypass switch but the VFD is required for starting. This has impacts on protection selection and control.

Figure 2 shows the one-line of a typical application where one VFD is shared by multiple motors. The VFD is used to start and run one motor at a time. If another motor is required to run, the running motor is transferred from the VFD to its own breaker or starter using the bypass/transfer switches and the VFD is then used to start and run the next motor.

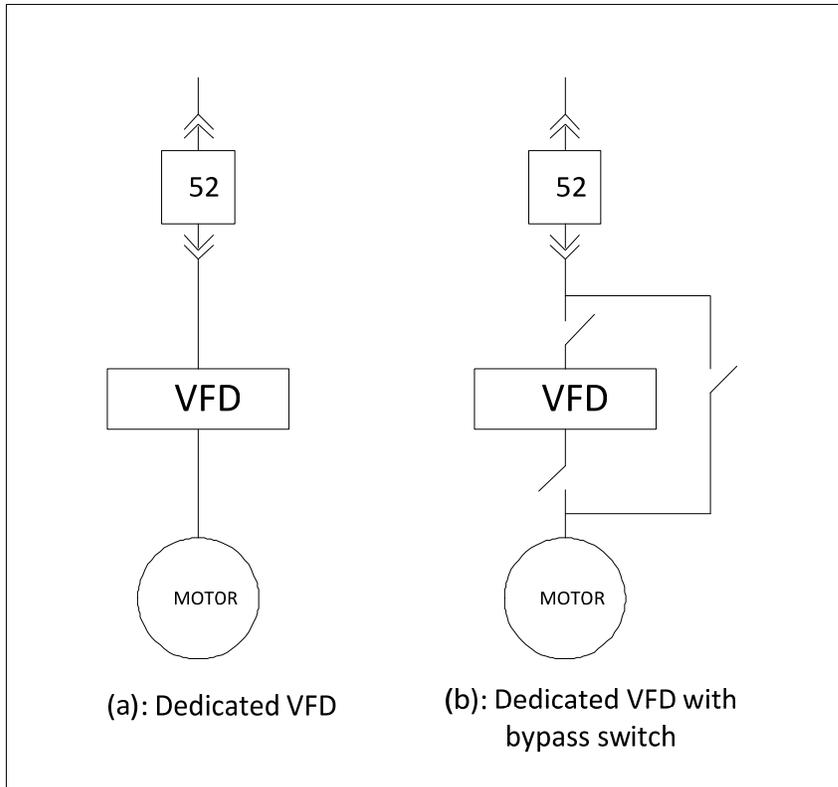


Figure 1: Typical dedicated VFD arrangements

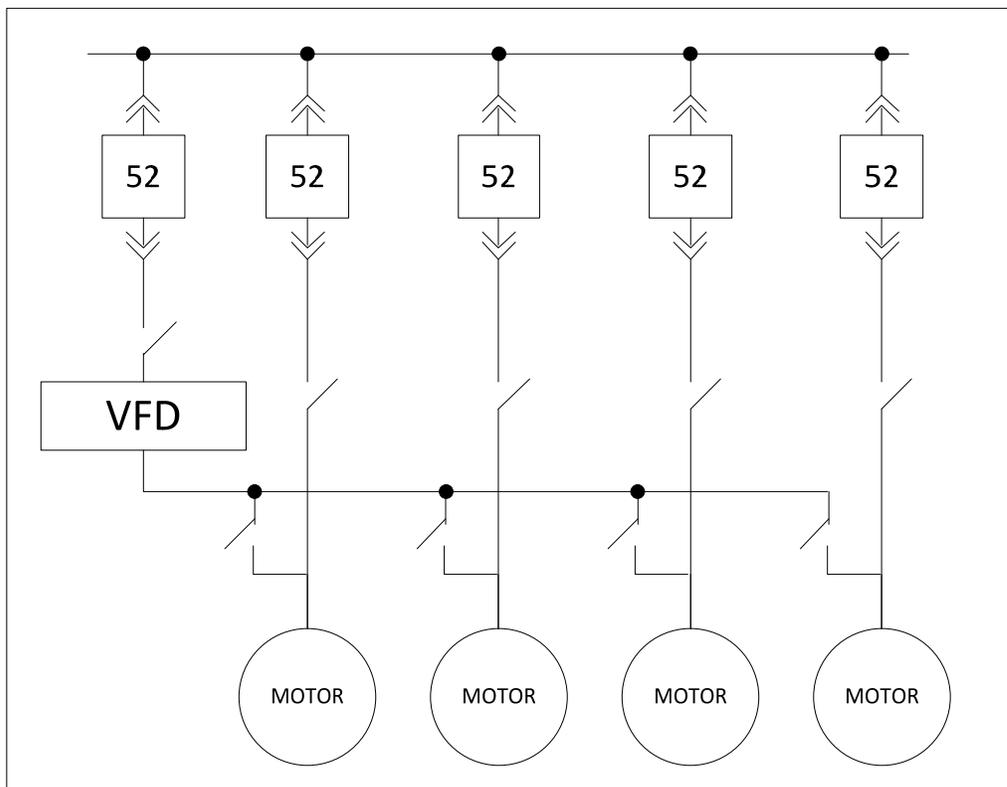


Figure 2: Typical shared VFD arrangement

### **VFD Internal Motor Protection Functions:**

VFDs typically include some basic motor protection as an integral part of the drive control system. The inherent nature of the inverter portion of the VFD limits the contribution of the VFD to short circuits in the motor. Typical short circuit contributions are less than 1.5 times motor full load current on a steady state basis. As a result, additional short circuit over-current protection (50) is generally not applicable to the motor although differential protection (87) may reduce motor damage due to a winding short circuit.

The motor stator is designed for a maximum flux density without saturating the iron. Since the flux density is directly proportional to the applied voltage and inversely proportional to the applied frequency, the motor has a maximum design Volts per Hertz (V/Hz) operating ratio. The VFD uses this V/Hz ratio to determine the maximum voltage allowed at any particular operating frequency. This control effectively limits iron damage due to excessive heating caused by over-excitation.

The VFD may include power quality functions such as over/under voltage and over/under frequency to assure that the incoming power quality is high enough to allow proper drive operation. It may also monitor total harmonic distortion (THD) of the voltage and/or current waveforms to detect supply or VFD problems including waveform notching. These power quality functions are fundamentally there to protect the VFD but they can inadvertently cause excessive process down-time if they are set too sensitive for the incoming power system.

### **Source Side VFD Protection:**

The VFD requires protection for short circuits in the VFD and the supply leads. For motor starter applications, this protection is typically provided by a set of power fuses. Proper sizing of these fuses is critical, especially if a bypass switch is included. For breaker applications this protection is typically provided by instantaneous phase (50P) and zero-sequence (50N or 50G) over-current elements (Figure 3). The 50P pick-up must be set higher than the maximum inrush of the drive and lower than the available short circuit current. The 50P pick-up must also be set higher than motor locked-rotor if a bypass switch is included and the motor is subject to across line starting with the bypass closed. Fixed time delay can be added but is usually not required for this application.

The neutral over-current (50N) element, which is based on the zero-sequence current calculated from the phase CTs, is generally applicable when the source power system is either solidly or low impedance grounded. The ground over-current (50G) element is based on separately measured zero-sequence current, usually using a low-ratio core-balance window CT around all three phase cables and is applicable to high-resistance grounded systems. For shielded cable (typical on medium voltage) care must be taken to properly wire the cable shield ground wires relative to the zero-sequence CT (see Figure 4). The pick-up of the 50N or 50G element must be set less than the available single-line-ground short circuit current. A short fixed time delay should be added to prevent false tripping due to transient signals generated by CT errors or stray flux.

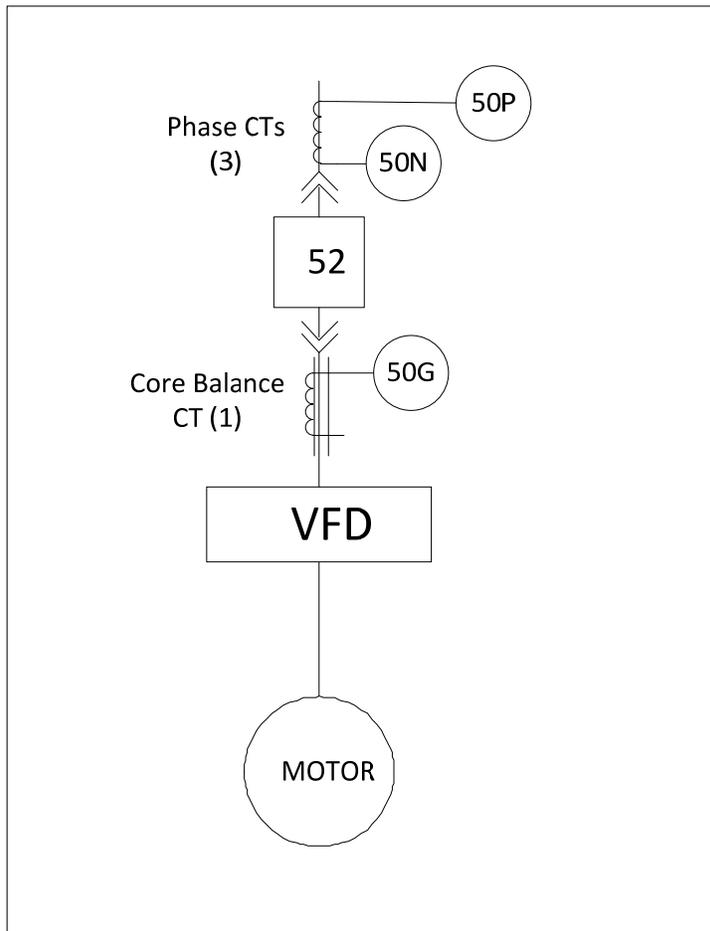


Figure 3: Typical short circuit protection for a VFD

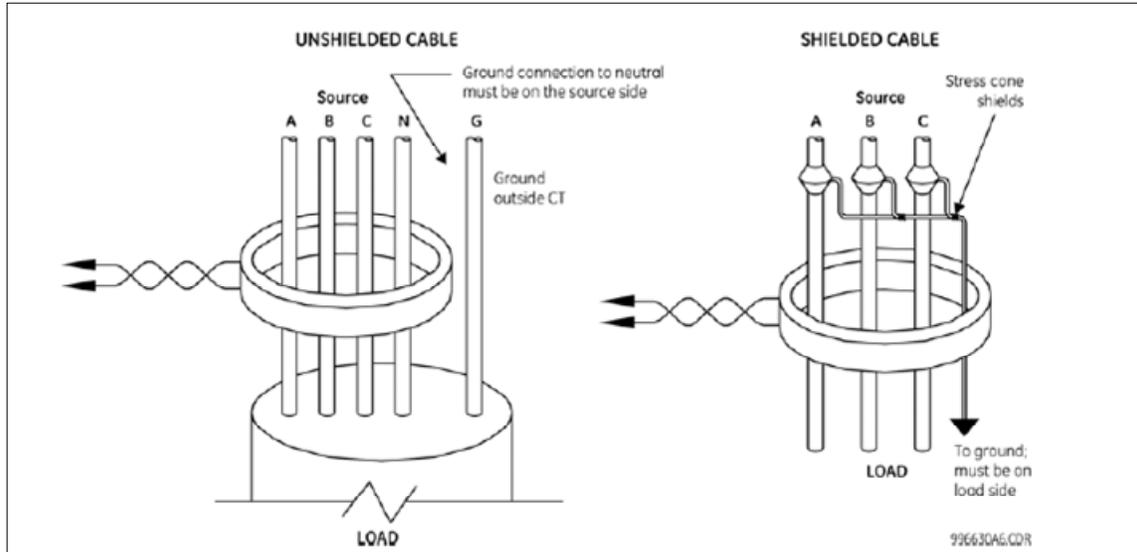


Figure 4: Zero-Sequence Core Balance CT Installation

The nature of the VFD control circuitry is such that VFD over-load is usually not a concern. However, inverse-time over-current elements (51P and 51N/G) can be used for short circuit protection of the drive. If a motor relay thermal over-load (49) element is used for the 51P to protect the VFD, care must be taken to fully understand the current-only behavior of the 49 element. 49 elements are thermal modeling functions that calculate the estimated motor stator winding temperature based on past and present motor loading. As a result, the time to trip for a particular amount of current will vary depending on the currently calculated motor temperature. For this reason, the use a 49 element as a 51P element is not recommended.

### **Load Side Motor Protection:**

It is sometimes desirable to include additional motor protection functions in addition to or redundant to the motor protection functions that are internal to the VFD control. In these cases a motor protection relay can be installed on the load side of the VFD (Figure 5). Careful selection of the relay is required to assure proper operation. Since the load side of the VFD operates at variable frequency it is critical that the relay selected has robust frequency tracking with a frequency range at least as large as the VFD operating range. Typical specification for frequency tracking is 20 – 65 Hz.

The voltage on the load side of the VFD is unrelated to the voltage on the source side of the VFD so VTs on the load side must be provided. The CTs and VTs on the load side must be capable of operating satisfactorily over the full frequency range. Relaying class CTs are typically adequate for this application although the CT manufacturer should be consulted. The published saturation curves for the CTs are typically based on 60 Hz excitation voltage. Since the CTs are iron core devices, the saturation voltage drops proportional to the drop in frequency so the curves can be scaled for any operating frequency.

The motor relay's thermal over-load element (49) can be applied on the load side to protect the motor's stator winding insulation from thermal damage. The 49 element calculates the temperature of the stator (hottest spot) based on the applied voltage and the loading current. In addition to the stator current heating ( $I^2R$ ), the applied V/Hz ratio is used to estimate flux density heating and negative-sequence unbalance in the phase currents is used to estimate rotor heating. Some 49 elements also include the core heating caused by the presence of voltage harmonics (especially important when operating at or above the motor's nameplate frequency).

Even though the short circuit current is limited by the VFD, it may be desirable to apply a differential (87) element to limit winding damage and to provide faulted phase identification (targeting). Figure 5 shows 87 protection using two sets of CTs. For this application CT performance is especially critical and both sets of CTs should have the same ratio and accuracy class.

Figure 6 shows 87 protection using just one set of phase CTs. In this application the CTs are window type core-balance CTs and the neutral-end power leads of the motor are routed through the individual phase CT windows such that the normal net flux is zero. In this application, CT accuracy class is not as important since the only time there is net flux is during an internal fault.

While the rotor heating caused by negative-sequence unbalance in the phase currents is included in the 49 element, it may be desirable to set a discrete negative-sequence over-current (46) element to protect the motor against an open phase on the VFD. The relay frequency tracking is critical for this element's performance since sequence component calculations are inherently based on fundamental frequency. The pick-up of the 46 element is usually a percentage of the positive-sequence current. There may also be a compensation factor which increases the pick-up during low-load times.

On certain applications (pumping and conveyors for example) the motor may actually be spun backwards by the load for a brief period following a motor stop. The motor or the driven load may be mechanically damaged if the motor is started during this back-spin condition. To prevent this, back-spin detection (BSP) may be applied to block motor starting. The BSP element senses the back-EMF generated by the motor residual field during back-spin. It is designed for applications where the back-spin will last for a relatively short period of time while the discharge pipe drains back through the pump or the conveyor rolls backwards until the brakes apply. It may not operate properly if the back-spin condition lasts more than a couple of seconds because the residual field in the stator will collapse.

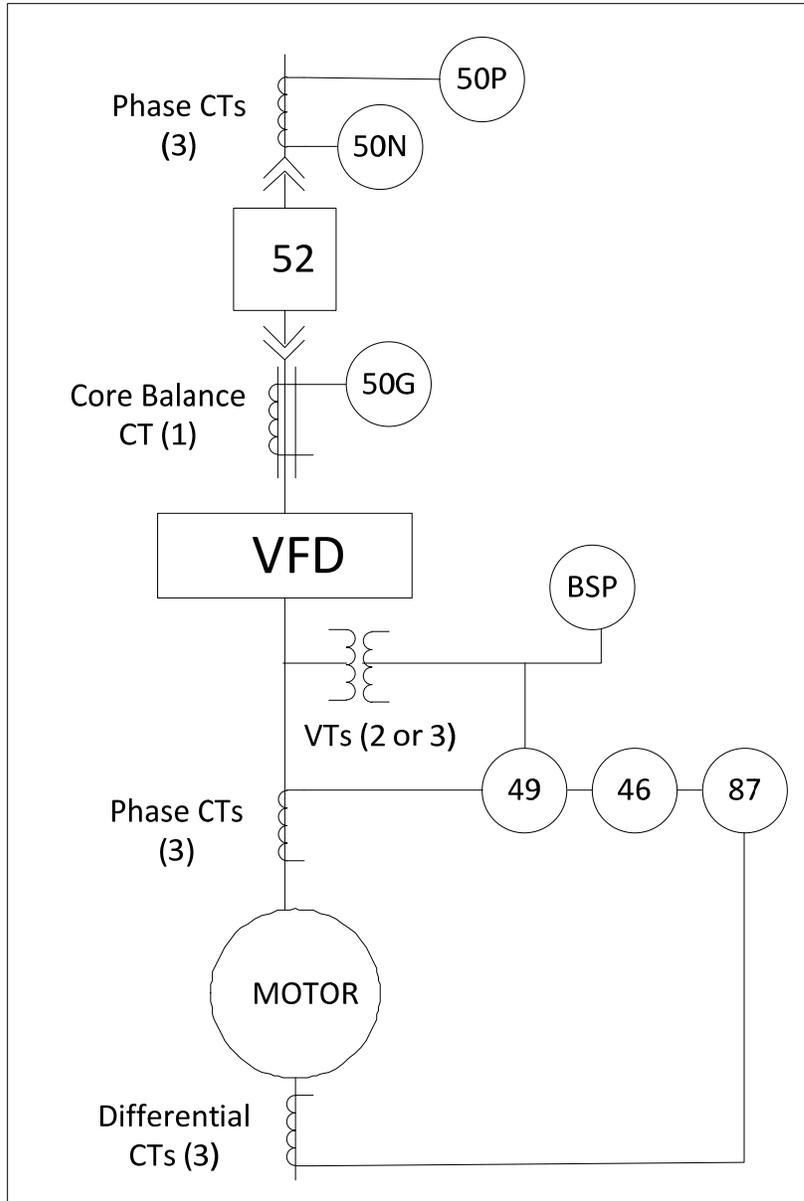


Figure 5: Typical load side motor protection

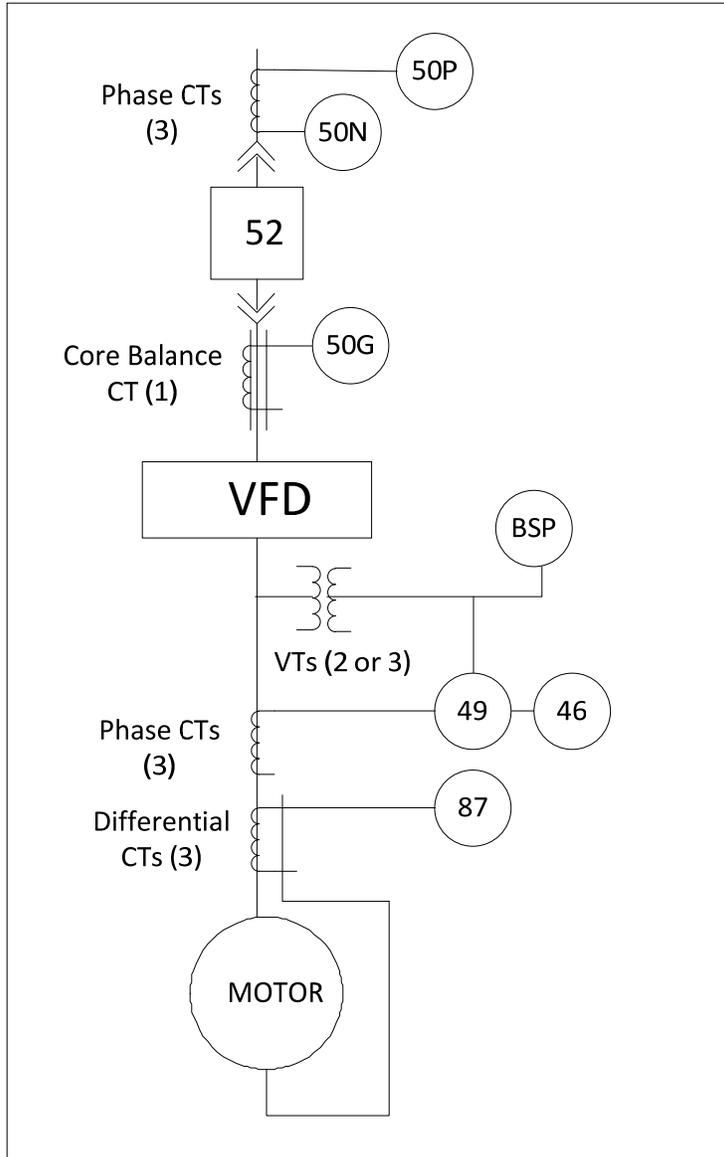


Figure 6: Typical load side motor protection using core-balance CTs for differential

### **Impacts of Bypass Switches:**

Bypass switches on VFDs pose interesting protection challenges. Fundamentally, different protection is required on the breaker or starter when the bypass switch is open than is required when it is closed. With the switch open, only short circuit protection is required. However, when the bypass is closed full motor protection is required. The simplest application may be to use a feeder relay with over-current protection and a separate motor relay (Figure 7). Over-current protection is required all the time so, assuming that the 50P pick-up is set higher than locked-rotor current if the motor is subject to across line starting while the VFD is bypassed, the feeder relay can remain in service regardless of the bypass switch position. The motor relay is only required when the bypass switch is closed so an interlock contact can be provided in the trip circuit. The motor relay 49 element may not produce accurate temperature model calculations when the bypass switch is first closed since the 49 element was looking at the VFD current before the bypass was closed rather than the motor current.

Depending on the capabilities of the relay used, it may be possible to use one relay and change setting groups when the bypass is closed. However, caution should be exercised any time setting group changes are made to assure that protection is available for any issue caused by the setting change initiator. In this case, if the drive is used to start the motor and then the bypass is closed with the motor running, one of the switches could suffer a mechanical failure and cause a short circuit. Tripping might be delayed if the relay is in the process of changing setting groups at the time of the short circuit. For this reason setting group changes should only be used when a given setting needs to be different from one operating condition to another and should not be used to enable new functions. Since the motor protection functions are only required when the bypass is closed it makes more sense to use the position of the bypass switch to block the motor protection functions when the bypass is open (Figure 8). This assures that the 50P and 50N/G functions are continuously available while the switches are being operated. The motor relay 49 element will not produce accurate temperature model calculations when the bypass switch is first closed since the 49 element was blocked before the bypass was closed.

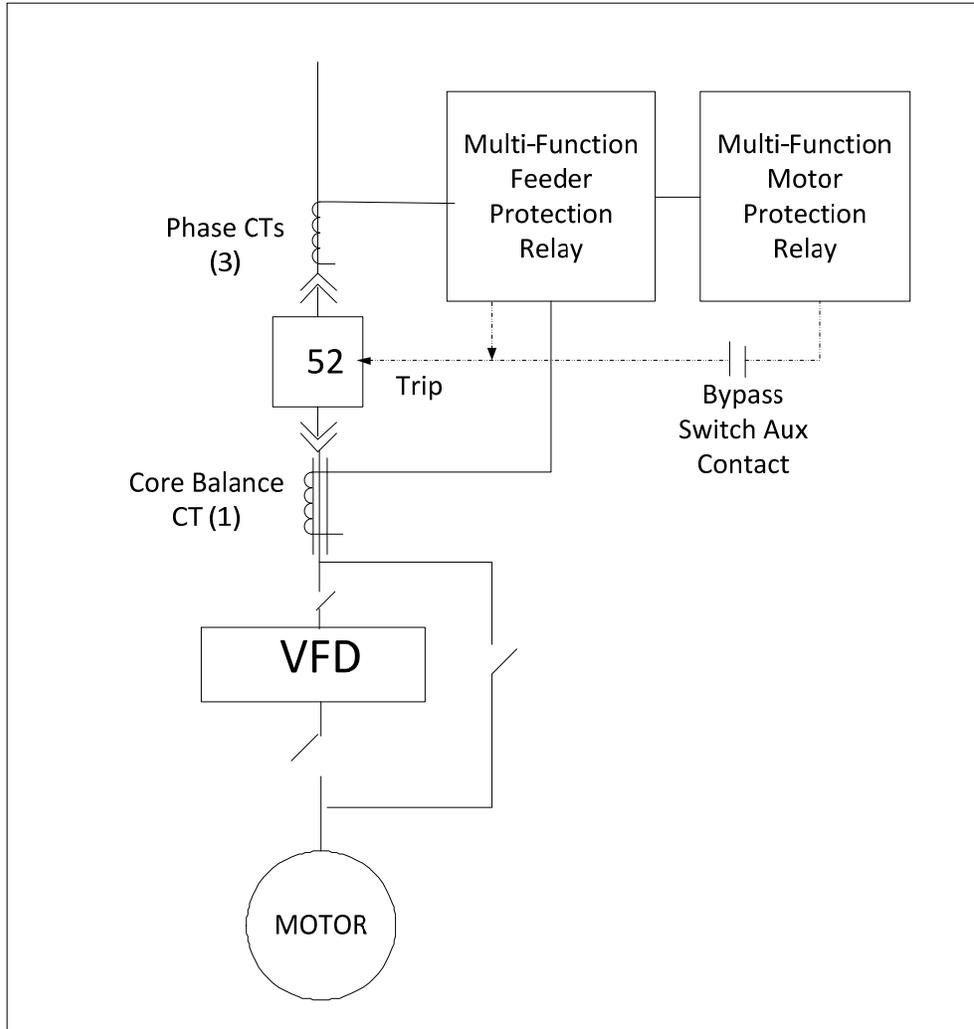


Figure 7: VFD with bypass switch and separate feeder and motor relays

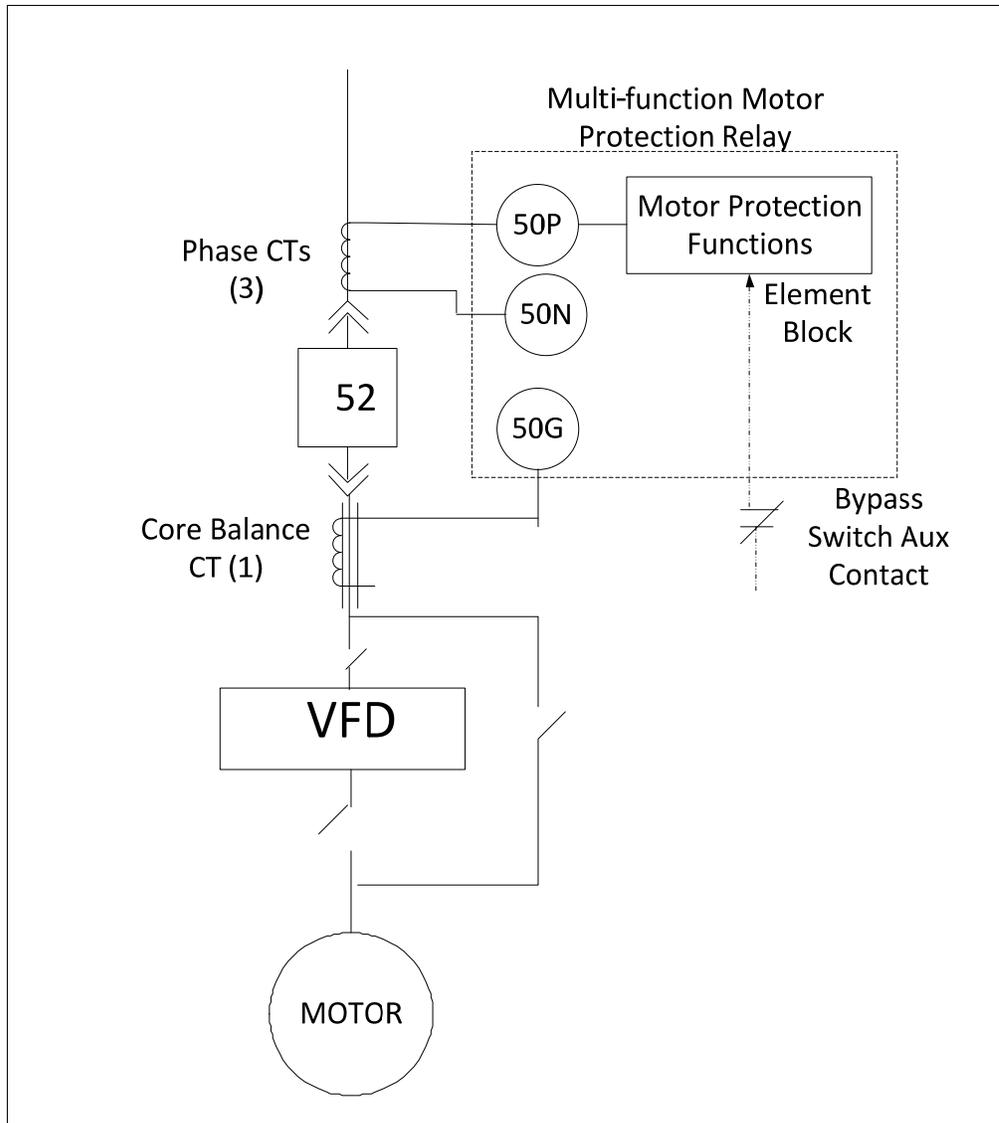


Figure 8: VFD with bypass switch and one motor protection relay

Another alternative for motor protection on a VFD with a bypass switch is to use load side motor protection (Figure 9). In this case, both the short circuit and motor protection remain in service at all times and the position of the bypass switch has no effect on the protection. The motor relay 49 element will produce accurate temperature model calculations regardless of the position of the bypass switch since it is always looking at the motor applied current and voltage.

Shared VFDs are really just special cases of a VFD with a bypass switch and any of the options listed above can be adapted to work.

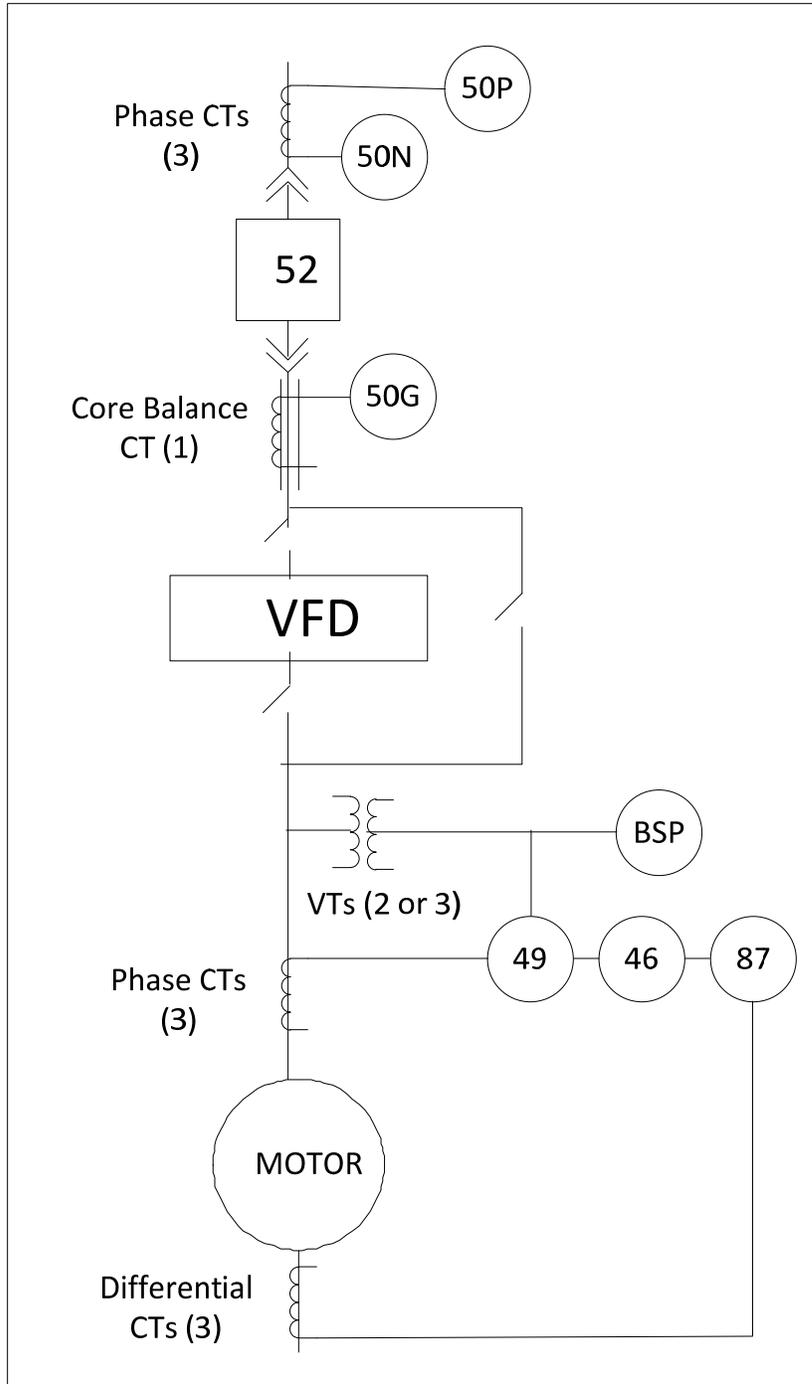


Figure 9: VFD with bypass switch and load side motor protection

### **Conclusions:**

Motor protection relays can be successfully applied to systems with VFDs. Special consideration for device performance under varying frequencies is required for devices installed on the load side of the VFD. VFDs with bypass switches offer a unique set of challenges and require careful analysis of protection performance during switching.

### **References:**

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“Maintenance Handbook for Protective Relaying”, Third Edition, GE Digital Energy, 650 Markland Street, Markham, ON Canada L6C 0M1