Impact of Variable Frequency Drive and Cyclic Loading on Multi-Function Motor Protection Relays

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Abstract

Multifunctional motor protection relays are associated with various challenges/problems when applied to the special purpose motor applications such as variable frequency drives (VFD) and cyclic loading. For the VFD motor applications, these challenges include distorted input signals; varying frequency; current and voltage measurements at load and source side of VFD, respectively; switching of the VFD bypass; etc. For cyclic load motor applications, variation in the current magnitude during a load cycle period can result in mal-operation of the thermal overload protection and less sensitivity to short circuit faults.

This paper is reviewing the aforementioned challenges, and is presenting solutions in order to establish a reliable protection solution that is secure and sensitive. To fully analyze the impact of VFD and cyclic load on multifunctional motor protection, various normal and faulted system conditions are simulated in the transient simulator software (PSCAD) in order to validate proper performance of the proposed solutions.

I. Introduction

Variable frequency drives, also known as adjustable speed drives (ASDs), are widely used to control speed of induction motors. The VFD controls speed by adjusting the frequency at the motor terminals and also adjusts voltage to maintain the Volts per Hertz (V/Hz) ratio. VFDs can be categorized into three design types: pulse width modulator (PWM), current source inverter (CSI) and variable voltage inverter (VVI) [1]. Each type has its own advantages and disadvantages. For example, PWM drives are more complex in design, but generate close to unit power factor with less distortion and a single PWM VFD can be used to feed multiple motors within VFD rating.

Figure 1 shows a single line diagram of the three common VFD topologies: (a) dedicated VFD for a single motor, motor start and run by the VFD; (b) single motor with a VFD and a bypass switch across it, motor start and run by the VFD or bypass VFD to directly fed from the system voltages; (c) single VFD with multiple parallel motors, VFD is required for starting only while bypassed during motor running [2].

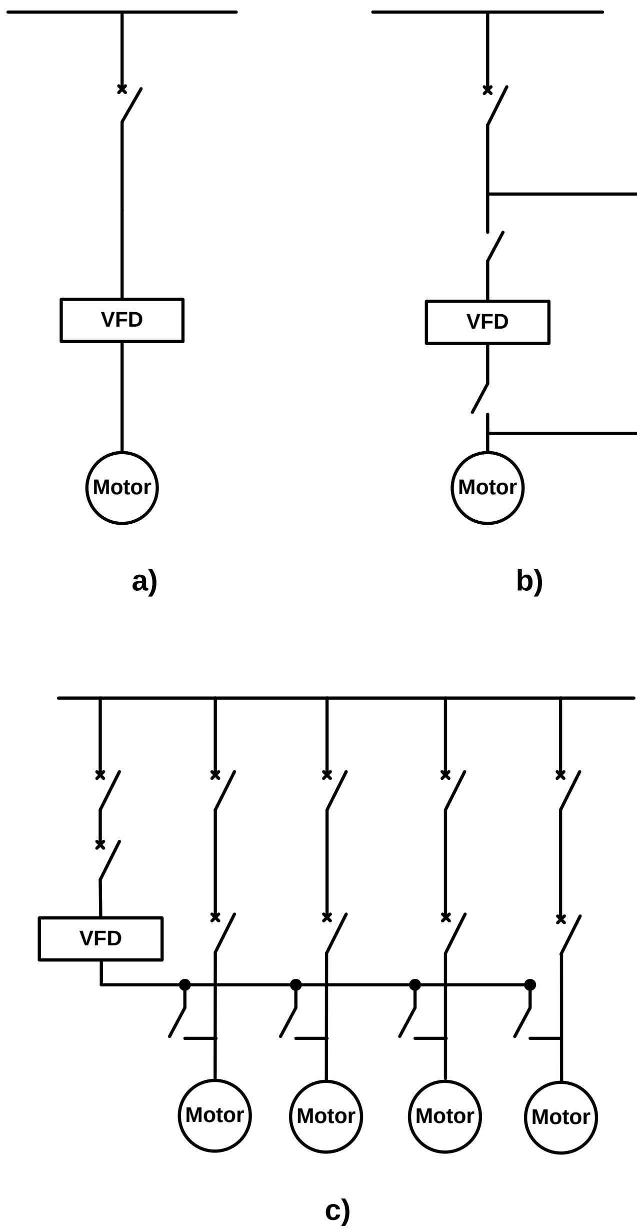


Figure 1 VFD topologies

Cyclic or reciprocating mechanical loading of motors can be found in applications such as crushers, pumps, cranes, compressors, movers etc. Load variation can change from very light to overload capability of the motor during a load cycle. As a result, load currents of a motor driving cyclic load can vary between very low to above the maximum allowable current during a load cycle.

Multifunctional motor protection relays experience various challenges and issues when applied to protect medium-voltage VFD and cyclic loaded motor applications. These challenges may include:

- Significant distortion in the motor input signals due to harmonics generated by the VFD operation
- Off-nominal starting frequency
- Varying starting frequency
- Normal load running at off-nominal frequency
- RMS vs DFT
- Variation in the shaft driven fan cooling
- Variation in the current magnitude in cyclic load applications
- Varying duty cycle
- Security vs sensitivity of various protection and monitoring functions

Sections II and III explain the aforementioned issues in more detail and present solutions to these problems so that a multifunctional motor protection relay can be applied to protect VFD and cyclic load motor applications with greater reliability. To fully analyze the impact of VFD and cyclic loading on multifunctional motor protection, various normal and faulted system conditions are simulated in transient simulator software (PSCAD/EMTDC [3]) in order to verify the proper working of the proposed solution.

II. Protection Challenges Associate with VFD Motor Applications

A. Distortion in the motor input signals

Motors driven by VFDs have significant harmonics content in the input signals. Harmonics in the input signals cause additional copper and iron losses in the stator and rotor. Harmonics currents flow in the motor stator and rotor and therefore produce heat. Overheating results in a decrease in the overall life of the motor.

Figure 2 shows phase “a” voltage and current signals fed into a motor from a 2^{nd} level PWM with switching frequency of 16 kHz. PWM switching frequency is normally in the range 500 – 20 kHz [4]. Since the switching frequency is very high compared to the fundamental frequency, the low order harmonics content in the current signals can be below 10% of fundamental frequency component. Voltages on the other hand are severely distorted, as compared to current signals, as shown in the Figure 3.

Thermal overload protection operating on the fundamental frequency cannot produce an accurate representation of the thermal influence, this factor worsens as the VFD topology becomes simpler, e.g. 2^{nd} level PWM inverter is simple but generates more harmonics than compared with a 3^{rd} or higher level inverters. Therefore, the thermal overload must operate on the measured true RMS currents to accurately reflect the additional motor heating due to harmonic contents in the current signals.

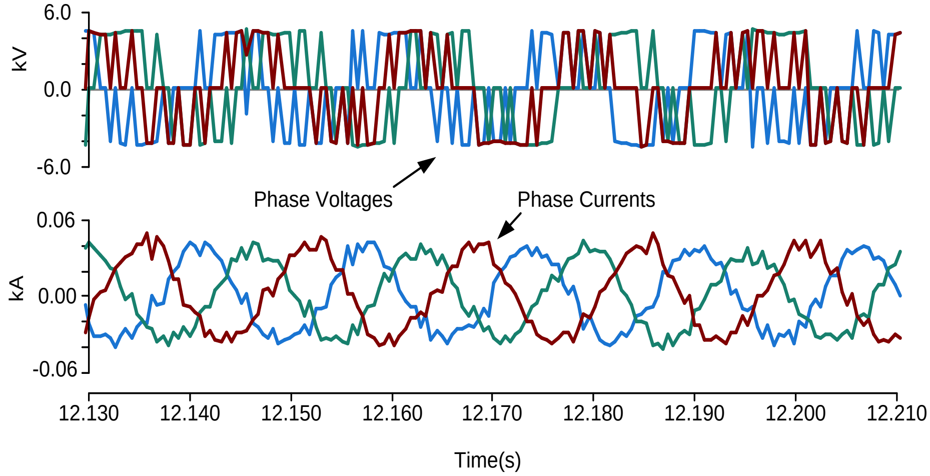


Figure 2 Motor input voltage and current signals

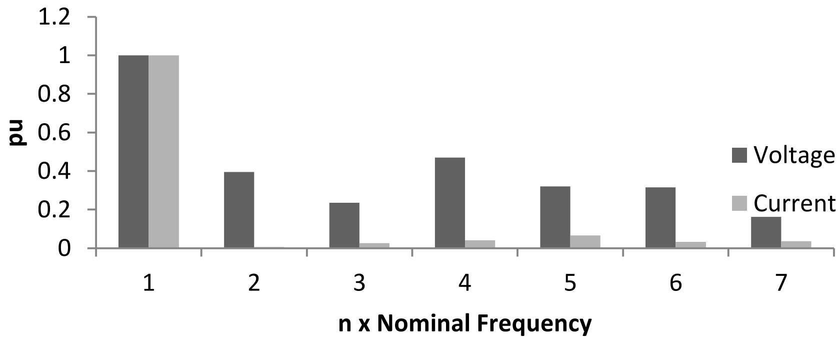


Figure 3 Harmonic contents in motor input signals

B. Starting of the motor fed through VFD

PWM type VFDs can be used as soft-starters starting the motor from low speed or frequency and accelerating to the desired speed or frequency level (off-nominal or rated level). Rate of change of speed or acceleration/deceleration time from one level to another is normally programmable in most of the modern VFDs. For example, VFDs allow programming of the total time required to accelerate from 0 to 60Hz in a range from 0.1 sec to 3000 sec in MV drives and 0.01 to 6000 sec in LV drives. Although the drive is capable of accelerating the motor with the defined rate, the motor or application may not accept such rates. If the accelerating time is set too low then the motor may draw too high current such that overcurrent relays within the drive or in the external motor relay may trip. Note: The speed range of VFD fed motor is normally defined as a part of its rating [4].

In multifunctional relays, DFT-type (discrete Fourier transform) and/or RMS-type (root mean square) techniques of fixed sampling frequency are normally used to estimate the phasor (magnitude and phase) of the sampled voltage and current signals. Estimation of the off-nominal frequency signal using the fixed sampling frequency estimators results in a significant error in the measurement. In VFD applications, the frequency of the motor input current signals during starting varies with a defined rate of change. Moreover, some applications require the motor to run at off-nominal frequency (speed) during the normal load conditions. Therefore, depending on the motor running condition, measurement error varies with the varying frequency. Figure 4 illustrates an example of a VFD fed motor input current signal and its frequency during motor start with a starting frequency of 3Hz and accelerating to the nominal frequency of 60Hz. The example of high acceleration starting in Figure 4 is just for the illustration purpose, which may not be a practical case.

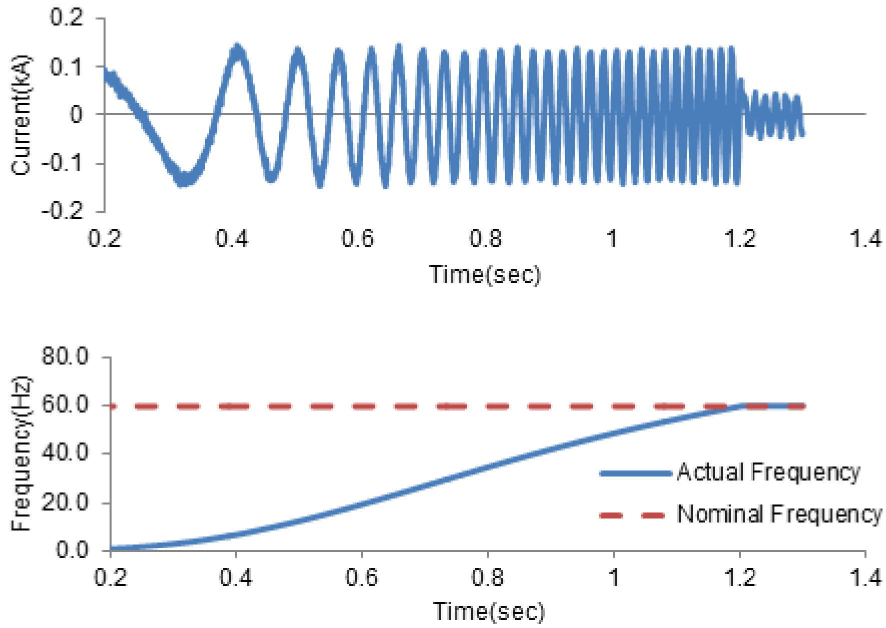


Figure 4 Example of motor starting current and change in frequency

Figure 5 demonstrates the magnitude estimation of the motor starting current using RMS- and DFT-type techniques having a fixed sampling frequency of 3840Hz and nominal frequency of 60Hz (sampling rate N equals 64samples/cycle). It shows significant error in the measurement which decreases as frequency approaches the nominal frequency level. This is due to the fact that with fixed sampling frequency, samples per cycle changes as frequency changes which results in the measurement error. For example, for a nominal frequency of 60Hz, N equals 64 samples in one cycle (Fs=3840 Hz) and for a frequency 50Hz, N will increase to 77 samples in one cycle, due to the change in the window length. Hence, using DFT with a fixed sampling frequency will not provide correct estimation of the phasors of a varying frequency input signal.

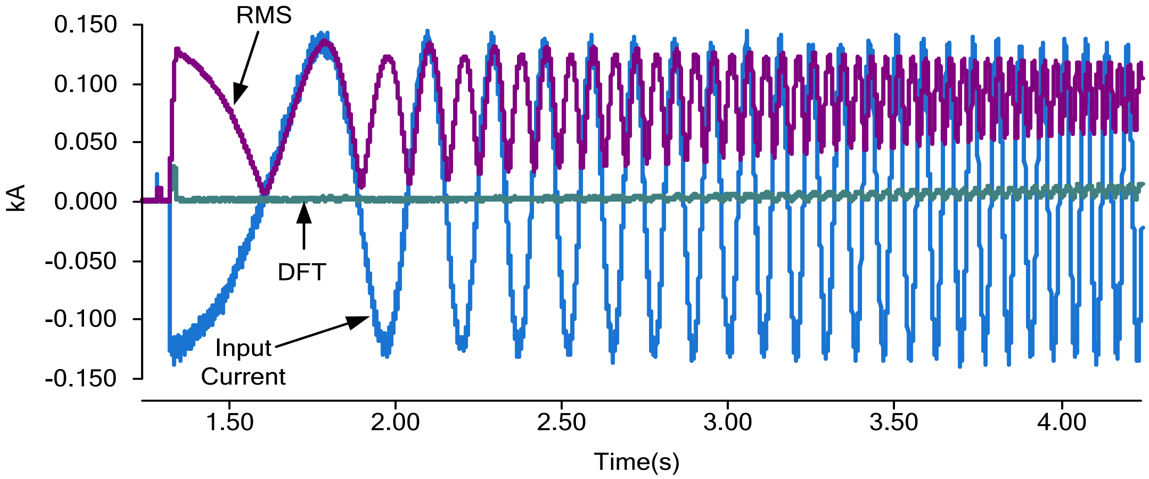


Figure 5 Magnitude estimation using fixed sampling frequency RMS and DFT

In order to overcome the dilemma of measurement error due to varying frequency during motor start and off-nominal frequency load running, it is necessary to correct the sampling frequency by properly tracking the motor input signal frequency. If a multifunctional relay [5] offers tracking of frequency in the range 3 Hz to 70 Hz then figure 6 shows the magnitude measurement using the RMS- and DFT-type estimators with auto adjustment of the sampling frequency based on the input frequency.It can be seen that the measurement error is now significantly decreased.

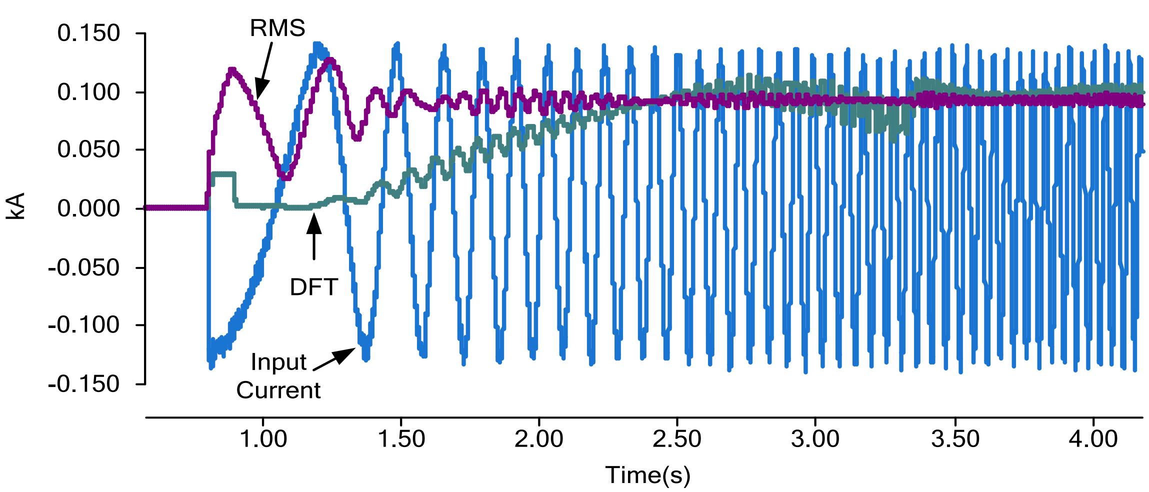


Figure 6 Magnitude estimation using adjusted sampling frequency RMS and DFT

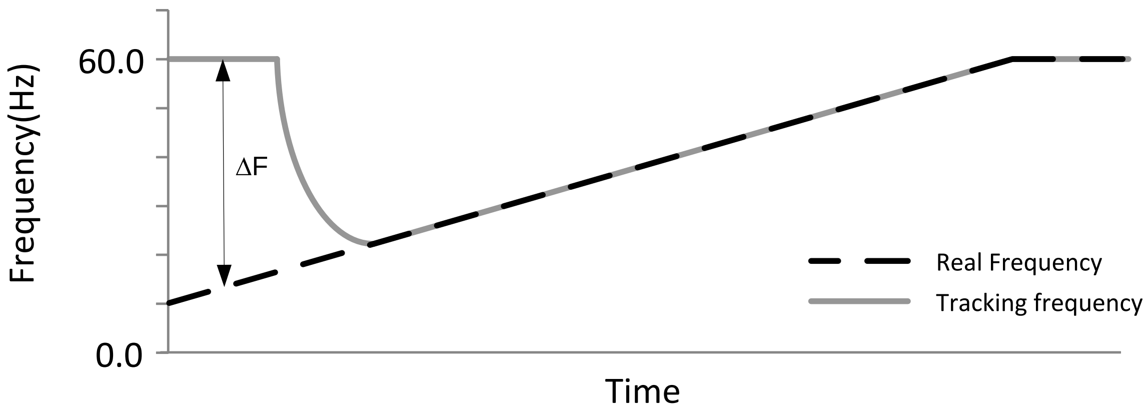
C. Starting Frequency Adjustment

Using tracking frequency in order to adjust the sampling frequency of the phasor estimators, helps to achieve correct measurement of the varying frequency input signals. However, as shown in Figure 6, the magnitude of the input signal still shows measurement error in the first few cycles. RMS magnitude shows large oscillations in measurement while DFT magnitude shows calculation delay until magnitude reaches the actual magnitude level. This is due to the processing time taken by the frequency tracking algorithm plus the intentional security delay of a few cycles. Intentional security delay helps to prevent frequency measurement error due to noise or system disturbances.

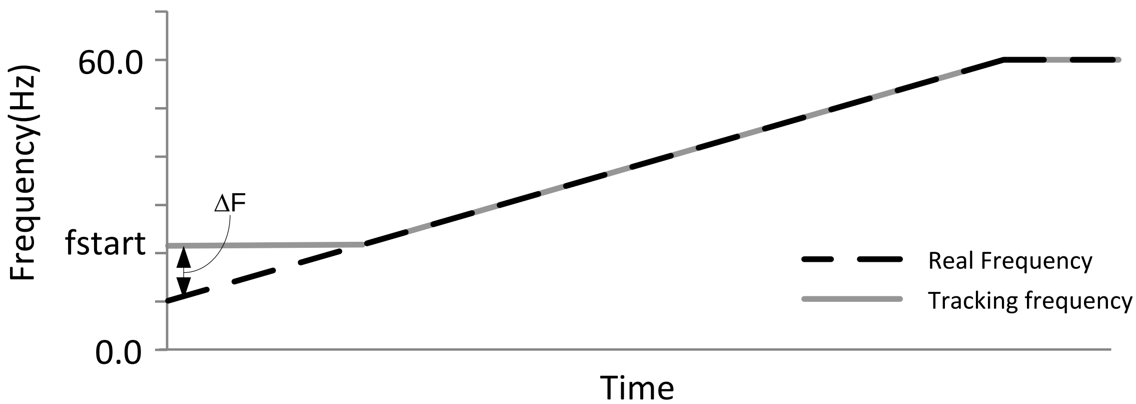
Measurement error due to the processing delay by the frequency tracking can be further reduced by forcing the tracking frequency to start tracking from the pre-defined starting-frequency. Normally, sampling frequency is adjusted based on the nominal frequency (e.g., 60Hz) until tracking frequency starts providing the actual frequency; see Figure 7(a). Measurement error is therefore large until frequency tracker starts providing the actual frequency. Measurement error will reduce as the difference (ΔF) between the estimated and real frequency reduces.

This issue can be solved if frequency tracking is forced to initialize at defined a frequency level known as “Starting Frequency, F_{start}” instead of nominal frequency. As soon as a motor starts, the sampling rate is adjusted as per the set starting frequency instead of nominal frequency until frequency tracking starts providing the real frequency. This feature will help to reduce the measurement error significantly by forcing reduction of the difference (ΔF) between the estimated and real frequency, as shown in Figure 7(b).

For example, in the application of a motor fed through a VFD that starts at frequency of 10 Hz, the relay engineer must use the Starting Frequency feature and program the starting frequency value to 10 Hz.



a)



b)

Figure 7 Illustration of Starting-Frequency feature

D. Selection of tracking frequency source-Voltages vs. Currents

As mentioned in section II A, a motor driven by a PWM type VFD has significant distortion in the input signals due to harmonics generated by the PWM inverter and switching losses. This distortion is not as significant in currents as in voltages. Typically, voltages are the best source of tracking frequency because of the signal level, however, due to significant distortion in the motor input voltages it is justified to use currents as a source for tracking frequency. In most cases, the current must be used because the VFD will not tolerate the added inductance of motor-side VTs and voltages measured at the source side of the VFD are nominal frequency voltages and, therefore, can't be used as a source to track the motor input signal frequency.

For the VFD topologies shown in Figure 1(b) and (c), when VFD is only used to start the motor and bypassed during load run conditions, it is important to switch the frequency tracking source from the motor currents during starting to the system voltages during running. This can be done by properly monitoring the status of the VFD bypass switch.

E. RMS vs DFT

Typically RMS- or DFT-type estimators are used to calculate phasors for the current based short circuit protection functions of modern microprocessor based relays. Because DFT extracts only the fundamental component of the input signal, it results in a lower estimate of the magnitude of the VFD supplied signals. However, in VFD applications, the distortion or harmonic contents in the current signal are not significant like the voltages (see Figure 2). The actual cause of the lower estimation of the magnitude using DFT-type, compared to RMS-type, is varying frequency rather than harmonics. If there is no frequency tracking available, DFT-type calculates lower magnitude than RMS-type estimator (see Figure 5). Current based short circuit protection elements that use DFT-type phasors to detect the presence of higher levels of fault currents will be affected. This issue can be solved by using the RMS-type estimator complemented with a peak sample detector to detect the maximum fault current level.

Undercurrent protection normally uses fundamental currents (DFT-type) to detect loss of load or undercurrent operating conditions of the motor. However, it is important to block the undercurrent protection during motor starting. The reason is: during motor starting, the current magnitude measurement (DFT-type) may remain below the undercurrent threshold for some duration of time until the current reaches the undercurrent threshold level. Duration of block time depends on the provision of tracking frequency.

Secondly, current based thermal protection can fail to accurately determine the heating replica when the motor is driven by the VFD. Motor thermal calculations must take into account the extra heat generated by the VFD waveform and reduction of the amount of heat removed in the VFD driven motors with shaft driven cooling fan, especially if the application is constant torque. Harmonics in the input signals cause additional copper and iron losses in the stator and rotor. Harmonic currents flow in the motor stator and rotor and therefore produce heat. Overheating results in decrease in the overall life of the motor. Since currents are measured at the motor side (load side) of the VFD, RMS currents must be used in the motor protection relay for the protection against short circuit and monitoring of the motor load and overload conditions. Relays that extract and operate on the fundamental frequency cannot produce an accurate representation of the thermal influence, a factor that worsens as the VFD topology becomes more rudimentary.

Distortion in motor input voltages are more significant than in currents and don’t appear sinusoidal. Moreover, phase voltages are measured at the bus side (source side) of the VFD, which don’t reflect the actual motor input voltages. Therefore, voltages measured at the bus side of the VFD are not suitable to be used for the motor voltage protection elements. Bus side voltages can only be used for power (kW or KVar) or power factor monitoring of the VFD input.

F. Measurement of false negative-sequence current

Detection of the unbalanced power supply is achieved by monitoring the sequence components of the motor currents. In three phase motors, negative-sequence reactance is 5 to 7 times smaller than positive-sequence reactance; therefore, even a small unbalance in the power supply will cause high negative sequence currents. Even though the VFD provides balanced power supply to the motor, false or spurious negative sequence current magnitudes up to 0.2pu can be found, as shown in Figure 8.

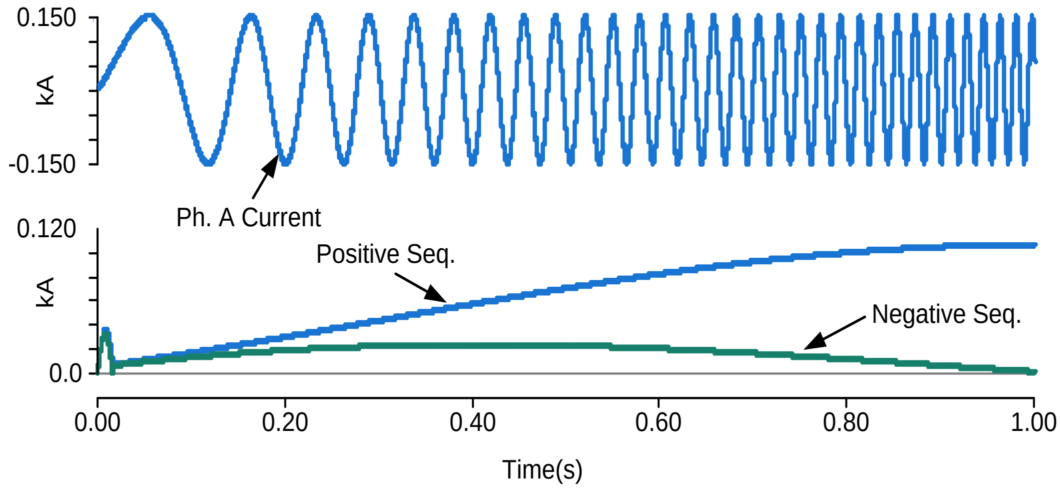


Figure 8 Positive- and negative-sequence components of motor starting current

As a result supply unbalance protection must be blocked during the motor starting, if there is no frequency tracking.

Secondly, the thermal model (see Appendix A) normally takes into account negative sequence currents to accurately estimate the additional heating because of the unbalanced power supply (or unbalanced phase currents) that can cause additional rotor heating. The thermal model must be made secure against false negative sequence current measurements. Figure 9 shows the estimation of the thermal capacity used (TCU) using the biased-RMS current and average-RMS current. Biased-RMS current is the current that uses both positive and negative sequence current in order to take into account additional heating due to unbalanced power supply (see Appendix A). Average-RMS current is the average of three RMS currents (see Appendix A). Figure 9 shows that the thermal model that uses the biased RMS current estimates significantly higher thermal capacity used (Biased TCU%) due to false negative sequence current than the thermal model using only using the positive sequence currents (TCU%). Therefore, it is important to block the use of negative sequence biased estimation of the motor heating during varying frequency start until proper tracking of frequency is provided.

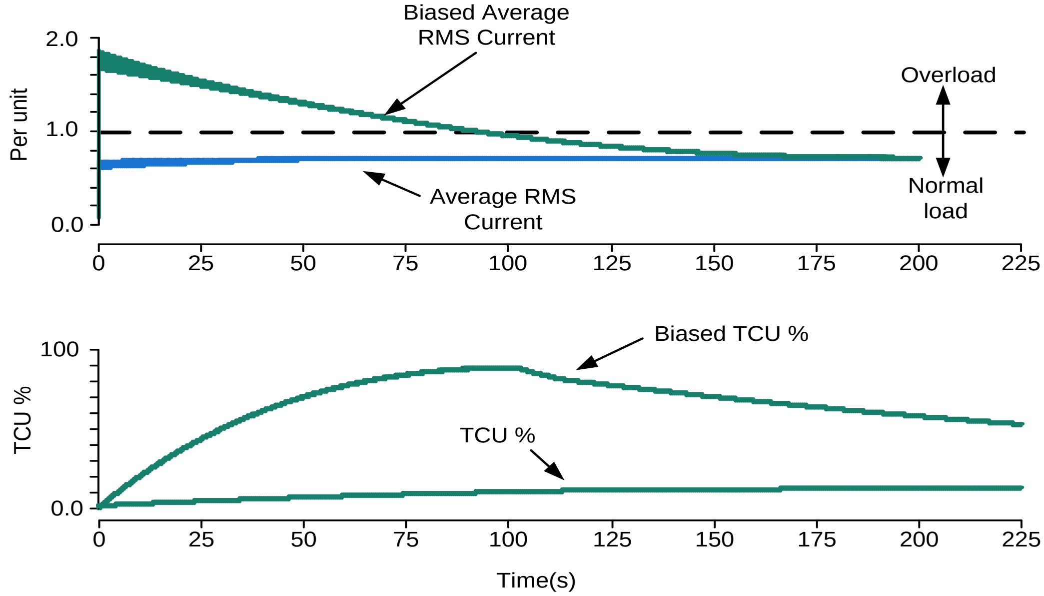


Figure 9 Positive- and negative-sequence components of motor starting current

G. Variation in the shaft driven fan cooling

In any motor that is not forced cooled, the cooling fan is attached to the motor shaft and cooling of the motor varies with frequency or speed of motor. Simple current based thermal protection can fail to calculate the reduced cooling that results from the varying fan speed since the given motor manufacturer damage curves are based on full speed operation only. Therefore, variation in the fan cooling must be taken into account in order to do best estimation of the motor heating.

Motor temperature measurement devices can help to correct the thermal capacity used or motor heating during motor starting. The common examples of the temperature measuring devices are transducers, thermistors, thermocouples and resistor temperature detectors (RTDs). Figure 10 shows thermal capacity used (TCU%) as a function of the stator temperature for a insulation class F motor (maximum allowable temperature of 155° C defined by NEMA MG1[6]) having ambient temperature of 40°C and normal running stator temperature of 130° C (80° C rise +ambient temperature). Therefore, to properly use the temperature or RTD biasing [5], it is important to know the ambient temperature, normal running motor temperature, maximum allowable temperature and hot/cold stall ratio. This information can be obtained from the motor data sheets.

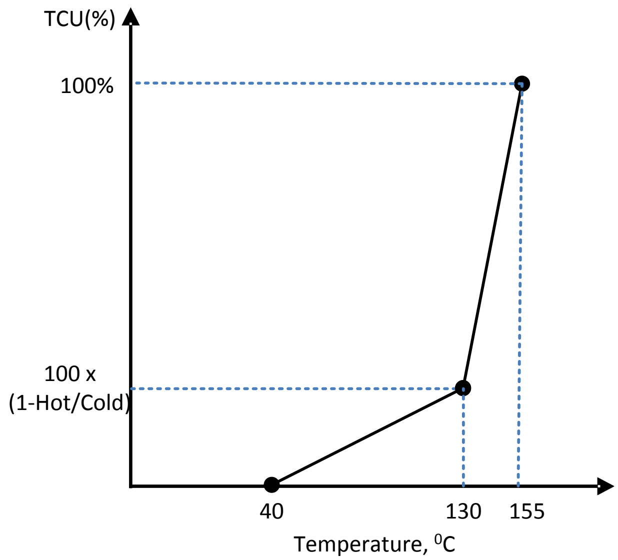


Figure 10 RTD Biasing [5]

The RTD biasing feature takes the maximum of the stator temperatures measured by the RTDs and calculates TCU using the following relations:

TCU calculation for normal running load:

$$TCU_{normal} = (1 - H/C) \times 100\% \quad (1)$$

TCU calculation when the stator temperature is between ambient and normal running temperatures:

$$TCU_{RTD} = \left(\frac{T_{actual} - T_{ambient}}{T_{normal} - T_{ambient}} \right) \times TCU_{normal} \quad (2)$$

TCU calculation when the stator temperature is between normal and maximum allowable temperature:

$$TCU_{RTD} = \left(\frac{T_{actual} - T_{normal}}{T_{\max} - T_{normal}} \right) \times \left(100 - TCU_{normal}\right) + TCU_{normal} \quad (3)$$

This solution helps to calculate the actual thermal capacity available for all motor conditions.

III. Protection Challenges Associate with Cyclic or Reciprocating Load Motor Applications

A. Variation in the current magnitude - Cyclic or reciprocating load

As mentioned earlier, current based thermal protection in most of today's multifunctional motor protection relays determines motor heating and cooling by monitoring motor input current. An overload condition is determined if current is above the rated full load current (FLA) allowing for the service factor of the motor. In order to determine proper heating of the motor, current-based thermal modelling is made adaptive to the motor status (stopped, starting, running with normal load, and running with overload) by monitoring load current. In cyclic load applications, load varies between light and above allowable load level during a load cycle. The motor starts heating up when it is running overload and cools down during the light load periods. Therefore, the thermal model must be intelligent and fast enough to properly reflect the motor heating and cooling throughout the load cycle.

1. Large Duty - Cycle Load

Figure 11(a) demonstrates the average of the three RMS phase currents (see Appendix A) of a large duty-cycle load of 60 seconds per duty-cycle and duty-cycle-ratio (D) of 100%.

Duty-cycle-ratio is defined as:

$$D = \frac{t_{low} \cdot I_{low}^2 + t_{high} \cdot I_{high}^2}{t_{low} + t_{high}} x100\%$$

I_{low} = motor current during the low cycle

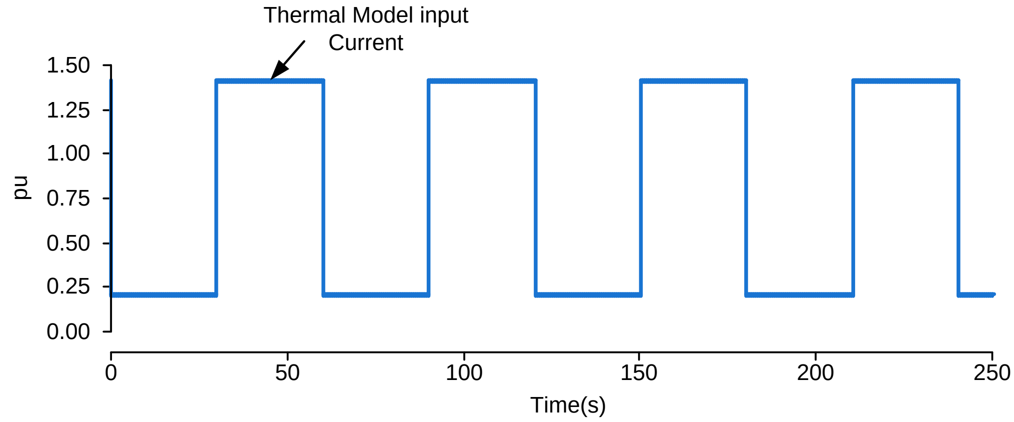
I_{high} = motor current during the high cycle

t_{low} = time interval for the low cycle

t_{high} = time interval for the high cycle

Based on duty-cycle-ratio, load can be categorized as balanced duty (D=100%), heavy duty (D>100%) and light duty (D<100%).

Figure 11 (b) demonstrates the performance of the thermal model for a balanced (D=100%) and heavy duty (D=110%) load. For the case when motor is running balanced duty cyclic load, the thermal model accurately reflects motor heating and cooling throughout the duty-cycle period such that thermal capacity used (TCU) remains below 100%. As expected, the thermal model operates for the case when the motor is running heavy duty cyclic loading. The operation of the thermal model for heavy duty cyclic loading confirms proper working of the thermal protection.



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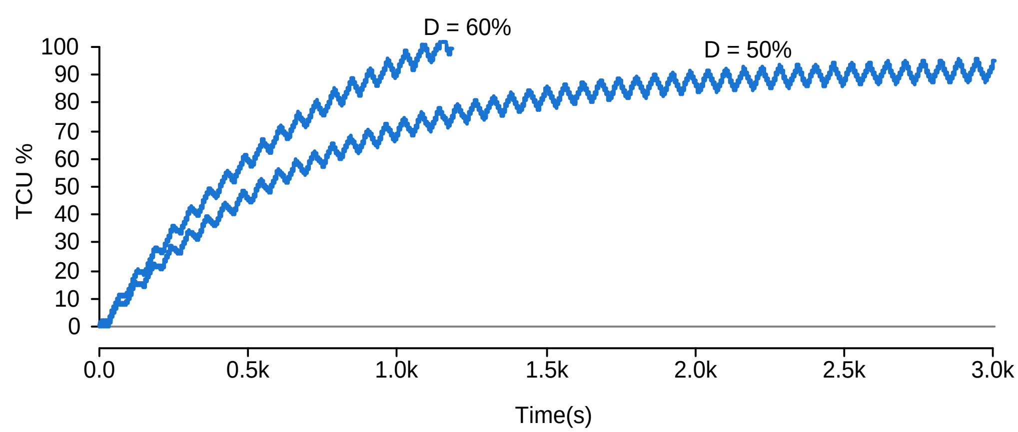

b)

Figure 11 Performance of current-based thermal model for large duty cycle of 50% and 60% duty ratios

2. Small Duty-Cycle Load

For the motor applications where the load cycle has a small duty-cycle length (≤32 power cycles) but is heavy duty in nature (D>100%) and the motor engineer decides to run the motor close to overload conditions, the thermal model can be complemented with an additional Averaging Load Filtering (ALF) feature. The ALF feature helps to determine the average of the cyclic overload current over the duty-cycle using the running average technique. Figure 12 illustrates the case of running heavy duty load (D=116%) with a 32 power frequency cycles per duty-cycle length. It can be seen in Figure 12 (c) that by using the ALF feature, input current to the thermal model is now the average of the cyclic current over duty cycle length of 32 cycles. Figure 12 (d) compares TCU with and without the ALF feature for the same cyclic load. Without the ALF feature TCU reaches to 100% and therefore operates the thermal model, whereas if ALF feature is used the thermal capacity remains below 100%.

However, the thermal model must operate to protect the motor from overheating for the cyclic load application with heavy duty-cycle-ratio, which can overheat the motor. Therefore, it is important to limit the ALF feature for the limited duty cycle period of maximum 32 cycles.

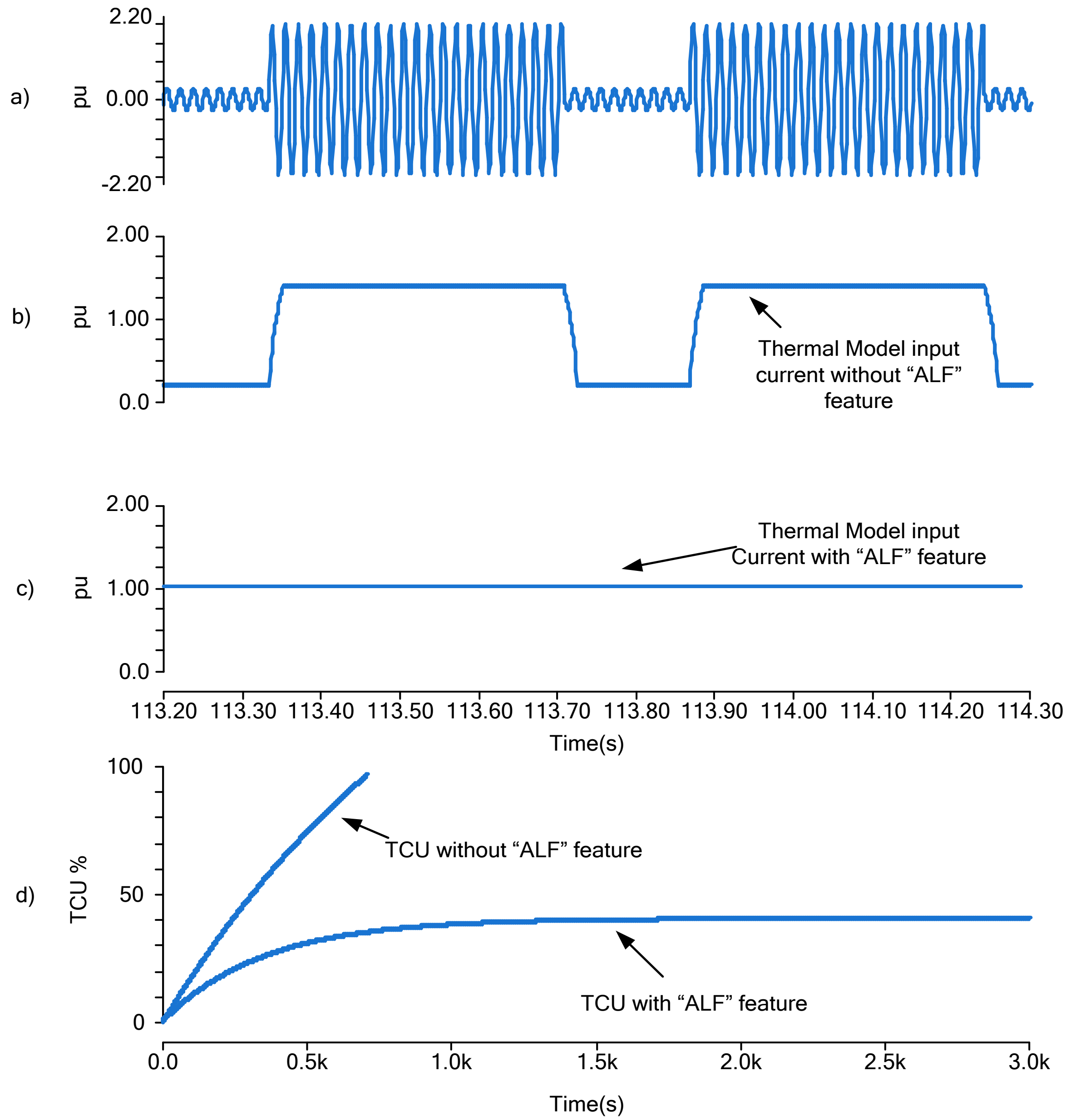

Figure 12 Performance of current-based thermal model for small duty cycle load of 50% and 70% duty ratios

B. Other considerations when running cyclic load

Trip or alarm pickup for the short circuit protection such as overcurrent must be set higher than the maximum overload current in the duty cycle period of the cyclic load. Cyclic loading can jeopardize the security of the protection functions such as under current and ground fault protection during the light load condition. Therefore, it is important to set the undercurrent or ground fault protection below the minimum of the cyclic load current.

In addition to the thermal model, cyclic load averaging technique can also be used to determine the inputs for the protection and monitoring elements like acceleration time, current unbalance, mechanical jam, overload, reduced Voltage Start(soft start), undercurrent, power factor, three-phase power(kW, kVar) and under power etc. However, ALF may increase the trip or alarm time for the duration equal to cyclic load length.

IV. Conclusions

This paper presented various challenges and solutions associated with multifunctional motor protection relays when applied to VFDs and cyclic load applications.

Performance of the motor relay installed on the load-side of the VFD is affected if proper consideration is not given under varying or off-nominal frequency motor operation. Varying or off-nominal frequency mainly results in the incorrect estimation of the current phasors using fixed-sampling frequency RMS- and DFT-type estimators. Proper tracking of frequency in addition to features like starting-frequency adjustment and averaging load (AL) helps to solve the varying frequency issues. For VFD applications, thermal protection must take into account additional motor heating due to current harmonics content and varying fan cooling. Using RMS currents and the RTD biasing feature can help to estimate the additional heating in the motor due to harmonics and varying fan cooling, respectively.

For cyclic load motor applications, the thermal model must properly reflect motor heating and cooling as load changes between the maximum and minimum load levels during cyclic load period. For balanced and light duty cycle loads, thermal capacity must remain below the threshold. However, the thermal model must protect the motor from overheating when running heavy duty cyclic loading, which can overheat the motor. In small duty-cycle applications, if the motor is required to run heavy duty load (duty-cycle-ratio > 100%), an additional ALF (averaging load filter) feature in the thermal model can help to keep the motor running. However, the thermal model must protect the motor from overheating when running large duty-cycle load of duty-cycle-ratio > 100%.

V. Appendix A

A current based thermal model determines heating and cooling of the motor windings using the following method based on current level criteria.

Heating: If input current to the thermal model is equal or greater than the overload pickup level then thermal capacity is determined using the following relation:

$$TC_{used(t)} = TC_{used(t-1)} + \frac{t}{t_{trip}} \text{x} 100\%$$

where:

t_{trip}	represents the time coordinate on the time-current motor thermal limit curve, corresponding to the equivalent motor current detected within any power cycle period of motor overload.
t	calculation time step

Cooling: If input current to the thermal model is less than the overload pickup level then thermal capacity is determined using the following relation:

$$TCU = (TCU_{start} - TCU_{end})(e^{-t/\tau_{cool}}) + TCU_{end}$$

where:

TCU_{start} = TCU value caused by overload condition.
TCU_{end}= TCU value dictated by the hot/cold curve ratio when the motor is running. This value is 0 when the motor is stopped).

$$TCU_{end} = \left(\frac{I_{eq}}{OL \times FLA}\right)\left(1 - \frac{hot}{cold}\right) \times 100\%$$

τ_{cool}= Cool Time Constant Running.
I_{eq} = average of the three RMS currents-thermal model input current
OL = Overload factor specified by the Motor Overload Factor setting.
FLA = Motor rated current specified by the Motor Full Load Amps setting.
hot / cold = hot/cold curve ratio

Thermal model input current is the equivalent current using the following equation:

$$I_{eq} = \sqrt{I^2 avg. \left(1 + K. \left(\frac{I\_2}{I\_1}\right)^2\right)},$$

where:
Ieq = thermal model biased motor load current
Iavg = average of three RMS currents

$$I_{avg} = \frac{1}{3}\left[I_{A(RMS)} + I_{B(RMS)} + I_{C(RMS)}\right]$$

I_1 = positive sequence current
I_2 = negative sequence current

K = constant defined by NEMA de-rating curve [6]

VI. References

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VII. Biography

Umar Khan received his B.E. degree from Ghulam Ishaq Khan Institute (GIKI), Pakistan, in 2005, and M.Sc. degree from Wroclaw University of Technology, Wroclaw, Poland, in 2009, and Ph.D. degree in electrical power system from University of Western Ontario, Canada, in 2013. Since 2013, he is working with GE Digital Energy, Canada. His current areas of interest are power system protection, control and monitoring.

Tom Ernst is a P&C Technical Application Engineer for the North American Commercial team. He has been with GE since 2011 supporting the Grid Automation Protection and Control Portfolio. Prior to joining GE, Tom has been with Minnesota Power as a Supervising Engineer, Delta Engineering International as a Manager of Electrical Engineering, HDR Engineering as a Manager of Electrical Engineering and Northern States Power as a Supervising Engineer. He received his Bachelor of Science in Electrical Engineering from the University of Minnesota in 1978 and his Master of Science in Power Systems from Michigan Technological University in 2008. He is a registered Professional Engineer in the State of Minnesota.

Stanley J. Eiskant was born in Sullivan MO, March 28, 1958. He received his BSEE from University of Missouri-Columbia in 1980. He joined Toshiba International Corporation in 1981 as an Engineer, He has had varied assignments in applications of motors, drives, and motor/feeder control systems. Mr. Eiskant is currently senior application engineer for Medium Voltage Switchgear & Controlgear.