Performance of CTs and Relays at Low Frequencies

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Abstract

When generators or motors are started via variable frequency drive (VFD), the initial frequency is very low, on the order of few hertz, and can be low for a considerable amount of time or even permanently. It is not well recognized in the industry about consequences of the low frequency for the currents transformers (CTs) performance and how this affects the protection performance as well. First of all, CTs are designed to operate at the nominal system frequency, at lower frequency CTs will saturate at much lower currents, this can happen even at CT nominal current. Secondly, there are limits of the system frequency measurements in the protective relays, which will impact the correct current magnitude estimation and therefore accuracy of the protection. And lastly, protective relays need full power cycle to measure current and power cycle will be considerably longer at lower frequency, therefore affecting fault clearance time.

This paper will educate engineers on how to take into account CTs and protective relay's performance at lower frequencies to ensure adequate protection. It will also explore other solutions to address impact of the low frequency on the CTs and protection.

I. Introduction

Variable frequency drives (VFDs) or adjustable speed drives (ASDs) have been widely used in industry to achieve the desired mechanical output of the motor by controlling voltage and frequency of the motor supply. Large electric motors, when started directly from the main power supply, draw excessive starting current resulting in the voltage dips and overheating of the rotor part. In such applications, VFD is used as a soft-starter to prevent heating due to excessive large starting current and voltage dips. By controlling the supply frequency while maintaining the flux to its rated value (V/Hz constant), desired acceleration and rotational speed are achieved using the VFD.

When VFD used as a soft-starter, it starts the motor from low speed (frequency) and accelerates to the desired speed level (off-nominal or rated). 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 60 Hz in a range from 1 sec to 3000 sec in MV drives and 1 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 protection built-in the drive or motor relay may trip. The speed range of VFD fed motor is normally defined as a part of its rating [1]. Figure 1 illustrates the current and frequency of the motor driven by the VFD.

This paper is reviewing the challenges associated with the performance of CTs and multifunctional relays when applied to low frequency applications like such as VFD driven motor applications. Current transformers are designed to operate at system frequency 50Hz or 60Hz. Over a frequency range near the nominal operating frequency of CT, the current transformer accurately replicates the primary currents to the secondary side of the CT. However, magnetizing inductance is frequency dependent, as frequency decreases; the magnetizing coil impedance also decreases resulting in the increase in the flux density and hence saturation of the core. Consequently, reliable operation of the motor protection relay can be jeopardized due to CT errors as a result of the de-rated CT excitation characteristic at low frequency currents. This paper intended to provide insight into CT performance at low frequencies so that improved performance of the relay can be achieved.

Section II reviews the basic magnetics of the current transformer. It reviews and explains (1) basic working principle of the CT, (2) fixed frequency analysis, (3) frequency dependent CT model and (4) excitation characteristic dependency on frequency.

Section III analyzes the impact of low frequency currents on performance of the CT. For this purpose, frequency dependent current transformer model is used as well as real CT. Theoretical model of Section II is used to produce the frequency dependent CT excitation characteristic. In order to verify the frequency dependent model, performance of the CT at low frequency currents is tested using the real CT in the laboratory. This helps us to validate and verify the relevance of the theoretical CT model with real CT. This section also explains: phasor measurement errors in the motor protection due to varying frequency challenges and their solutions associated with motor protection when applied to low frequency motor operation.

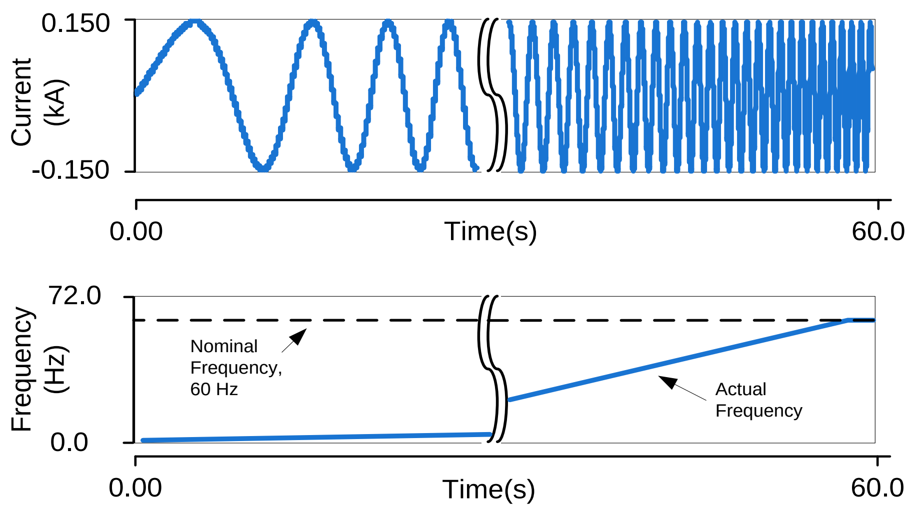


Figure 1 Example of motor starting current and change in frequency

II. Magnetics of the Current Transformer

Basic principles related to current transformers are reviewed first to develop the frequency dependent CT model for the analysis purposes.

A. Excitation characteristics

First, it is important to discuss the CT excitation characteristic and its key parameters prior to establish the current transformer saturation model. Figure 2 shows CT excitation characteristic. This curve illustrates the behavior of magnetic flux density, *B* (units Tesla) as a function of magnetic field, *H* (units Ampere-turns), also known as *B* vs H curve. Converting the magnetic analogies to electrical, *B* vs *H* curve can be represented as a secondary side excitation voltage (V_e) and secondary side excitation currents (I_e), also known as V_e vs I_e curve.

As illustrated by the Figure 2, the curve shows two regions of CT operation, linear and non-linear. In the linear region, slope of the curve is greater than 1 and slope is less than 1 in the non-linear region. Three points are normally required to define the curve: knee point *(V_K, I_K),* normal operating point below the knee point (V_n, I_n) and above the point (V_S, I_S). Excitation voltage, V_S is the voltage required to develop 10A excitation current I_S. These points can be obtained from the excitation curve of the current transformer.

In the linear region, CT operates as an ideal current transformer, transforming primary to secondary as per the turn ratio. In the non-linear region, as the excitation or magnetizing current increases, CT enters into non-linear part of the characteristic, resulting in saturation of the transformer. When the CT saturates, it requires high excitation current in order to magnetize the core. More of the primary current is now used to magnetize the CT than to run the load. Consequently, secondary of the CT becomes distorted.

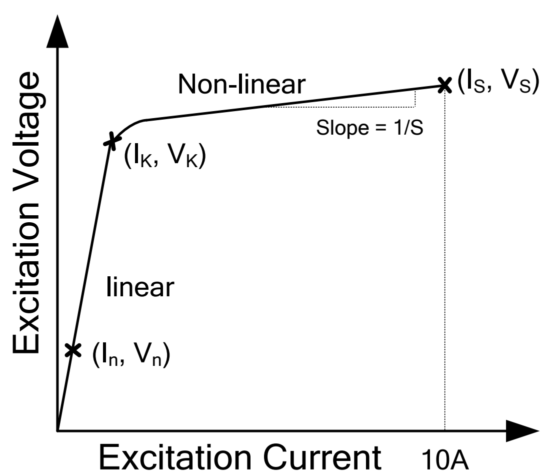


Figure 2 Current transformer excitation characteristics

B. Equivalent circuit of the current transformer

For protection studies, a simplified circuit diagram as shown in the Figure 3. The magnetizing branch is located on the secondary side and is represented with a non-linear inductor L_{mag}.

Using circuit of Figure 3, the equivalent circuit equation can be derived as below:

$$v_e(t) = i_{load}(t)R + L_{sec}\frac{di_{load}(t)}{dt} \qquad (1)$$

where $R = R_{sec} + R_{load}$

We can write the currents distribution equation per Kirchhoff's Current Law in the CT secondary circuit as follows:

$$i_{sec}(t) = i_e(t) + i_{load}(t) \qquad (2)$$

Non-linear nature of the excitation current as a function of flux linkage or excitation voltage is developed based on the saturation model presented in [2]. Various approaches are available in the literature to establish the excitation characteristic (*V-I* or ϕ-*I*), CT saturation model in this paper is based on [2]. Reference [2] presents a simplified saturation model of the CT, which has been validated with the real current transformers in the laboratory tests.

According to the Faraday's law, change in flux must change the voltage (v_e) across the magnetizing branch. The relation between the voltage and flux can be written as:

$$v_e(t) = N\frac{d\Phi(t)}{dt} \qquad (3)$$

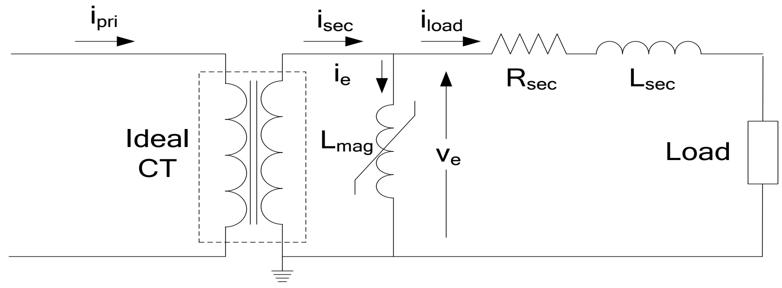
For a sinusoidal voltage, flux is also sinusoidal

$$\Phi = \Phi_{max}\ sin(2\pi ft) \qquad (4)$$

Replacing Φ in (3) with (4):

$$v_e(t) = N\frac{d\Phi_{max}\ sin(2\pi ft)}{dt}$$
$$v_e(t) = 2\pi f\ x\ N\ x\ \Phi_{max} cos(2\pi ft) \qquad (5)$$

Using (5), Φ_{max} can be written as



R_{sec}: secondary winding resistance
i_{pri}: primary winding current
L_{sec}: secondary winding inductance
i_{sec}: secondary winding current
L_{mag}: magnetizing inductance
i_e: magnetizing branch current
Load: relay load
i_{load}: secondary winding current
v_{mag}: voltage across magnetizing branch

Figure 3 Equivalent circuit diagram of current transformer

$$\Phi_{max} = V_{e\,max} \frac{1}{2\pi f \; x\, N} \tag{6}$$

where, f is the signal input frequency, N is the turns ratio and $V_{e\,max}$ equals $\sqrt{2}V_e$

C. Laboratory test bench

Real typical MV motor current transformer having excitation curve shown in the Figure 4 and CT data in the Table 1, is used to validate the frequency dependent model of Section IID. V-I curve is measured for the nominal (60 Hz) and off-nominal (40, 20, 10, 5 Hz) motor operating frequencies. Secondary excitation test method [3] is used to establish the frequency dependent V-I curve of the current transformer. With the primary circuit open, varying voltage is applied at the CT secondary terminals and the current in the secondary winding is measured at each level of applied voltage. Figure 5 shows the excitation test circuit and laboratory test bench used for the *V-I* measurements.

Table 1: CT data

Required Data	
Relay Class	*C20*
Turn ratio	*100:5*
Frequency	*60 Hz*
Secondary winding resistance (R)	*0.062 ohms*
Voltage (Vs) at 10A excitation current	*36.7 V*
Slope (S)	*2.5%*
Knee point voltage (V_{knee})	*26 V*
Saturation Voltage (V_{Sat})	*36.5 V*

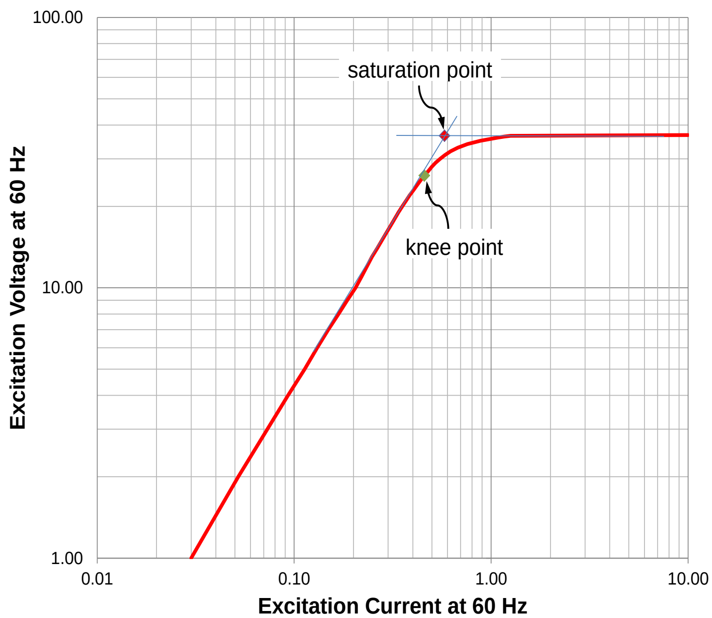
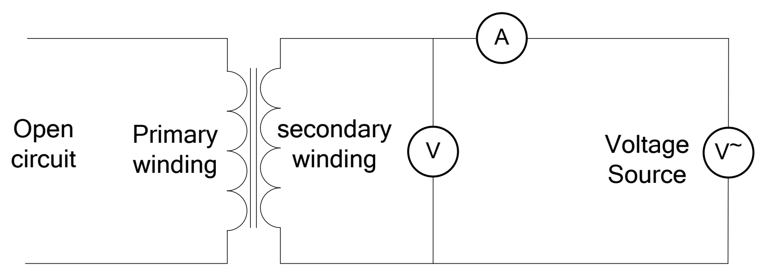
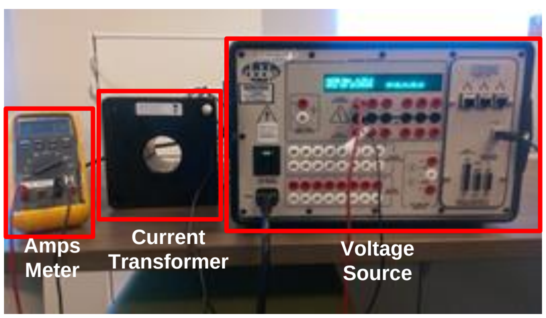


Figure 4 Measured excitation characteristic of Class C20 current transformer with turn ratio 100:5



a)



b)

Figure 5 (a) Excitation test circuit, (b) excitation test bench

D. *Development of the frequency dependent CT model*

In order to study and analyze the behavior of CT at low frequency currents, it is important to model the frequency dependent excitation characteristic (*V-I* or ϕ-*I*) of the magnetizing branch. As we know, the core of the CT is designed for a uniform flux density (*B*) at given volts per turn at constant frequency. Such that voltage (V_e) can be defined as a function of flux density (B_{max}), cross-sectional area of the core (A_{core}) and frequency:

$$V_e = 4.44f \; x \, N \, x \, B_{max} \; x \, A_{core} \Rightarrow B_{max} = \frac{V_e}{4.44f \; x \, N \, x \, A_{core}} \qquad (7)$$

Equation (7) suggests that when magnetic circuit is excited by the sinusoidal voltage, the ratio between the voltage and frequency must be kept constant in order to establish a uniform flux density. Over- or under excitation of the magnetic core will happen, if frequency is changed above/below the allowable limit without changing the voltage. Magnetizing inductance is frequency dependent, as frequency decreases; the magnetizing coil impedance also decreases resulting in the increase of the flux density and hence the saturation of the core.

Current transformer having excitation curve shown in Figure 4 and CT data in Table 1, is used as an example for the analysis purposes.

Based on (7), flux density must be kept constant in order to operate the current transformer in the allowable excitation limits. If CT is operated at low frequency then voltage must be reduced such that flux density remains uniform. Using this fact, saturation characteristic of the CT can be estimated at the low frequencies.

For example: using the data of Table 1 in equation (7), peak flux linkage can be calculated as:

$$\Phi_{max} = \sqrt{2} V_s \frac{1}{2\pi f \; x \, N} = 6.87x10^{-3} \; Wb - turns$$

When motor-fed-through-VFD is running at 20Hz frequency, peak flux density of $6.87\text{x}10^{-3}$ *Wb-turns* will be developed when peak excitation voltage V_S $(=V_{e\,max})$ is:

Table 2: De-rated CT data

	40Hz	*20Hz*	*10Hz*	*5Hz*
Relay Class	*C20*			
Turn ratio (N)	*100:5*			
Secondary winding resistance (R)	*0.062 ohms*			
Voltage (Vs) at 10A excitation current	*24.4V*	*12.3V*	*6.1V*	*3.05V*
Knee point Voltage (V_{knee})	*17.33V*	*8.66V*	*4.33V*	*2.16V*
Saturation Voltage (V_{Sat})	*24.33V*	*12.16V*	*6.08V*	*3.04V*

$$V_s = \frac{2\pi f \; x \, N \, x \, \Phi_{max}}{\sqrt{2}} = 12.22V$$

Figure 6 shows the V-I curve measured using the laboratory test bench (shown in Figure 5). It is evident from the Figure 6 that when the frequency is 20Hz, voltage required to produce the same flux density is now reduce by the factor below:

$$V(@F) = V(@F_n)\; x\; \frac{F}{F_n} \tag{8}$$

where F_n is the nominal frequency and F is the actual motor input frequency.

Hence when the frequency is 20 Hz the voltage must be equal to 12.22V to develop the required flux density. Table 2 shows de-rated CT data for operating frequency 40, 20, 10 and 5 Hz.

III. Simulation Results and Impact to Protection Relays

Proper operation of the relay is largely influenced by the CT performance. If properly selected, under normal steady state conditions, a CT operates in its linear part

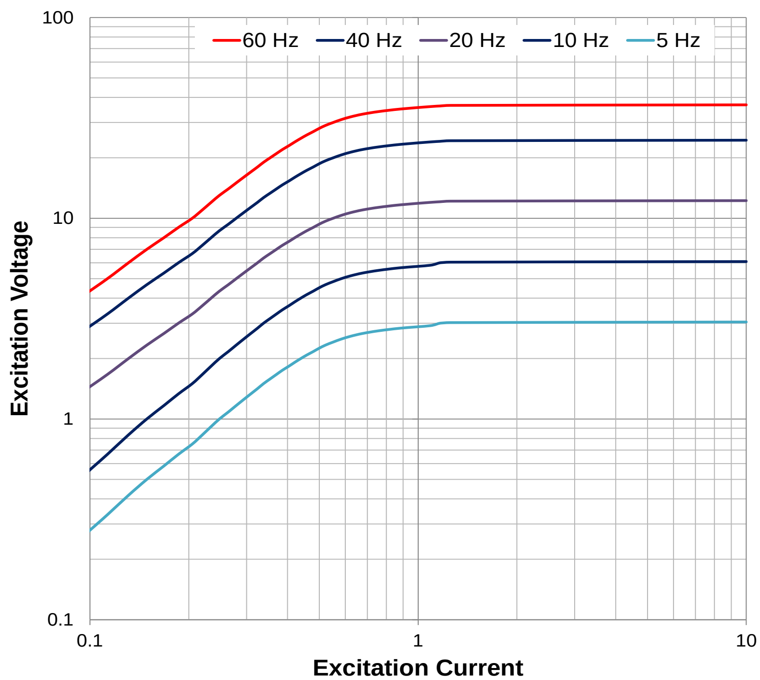


Figure 6 Measured V-I characteristic for 60, 40, 20, 10 and 5 Hz motor operating frequencies

of the excitation curve (Figure 2). However, short circuit current can be steady state (purely AC) or transient (DC component in the fault current) in nature. For the short circuit analysis, in addition to off-nominal low frequency, the other factors that influence the CT performance are effective burden on CT terminals, magnitude and duration of the DC component in the fault current and residual flux. In VFD motor applications, low frequency operation influences the CT performance and hence operation of the protection relays.

Frequency dependent saturation model established in section II and laboratory measurements of V-I current are used to model the CT for simulation purposes. Important parameters considered for analysis purposes are:

- Effective burden on CT terminals: 0.37 ohms, which includes Relay 0.008 ohms [4], CT lead 0.3 ohms (AWG 8 and loop length of 145 meters) and CT winding resistance 0.062 ohms.
- X/R ratio of 15 for a motor ratings of 440 HP, 2.3 kV, 60 Hz and service factor (SF) of 1.15 and power factor of 0.87 at 100% load.

Performance of the CT during all the above mentioned motor steady state operating conditions and short circuit conditions are further analyzed and discussed as follows.

A. Motor load conditions

Maximum allowable motor loading condition is defined by the parameter *Service Factor (SF)* provided in the motor data sheet. In order to load a motor in its thermal limits, maximum loading is limited by the multiple of SF. For example: for the motor under consideration having rated HP of 440 (full load amps, FLA, 82 A) and SF=1.15, the maximum allowable loading of the motor is limited to 440 HP x 1.15 (506 HP or 94A).

At the maximum allowable loading condition, motor draws 94A amps (FLA x SF), current transformer operates in the linear region for all input frequency levels.
Linear operating range of the current transformer, under test, can be calculated using information available in Table 2. Up to this range, excitation current is negligible (0.6A when CT is operating at nominal frequency).

Note: Motor under normal running load conditions with very low operating frequencies, as shown in Table 2, are not the practical cases. Authors used these values for the example purposes. However, under short circuit or non-steady state conditions when VFD driven motor is in the starting mode of operation, consideration of the low frequencies is important when analyzing CT and relay performances.

For example, when input frequency is 60Hz, the maximum primary current level (reference level) above which CT enters into saturation zone resulting into distorted secondary current can be calculated as:

$$I_{Sat} = \frac{Saturation\,Voltage}{Effective\ Burden\,on\,CT\ terminals} x Turn\ Ratio$$
$$= \frac{36.5}{0.37} x\,20 = 1973A$$

Similarly, reference level for off-nominal low frequencies is calculated as shown in the Table 3. It can be seen that maximum allowable motor loading is well below the reference level and therefore, excitation current is negligibly small and lies is in the linear part of the excitation curve. It can also be observed that reference level decreases as the operating frequency decreases.

B. Locked-rotor condition

During locked-rotor condition, the motor current may reach or exceed seven times the rated full load current [5].. Rotor condition may not be a concern in motor applications when motor is driven by a VFD due to the reason that VFD confines motor operation to its torque speed characteristic during motor starting and running conditions [6].

C. Short circuit condition

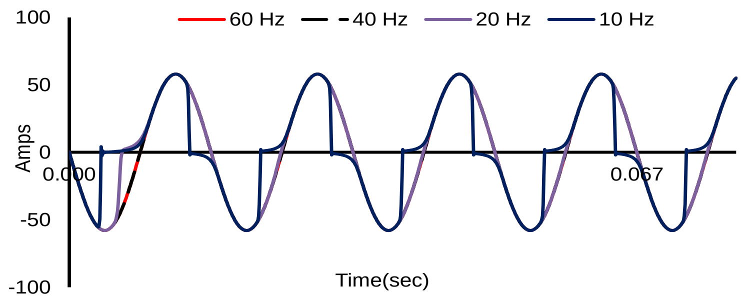
Current during short circuit can be significantly higher than the rated full load amps. As mentioned earlier, short circuit can be steady state or transient in nature. We will analyze both states in detail.

1) Steady state short circuit

Steady state short circuit current is purely AC in nature without DC component. Therefore, current level above the reference level I_{Sat}, as determined in Table 3, will result in saturation of the current transformer.

Figure 7illustrates the sinusoidal waveforms and magnitudes of the secondary currents at different operating frequencies. Short circuit is purely AC in nature with magnitude of 820A RMS on CT primary. As can be seen in Figure 8, the short circuit current (1000A) is below the reference level 1973A and 1315A for 60 Hz and 40 Hz, respectively, therefore, secondary of the CT is undistorted. However, short circuit current (1000A) is above the reference level 657 and 329A, therefore, CT, operating at 20 and 10 Hz, has distored secondary current, which is significantly distorted at 10Hz.

In VFD motor application, in order to avoid CT saturation in steady state short ciruit conditions, lowest operating frequency must be conisdiered when specifying CT. Assuming lowest operating frequency is 20 Hz, CT saturation voltage level must satisfy the following relation to avoid saturation when operating at 20 Hz:



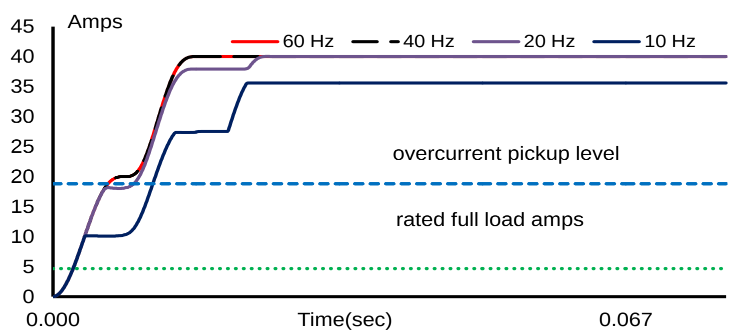


Figure 7: Sinusoidal and RMS measurement of the steady state short circuit secondary current

$$V_{Sat}(@60hz) > \frac{I}{Turn\,Ratio} \, x \, Z_{eff} \, x \, \frac{F_n}{F_m}$$

$$V_{Sat}(@60hz) > \frac{820A}{20} \, x \, 0.37\Omega \, x \, \frac{60Hz}{20Hz}$$

$$V_{Sat}(@60hz) > 45V$$

where F_n is the nominal frequency and F_m is the lowest operating frequency in the VFD motor application.

2) Transient short circuit

Transient or asymmetrical current contains decaying DC component in addition to AC component. Magnitude and duration of the decaying DC component depends on the system X/R ratio and fault inception point referenced to the voltage signal (known as

Table 3: Maximum allowable burden current

	40Hz	*20Hz*	*10Hz*	*5Hz*
Effective burden at CT terminals	*0.37 ohms*			
Saturation Voltage (V_{Sat})	*24.33V*	*12.16V*	*6.08V*	*3.04V*
Saturation Current (I_{Sat})	*1315A*	*657A*	*329A*	*164A*

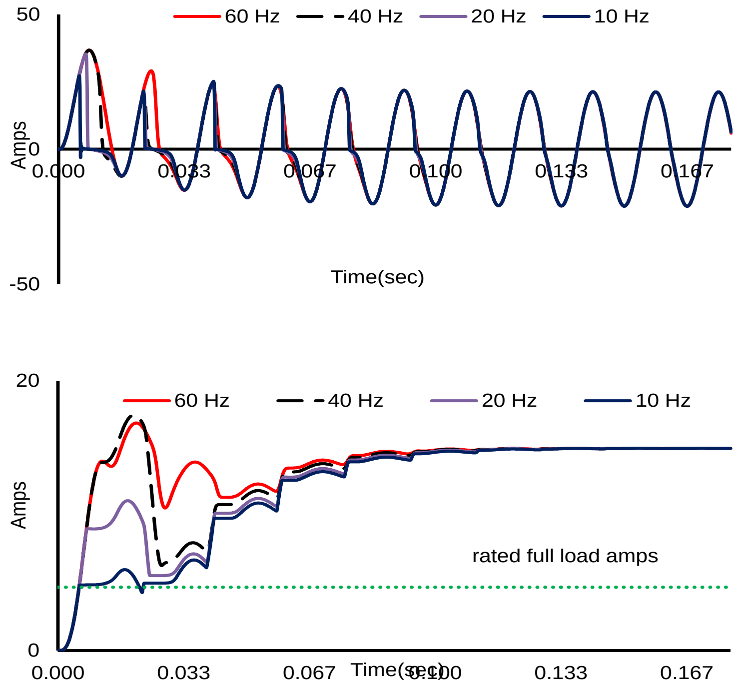


Figure 8: Sinusoidal and RMS measurement of the steady state short circuit secondary current

Point-on-Wave POW). Figure 8 illustrates the signatures of secondary currents when current transformer is operating at 60, 40, 20 and 10 Hz while the short circuit current is transient in nature with AC magnitude of 300A RMS (3 pu at base 100A) at CT primary. It can be observed that DC component magnifies the total asymmetrical current to more than 800 A. resulting in saturation of the current transformer for all frequency levels.

In VFD motor application, in order to avoid CT saturation in transient short ciruit conditions, CT saturation voltage level must satisfy the following relation [7] to avoid saturation when operating at 20 Hz:

$$V_{Sat}(@60hz) > \frac{I_F}{Turn\,Ratio} x\, Z_{eff}\, x \left(1 + \frac{X}{R}\right) x\, \frac{F_n}{F_m}$$

$$V_{Sat}(@60hz) > \frac{300A}{20} x\, 0.37\Omega\, x\, (1+15)\, x\, \frac{60Hz}{20Hz}$$

$$V_{Sat}(@60hz) > 265V$$

where F_n is the nominal frequency and F_m is the lowest operating frequency in the VFD motor application.

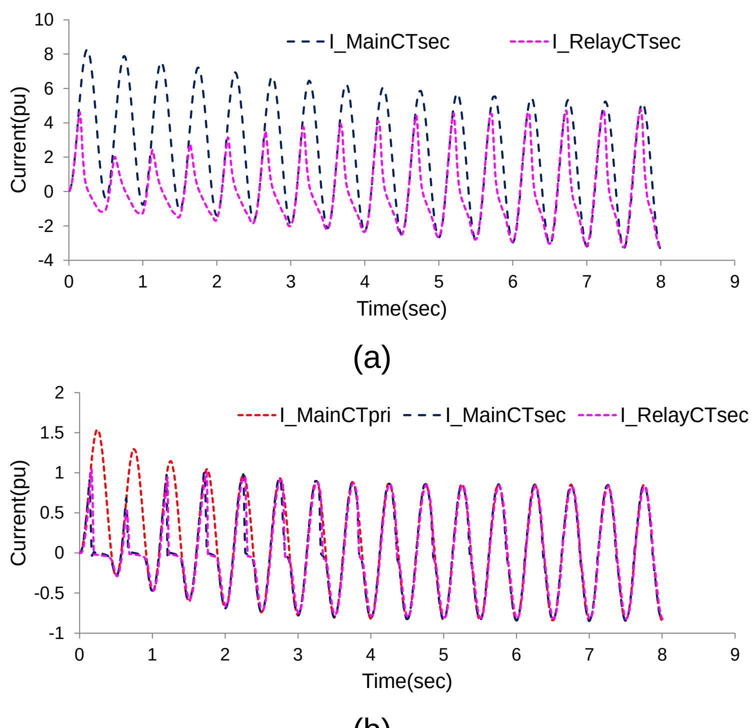
D. Impact on protection relays

1) The above analysis shows that a main CT is more likely to saturate as the frequency decreases from the nominal frequency, which could impact the performance of the protection functions. Magnetics in the relay used as current transducers are also current transformers. Therefore, performance of relay current transducers at low operating frequencies is important to analyze before addressing the impact of low operating frequency at relay protection functions.

For investigation purposes, relay CT has been tested at as low as 2Hz input signal when (1) the main CT is a high quality CT having high V_{knee} such that it doesn't saturate at low operating frequencies (2) the main CT is a low quality CT having low V_{knee} such that it saturates at the low operating frequencies.

It can be seen in Figure 9 (a) that when input (I_MainCTsec) to the relay is undistorted, secondary of the relay CT *(I_RelayCTsec)* saturates and doesn't reflect the terminal currents when operating at 2 Hz. Degree of saturation decreases as the operating frequency increases.

On the contrary, when input (I_MainCTsec) to the relay is highly distorted,



(a) (b)

Figure 9 Testing of the internal current transformer of the relay when (a) input signal is transient and undistorted, (b) input signal is transient and distorted

I_RelayCTsec properly reflects the I_MainCTsec, which means that there is no impact on the relay CT due to the fact that input to the relay is saturated and magnitude is significantly small as compared to the undistorted current *(I_MainCTpri),* as shown in Figure 9(b).

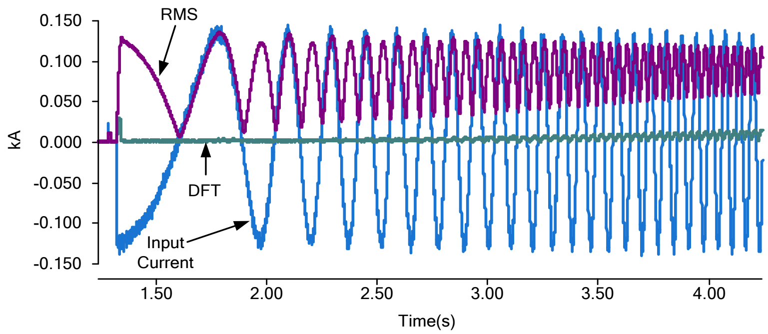
2) Multifunctional protection relays experience various challenges and issues when applied to low frequency input signals. Today's relays not only offer protection but incorporate monitoring and control functions as well. Therefore, protection as well as monitoring functions must be taken into account when applying the low frequency input signals. In addition, impact of low frequency is not just limited to CT saturation but also impacts phasor measurements, metering and monitoring elements.

As mentioned in the Section I, in VFD applications, the frequency of the motor input current signals during starting varies from low frequency to the desired frequency level 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.

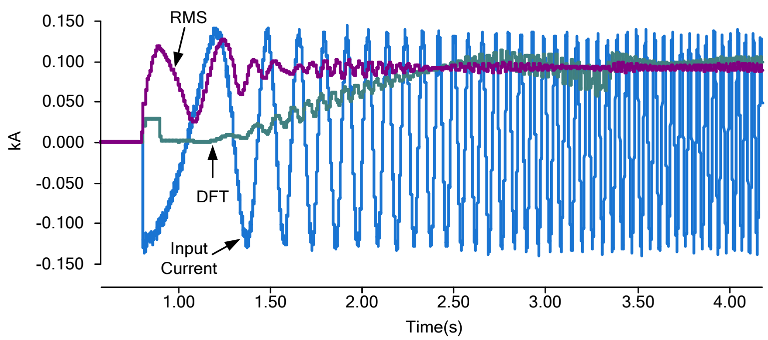
Figure 10 (a) demonstrates the magnitude estimation of the motor starting current using RMS- and DFT-type techniques having a fixed sampling frequency of 3840Hz and nominal frequency of 60Hz (sampling rate N equals 64samples/cycle). It shows significant error in the measurement which decreases as frequency approaches the nominal frequency level. This is due to the fact that with the 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 estimations techniques with a fixed sampling frequency will not provide correct estimation of the phasors of a varying frequency input signal.

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 input signals. The actual cause of the lower estimation of the magnitude using DFT-type, compared to RMS-type, is varying frequency. If there is no frequency tracking available, DFT-type calculates lower magnitude than RMS-type estimator (see Figure 10). 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, but such estimator accuracy will not be great.

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. As shown in Figure 10(b), magnitude of the input signal still shows measurement error in the first few cycles. RMS magnitude shows large oscillations in measurement while



(a)



(b)

Figure 10 Magnitude estimation using (a) fixed sampling frequency (b) adjusted sampling frequency

DFT magnitude shows calculation delay until magnitude reaches the actual magnitude level.

This issue can be solved if frequency tracking is forced to initialize at defined a frequency level known as “Starting Frequency, Fstart” 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 10 (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.

3) Undercurrent protection typically 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

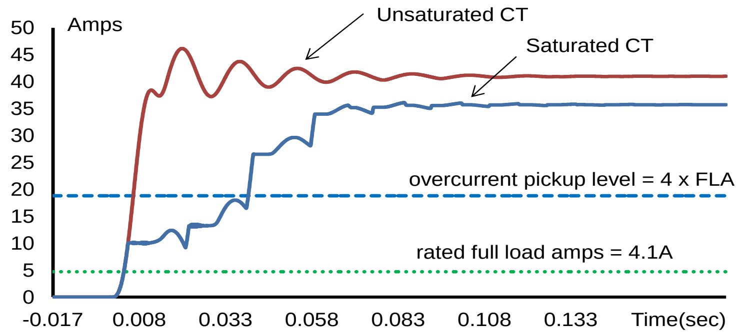


Figure 11: Sinusoidal and RMS measurement of the steady state short circuit secondary current

undercurrent threshold level. Duration of block time depends on the provision of tracking frequency.

4) Differential protection performance during external fault: Single- or dual-slope characteristic and higher pickup are typically used to prevent mal-operation of the differential protection in the event of an external fault with CT saturation. However, it won't impact the differential operation because both ends CTs see the same low frequency currents resulting in zero or very small false differential current measurement.
5) Differential protection performance during internal fault: However, in case of the internal fault terminal CTs will see a high fault current. Differential protection must now operate to isolate the motor from the system. However, when VFD fed motor is operating at low frequency, fault current can saturate the CT if not properly selected, as discussed in section IIIC. Operation of the differential protection may be in jeopardy, if differential is set not too sensitive.

6) Overcurrent protection can be affected in the VFD motor application when motor is running at low speed or low frequency. Figure 11 shows that when CT is properly selected considering low frequency into account (as discussed in section IIID) overcurrent correctly operates as soon as the primary current reaches the pickup level. However, in case of CT saturation, secondary current doesn't replicate the primary current and reaches the pickup level after 33msec, resulting in delayed operation of the overcurrent, which can result in the severe damage to the motor as energy accumulation in the low frequency currents is significantly very large compared to higher frequency.

This problem can be solved by (1) proper selection of current transformer (2) lower setting of the overcurrent pickup level, care must be taken that overcurrent must be select about the maximum allowable load current that equals SF x FLA.

7) Many of the today's digital relays provide multi setpoint groups; when required protection settings can be switched to different settings for a different operating

condition [4]. In VFD motor applications having prolonged low frequency motor operation, adjustment to the protection settings can be achieved by automatic switching between groups at different frequency levels.

IV. Conclusions

This paper discussed multifunctional motor protection relay performance dependability on current transformer in VFD driven motor applications.

Current transformers are normally designed to operate at the nominal system frequency 50Hz or 60Hz. In variable speed drive motor applications having prolonged low frequency motor operation; this can result into saturation of the CT. As the frequency decreases, the voltage across the CT magnetizing branch decreases as well in order to maintain the flux density. As a result, CT excitation characteristic is now de-rated to lower level. As a consequence, reliable operation of the motor protection relay can be jeopardized with CT saturation happening at low frequency currents even at low level currents.

Low off-nominal frequency motor operation not only de-rate the CT excitation characteristic, but results in significant increase of the phasor measurement error in the relay, if there is no proper frequency tracking.

At low frequency operation, it is likely that CT saturates during the short circuit condition, it is highly recommended to lower the pickup settings of overcurrent protection and block undercurrent relay during motor start. In an event of external fault with CT saturation, differential protection remains secure. Proper differential protection operation during external/internal with CT saturation can be achieve using the CT saturation detection technique complement with fault direction.

V. References

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VI. Biography

Umar Khan (M'08) 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.

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