Performance of CTs and Relays at Low Frequencies

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Objective

From this paper/presentation you will learn:

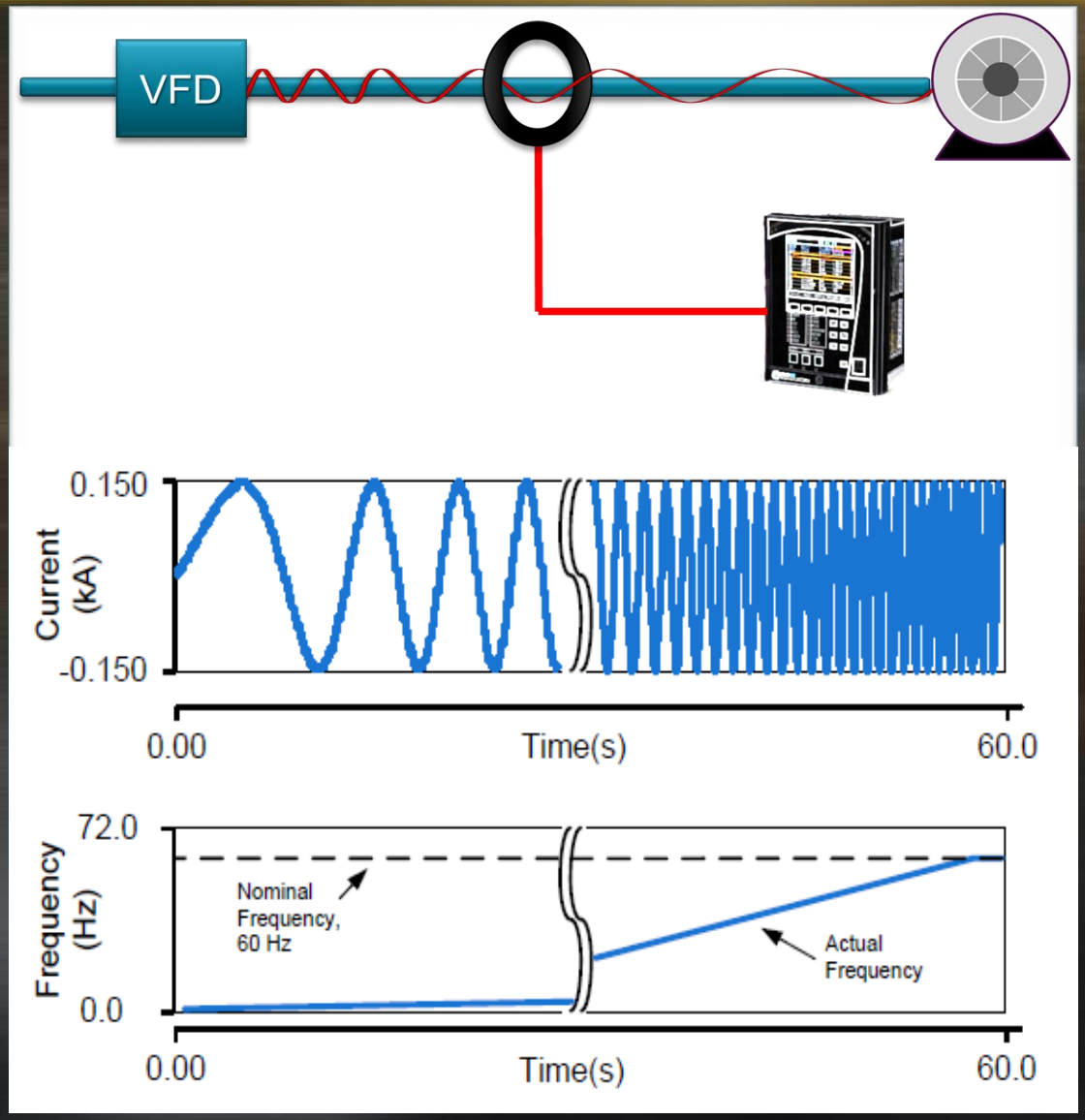
- Why current transformer (CT) and relay operating at low frequency is a concern?
- How low frequency operation can impact the CT and relay performance?
- What are the various steps to follow in order to ensure adequate protection?

Presentation Layout

- Introduction
- CT Magnetics and Frequency Dependent CT Model
- CT Performance at Low Frequencies – Simulation Results
- Relay Performance at Low Frequencies – Simulation Results
- Conclusions

Introduction – VFD Driven Motor

- VFD used a soft starter
- Frequency varies from low level to normally load running level
- Programmable acceleration and deceleration rate
- Prolonged low frequency operation (8-23Hz)



Introduction – Impact on CT & Relay

Analysis of CT Performance:

- Starting
- Locked Rotor
- Normal Loading
- Overloading
- Short Circuit

Analysis of Relay Performance:

- Relay Current Magnetics
- Magnitude and Phase Measurements
- Protection Performance

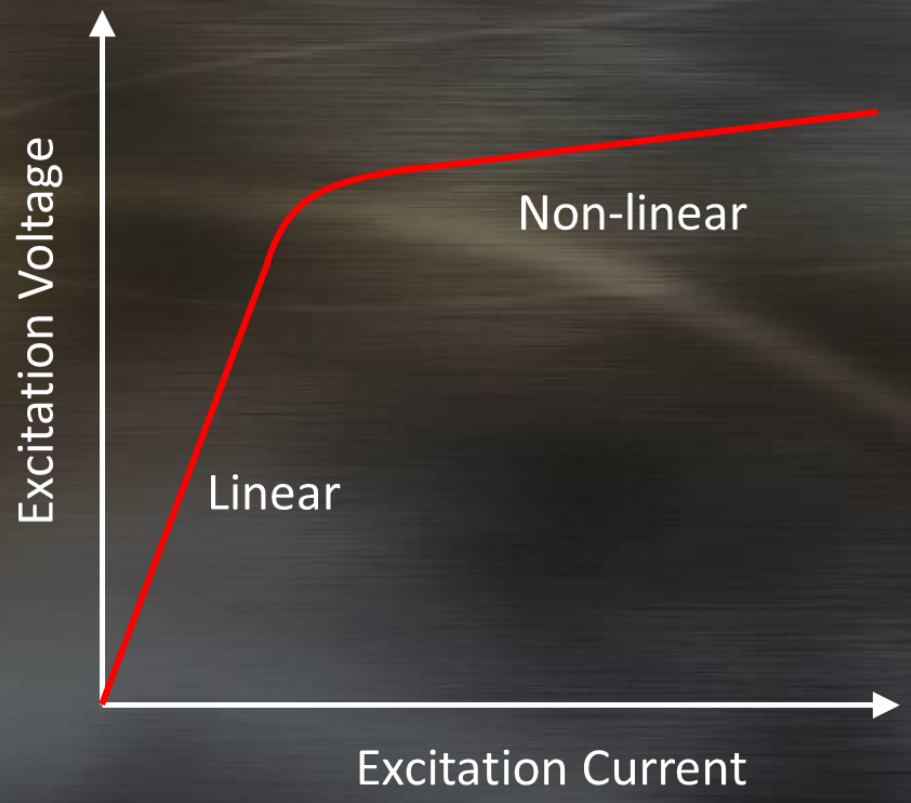
CT Magnetics

For simulation purposes, a frequency dependent CT model is developed, which involves following stages:

- Review of the Excitation Characteristics
- Equivalent Circuit Model
- Frequency Dependent Model
- Laboratory Test Bench

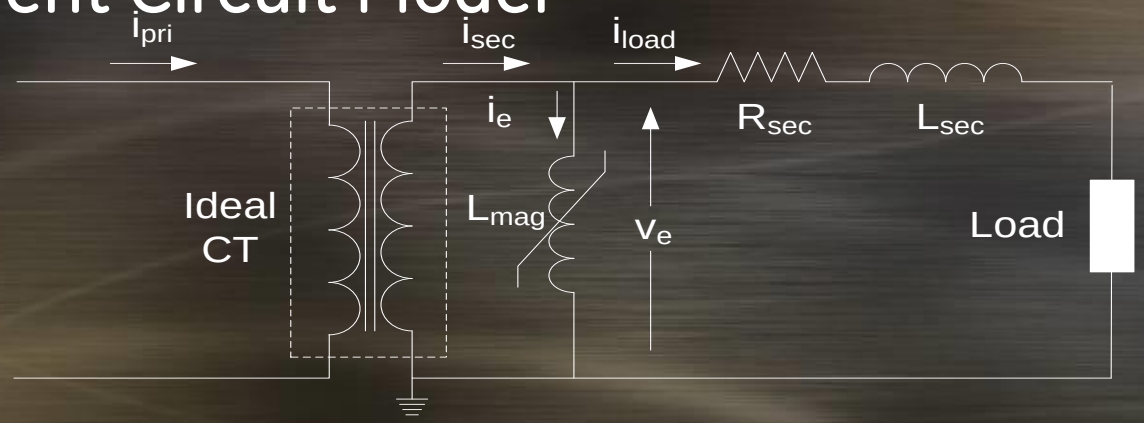
CT Magnetics

Excitation Characteristics

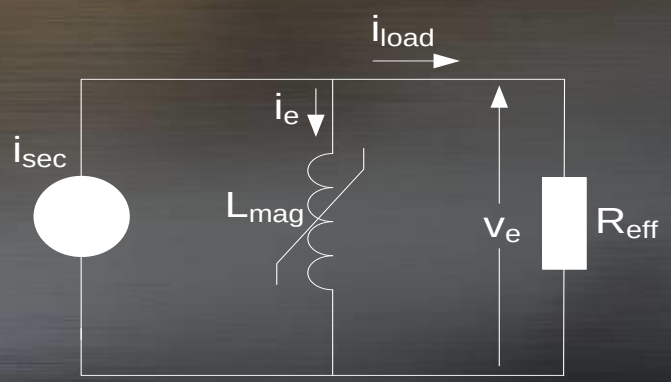


CT Magnetics

Equivalent Circuit Model



CTs are designed to operate at nominal system frequency.

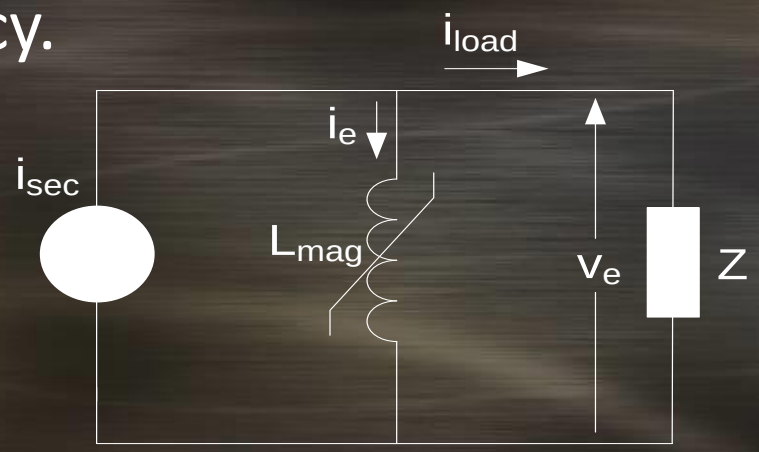


At nominal frequency (f_n) suppose:

- Xmag (@ f_n)= 2 x Pi x f_n x L_{mag}
- Load impedance = R (mostly resistive, fixed)
- Saturation Voltage = $V_{sat}(f_n)$
- At V_{sat}(@60Hz), I_{sat} is on the edge of the linear characteristic, increasing load current would cause saturation of magnetizing branch

Frequency Dependent CT Model

CTs are designed and specified to operate at nominal system frequency.



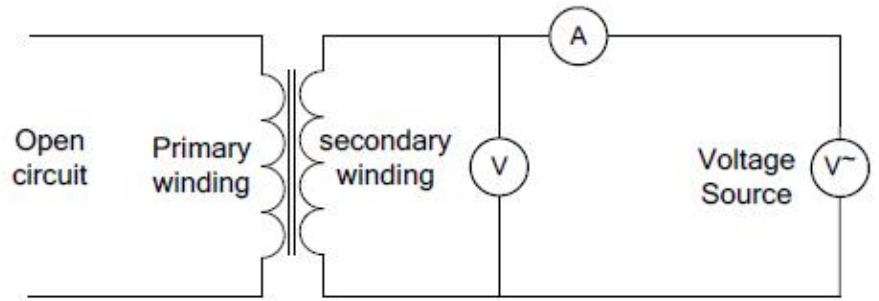
$$B\,(f_n) = B\,(f)$$

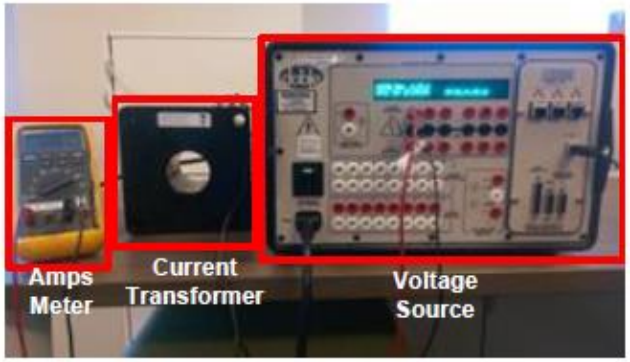
$$\frac{V_e\,(f_n)}{4.44\ x\ fn\ x\ N\ x\ A_{core}} = \frac{V_e\,(f)}{4.44\ x\ f\ x\ N\ x\ A_{core}}$$

$$\frac{V_e\,(f_n)}{f_n} = \frac{V_e\,(f)}{f}$$

Frequency Dependent CT Model

To confirm validity of this relation we have tested the real current transformer using the Laboratory Test Bench

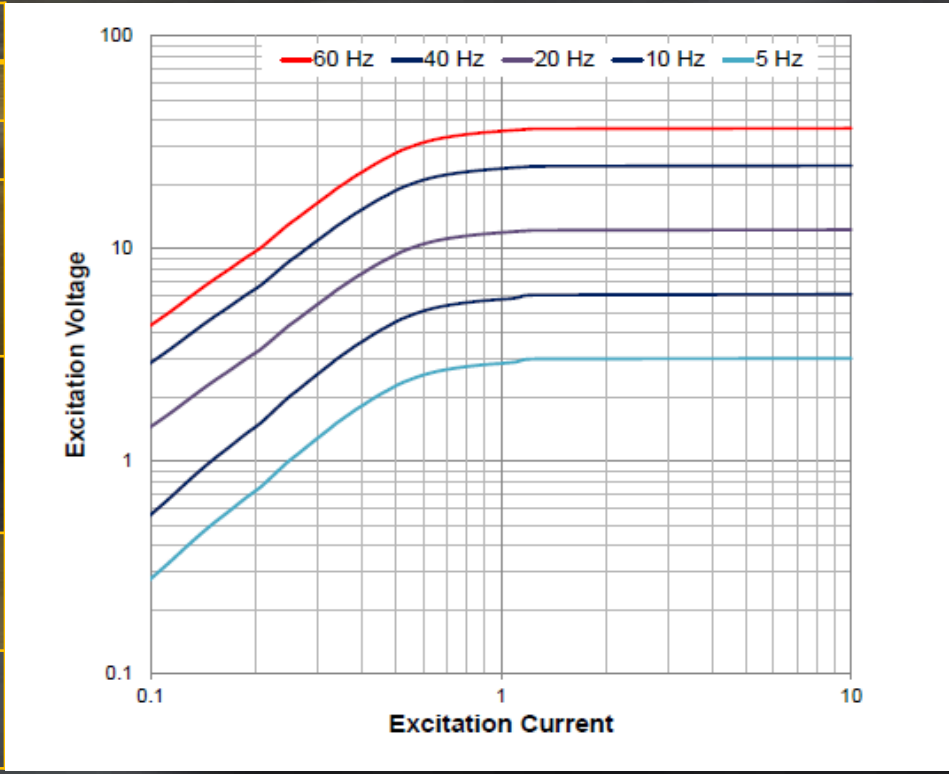




Frequency Dependent CT Model

$$\frac{V_e(f_n)}{f_n} = \frac{V_e(f)}{f}$$

	60Hz	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	36.7V	24.4V	12.3V	6.1V	3.05V
Knee point Voltage (V_{knee})	26V	17.33V	8.66V	4.33V	2.16V
Saturation Voltage (V_{Sat})	36.5V	24.33V	12.16V	6.08V	3.04V



CT Performance at Low Frequency

Following system conditions are considered for analysis purpose:

- Starting
- Locked Rotor
- Normal Loading
- Overloading
- Short Circuit

CT Performance at Low Frequency

Motor Load Conditions:

Motor Ratings:

- 440 HP, 2.3kV, 82 A Full load Amps, 1.15 SF and 15 X/R
- Maximum Allowable Loading: 440 HP x 1.15 (506HP or 94A)

Service factor (SF) defines the maximum allowable motor loading

CT Performance at Low Frequency

Motor Load Conditions:

At 60Hz the maximum primary current level above which CT enters into saturation zone is:

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

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

CT Performance at Low Frequency

Motor Load Conditions:

	40Hz	20Hz	10Hz	5Hz
Effective resistive burden at CT terminals	0.37 ohms			
Saturation Voltage (V_{Sat})	24.33V	12.16V	6.08V	3.04
Saturation Current (I_{Sat})	**1315A**	**657A**	**329A**	**164A**
CT Saturates	**No**	**No**	**No**	**No**

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.

CT Performance at Low Frequency

Locked Rotor Condition:

During locked-rotor condition, current may reach up to 7 times (or above) the rated full load current

LRC = 7 x 82A = 574 A

	40Hz	20Hz	10Hz	5Hz
Effective burden at CT terminals	0.37 ohms			
Saturation Voltage (V_{Sat})	24.33V	12.16V	6.08V	3.04
Saturation Current (I_{Sat})	**1315A**	**657A**	**329A**	**164A**
CT Saturates	**No**	**No**	**Yes**	**Yes**

CT Performance at Low Frequency

Locked Rotor Condition:

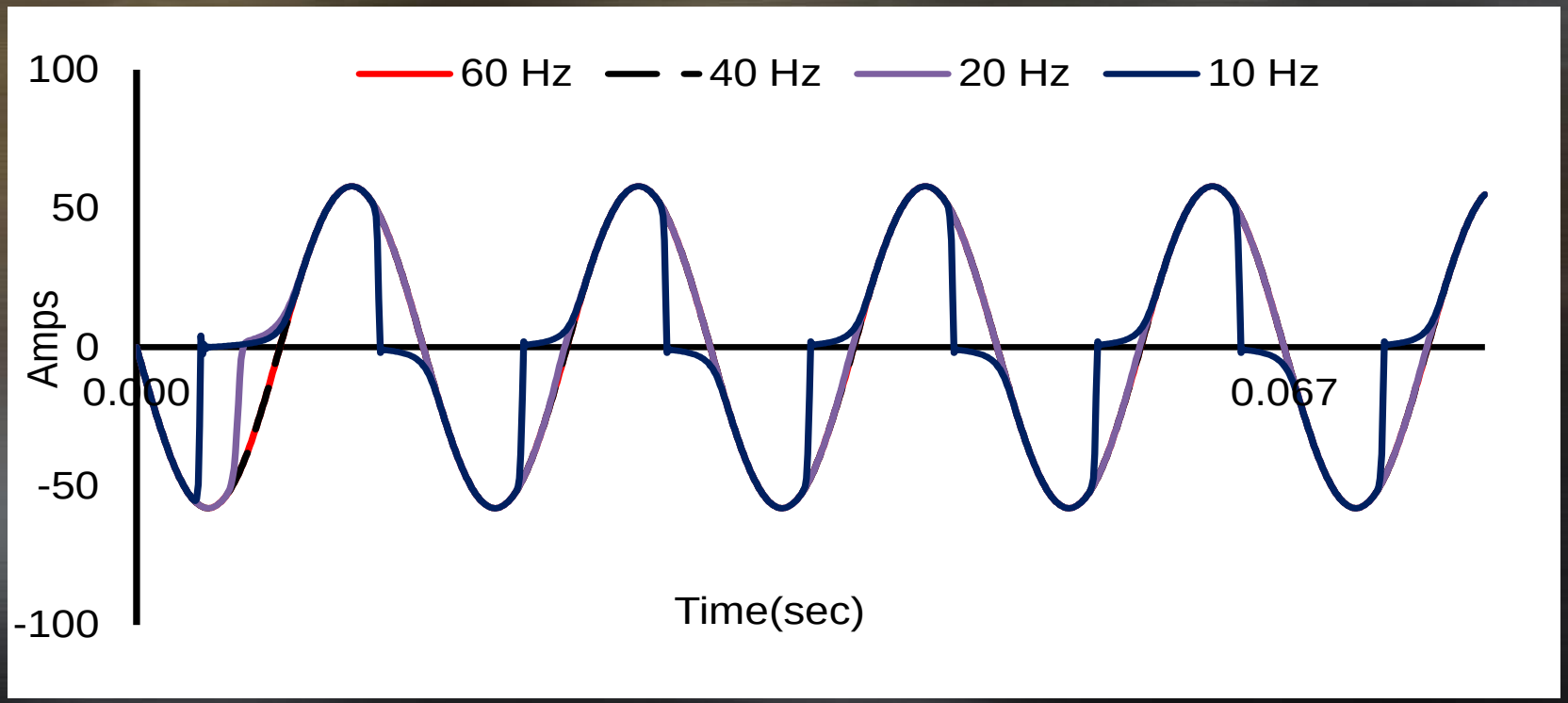
Locked rotor condition may not be a concern in motor applications when motor is driven by a VFD due to the reason that VFD confines motor operation to its torque speed characteristic during motor starting and running conditions

	40Hz	20Hz	10Hz	5Hz
Effective burden at CT terminals	0.37 ohms			
Saturation Voltage (V_{Sat})	24.33V	12.16V	6.08V	3.04
Saturation Current (I_{Sat})	**1315A**	**657A**	**329A**	**164A**
CT Saturates	**No**	**No**	**Yes**	**Yes**

CT Performance at Low Frequency

Short Circuit

Both steady state (purely AC) and transient (DC +AC) are analyzed. Steady state short circuit of magnitude 10 x FLA is applied.



CT Performance at Low Frequency

Short Circuit Condition

For example: To avoid saturation at 20Hz, CT saturation voltage must satisfy the following relation:

$$V_{Sat}(@60Hz) > \frac{I_f}{Turn\ Ratio}\ x\ Reff\ x\ \frac{F_n}{F}$$

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

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

Required Data	
Relay Class	C20
Turn ratio	100:5
Frequency	60 Hz
Saturation Voltage (V_{Sat})	**~~36.5 V~~ 45V**

CT Performance at Low Frequency

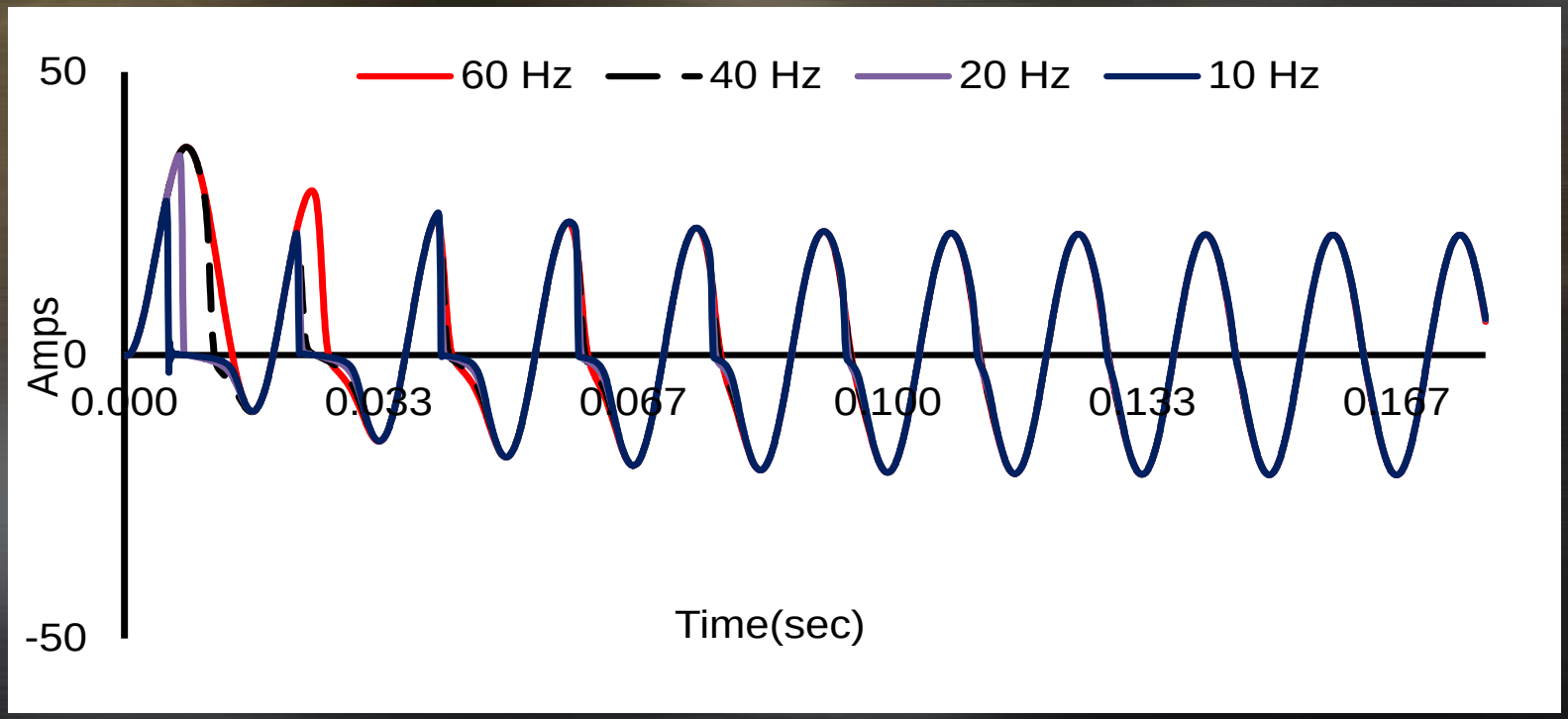
Transient Short Circuit Condition

- Contains decaying DC component
- Magnitude and duration of the decaying DC component depends on the system X/R ratio and fault inception point on the voltage signal

CT Performance at Low Frequency

Transient Short Circuit Condition

- Short circuit of magnitude 300A RMS applied with DC component that magnifies the total asymmetrical current to more than 800 A



CT Performance at Low Frequency

Transient Short Circuit Condition

For Example: To avoid saturation at 20Hz, CT saturation voltage must satisfy the following relation:

$$V_{Sat}(@60Hz) > \frac{I_f}{Turn\ Ratio}\ x\ Reff\ x\ \left(1 + \frac{X}{R}\right)\ x\ \frac{F_n}{F}$$

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

Required Data	
Relay Class	C20
Turn ratio	100:5
Frequency	60 Hz
Saturation Voltage (V_{Sat})	~~36.5 V~~ 265V

Relay Performance at Low Frequency

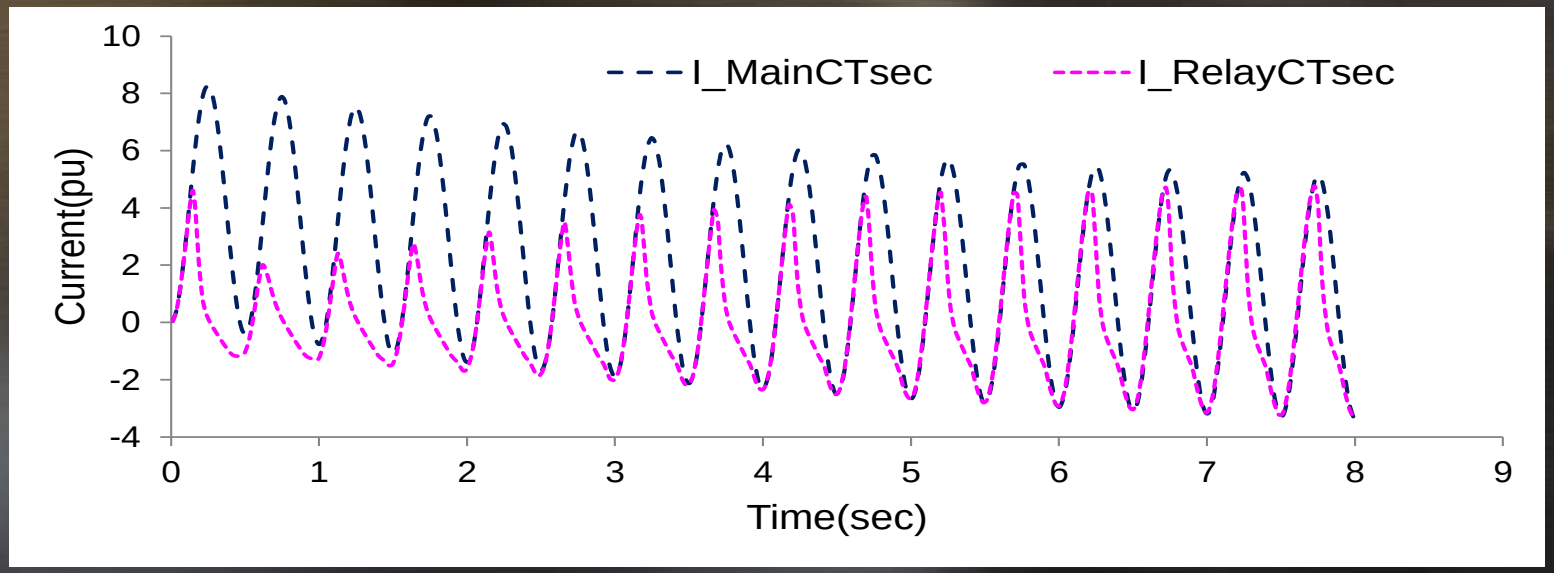
Relay Magnetics

- Magnetics in the relay used as current transducers are also current transformers.
- Therefore, performance of the current transducers at low operating frequencies is very important

Relay Performance at Low Frequency

Relay Magnetics

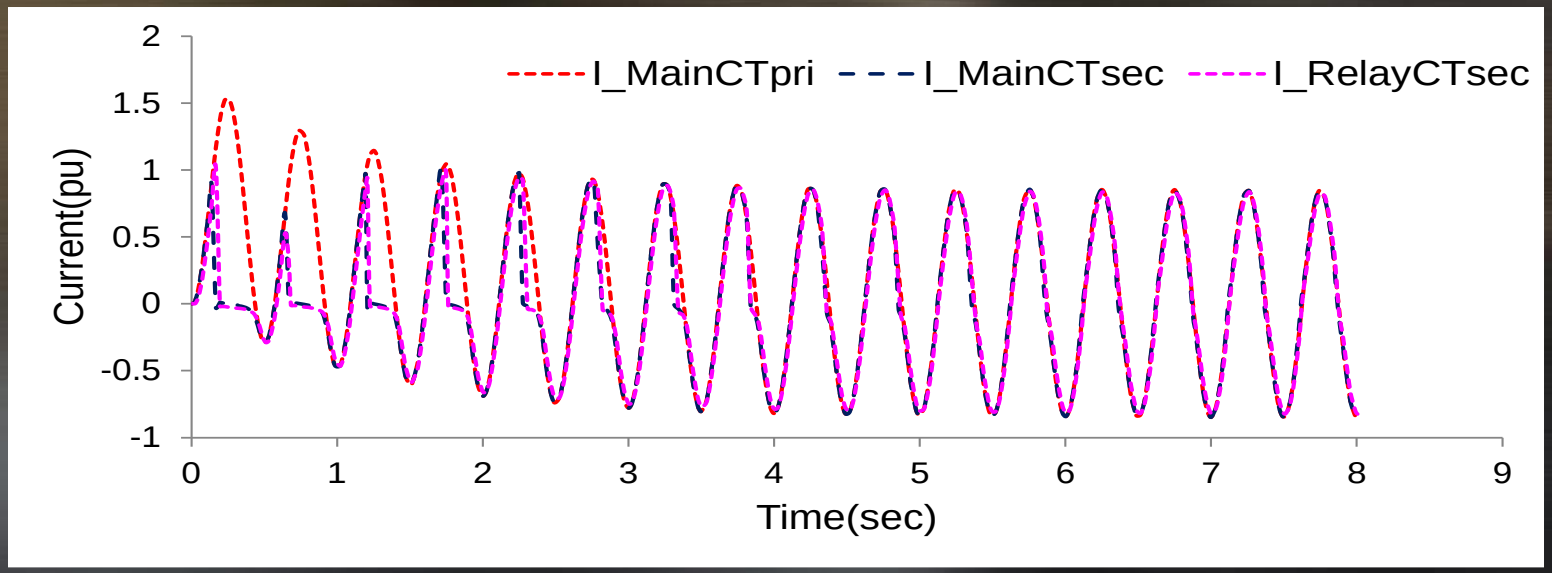
Case 1: Main CT is not saturated and 3pu (RMS) current of 2Hz is applied at the relay terminal



Relay Performance at Low Frequency

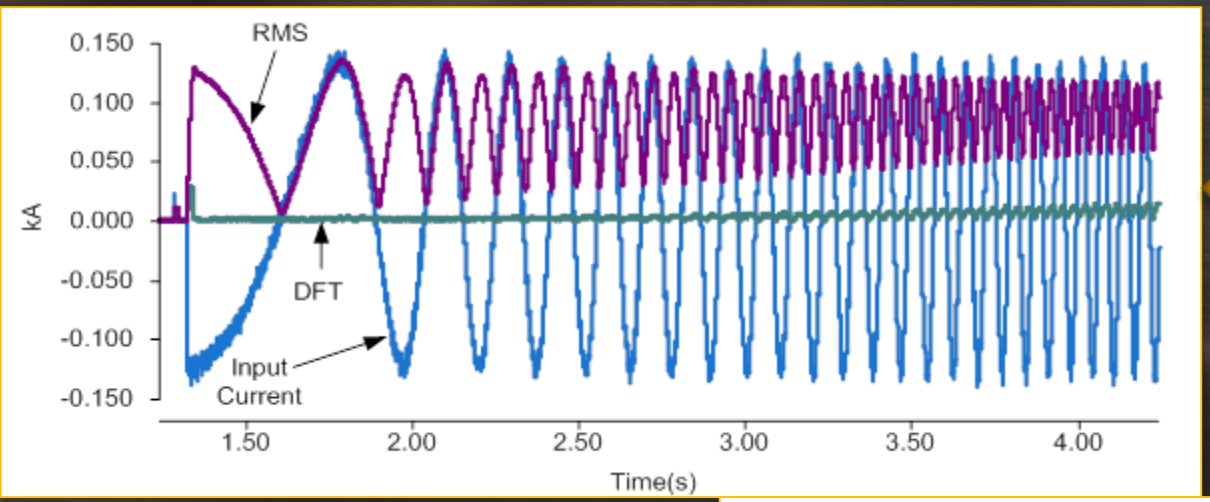
Relay Magnetics

Case 2: Main CT is saturated and 1pu (RMS) current of 2Hz is applied at the relay terminal



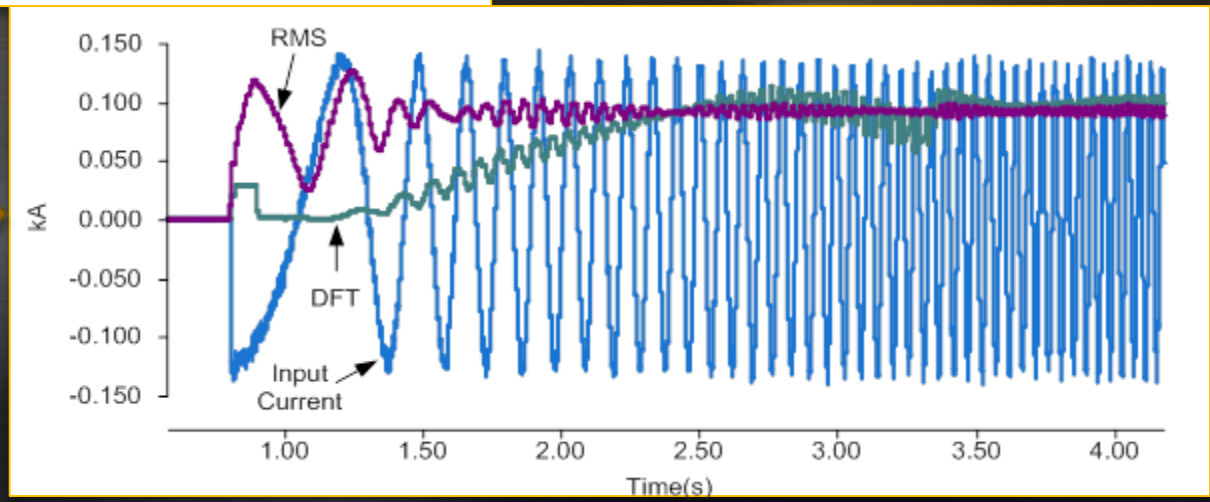
Starting of the motor fed through VFD

Relay Phasor Measurements



Large measurement error when Sampling Frequency of 3840 Hz is fixed

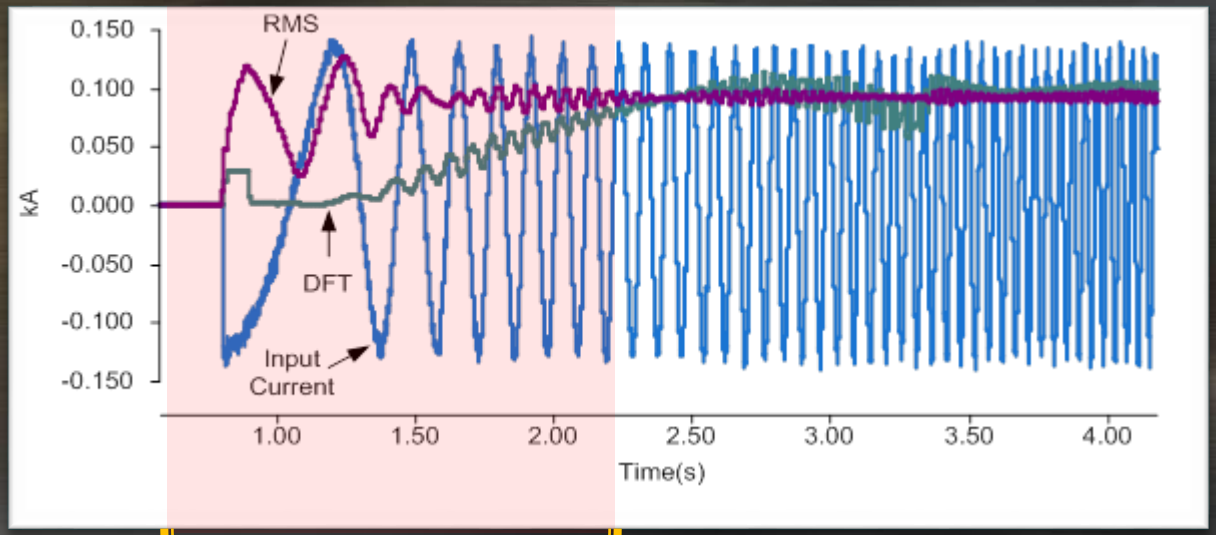
Sampling frequency adjustment by tracking frequency



Relay Performance at Low Frequency

Relay Phasor Measurements

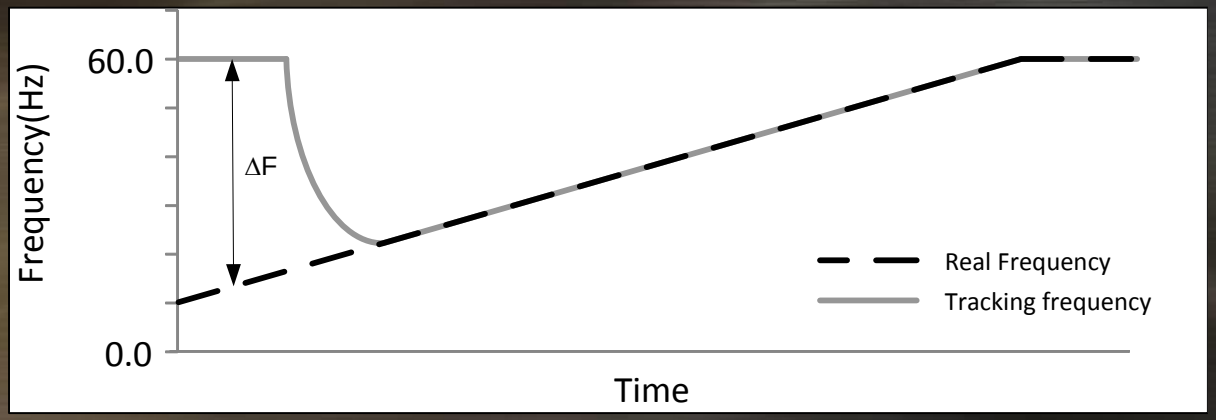
The problem is not yet fully solved: magnitude of the signals still shows measurement error during the first few cycles



RMS magnitude shows large oscillations in measurement while DFT magnitude shows calculation delay until magnitude reaches the actual magnitude level.

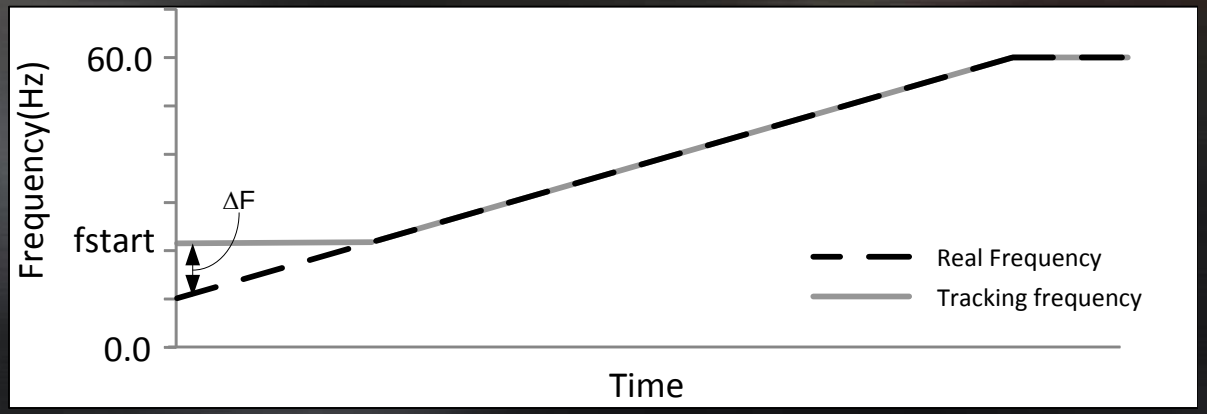
Relay Performance at Low Frequency

Solution 1: Adjustment to Frequency Estimation



Normally, sampling frequency is adjusted based on the nominal frequency (e.g., 60Hz) until tracking frequency starts providing the actual frequency

Solution is to force the tracking frequency to start tracking from the pre-defined **<u>Starting-Frequency</u>**



Relay Performance at Low Frequency

Solution 2: Fast Frequency and Magnitude Estimation during VFD Starting

- Three-sample based estimation of frequency

$$f(n) = \frac{1}{2\pi k T_s} \arccos\left\{ \frac{1}{2} \frac{u(n-2k)u(n-k) - u(n)u(n-3k)}{u(n-k)u(n-k) - u(n)u(n-2k)} \right\}$$

$$favg(n) = \frac{1}{N} \sum_{i=0}^{N-1} f(n-i)$$

- Fast magnitude Estimation using 8 number of taps of the short window FIR orthogonal filter

Relay Performance at Low Frequency

Undercurrent Protection

- Fundamental currents (DFT-based) are preferred to detect loss of load or undercurrent operating conditions
- It is important to block the undercurrent protection during motor starting
- The reason is: during motor starting, the current magnitude measurement (DFT-based) 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.

Relay Performance at Low Frequency

Differential Protection – External Faults

- 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.
- **Low frequency operation won't impact the differential operation because both ends CTs (same CT ratio and magnetizing characteristic) see the same low frequency currents resulting in zero or very small false differential current measurement.**

Relay Performance at Low Frequency

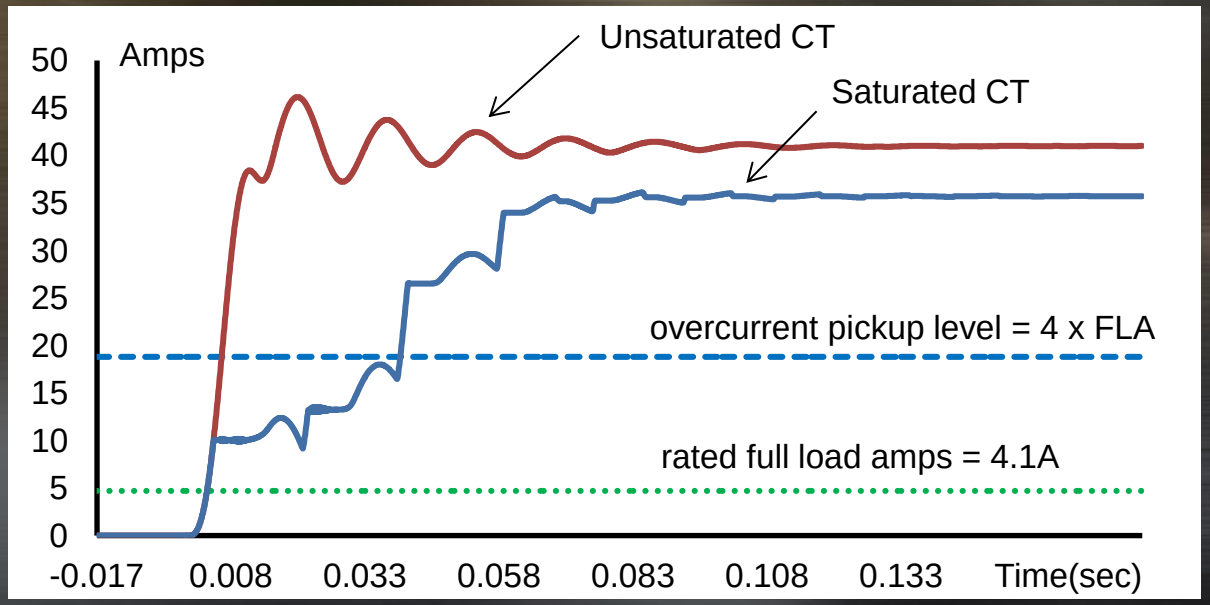
Differential Protection – Internal Faults

- When VFD fed motor is operating at low frequency, fault current can saturate the CT if not properly selected. Operation of the differential protection may be in jeopardy, if differential is set not too sensitive.

Relay Performance at Low Frequency

Overcurrent Protection

- Overcurrent protection can be affected in the VFD motor application when motor is running at low speed or low frequency.



Conclusions

- CTs and multifunctional motor protection relay performance at low operating frequency in VFD driven motor applications is discussed
- Frequency decreases → Voltage decreases as well; in order to maintain the flux density → resulting in de-rated CT excitation characteristic → more likely to saturate at low level short circuit currents
- Significant increase in the phasor measurement error when there is no proper frequency tracking
- It is likely relay current transformers saturate at low frequency
- For OC protection, it is recommended to lower the pickup settings
- Blocking of the undercurrent protection during motor start
- In an event of external fault with CT saturation, differential protection remains secure.

Thank You

Questions?