Current Transformer Selection Techniques for Low-Voltage Motor Control Centers

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CURRENT TRANSFORMER SELECTION TECHNIQUES FOR LOW-VOLTAGE MOTOR CONTROL CENTERS

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Abstract**—**This paper provides a clear set of procedures and equations to follow in optimal current transformer selection for low-voltage motor control centers. Methods of using protective relay settings to minimize current transformer cost and size are also shared. The selection criteria are explained from the fundamental principles of operation of a current transformer and a protective relaying device. This paper shows how the current transformer ratio, voltage knee points, and relay protection elements can be selected together simultaneously to provide a low-cost, high-performance system.

This paper describes a case study in which the authors developed a simplified set of current transformer selection criteria for compact IEC low-voltage motor-control center drawers at a large oil and gas field in Central Asia.

Index Terms—Current transformer, motor control centers, protection, metering, selection technique.

I. INTRODUCTION

Using current transformer selection techniques optimized for medium-voltage switchgear commonly results in the selection of current transformers (CTs) that are too large and heavy for use inside low-voltage motor control centers. The authors were recently challenged with finding a simplified set of current transformer selection criteria for over 5,000 low-voltage drawers to be installed at a large oil and gas field located in Central Asia. The loads on these drawers range up to 2,500 full-load amperes with fault currents up to 20 kA. The current transformers selected must be very small because most of the low-voltage drawers are of compact IEC removable drawer type construction.

The paper starts with a problem statement, which is followed by a short background on CT saturation modelling. Criteria for selecting CTs for low-voltage motor control centers are then proposed based on fundamental CT parameters. The CT selection criteria are then validated using a real-time simulation system connected to a representative protective relay. The paper then provides a robust and proven CT selection process that works equally well for all IEEE and IEC protection-class CTs. These techniques are justified by simplifying and mathematically characterizing CTs and digital protective relay elements.

A single set of CT selection criteria is required for all low-voltage motor relays (LVMRs) at the facility discussed in this paper because the drawers can be interchanged for multiple functions in the field, such as cable feeder, motor, lighting, heater tape, and motor protection applications. For example, a drawer initially used to protect a motor can be used to protect a feeder cable in the future. An LVMR acting as a feeder relay requires instantaneous (50) and time overcurrent (51) elements, whereas the same LVMR requires thermal (49) and phase unbalance (46) elements when acting as a motor relay. Fig. 1 shows that 46 and 49 elements used on motor applications open a contactor. The 50 and 51 elements are used to shunt trip the molded case circuit breaker (MCCB) for the feeder application.

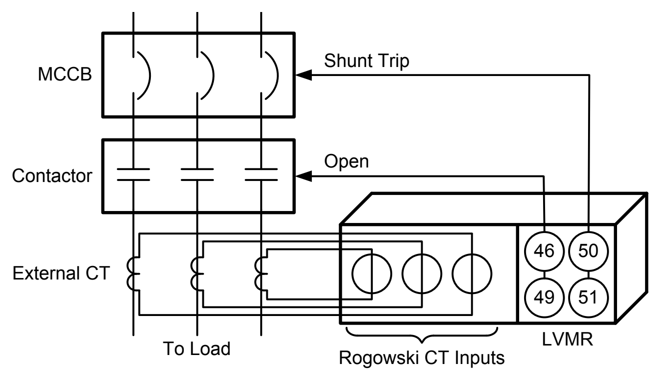

Fig. 1 LVMR With an External CT

II. PROBLEM STATEMENT

The CT selection for this case study is more complex than usual for a number of reasons. First, the LVMR has a built-in air-turn CT input, known as a Rogowski coil, with limited sensitivity under low current levels. A Rogowski coil is a wound coil of wire acting to measure current without an iron core. Rogowski coils do not saturate like conventional CTs. The LVMR Rogowski input requires an external traditional CT (steel core) for full-load currents above 128 A, as shown in Fig. 1.

LVMR circuitry and firmware amplify and integrate the currents detected in the Rogowski CT coils. Because of this digital integration, the metering accuracy of the LVMR is a function of the CT ratio (CTR) and secondary current from an external CT.

The shunt trip method of tripping the MCCB allows for safer and more reliable protection coordination than the MCCB can provide. The MCCB shown in Fig. 1 includes coarsely adjustable 50 and 51 elements.

Protection system coordination with an LVMR is safer than MCCB-only protection because it provide remote-controlled multifunction protection capabilities. For example, changing the protection settings inside the LVMR can safely be performed while the motor control center (MCC) is energized. Modifying or confirming the MCCB settings requires a human to extract the IEC drawer. Withdrawing or opening an MCCB door presents a potentially dangerous situation due to incident energy levels.

LVMRs also provide a more reliable protection system than MCCB-only protection. MCCBs are commonly permanently damaged after they interrupt fault currents. MCCBs have no alarms to advise operations personnel of the MCCB health status. Testing an MCCB, therefore, requires damaging the MCCB. LVMRs automatically report their health status. LVMRs have on-board diagnostics that advise operations personnel of the health status of the MCCB and the contactor.

To fit into the small IEC drawers, the CT size had to be minimized. Compact IEC drawers where chosen for this facility to reduce the cost, size, and transportation logistics of MCCs and the transportable buildings they reside in. Smaller CTs require that the cross-sectional area for the CT steel cores be minimized. CTs with smaller cross-sectional steel cores saturate at lower secondary voltages, thereby limiting the amount of current flowing into the LVMR. These smaller currents associated with saturation can limit the metering and protection functions in the LVMR if the CTs are not properly selected.

CTs must be selected for a wide amperage range because the same LVMR is used for both protection and metering. The process controls and power management systems require accurate real-power metering from the LVMR. These systems require accuracy during operation near the full-load ampere (FLA) rating of the load. This metering is used for load shedding, visualization, oscillographic reporting, and other functions. For example, the LVMR is configured to capture oscillography when the MCCB opens due to fault conditions.

Protection elements within the LVMR require accurate current metering. Thermal (49) and phase-unbalance (46) protection elements require metering to be accurate up to a worst case of 15 times FLA (depending on the motor starting inrush currents). Instantaneous (50) and time-overcurrent (51) elements require accurate measurement of current into the LVMR during bus and cable faults at levels near 20,000 A primary.

III. BACKGROUND

This section is a refresher on the saturation of protection-class CTs. Fig. 2 shows a classical representation of a CT [1].

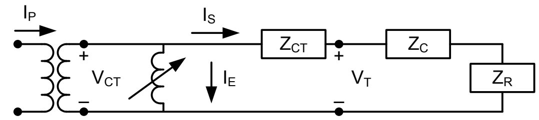

Fig. 2 Classical CT Model (Refer to the Nomenclature section for definitions of terms)

For nonsaturated operation (i.e., when I_E is small), the equation to determine the secondary CT voltage is shown in (1).

$$V_{CT} = I_S \bullet (Z_R + Z_C + Z_{CT}) \quad (1)$$

Equation (1) can be simplified by assuming that the conductor burden (Z_C) is zero because the CT burden (Z_{CT}) is much greater than the conductor burden ($Z_{CT} >> Z_C$). This is because of the short wire lengths between the CTs and the relays. Z_R is also zero because the Rogowski coils offer no additional burden resistance. Because the reactive component of Z_{CT} is much smaller than the resistance of the CT secondary, (1) can be approximated by (2). R_{CT} is the resistive portion of Z_{CT}.

$$V_{CT} = I_S (R_{CT}) \quad (2)$$

Primary CT currents at the saturation point can then be estimated by (3). V_K is the voltage knee point shown in Fig. 3. Note that dc offset currents are neglected in this simple calculation.

$$\text{Primary Saturation } (I_P) = \text{CTR}\left(\frac{V_K}{R_{CT}}\right) \quad (3)$$

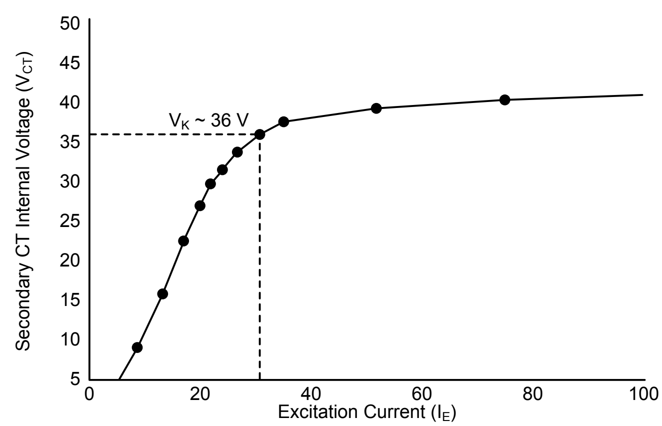

Fig. 3 3 VA 5P10 200:1 CT Curve With CT Resistance of 0.9 Ω and V_K = 36 V (Refer to the Description of IEC Protection-Class CTs section for details on how to interpret this CT rating)

Fig. 3 shows a sample CT saturation curve for a CT commonly used in LVMR applications. Using (3), the LVMR starts losing accuracy due to saturation when the primary current (I_P) exceeds 8 kA, as shown in (4).

$$\text{Primary Saturation } (I_P) \sim 200\left(\frac{36\,\text{V}}{0.9\,\Omega}\right) \sim 8\,\text{kA} \tag{4}$$

IV. PROPOSED SOLUTION

This section describes simplified CT selection criteria that are based on system fault levels, CTR, voltage knee point (V_K), R_{CT}, and LVMR protection and metering characteristics. This method selects both the CT and the protection scheme together such that the LVMR has accurate metering under normal conditions and fault detection capabilities under high current levels.

The preferred method of the authors is to provide a CT manufacturer with a CT ratio and an equation relating V_K to R_{CT}. The CT manufacturers can then quickly sort through their inventory of CTs and provide several viable options. This has proven to be a simple and reliable method for selecting CTs of the least cost and the required performance.

To avoid relay misoperation under fault conditions, the following general principles are used in selecting CTs:

1. CT voltage knee points are selected based on R_{CT} and secondary currents, as shown in (2).
2. CT sizes are reduced if the instantaneous (50) and time-overcurrent (51) relay protection elements can trip before the CT fully saturates.
3. The CTs must be sized so that they do not saturate during the normal current inrush associated with motor starting.
4. Minimizing the number of acceptable protection elements simplifies the CT selection criteria.

A. CTR Selection Criteria

Protection-class CTs most commonly come with either 1 A or 5 A rated secondary windings. CTs used outside of North America are typically 1 A secondary-rated and are designated by IEC 61869-2 standards. CTs used inside North America are typically 5 A secondary-rated and are designated by IEEE C57.13 standards. Fig. 3 shows the CT saturation curve for a 1 A CT.

The test setup shown in Fig. 4 was used to determine the metering accuracy of the LVMR. The test system was set up using a real-time Electromagnetic Transients Program (EMTP) simulation environment. Inside the EMTP simulation, a generation source, load, and CT were modelled. The CT model included saturation characteristics that came from manufacturer data sheets. CT hysteresis was not modelled in these tests.

Low-level currents from the real-time EMTP system were fed to a three-phase amplifier. The amplifier outputs were injected through the LVMR Rogowski inputs. The amplification hardware had a 30 A continuous output limitation. The 30 A limitation was raised by wrapping multiple turns through each phase of the LVMR Rogowski CT inputs.

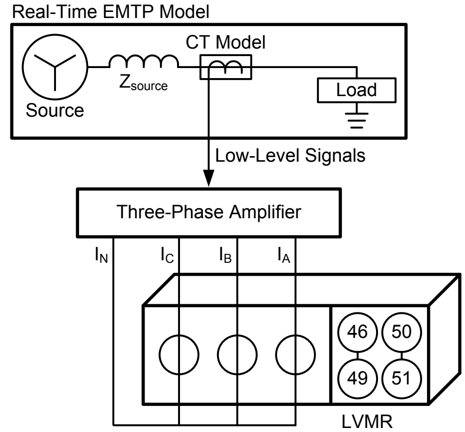

Fig. 4 Test Setup

LVMR meter accuracy testing was done for a range of CTR and FLA settings in the LVMR. For all ranges of settings, the LVMR was found to measure less than 2 percent error if the currents into the Rogowski inputs were kept greater than 0.2 A for a 1 A CT or greater than 0.5 A for a 5 A CT. The 0.2 A limit for a 1 A CT is shown as the metering accuracy limit line with a slope of CTR/FLA = 5.0 in Fig. 5. The 0.5 A limit for a 5 A CT is shown as the metering accuracy limit line with a slope of CTR/FLA = 10 in Fig. 6.

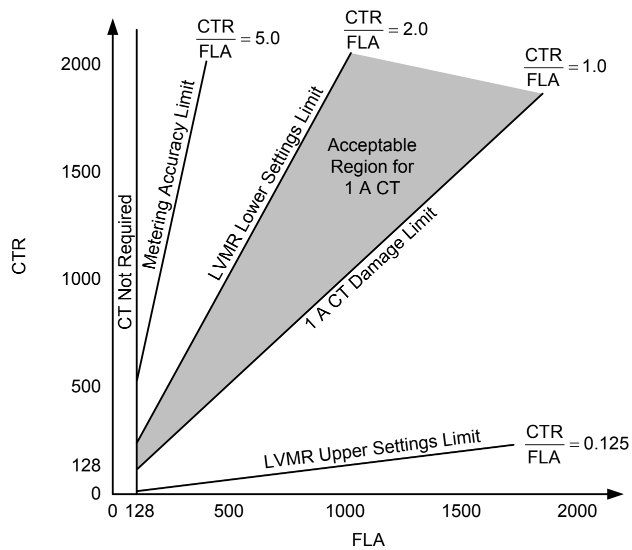

Fig. 5 1 A CTR Limits

The secondary FLA setting in the LVMR must be set between 0.5 and 8 A for external CTs. This constitutes another boundary condition for optimal CTR selection. The 0.5 A limit for both the 1 A and 5 A CTs is shown as the LVMR lower settings limit line with a slope of CTR/FLA = 2.0, and the 8 A limit corresponds to the CTR/FLA = 0.125 LVMR upper settings limit lines in Fig. 5 and Fig. 6.

The 1 A CTs that were evaluated became damaged if continuous current exceeded 1.2 A continuously. The 5 A CTs that were evaluated were damaged if continuous currents exceeded 6 A continuously. To prevent CT damage, the 1.2 A limit for a 1 A CT is depicted as the 1 A CT damage limit line with a slope of CTR/FLA = 1.0 in Fig. 5, and the 6.0 A limit for a 5 A CT is depicted as the 5 A CT damage limit line with a slope of CTR/FLA = 0.2 in Fig. 6. Limiting CTR/FLA to 1 A and 5 A respectively left a 20 percent overload capacity in case the FLA of the load was changed in the field.

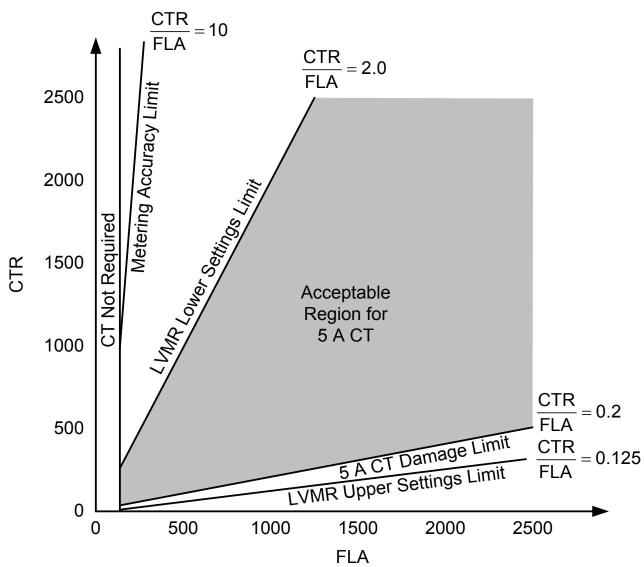

Fig. 6 5 A CTR Limits

All of the aforementioned settings, accuracy, and CT damage limitations can be summarized for CTR selection as shown in (5) for a 1 A CT and (6) for a 5 A CT.

$$0.5\,\text{A} \le \frac{\text{FLA}}{\text{CTR}} \le 1\ \text{A} \tag{5}$$

$$0.5\,\text{A} \le \frac{\text{FLA}}{\text{CTR}} \le 5\ \text{A} \tag{6}$$

B. Description of IEC Protection-Class CTs

IEC protection-class (P) CTs defined by IEC 60044-1 are rated as shown by the following example:

3 VA 5P10 200:1

where:

200:1 is the CTR.

The secondary rating of the CT is 1 A.

5P is the accuracy class.

10 is the accuracy limit factor (ALF).

3 VA is the accuracy power.

The rating of this CT indicates a maximum of 5 percent total error at 10 times rated current, assuming the load consumes 3 VA or less at 1 A secondary conditions. Note that the IEC form of CT rating does not directly supply the CT secondary resistance or voltage knee point required by the analysis. Thus, even with this elaborate IEC designation, it is still necessary to ask the CT manufacturer for the saturation curve and secondary resistance to properly characterize the CT.

C. Choice of LVMR Protection Elements

Part of the strategy for developing simplified CT selection criteria (equations) is using a minimal set of protection elements with known and tested characteristics.

The LVMR provides several different protection functions [2]. It is imperative to select a CT for which saturation does not affect the protection element operation. The typical LVMR protection elements used and affected by saturation are the inverse definite minimum time element (51) and the instantaneous overcurrent element (50). The thermal (49) and phase unbalance (46) elements are not affected by saturation so long as saturation does not occur during inrush associated with motor starting. All other protection functions used for this project in the LVMR were determined to operate in the nonsaturated CT region and so are not evaluated in this paper.

Fig. 7 shows the IEC Class A standard inverse time overcurrent (51) curve (curve type C1) used at all LVMR locations on this project. Saturation must not occur prior to the instantaneous trip region of each time dial curve for the 51 element to operate correctly over the timed overcurrent region of the curves. Note that in Fig. 7 the x-axis is in units of multiples of the secondary pickup current. For example, a 1 A relay with 1.5 A pickup setting enters the instantaneous trip region at 1.0 A • 1.5 • 30 = 45 A secondary current.

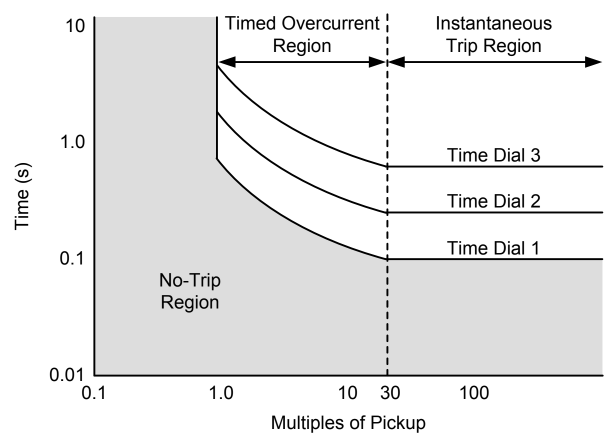

Fig. 7 IEC Standard Inverse Time Overcurrent Curve

D. Cosine Peak Adaptive Filtered Protection Elements

The LVMR instantaneous elements contain cosine peak adaptive filtering, as shown in Fig. 8 [3].

Cosine peak adaptive filtering uses digital measurement techniques to maintain 50 element speed and reliability during highly saturated current waveforms. This filter works by using the fundamental component magnitude measurement (cosine filtering) during nonsaturated conditions and a bipolar peak measurement during saturated conditions. This is required because digital relays normally cannot make accurate measurements of fault current once CT saturation occurs. Note that the cosine peak adaptive filter only works for 50 elements.

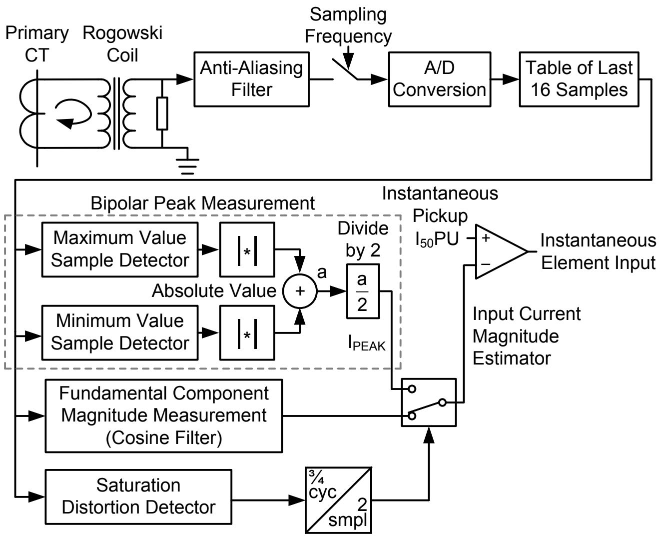

Fig. 8 Cosine Peak Adaptive Filter [3]

As shown in Fig. 8, the LVMR switches from cosine-filtered measurements to bipolar peak measurements for the instantaneous element (50) when the current is greater than eight times the CT secondary rating (e.g., 8 A for a 1 A CT) and the saturation distortion detector measures a harmonic distortion index greater than 1.75.

The distortion index measurement is given by (7).

$$\text{Distortion Index (DI)} = 1 + \frac{|A2| + |A3|}{|A1|} \tag{7}$$

where:

A1 is the peak value of the fundamental component of the cosine filter.

A2 is the peak value of the second-harmonic component of the cosine filter.

A3 is the peak value of the third-harmonic component of the cosine filter.

Fig. 9 shows a typical example of the current measured by a LVMR during saturated-CT conditions. The highly distorted waveform is the secondary CT current as measured by the LVMR. Note that the peaks are clipped by internal relay hardware and firmware scaling limits. The waveform is also highly distorted within the measurement range of the relay due to CT saturation.

If Fig. 9 were an ideal CT, it would provide 1,000 A secondary current. The reality is that the CT saturated, the LVMR digital processing clipped the saturated values at 200 A, and the LVMR cosine filter measured 100 A. In extreme cases of saturation, the cosine filter measures closer to 0 A while the peak detector measurement continues to measure 200 A. The peak detector therefore helps ensure fast tripping under extremely saturated CT conditions.

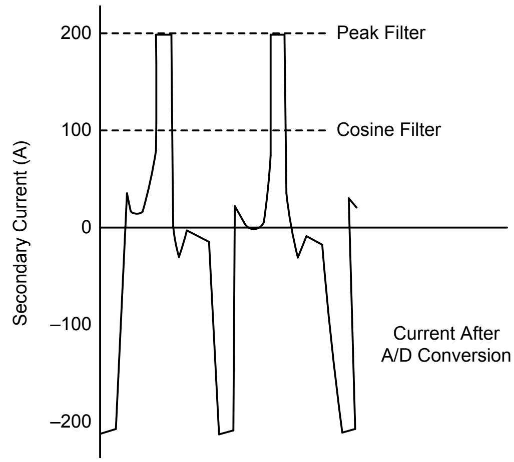

Fig. 9 Example LVMR Current Measurement During Saturated CT Conditions

Cosine peak adaptive filtering offers a convenient method to reduce CT size and cost when used in the following fashion:

1. All 50 elements use the cosine peak adaptive filtering method.
2. Every 51 element is accompanied by a backup 50 element.
3. The backup 50 element pickup is set above inrush currents and below 30 times the pickup current (the instantaneous trip region).
4. The backup 50 element pickup time is set less than the 51 element definite pickup time (e.g., 0.1 seconds for Time Dial 1, as shown in Fig. 7).
5. For simplification, at this particular facility all backup 50 element pickups are set at 30 times the 51 pickup. All backup 50 element pickup times are set at 4 cycles (0.080 seconds).

E. CT Sizing for Motor Thermal Elements

The 49 and 46 elements must have accurate metering for motor inrush, thermal overload, and unbalance conditions. Motor inrush conditions typically range between 5 and 15 times FLA, thermal overload conditions typically range between 2.5 and 10 times FLA, and unbalance is 5 to 80 percent between the phases depending on the motor and load characteristics. Considering the largest inrush condition provides the criterion shown in (8).

$$V_K > 15 \cdot \left(\frac{FLA}{CTR}\right) \cdot (R_{CT}) \tag{8}$$

From Fig. 5 and Fig. 6, the largest FLA/CTR ratio that will be selected is 1 for a 1 A CT and 5 for a 5 A CT (1/0.2). These assumptions reduce (8) into (9) for a 1 A CT and into (10) for a 5 A CT.

$$V_K > 15 \cdot R_{CT} \tag{9}$$

$$V_K > 75 \cdot R_{CT} \tag{10}$$

F. CT Sizing for Time-Overcurrent Elements

The equation identified for the CT manufacturer must prevent saturation during any part of a standardized time-overcurrent curve. For this project, the authors chose an IEC Class A standard inverse overcurrent (51) curve (curve type C1). As shown in Fig. 7, these 51 elements revert to a definite time at 30 times secondary current. It is therefore necessary to ensure that the CT does not saturate below 30 times secondary currents.

Equation (11) calculates the voltage knee point requirement to ensure nonsaturation up to the definite time portion of the IEC standard inverse time overcurrent curve.

$$V_K > 30 \bullet I_{pickup} \bullet R_{CT} \tag{11}$$

Note that X/R ratios affecting the dc offset are ignored at this stage to simplify the criteria for CT selection. Testing using worst-case X/R ratios, as described later in this paper, justifies these simplifications.\

The LVMR in question limits the 51 pickup setting to 8 A for a 1 A CT and 32 A for a 5 A CT. If the 51 pickup setting current is unknown, the worst-case V_K sizing criteria is shown in (12) for a 1 A CT and in (13) for a 5 A CT.

$$\begin{aligned} V_K &> 30 \bullet 8\,\text{A} \bullet R_{CT} \\ V_K &> 240 \bullet R_{CT} \end{aligned} \tag{12}$$

$$\begin{aligned} V_K &> 30 \bullet 32\,\text{A} \bullet R_{CT} \\ V_K &> 960 \bullet R_{CT} \end{aligned} \tag{13}$$

At this point, it is worthwhile to stop and check the credibility of (12) and (13) as criteria for CT sizing. Based on the authors' experience, (12) can be accomplished with approximately a 30 VA 5P10 CT, and (13) can be accomplished with approximately a 120 VA 5P10 CT. This is a problem because the MCC drawers can only accommodate the size and weight of about a 10 VA 5P10 CT (which weighs about 12 lbs and is about 6 in tall). A 120 VA CT weighs over 100 lbs.

G. Protecting the CT From Damage Creates a Convenient CT Sizing Criterion

The need to prevent CT damage requires 51 settings to be much lower than the 8 A and 32 A of (12) and (13). Referring back to the damage curves of 1 A and 5 A CTs, the 1 A CTs in consideration are permanently damaged at amperages exceeding 1.2 A for prolonged periods. The 5 A CTs in consideration are permanently damaged at amperages exceeding 6 A for prolonged periods. These amperage levels set a practical upper limit for the 51 pickup settings of both the 1 A and 5 A CTs at 1.2 A and 6 A, respectively. To ensure protection during highly saturated conditions, 50 elements are then set at 36 A and 180 A, respectively.

Because of the cosine-filter-protected 50 element, CT lower limits can be selected via (14) and (15).

$$\begin{aligned} V_K &> 30 \bullet 1.2\,\text{A} \bullet R_{CT} \\ V_K &> 36 \bullet R_{CT} \end{aligned} \tag{14}$$

$$\begin{aligned} V_K &> 30 \bullet 6\,\text{A} \bullet R_{CT} \\ V_K &> 180 \bullet R_{CT} \end{aligned} \tag{15}$$

By standardizing on 50 and 51 elements, the authors were able to choose (14) as the V_K-versus-R_{CT} criterion for CT sizing for the facility in question. To simplify CT selection criterion, all LVMRs have a 51 element set at 1.2 A to prevent CT damage. All LVMRs also have a 50 element set at 36 A to supplement the 51 element with the cosine peak adaptive filter protection.

Based on the authors' experience, (14) can be accomplished with approximately a 4 VA 5P10 CT, whereas (15) can be accomplished with approximately a 20 VA 5P10 CT. The 1 A CT will fit in the drawer, whereas the 5 A CT will not.

V. CT SECONDARY AMPERAGE

As shown in in Fig. 5 and Fig. 6, a 5 A secondary CT works for a wider range of FLA settings than a 1 A secondary CT. This reduces the amount of time required to select, test, and validate the CTR. Furthermore, a 5 A CT provides a higher resolution metering accuracy under low-load conditions. A 5 A CT offers more flexibility in pickup settings ranges in the LVMR, and 5 A CTs are more adaptable during commissioning and startup when loads' FLAs are being changed. Because of the wider selection range of CTR/FLA, fewer models of 5 A CTs would be required for the system in question. Unfortunately, all of the 5 A secondary CTs that satisfied the requirements for V_K and CTR were too large to fit into the IEC drawers.

The 1 A CT has a very narrow range of CTR. The 1 A CT that meets the V_K requirements fits into the IEC drawers. The 1 A CT is also more economical. Therefore, a 1 A secondary CT was selected for this low-voltage application.

VI. VALIDATION

This section shows how the CT voltage knee point selection criterion in (14) was validated for a range of 1 A CTs using hardware-in-the-loop simulations with an actual LVMR. The test setup shown in Fig. 4 was used for this procedure.

The source modelled in Fig. 4 is at 380 V with a source impedance (Z_{source}) calculated to provide the maximum assumed fault current of 20 kA. The inductance and resistance of Z_{source} were set to the worst-case ratio (X/R) of 17. Batteries of tests were run to confirm that the simplified CT selection assumptions work for worst-case dc offset and fault conditions.

For each test, a battery of faults at different times in the voltage waveform was applied at 20 kA to verify the operation of the 51P element in the LVMR. In all cases, a 50 element with cosine peak adaptive filtering was set at a 30 A secondary pickup and a 0.1-second pickup time. 51P elements were set to 1.0 A as the worst representative case allowed. All tests were run with the LVMR having FLA settings of both 0.5 A and 1.0 A (the boundary conditions of Fig. 5).

Nine different models of CTs were used in the tests. These CTs had a V_K ranging from 20 to 60 V and an R_{CT} ranging from 0.9 to 15 Ω. Only 1 A CTs were tested.

During the tests, a real-time digital simulator sent the start of the fault time to the LVMR via a digital 24 V signal. The LVMR recorded the time between the fault and trip in an onboard sequence of events recorder. If the LVMR tripped within 2 seconds, the test was considered to pass and is shown by an *X* in Fig. 10. If the LVMR tripped after a 2-second interval, the test was considered to be delayed and is shown by a circle with a dot in Fig. 10. Any fault event for which the LVMR did not trip was considered to be failed and is shown by a circle in Fig. 10.

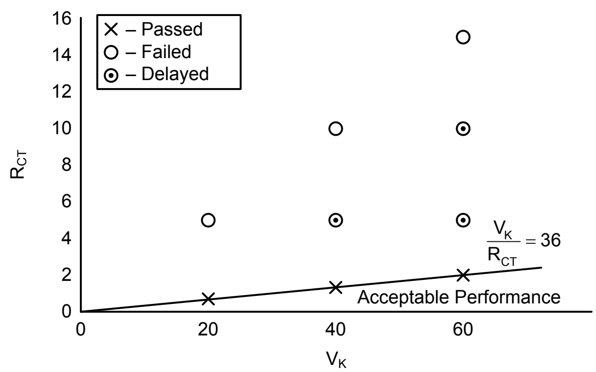

Fig. 10 LVMR Responses for Different Levels of CT V_K and R_{CT}

As shown in Fig. 10, this testing proved that the assumed criterion of (14) is acceptable for all of the CTs at this facility. Note that CTs with half the required V_K still provided enough energy to the bipolar peak detector to successfully operate, with some small delay.

VII. CT SELECTION PROCEDURE

This section describes a simplified process for evaluating CT models for any application using a Rogowski-style LVMR. The process for a one-time development effort is as follows (this process cannot be automated):

1. Derive a set of reasonable CTR boundary conditions, such as those shown in Fig. 5 or Fig. 6.
2. Derive a set of V_K versus R_{CT} mathematical relationships, such as those shown in (14) and (15).
3. Use cosine peak detector logic, as shown in Fig. 8, and a 50 element setting calculated by (11).
4. Gather a large set of CT saturation curves with a wide range of CTR values from a trusted CT manufacturer. Give the CT manufacturer the desired CTR ranges and equations relating V_K to R_{CT}.
5. Validate the simplified V_K versus R_{CT} mathematical relationships with a real-time modelling environment, a three-phase amplifier, and the actual LVMR. Model the worst-case X/R to affect dc offsets and the worst-case bus fault levels.
6. Determine which CTs provided by the manufacturer pass the criteria. This becomes an approved-CT selection list.

The process for a repeated CT selection effort is as follows (this process can be automated):

1. Identify the load FLA.
2. Select a CT from the approved-CT list which has an acceptable CTR.
3. Confirm that the selected CT meets the V_K versus R_{CT} mathematical relationship.

VIII. EXAMPLE CT CALCULATION

The following procedure demonstrates how to select a CT using the CT selection procedure from the previous section. This example will use Fig. 5 and (14) to make a 1 A CT selection. The example load has an FLA of 400 A.

1. Collect performance information from a range of likely 1 A CTs. Table I shows the CTs used for this example.
2. Calculate the minimum and maximum CTR according to Fig. 5.

   Maximum CTR = 2 • FLA = 800:1.

   Minimum CTR = FLA = 400:1.
3. Select a CT from Table I that meets the CTR criteria. CT Numbers 3 and 6 with 500:1 CTR meet the criteria in this example.
4. Confirm that the CT meets the voltage knee point curve requirements of (14).

   CT Number 3: V_K/R_{CT} = 36.58.

   CT Number 6: V_K/R_{CT} = 10.18.

Only CT Number 3 has the sufficient V_K/R_{CT} ratio (i.e., greater than 36), thus CT Number 3 is chosen in this example.

TABLE I
EVALUATED CT MODELS

CT Number	Parameters	CTR	Voltage Knee Point (V)	CT Resistance (Ω)
1	10 VA 5P10	1000:1	129	4.26
2	3 VA 5P10	200:1	36	0.9
3	3 VA 5P10	500:1	75	2.05
4	3 VA 5P10	2000:1	275	8.7
5	3 VA 5P10	200:1	43	4.4
6	3 VA 5P10	500:1	56	5.5
7	3 VA 5P10	2000:1	147	20.6

IX. CONCLUSIONS

The following conclusions can be drawn from this paper:

1. The 1 A CT is preferable to the 5 A CT in this application because of its smaller size. A 5 A CT cannot fit into the compact drawers and still meet the V_K-versus-R_{CT} criteria.
2. For the LVMR in question, five-ampere secondary CTs are generally easier to select than 1 A CTs because they work for a wider range of FLA, provide higher resolution metering accuracy under low-load conditions, and offer more flexibility in pickup settings ranges.
3. The CT selection procedure in this paper is applicable to all IEC and IEEE classifications of protection-class CTs because it relies on the first-principle behaviors of CTs rather than a standard.
4. For a 1 A CT used with this LVMR, a CTR must be selected to keep the secondary currents between 0.5 and 1 A during normal operation.
5. CT size and cost are reduced by restricting the LVMR 51 element upper limit settings and using backup 50 elements that contain cosine peak adaptive filtering.
6. Providing a CT manufacturer a CT ratio and an equation relating V_K to R_{CT} is a simple and reliable method for finding CTs of the least cost, smallest size, and required performance.
7. For the application in question, the necessity to protect the CTs from damage required a standardized 51 element. CTs sized for all possible LVMR 50 and 51 setting ranges would have required a much larger CT. The CTs selected ensure proper 49 and 46 element behavior.
8. For the application in question, the authors standardized on 50 and 51 elements to simplify the CT selection criterion. All LVMRs have a 51 element set at 1.2 A to prevent CT damage. All LVMRs also have a 50 element set at 36 A to supplement the 51 element with the cosine peak adaptive filter protection. Additional 51 and 50 elements can be set in the LVMRs to provide feeder coordination.
9. For the application in question, the authors validated that the V_K-versus-R_{CT} criterion of (14) works with a sufficient safety margin for fault conditions less than 20 kA and an X/R less than 17.

X. NOMENCLATURE

46	Phase-unbalance protection element.
49	Motor thermal protection element.
50	Instantaneous protection element.
51	Time-overcurrent protection element.
I_E	CT excitation current.
I_P	Primary CT current.
I_{pickup}	Relay secondary current pickup setting.
I_S	Secondary CT current.
MCC	Motor control center.
MCCB	Molded-case circuit breaker.
R_{CT}	CT resistance.
V_{CT}	Secondary CT internal voltage.
V_K	Saturation knee point voltage.
V_T	Secondary CT terminal voltage.
X/R	Transient decay time constant of the dc offset currents that occur naturally in all power systems.
Z_C	Conductor impedance (burden).
Z_{CT}	CT impedance (burden).
Z_R	LVMR impedance (negligible burden).
Z_{source}	Thevenin impedance of power system at point of LVMR connection.

XI. REFERENCES

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XII. VITAE

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