

# An Analysis and Protection Strategy for Series-Connected Converter Transformer

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# AN ANALYSIS AND PROTECTION STRATEGY FOR SERIES-CONNECTED CONVERTER TRANSFORMERS

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**Abstract** – This paper introduces a transformer protection strategy tailored for series-connected converter input transformers in a high-power industrial drive system at a remote mining facility. The system comprises 3 dry-type transformers with series-connected primary windings feeding an 18-pulse rectifier. Two consecutive transformer overheating failures, shortly after planned maintenance, prompted a detailed investigation into the cause of the failures. While conclusive event data were unavailable, the investigation concluded that the presence of eddy currents in nonlaminated components of the transformer structure from excessive stray flux due to transformer saturation likely caused the overheating; the most likely cause of transformer saturation is unbalanced load conditions due to a power electronics malfunction. The proposed protection scheme monitors voltage and current balance across transformer pairs, evaluating fundamental, root-mean-square, and harmonic components. A fixed quantity comparison method is employed to detect deviations in voltage and current magnitudes. Additionally, the system monitors abnormal harmonic levels, particularly low-order harmonics, which are strong indicators of core saturation. The system also includes high-resolution waveform capture and load profiling for improved visibility of the drive system.

**Index Terms**—Series-connected transformers, converter transformers, ANSI 60, harmonic monitoring, transformer saturation, power electronics, stray flux, transformer overheating

## I. INTRODUCTION

A large-scale, open pit, hard rock gold mine operates a fixed plant concentrator designed to process 2300 tons per operating hour (TPOH) of ore at a grade range of 0.8 to 1.2 grams per ton in a remote northern location. The grinding process is facilitated by four large mills, set up as two parallel lines, each one having one dual-pinion semi-autogenous grinding (SAG) mill that is 20 ft in length by 36 ft in diameter and one dual-pinion ball mill that is 40.5 ft in length by 26 ft in diameter. In the SAG mill, ore is ground to a particle size range between 2 and 200 mm, and further reduction is achieved in the ball mill to the targeted size of 130 microns.

Each mill drive system consists of two 7.5 MW synchronous low-speed motors with a rated speed of 180 rpm, directly coupled to the mill, with a torque limiting coupling in place of an air clutch. A single 18-pulse variable-speed drive is used to control both

synchronous machines, with one acting as the leader and the other as the follower. The drive uses three parallel active rectifier units (ARUs) feeding a common direct current (dc) bus providing power for the two inverter units (INUs), one controlling each motor.

Three series-connected power transformers provide isolation from the network, voltage adaptation, and vector shift for the converter input. One converter transformer feeds each ARU. The transformers are each 6534 kVA, 4796/2923 kV; dry-type; air-cooled; and constructed of three separately wound coils consisting of a copper primary winding with an aluminum secondary winding, which are epoxy-treated using vacuum pressure impregnation. The phase shifts of the secondary windings of the three transformers are 0, +20, and –20 degrees to feed the 18-pulse rectifier system. Figure 1 shows a basic diagram of the mill drive system electrical power arrangement.

Since grinding is an initial stage in the mineral recovery process, for which there is no redundancy or ability to bypass, unplanned downtime of only one mill results in a 50 percent reduction of plant throughput. Additionally, as continual optimizations have resulted in throughput increases to an average of 3200 TPOH, unplanned downtime results in even greater production loss. As a result, the reliability and high availability of the four grinding mills are crucial to meeting the ever-increasing production targets.

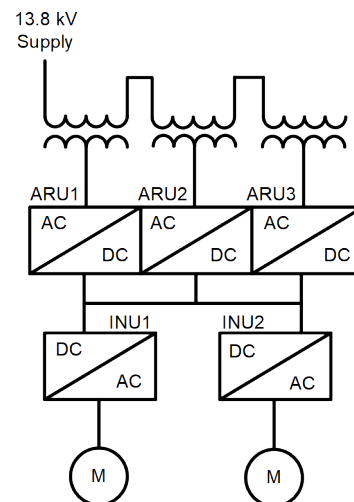


Figure 1 Drive System Simplified One-Line Diagram

## II. BACKGROUND AND PROBLEM STATEMENT

On August 22, 2023, 13 hours after SAG Mill 1 was restarted, following a planned shutdown, the mine experienced the failure of Converter Transformer 3 (T3). The failure resulted in a fire within the transformer, which destroyed the U-phase winding and caused superficial damage to V-phase and W-phase windings. Section III describes the construction of the transformers and designations of the windings.

A spare converter transformer was installed in the mine to replace the failed transformer. On August 25, 2023, the mine then experienced a second failure of SAG Mill 1 T3, 19 hours after restarting. The failure resulted in a fire that destroyed the V-phase and W-phase windings, with superficial damage to the U-phase windings, as shown in Figure 2.



Figure 2 Damage Due to Second Failure

The investigation that followed revealed that neither transformer failure was the result of any defect with the transformers themselves or the primary power or protection systems. Additionally, by analyzing the coil temperature trends that were available via the coil temperature sensors and data historian software used by the mine, it was discovered that on both occasions the transformer coils did not reach overtemperature conditions until after the fire broke out.

The investigation concluded that both failures had been the result of a defect, due either to a faulty component or human error, caused when components had been replaced in the ARUs during the planned maintenance shutdown immediately preceding the transformer failures. The defect resulted in a misfiring of the integrated gate-commutated thyristors (IGCT) of the ARUs and either harmonic or dc injection in the secondary winding of T3. This disrupted the primary voltage divider, which is normally balanced evenly across the three transformers due to their equivalent impedances and loads. The unbalanced primary voltage across the three transformers resulted in core saturation of T3, which caused stray flux and then eddy currents in metal components external to the core. The eddy currents caused excessive heating particularly in the aluminum bus exiting the secondary winding of the coils, which melted, dripping onto the epoxy coating of the coils and setting them on fire.

Both the in-service and spare transformer were critically damaged. Due to its unique specification and application, SAG Mill 1—and hence an entire grinding line—was inoperable for

more than 23 days while a new transformer was manufactured. This resulted in the largest production loss in the history of the mine. Since none of the existing protection and control systems in place were able to detect the fault, the mining operation started developing a custom transformer protection system specifically capable of detecting the fault conditions that led to the failure.

## III. SYSTEM ARCHITECTURE AND TRANSFORMER CONFIGURATION

The drive system consists of three dry-type converter input transformers (T1, T2, and T3) with their primary windings connected in series. T1, the transformer located farthest upstream, is connected to a 13.8 kV substation bus. Under normal operating conditions, the voltage is divided evenly across the three primary windings. In essence, the three transformers form a voltage divider across three primary windings due to their respective equivalent impedances (transformer plus load). Each transformer feeds one ARU. See Figure 3 for a high-level three-line diagram of the primary and secondary windings of the converter transformers.

The advantages of applying multiple transformers with series-connected primary windings over a converter input transformer with multiple secondary windings are that current is forced to divide equally among the secondary windings without the need for interphase transformers and the design of each individual transformer is kept simple [1].

The 13.8 kV feeder that feeds the converter transformers is protected by a feeder protective relay providing phase and ground overcurrent protection.

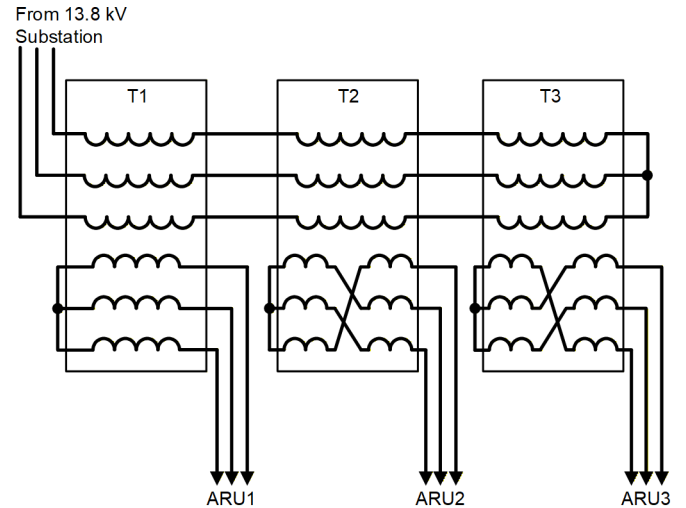


Figure 3 Drive Input Transformer Three-Line Diagram

Each transformer is constructed on a standalone three-legged core. The windings are connected per IEC vector groups [2], summarized in Table I.

| TABLE I<br>IEC TRANSFORMER VECTOR GROUPS |          |         |
|------------------------------------------|----------|---------|
| T1                                       | T2       | T3      |
| IIIy0                                    | IIIz0:40 | Yz11:20 |

The vector groups are interpreted as follows:

- **Illy0:** The primary consists of three isolated series connections, and the secondary is an ungrounded wye connection.
- **Illz0:40:** The primary consists of three isolated series connections, and the secondary is an ungrounded zigzag connection, which lags the primary by 0 hours and 40 minutes. Since 1 hour is 30 degrees, 40 minutes is 20 degrees.
- **Yz11:20:** The primary is ungrounded wye-connected, and the secondary is an ungrounded zigzag connection, which lags the primary by 11 hours and 20 minutes. 11 hours is 330 degrees and 20 minutes is 10 degrees. 340 degrees lagging is 20 degrees leading.

The corresponding phase shifts are shown in the phasor diagrams in Figure 4, captured during normal operation.

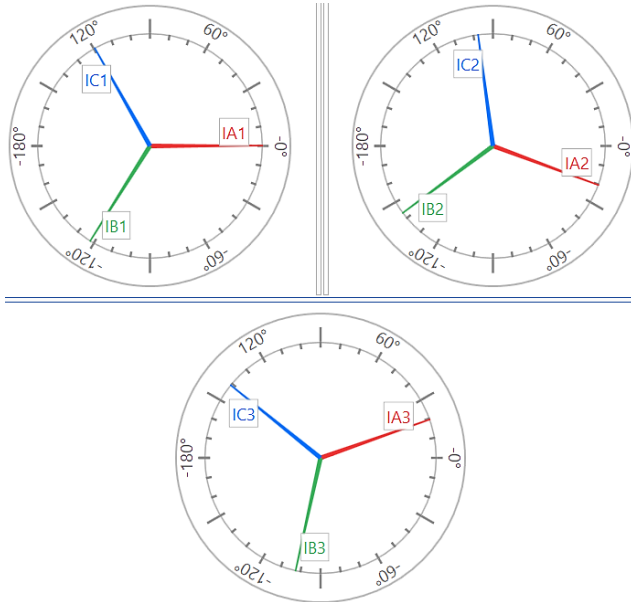


Figure 4 Transformer Current Phase Shifts

The primary sides of all three transformers are wound identically with the only difference being a connecting link, which needs to be placed on the neutral of the T3 primary winding to complete the wye (star) connection. In all three transformers, the primary side consists of two separate windings with taps to allow for off-load tap changing. For example, the T1 U-leg primary side consists of windings T1-1U1 and T1-1U2.

As shown in Figure 5, Transformer T1 has a single winding on its secondary, while Transformers T2 and T3 have two windings for a zigzag connection.

Transformers T2 and T3 are interchangeable, as they are wound identically to each other on both primary and secondary, and only differ in placement of connecting links.

- **Primary:** There is no connecting link on T2 (for Ill winding connection), but a connecting link is required on T3 (for wye connection).
- **Secondary:** A different connecting link placement creates the desired phase shift.

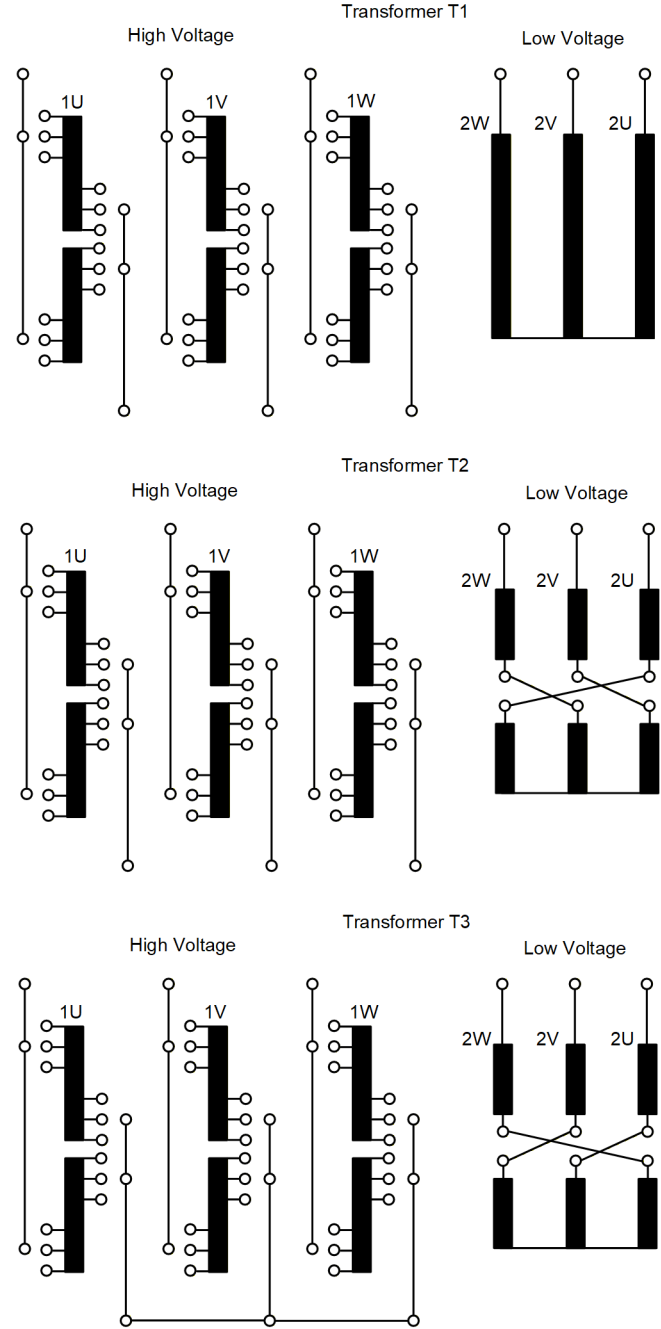


Figure 5 Transformer Winding Connections

#### IV. PROTECTION PHILOSOPHY AND DESIGN OBJECTIVES

##### A. Voltage and Current Balance (ANSI 60) Elements

The three transformers are designed with identical impedances connected in series on the primary side. This connection type creates a voltage divider network on the primary side. However, the voltage divider is not only related to transformer impedances; it is also impacted by the load impedance, as shown in Figure 6.

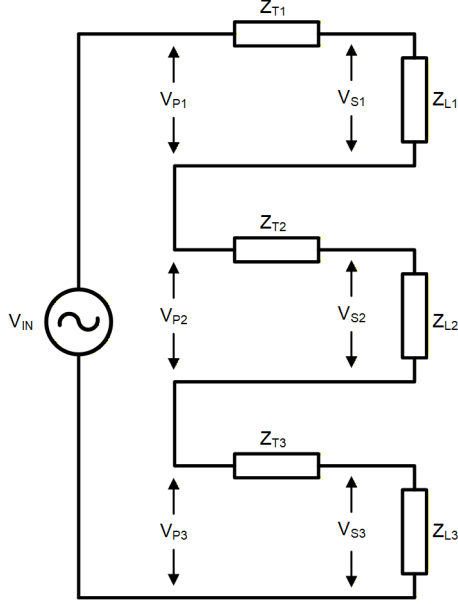


Figure 6 Equivalent Circuit for Voltage Divider

The following legend applies to Figure 6:

- $V_{IN}$  is the source voltage.
- $V_{P1}$ ,  $V_{P2}$ , and  $V_{P3}$  are the voltages reflected on the primary windings of T1, T2, and T3, respectively.
- $V_{S1}$ ,  $V_{S2}$ , and  $V_{S3}$  are the voltages reflected on the secondary windings of T1, T2, and T3, respectively.
- $Z_{T1}$ ,  $Z_{T2}$ , and  $Z_{T3}$  are the simplified equivalent impedances of T1, T2, and T3, respectively, as seen from the primary side (ignoring the shunt magnetization branch).
- $Z_{L1}$ ,  $Z_{L2}$ , and  $Z_{L3}$  are the equivalent impedances of the connected load as seen from the primary side.

Since the transformers have matched impedances,

$$Z_{T1} = Z_{T2} = Z_{T3} = Z_T \quad (1)$$

The voltage divider equations yield the following:

$$V_{Pn} = \frac{Z_T + Z_{Ln}}{3Z_T + (Z_{L1} + Z_{L2} + Z_{L3})} V_{IN} \quad (2)$$

where  $n = 1, 2$ , or  $3$  corresponding to Transformer T1, T2, or T3, respectively.

In a balanced load condition,

$$Z_{L1} = Z_{L2} = Z_{L3} = Z_L \quad (3)$$

Combining (2) and (3), the voltage divider for a balanced load condition becomes:

$$V_{Pn} = \frac{Z_T + Z_L}{3Z_T + 3Z_L} V_{IN} = \frac{1}{3} V_{IN} \quad (4)$$

Now, consider an unbalanced load scenario where the load impedances are not equal; for example, a 5 percent increase in apparent impedance of the load on T3.

$$Z_{L1} = Z_{L2} = Z_L, \quad Z_{L3} = 1.05Z_L \quad (5)$$

$$V_{P1} = V_{P2} = \frac{Z_T + Z_L}{3Z_T + 2Z_L + 1.05Z_L} V_{IN} = \frac{Z_T + Z_L}{3Z_T + 3.05Z_L} V_{IN} \quad (6)$$

$$V_{P3} = \frac{Z_T + 1.05Z_L}{3Z_T + 3.05Z_L} V_{IN} \quad (7)$$

$$V_{P3} > V_{P1} \text{ and } V_{P3} > V_{P2} \quad (8)$$

It can be concluded that any unbalance between the loads on T1, T2, and T3 will disrupt the voltage divider on the primary side. Although transformers are subject to variations in transformer impedance of up to 10 percent of the specified impedance for dry-type transformers [3], it is expected that this variation in transformer impedances would have a negligible impact to the voltage divider circuit since the impedances are dominated by the load impedance (i.e.,  $Z_{Ln} \gg Z_{Tn}$ ).

It is critical to maintain the voltage divider balance on the primary of the transformers to keep each winding within its rated voltage since sustained overvoltage can lead to transformer overexcitation [4].

The aforementioned discussion and calculations consider balanced 60 Hz, three-phase load on all three transformers, with one transformer seeing a different load. It is unlikely that failed power electronics will have a significant impact on the 60 Hz component of the signals, and therefore, it is critical to monitor for fundamental (filtered for 60 Hz component only), rms (containing 60 Hz and harmonic components), and select individual harmonic components on each of the phase-to-phase voltages.

To measure unbalance between transformers, it is sufficient to measure the secondary side voltages for simplicity of design and cost reduction. The phase-to-phase voltages on the primary windings of each transformer are different due to the series-connected primaries, while the phase-to-phase voltages on secondary windings of three transformers are equal under normal operating (balanced load) conditions. Therefore, potential transformers (PTs) of the same rating can be used to measure voltages on the secondary of the transformers.

In addition to monitoring for voltage balance (ANSI 60), it is beneficial to expand this element to detect balance in fundamental and rms components of per-phase currents. It is expected that under normal operating conditions, all three 6-pulse rectifiers will draw the same magnitude current and any abnormality within the drive system will lead to a loss of balance between currents drawn from the three transformers.

Each input transformer in this application feeds a 6-pulse rectifier, which forms an overall 18-pulse rectifier system. Under normal operation, it is expected to observe higher-order and balanced harmonic current drawn by the rectifier unit. In the case of 18-pulse rectifiers, only harmonics of 17, 19, 35, 37, and greater orders are theoretically present in the input current. However, because each of the three transformers is feeding a 6-pulse rectifier, harmonics of orders 5, 7, 11, and 13 are also expected to be present [5] in the individual transformer secondary currents. In this paper, harmonics of orders 5, 7, 11,

and 13 are referred to as characteristic harmonics (of a 6-pulse rectifier).

The voltage harmonic balance elements were implemented for characteristic harmonics that are expected to be present at the input of each 6-pulse rectifier under normal operation.

Balance elements were implemented to run for each pair of transformers: T1-T2, T2-T3, and T3-T1.

There are two options for defining the balance element characteristic: a fixed quantity or a fixed percentage, as shown in Figure 7 and Figure 8, respectively.

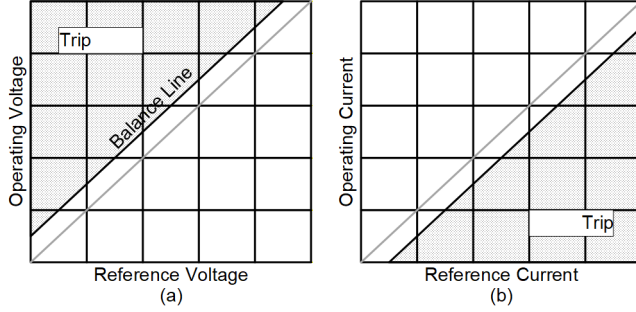


Figure 7 Fixed Quantity Balance Element

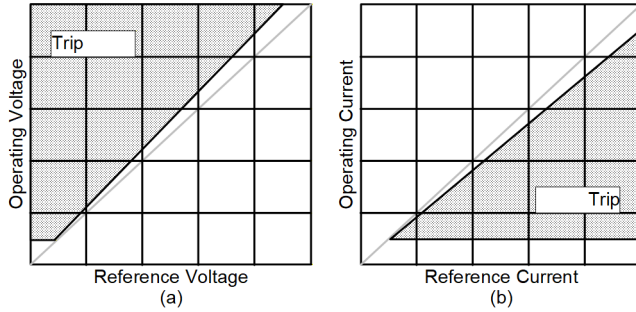


Figure 8 Fixed Percentage Balance Element

The operating and reference quantities are any of the phase-to-phase voltages or per-phase currents. The operating quantity refers to the measurement from the first transformer, and the reference quantity is the measurement from the second transformer in each pair. For example, for T1-T2 VAB fundamental balance logic, the operating quantity is T1 VAB fundamental magnitude and the reference quantity is T2 VAB fundamental magnitude.

The advantage of a fixed percentage balance element is its self-adjusting sensitivity where the element is more sensitive for lower operating quantities but requires caution to enable the element only when a minimum magnitude of the operating quantity is available to avoid unintended operation due to high sensitivity in the low magnitude region. The minimum operating magnitude supervision is represented as a no-trip region for low operating quantities in Figure 8. The fixed percentage characteristic is desirable when the reference quantity is stable during abnormal conditions and sufficiently large (close to 1 per unit) to prevent division-by-zero errors.

In this application, during any abnormalities, it is expected that the voltages on the two transformers connected to healthy rectifiers will be stable and close to 1 per unit. However, there is high variability with current measurements, as current drawn by the rectifiers will vary during different loading conditions, and hence, a sufficient reference quantity is not guaranteed to be present. As a result, a fixed quantity balance element is preferred over a fixed percentage balance element for this application.

The trip region is defined as the region above the balance line for voltage balance elements, whereas it is defined as the region below the balance line for current balance elements. If a faulty ARU was drawing less current than the two healthy ARUs, the transformer feeding the faulty ARU would appear to be at a higher impedance than the others in the primary voltage divider and therefore have greater voltage applied to its primary winding. Hence the affected transformer is expected to experience undercurrent and overvoltage on its secondary winding.

The balance element is implemented by establishing the following difference equations:

$$DV_{ABfundT12} = V_{ABfundT1} - V_{ABfundT2} \quad (9)$$

$$DV_{ABrmsT12} = V_{ABrmsT1} - V_{ABrmsT2} \quad (10)$$

$$DV_{ABHARMMnT12} = V_{ABHARMMnT1} - V_{ABHARMMnT2} \quad (11)$$

$$DI_{AfundT12} = I_{AfundT1} - I_{AfundT2} \quad (12)$$

$$DI_{ArmsT12} = I_{ArmsT1} - I_{ArmsT2} \quad (13)$$

These equations are for VAB (similar to VCB) and IA (similar to IB and IC) unbalance on the T1-T2 transformer pair, and similar magnitudes are computed for the T2-T3 and T3-T1 pairs. HARMMn refers to 5th, 7th, 11th, and 13th harmonic voltage magnitudes.

The phase-to-phase voltage and per-phase current magnitude differences are then compared with user-settable set points, and the output of each comparator is fed to an individual integrating timer prior to declaring an alarm. Note that the voltage balance element is designed to respond to high voltage characteristics as shown in Figure 7a, while the current balance element responds to low current characteristics as shown in Figure 7b. To create this difference in characteristics, the voltage balance comparator will operate when DV is above the set threshold, while the current balance comparator will operate when DI is below the negative threshold (threshold with a negative multiplier) set point.

Furthermore, the voltage-based balance elements are supervised with loss-of-potential (LOP) detection logic. The LOP logic is used to detect blown PT fuses and disable the balance elements that rely on voltage measurement inputs. Figure 9 shows a basic logic diagram of the fixed quantity balance element.

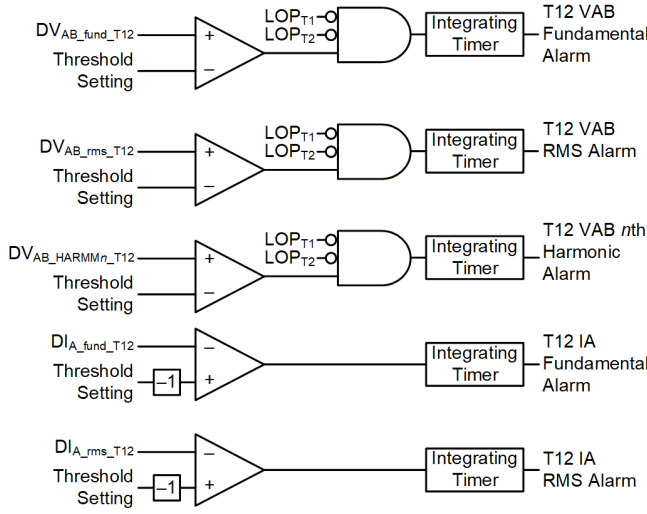


Figure 9 Balance Element Logic Diagram

### B. Presence of Harmonics

Transformer saturation can lead to the presence of lower-order harmonics, and the exact order of harmonic depends on if core saturation occurs on a full cycle or a half cycle.

Full-cycle saturation can occur during overvoltage conditions caused by unbalanced load between the three transformers. It is expected to see lower-order odd harmonics in the case of full-cycle saturation [6].

Half-cycle saturation can occur if a failed IGCT results in a half-wave rectification of current. The waveform shape of half-cycle saturation has similar characteristics to the typical waveform for transformer inrush. It is expected to see lower-order even harmonics in the case of a half-cycle saturation or transformer inrush [6].

Monitoring for the presence of abnormally high magnitude, low-order harmonics can indicate if the transformer is saturating and the type of saturation. Therefore, it is critical to consider a monitoring solution capable of measuring a wide range of harmonics to understand which magnitude of low-order harmonics is present under steady state at different loading conditions, and what levels of harmonics are considered abnormal and if action must be taken.

With the series connection of the primary windings of the three transformers, it is not expected to see the typical harmonics in the currents due to core saturation. Core saturation results in a reduction of the instantaneous reactance of the coil during parts of the power system cycle. When primary windings are connected in the typical parallel configuration, the nonlinear variation in instantaneous impedance results in harmonic current flow that is easily measurable. In this series configuration, the impedance of the windings of the two unsaturated cores will remain relatively linear and unchanging, which will greatly reduce the harmonic content of the current. It is expected that voltage measurements will be better able to identify overexcitation of a core, which will indicate stray flux that can heat nonlaminated components.

Per simulations and experiments on a 15 kVA transformer bank documented in [6]:

- In a half-cycle-saturation condition (transformer inrush), the second harmonic as a percentage of fundamental frequency current can exceed 60 percent.
- In a full-cycle-saturation condition (150 percent overvoltage), the 3rd, 5th, and 7th harmonics as a percentage of fundamental frequency current reached 49.2 percent, 21.7 percent, and 8.1 percent, respectively.

As discussed earlier, under normal loading conditions, harmonics of orders 5, 7, 11, and 13 are expected to be present at the secondary of the three transformers due to the nature of the power electronics.

Considering experimental measurement results from [5] for an 18-pulse rectifier composed of three 6-pulse rectifiers fed from two types of 4-winding transformers ( $Dy1z1 + 20^\circ z1 - 20^\circ$  and  $Dd0diii0 + 20^\circ diii0 - 20^\circ$ ), the following harmonic spectra peaks (percent of fundamental) were observed at 100 percent load at the input of each 6-pulse rectifier:

- 5th harmonic of approximately 20 percent
- 7th harmonic of approximately 12 percent
- 11th harmonic of approximately 4 percent
- 13th harmonic of approximately 2.5 percent

Harmonic alarm thresholds can be configured at the secondary of each transformer based on the experimental and simulation results discussed in [5] and [6]. Since characteristic harmonic content of 5th, 7th, 11th, and 13th orders are expected to be measured at the output of each converter transformer (the input of each 6-pulse rectifier) during normal operation, a critical alarm can be triggered for the presence of low-order noncharacteristic harmonic content of 2nd, 3rd, and 4th orders, and a different category of alarms can be triggered for higher-than-expected characteristic harmonic content. As discussed earlier, the series connection of transformer primaries greatly reduces measurable harmonic content of the currents, and therefore, observing the voltage measurements provides a better representation of the harmonic content and the overvoltage that can lead to core saturation. Both overcurrent and overvoltage harmonic triggers were employed in this application.

## V. HARDWARE AND INSTRUMENTATION

Since the primary function of the system is to monitor unbalance between transformers, metering-class current transformers (CTs) are deemed appropriate for this application. In scenarios where installation space is constrained, Rogowski coils may be employed as an alternative to conventional CTs. The flexible, rope-style Rogowski coils are particularly advantageous for accommodating tight spatial configurations.

For voltage measurement, voltage transformers (VTs) with suitable voltage ratings must be retrofitted on the secondary terminals of the transformer. Alternatively, existing VTs may be used to provide the necessary voltage-sensing functionality.

The most effective approach to measure volts per turn imposed on the secondary winding is measuring the voltage directly across each secondary winding. Wye-connected VTs with a grounded primary neutral would not provide reliable information due to the ungrounded neutral connection of the converter transformers. To obtain reliable measurements, the VT primary neutral needs to be bonded to the ungrounded neutral

point of its respective converter transformer. This VT connection was deemed to be unsatisfactory, as bonding of the VT and converter transformer neutrals would compromise the neutral insulation, resulting in greater exposure to failure of the insulation. It was ultimately decided to use the available line-to-line voltage measurements from existing open delta-connected VTs instead of the added expense and complications of introducing new wye-connected VTs.

Figure 10 illustrates the connection scheme for the monitoring system with respect to the CTs and VTs.

The monitoring system consists of three power quality (PQ) meters, one per transformer, capable of extracting a wide range of harmonic quantities from the measured voltages and currents. Additionally, an automation processor capable of analog measurements, mathematical computations, and logic functions is utilized to derive fundamental frequency and rms quantities from current and voltage measurements.

Balance protection functions are implemented within the processor. The rms and fundamental phase-to-phase voltage and per-phase current balance elements are implemented using the analog quantities measured directly by the processor. The 5th, 7th, 11th, and 13th harmonic phase-to-phase voltage balance elements are implemented using the analog quantities measured by the PQ meters and transferred to the processor via communications. Table II summarizes the balance elements enabled for each transformer pair, as well as the total number of balance elements activated in the processor.

TABLE II  
BALANCE ELEMENTS PER TRANSFORMER PAIR

|                                            | Fundamental | RMS | 5th | 7th | 11th | 13th | Total |
|--------------------------------------------|-------------|-----|-----|-----|------|------|-------|
| VAB                                        | 1           | 1   | 1   | 1   | 1    | 1    | 6     |
| VCB                                        | 1           | 1   | 1   | 1   | 1    | 1    | 6     |
| IA                                         | 1           | 1   | –   | –   | –    | –    | 2     |
| IB                                         | 1           | 1   | –   | –   | –    | –    | 2     |
| IC                                         | 1           | 1   | –   | –   | –    | –    | 2     |
| Balance elements for each transformer pair |             |     |     |     |      |      | 18    |
| Balance elements enabled in the processor  |             |     |     |     |      |      | 54    |

The processor executes all 54 balance elements within a 4 ms processing cycle. However, the harmonic balance elements are subject to additional timing constraints because the analog quantities of the processor are acquired from external PQ meters.

- Nonsimultaneous source data updates: Each PQ meter updates its harmonic analog quantities once every 12 power system cycles (200 ms for a 60 Hz system); as a result, it is expected that the three PQ meters will update their quantities at different times.
- Communications latency: This refers to the time required for data to travel from the PQ meter to the processor, which contributes to overall timing performance. However, communications latency is not a critical constraint because high-speed detection is not essential for the balance element since unbalanced loading between transformers is expected to cause gradual heating rather than an immediate risk of damage, and in many cases, the power electronics control system can self-correct the unbalance.

To combat the timing constraints, integrating timers are implemented instead of traditional (definite-time) timers. In addition to offering better handling of intermittent input signals, integrating timers are more suitable when stress is cumulative, such as thermal stress caused by power electronics malfunction.

The harmonic overvoltage and overcurrent alarm triggers are implemented within the individual PQ meters. The overvoltage and overcurrent triggers are implemented as both absolute magnitude comparators and as percentage-of-fundamental comparators.

Once any of the configured alarms in either the processor or the PQ meters is picked up, the processor triggers a waveform capture at a resolution of 8 kHz with a specified prerecorded length. This capture can be retrieved as an IEEE Std C37.111-compliant [7] Common Format for Transient Data Exchange (COMTRADE) file for investigating conditions causing the event occurrence.

The use of a satellite clock for time synchronization enables all devices to coordinate time across the system, ensuring they all operate on the same time scale. This is crucial for accurate event logging, oscillography, and correct interpretation of fault events.

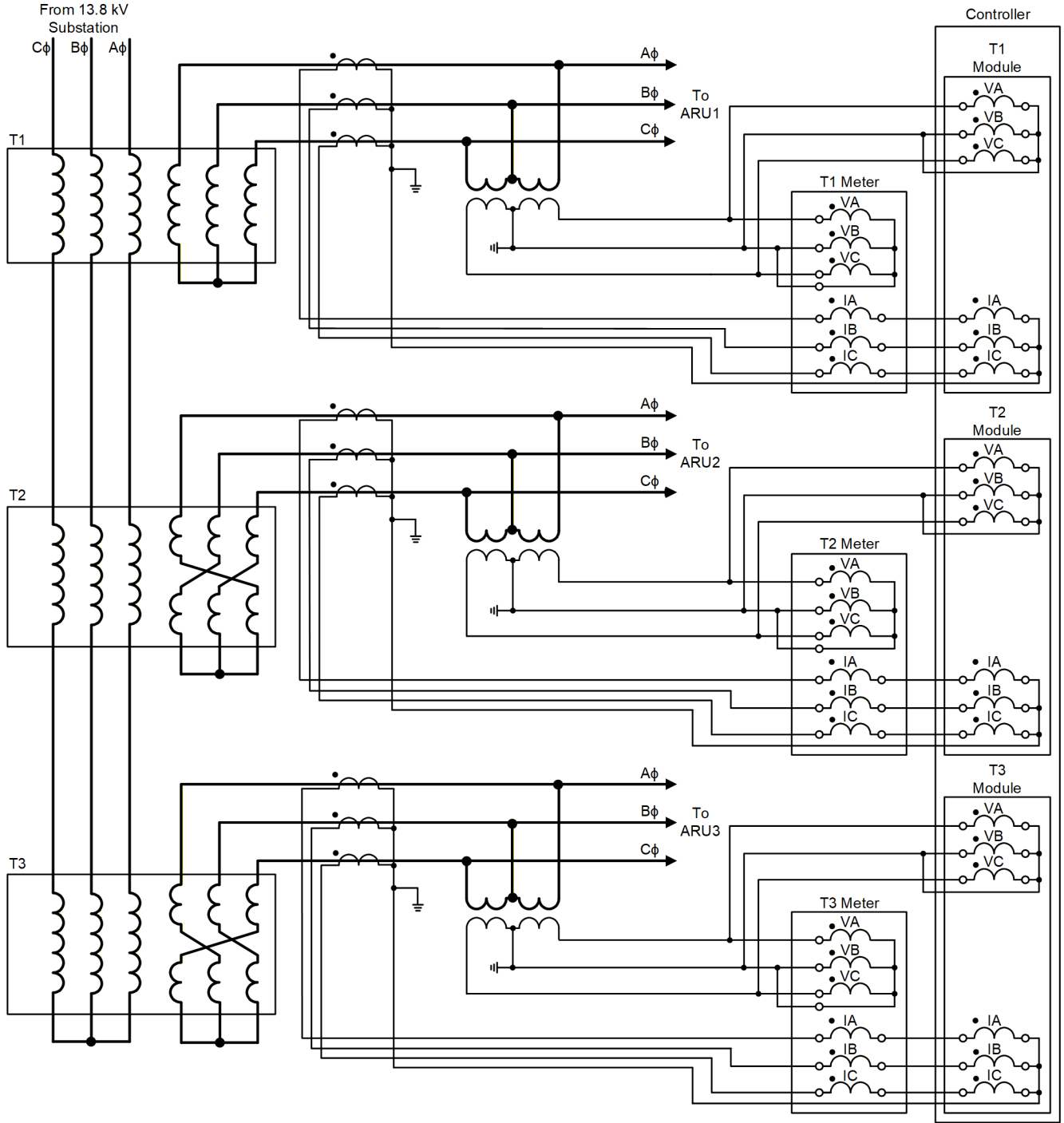


Figure 10 Monitoring System AC Diagram

## VI. NETWORK ARCHITECTURE

Efficient communications are essential for the reliable operation of the monitoring system. To achieve this, the network architecture incorporates multiple communications protocols to ensure seamless integration of all system components.

Harmonic measurements from the PQ meters are transmitted using a combination of the IEEE C37.118 synchrophasor data transfer protocol [8] and IEC 61850 Generic Object-Oriented

Substation Event (GOOSE) protocol [9], enabling real-time data transfer. The combination is used because the specific PQ meter model is limited to a maximum of four IEEE C37.118 data points. Fifth and seventh VAB and VCB harmonic magnitudes were transferred over IEEE C37.118 protocol while the remaining harmonic magnitudes were sent over IEC 61850 GOOSE protocol. Additionally, the PQ meters provide a discrete output wired to the digital input module of the processor. This output is asserted when configured alarms are triggered within the PQ

meters, and these alarms are used to initiate waveform capture in the processor.

Analog inputs to the processor are hardwired to capture CT and VT measurements, as detailed in previous sections. The metering modules communicate with the processing unit using EtherCAT® protocol [10]. Furthermore, the processor hosts a Modbus Transmission Control Protocol server to interface with a historian for long-term data storage.

Finally, all devices—including meters and the processor—synchronize their time references with the satellite clock using the Inter-Range Instrumentation Group time code format B (IRIG-B) protocol, ensuring precise time alignment across the system.

Figure 11 illustrates the defined network architecture.

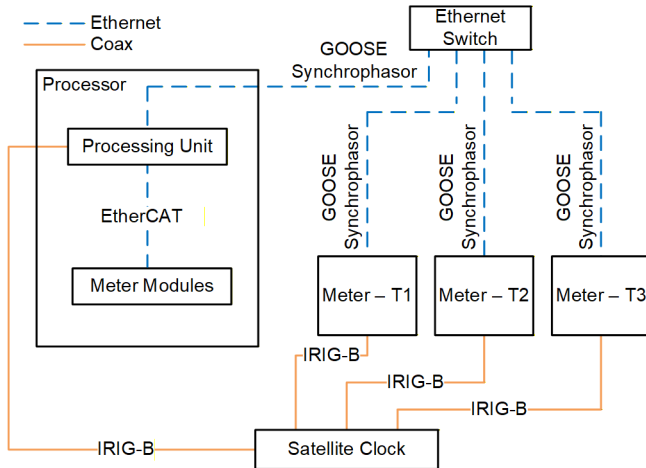


Figure 11 Network Architecture

## VII. COMMISSIONING AND OBSERVATIONAL PERIOD

The transformer monitoring system was commissioned in March 2025, followed by a data trending and observation period to fine-tune the initial threshold settings.

One key observation upon review of the data trends was the presence of higher voltage unbalance between the transformers under unloaded conditions as compared to normal (loaded) operation of the motors. The drive system was stopped and restarted by the process control system multiple times during the observation period, and with the drive in the idle state (unloaded), the rms and fundamental voltage difference on the secondary of the transformers exceeded 80 V primary (2.72 percent nominal), while under loaded condition, the voltage difference was consistently computed below 10 V primary (0.3 percent nominal). The 5th harmonic magnitude also temporarily exceeded 50 V primary during the shutdown and restart sequence. These readings were above the initial thresholds. Figure 12 shows a time versus fundamental voltage magnitude difference between T2 and T3, where a shutdown occurred, corresponding to the spike in the voltage magnitude difference.

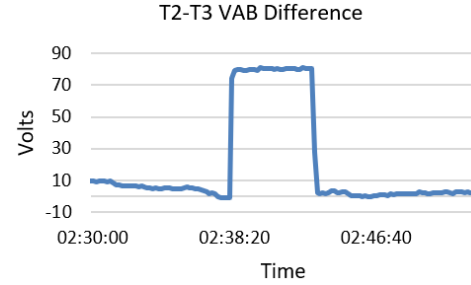


Figure 12 T2-T3 Fundamental VAB During Shutdown and Restart Sequence

There is a minimal chance of the voltage divider circuit (the primary winding connection of the three transformers) failing under low load conditions. This is because under low load, the impedances are dominated by the transformer internal impedances, which are expected to remain constant. As a result, no added benefit is gained from increasing the balance element thresholds (i.e., decreasing sensitivity) to address rare low load conditions. Instead, it was decided to block all balance elements under low load conditions (rms current < 5 percent).

During unloaded events, it was also observed that harmonic overcurrent alarms operating on the basis of percentage-of-fundamental quantities also produced nuisance alarms. The percentage-of-fundamental quantities become oversensitive in such situations due to minimal presence of the fundamental component (small denominator). It was therefore decided to supervise the percentage-of-fundamental-based alarm functions with a confirmed presence of a minimum fundamental magnitude.

## VIII. CONCLUSION

The investigation into consecutive failures of series-connected converter transformers at the remote mine revealed that conventional protection schemes are not designed for detecting conditions such as unbalanced loading and harmonic distortion caused by power electronics malfunctions. These conditions led to core saturation, stray flux, and severe overheating of nonlaminated components, ultimately resulting in catastrophic failures.

The proposed protection strategy aims to address these gaps through three key elements.

- Voltage and current balance: By monitoring fundamental, rms, and harmonic components of phase-to-phase voltages and per-phase currents across transformer pairs, the system detects deviations in the primary voltage divider caused by load unbalance.
- Monitoring for abnormal harmonic levels: The presence of abnormal low-order harmonics (e.g., second, third, and fourth) serves as a strong indicator of core saturation. Experimental and simulation data references guided threshold settings, with alarms implemented for both absolute magnitudes and percentages of fundamental quantities.
- High-resolution waveform capture and profiling: Continuous logging and event-triggered waveform capture provide visibility into transient and steady-state conditions, enabling root-cause analysis and fine-tuning of thresholds.

Commissioning and observation validated the system functionality, with adjustments made to block balance elements under low-load conditions and supervise percentage-based harmonic alarms to prevent nuisance alarms.

This proposed protection strategy can significantly improve reliability and availability of critical grinding circuits, mitigating the risk of extended downtime and production loss.

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## X. VITAE

Kamran Heshami, PEng, received his BAsC in electrical engineering from the University of Waterloo in 2015 and an MEng in electrical power engineering from the University of Waterloo in 2024. In 2015, he joined Schweitzer Engineering Laboratories, Inc. (SEL) as a project engineer in SEL Engineering Services, Inc. (SEL ES) in Toronto, Canada. He is a registered professional engineer in the Canadian provinces of Ontario, British Columbia, Manitoba, Saskatchewan, Newfoundland and Labrador, Nova Scotia, New Brunswick, and Prince Edward Island.

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