Analysis of Selected Motor Event and Starting Reports

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Abstract—**Motors are estimated to be one of the most numerous components of the electric power system. As the device that takes electrical energy and converts it to the mechanical energy needed to power processes, a motor that is unnecessarily out of service can bring an entire process to a halt, resulting in a significant loss of revenue. Conversely, the expense and time to replace a large motor damaged beyond repair mean that failing to quickly and dependably protect a motor is also a concern. Because there are many common failure modes (mechanical, electrical, thermal, and so on), root-cause analysis of a motor failure can be involved.**

This paper investigates several real-world events with data from both motor starting reports and event records. The data demonstrate the value of having devices capable of recording motor data during starts and fault events and of capturing and reviewing such data for the purpose of determining root cause. Lessons learned are shared to help in troubleshooting motor problems and to avoid potential misoperations in motor protection.

I. INTRODUCTION

Michael Faraday is well known for his discovery of electromagnetism and for developing the first electric motor. William Sturgeon, Joseph Henry, Andre Marie Ampere, and Thomas Davenport built on Faraday's discoveries to further develop direct current (dc) motors. Nikola Tesla was the first to invent the alternating current (ac) motor that is commonly used today in industry [1].

Since the invention of the electric motor, engineers have discovered numerous uses for this valuable tool. Today, electric motors are used in every industry, accounting for more than 50 percent of the electrical load in the United States. Most industrial consumers can attribute more than 85 percent of their electricity bill to electric motors [2].

Electric motors play an important role in the world as we know it. Without them, many conveniences we take for granted would not be available. Therefore, it makes sense that every effort should be made to provide adequate protection and monitoring of these valuable assets.

However, despite the acknowledged importance of motors, there is a tendency to ignore the data available from modern motor protection relays. Many companies prefer to simply replace a failed motor with a spare rather than repair the failed equipment and thus feel that analyzing relay data is not worthwhile.

There are several good reasons that exist for replacing a failed motor rather than repairing it. The first, and most common, is the reduced downtime. In most cases, it is significantly faster to replace a failed motor. Because the cost of not operating is typically the largest cost associated with a failed motor, it is logical to aim to minimize the downtime.

Although the cost of purchasing a new motor is often greater than the cost of repairing a failed motor, the new cost is typically only 1 to 5 percent of the total life-cycle cost of the motor [2]. This small percentage can cause the incremental cost of purchasing a new motor to be overlooked in the decision-making process.

Further amplifying this point is the fact that the efficiency of a particular application can often be increased by purchasing a new motor. Motor repairs typically lead to a loss of up to 2 percent efficiency, while purchasing a premium efficient motor or more appropriately sized motor could improve efficiency by as much as 5 percent. This can translate into significant savings over the life of a motor [3].

In the rush to get the process operational, valuable data available from motor protection relays are often ignored and valuable lessons are missed. A survey conducted by Thorsen and Dalva found that approximately 80 percent of the reported motor failures listed "not specified" as the root cause of failure [4].

Knowing the root cause of a failure may not allow us to prevent a reoccurrence of the failure for every case listed. However, it is safe to say that by reducing the number of unknown root-cause failures on a system, we can apply improvements to reduce the number of failures and thus reduce costly downtime for a plant.

This is true because not all motor failures begin in the motor. The root cause of the problem may not be located in the motor at all. Therefore, replacing the motor is like applying a bandage rather than correcting the issue. It is important for us as engineers to solve the real problem, or it will surface again, resulting in more motor failures and costly downtime.

In addition, relay misoperations do occur. Analyzing event data from these cases can lead to improvements in the security of a scheme, thus preventing future misoperations and unnecessary downtime.

Therefore, the purpose of this paper is to highlight the value of analyzing the event report, starting, and trending data provided by microprocessor-based motor protection relays. Data from real-world cases are presented and lessons learned from each case are discussed in detail to aid users in the application of motor protection relays and the analysis of data from their own system.

II. EVENT 1: MOTOR START REPORTS REVEAL MECHANICAL PROBLEM

In December 2010, a 4,500 hp motor driving a compressor tripped off during several successive starting attempts. The microprocessor-based motor protection relay gave an indication that the machine tripped on thermal overload during the normal starting process. Event reports from the relay were downloaded. Fig. 1 shows the oscillograph data from the event.

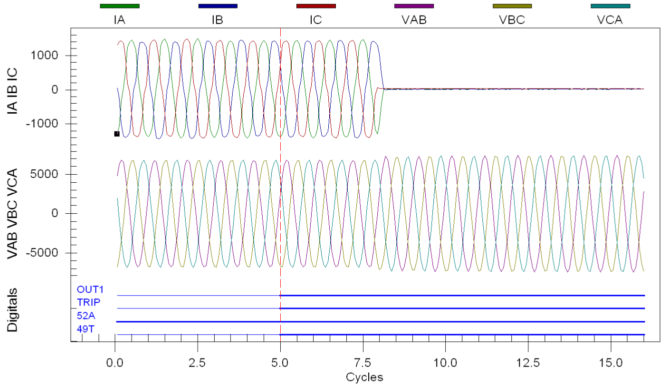

Fig. 1. Event report from a microprocessor-based relay showing a trip on thermal overload

We can see from the oscillograph that the currents appear to be balanced. This machine has a rated full-load amperes of 333 A. The current magnitude shown in Fig. 1 is approximately 4.4 times the rated current. In addition, the 49T bit is an indication that the relay thermal overload protection called for the trip.

Because the event report alone in this case is not enough to pinpoint the problem, several motor start reports were retrieved from the microprocessor-based relay. This particular relay stored start reports from the last five motor starts. The latest motor start report is shown in Fig. 2. The current magnitudes for A-, B-, and C-phase currents and the thermal capacity used (TCU) are plotted against time. The abrupt drop in current to zero at approximately 14.8 seconds after the motor start was attempted gives us further confirmation that the relay tripped on thermal overload.

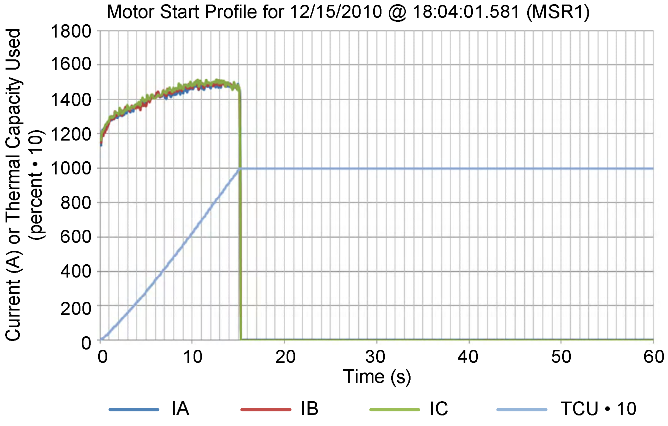

Fig. 2. Motor start report data for the most recent start

In order to verify correct operation of the relay, the thermal overload settings were reviewed. The published literature for the particular microprocessor-based motor protection relay gave a closed form equation for calculating the expected trip time for a fixed level of current. Equation (1) is the equation for trip time for a cold motor, and (2) is the equation for trip time for a hot motor.

$$T_p = \frac{90 \cdot \text{Curve}}{I^2} \tag{1}$$

$$T_p = \frac{75.6 \cdot \text{Curve}}{I^2} \tag{2}$$

where:

Curve is the curve relay setting.

I is the current in per unit of full-load current.

From the relay settings, the curve setting was equal to 3. Substituting a current value of 4.4 per unit and a curve setting of 3 into (1) and (2) yields trip times of 13.94 seconds and 11.71 seconds, respectively. We can interpret from the results that the current was not at 4.4 times full-load amperes for the duration of the start, because the actual tripping time per the motor start report appears to be closer to 14.8 seconds, indicating that the current was less than 4.4 times full-load current for some of the time. Assuming a hot start, if we plot the starting current from the motor start report against the relay characteristic, as shown in Fig. 3, we can see the starting current intersecting the relay hot trip curve just before tripping. What is interesting to note from Fig. 3 is that the motor manufacturer also provided a thermal limit curve. This thermal limit curve is also plotted. We can see that even though the starting current intersected the relay tripping characteristic, it did not reach the published thermal limit curve from the motor manufacturer.

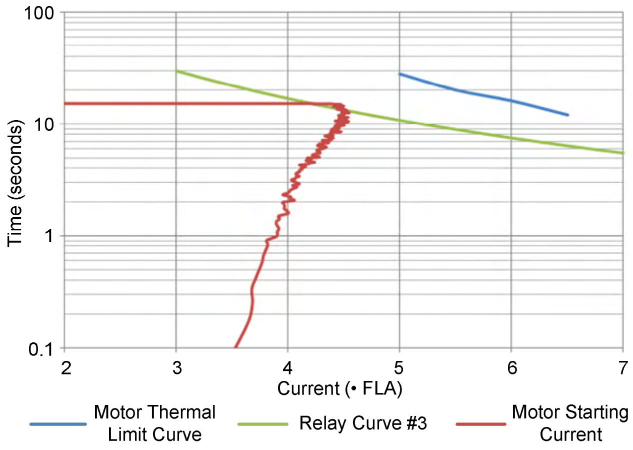

Fig. 3. Motor starting current, relay trip characteristic, and hot thermal damage curve on the plot of time versus current

Based on (1), (2), and Fig. 3, we can assert that the relay operated consistently with the published trip characteristic and the settings. So why did the relay trip? Were the curve settings set too fast? Could an adjustment to the relay curve setting be the solution?

After talking to the electricians, the motor had started fine in the past with the same settings. Several of the older motor start reports had recorded successful starts. Fig. 4 is a plot of a motor start report from September 2010 showing a successful start. It is important to note that the motor took only approximately 13.3 seconds to start and the maximum starting current was 1,446 A or 4.3 per unit. So the duration of the start and the peak current magnitude were both smaller for the successful start in September.

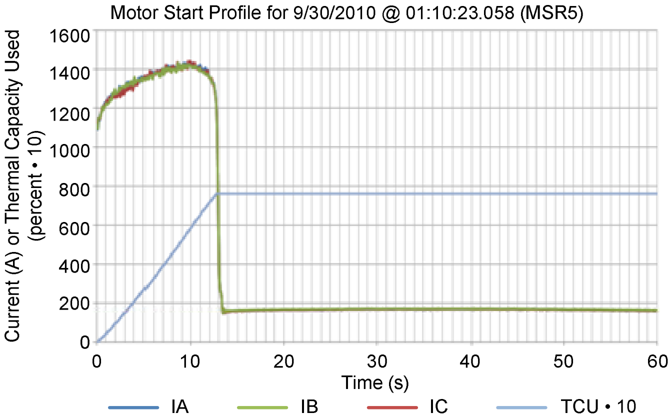

Fig. 4. Motor start report data for a successful start in September

If we look at the other five motor start reports, paying specific attention to the peak current and the time it took the motor to start, we can perhaps draw some conclusion or trend. The start time and maximum current for the motor start reports are shown in Table I.

TABLE I
MOTOR START REPORTS

Report	Date	Start Time (s)	Maximum Current (A)
MSR5	9/30/2010	13.3	1,446
MSR4	10/12/2010	15.5	1,492
MSR3	12/15/2010	15.1*	1,531
MSR2	12/15/2010	11.3*†	1,506
MSR1	12/15/2010	15.3*	1,515

* Relay tripped before motor reached full speed. Time listed is the relay trip time.

† Shortened trip time for MSR2 because the motor start was attempted before the motor had cooled.

We can observe that for the two successful starts, the starting time was less than 15.5 seconds and the current never exceeded 1,500 A. However, in December, the three unsuccessful starts that resulted in trips all had maximum currents above 1,500 A and the relay tripped in approximately 15 seconds. There appears to have been a slight increase in the current magnitude this motor was drawing during starts between September and December.

We noticed in Fig. 3 that there was ample room between the motor manufacturer thermal limit curve and the relay tripping characteristic. The decision was made to adjust the curve setting from 3 to 4. This would not compromise the thermal protection of the motor and would perhaps allow enough time for the motor to start. The relay setting was changed, and a motor start was attempted. The resulting motor start report is shown in Fig. 5.

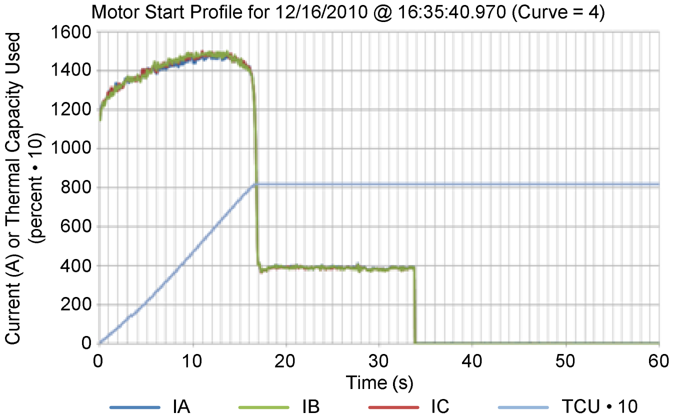

Fig. 5. Motor start report for a start after changing the curve setting to 4

We notice that this time the motor did come up to speed. However, if we look carefully, the running current is approximately 400 A. This is 1.2 times the rated full-load value of the motor. The machine was stopped. What changed?

The compressor coupled to this machine had undergone extensive rework just prior to December. In this case, the motor start reports provided a valuable indication that something was wrong with the mechanical load coupled to the motor. At one point, it was theorized that system changes and excessive voltage drop may have been contributing factors to the trouble starting. Having the motor start reports, which include voltage magnitudes, helped to disprove this theory. The voltage magnitude profile during the successful start in September is almost exactly the same as the voltage magnitude profiles of the attempted starts in December.

This event highlights the importance of saving and monitoring these reports as well as making use of trending features common to microprocessor-based motor protection relays to help benchmark and track motor performance. One possibility to consider is to include the gathering of motor start report data after motor or mechanical work is done to a machine as part of the process of putting that machine back into service.

III. EVENT 2: CURRENT UNBALANCE ELEMENT TRIPS DURING STARTING

In April 2010, a 375 hp motor suffered an unbalance trip while starting. It was assumed that two current transformer (CT) secondary wires were rolled going to the relay. Therefore, the A- and C-phase wires were swapped in an attempt to correct the assumed problem, and the motor was started again. Despite the wiring change, once again, the relay tripped on unbalance. Assuming the wrong wires had been swapped, the B- and C-phase wires were rolled and the motor was started for a third time, and the relay tripped on unbalance for the third time.

The motor was applied to an ACB system. Fig. 6 shows the phasor relation from the initial trip. As expected, the phase current lags the phase-to-phase voltage by approximately 45 degrees.

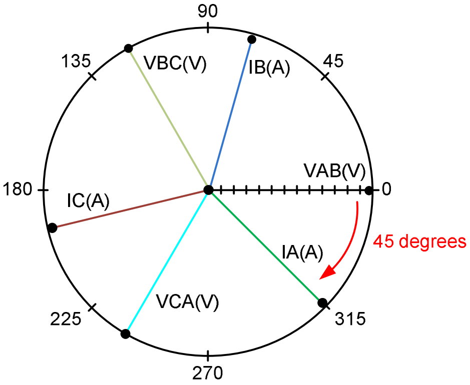

Fig. 6. Motor start phasor relation

The relay was set with the following related settings:

PHROT := ACB
CTR1 := 10 (or 50:5)
FLA1 := 38.9 A primary
50Q1P := 0.50 multiples of FLA1
50Q1D := 0.10 seconds
46UBT := 20 percent
46UBTD := 5 seconds
46UBA := 10 percent
46UBAD := 10 seconds

From the relay event report shown in Fig. 7, we can see that the 50Q1T element caused the trip. From the previous settings, we know that this element is set to operate when the negative-sequence current (3I2) is greater than half of the full-load amperes (FLA1), or 19.5 A primary.

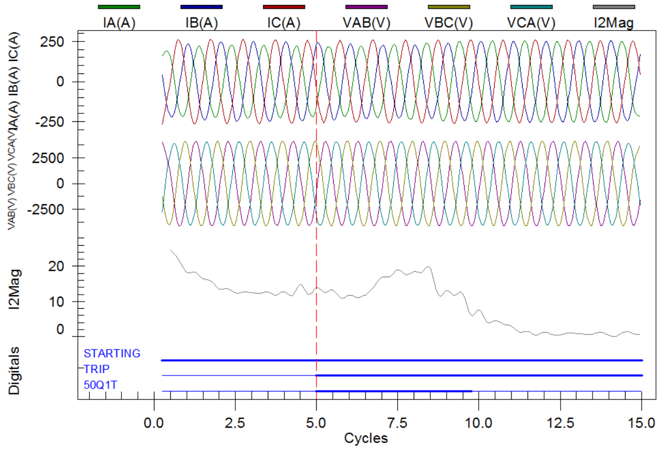

Fig. 7. Initial unbalance trip

Fig. 7 shows that the I2 magnitude at the time of the trip was approximately 12 A primary. This means that 3I2 was approximately 36 A primary and well above the pickup threshold of 19.5 A primary. However, the event report also shows that less than 5 cycles after the trip was issued, the negative-sequence current magnitude (3I2) dropped below the pickup threshold of the 50Q1 element.

The asserted STARTING bit indicates the motor was in the process of starting when the trip occurred. Comparing the current magnitude to the FLA1 setting (260/38.9 = 6.7), we can tell that the trip occurred early in the starting sequence.

Because a motor draws approximately six times its full-load amperes during a start, it is common for the CTs to experience some saturation. Therefore, unbalance elements should not be set to operate instantaneously because they can operate on false unbalance quantities that result from CT saturation. It is important to remember that the threat of damage posed by negative-sequence currents is thermal in nature. Therefore, equipment will not be damaged instantaneously.

One reference recommends that a definite-time element operating on negative-sequence current be set at 1.5 A secondary with a 4-second delay to ride through the saturation that can occur during a start. This setting ensures the security of the element [5].

This case also highlights the value of event report analysis. Had the users looked at the event report after the initial trip, they would not have spent time rolling wires and would have modified the settings, thus reducing the downtime caused by the event.

IV. EVENT 3: DIFFERENTIAL ELEMENT TRIPS DURING STARTING

In November 2010, a 16,000 hp motor tripped during starting from a current differential fault. The particular motor installation made use of a self-balancing differential scheme. This scheme is applied where access to all six motor leads is available. A simplified three-line diagram of the installation is shown in Fig. 8.

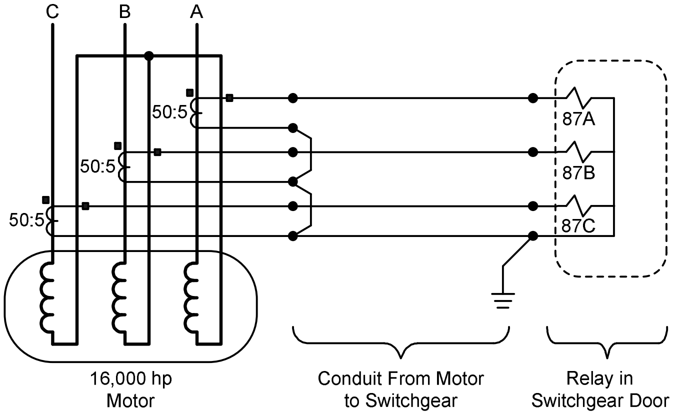

Fig. 8. Simplified three-line diagram

Self-balancing differential protection consists of a window-type CT where the incoming and outgoing cables are routed through the same CT and connect to an overcurrent relay per phase. Fig. 8 shows the relays as 87A, 87B, and 87C. The protection function being performed is differential; however, this is accomplished through an overcurrent algorithm in the device. The 87 ANSI designation was used because this microprocessor-based relay has a set of inputs (87A, 87B, and 87C) specifically designated for differential protection and other current inputs dedicated for other motor protection functions, such as overcurrent protection and thermal overload protection.

During normal operation and starting, the fluxes from the two cables cancel and the net flux results in no current in the CT. Saturation during starting is not a concern for self-balancing differential protection, unlike full phase differential protection, which uses two sets of CTs. An excellent overview of self-balancing differential is provided in [6]. In addition, typical settings recommendations are 2 to 5 percent of the rated machine current [7], 0.25 A secondary pickup with a 50:5 CT [8], and 0.5 A secondary pickup with a 50:5 CT and a 1- to 2-cycle time delay [9]. From these recommendations, we can see that self-balancing differential protection offers speed, security, and sensitivity.

The settings for this particular relay are the following:

CTR87M = 10 (or 50:5)
87M1P = 2.0 A secondary
87M1TD = 0 seconds

There is no set time delay; however, the pickup is larger than some of the settings recommendations discussed in the previous paragraph. The microprocessor-based relay event report data for the trip are shown in Fig. 9. We can see that the currents and voltages appear very balanced and below the full-load ampere rating of the motor. In addition, we see approximately 5 A secondary of differential current just as the relay tripped. Also noteworthy is that all three differential currents (87A, 87B, and 87C) are almost perfectly in phase with roughly equal magnitudes, indicative of zero-sequence current.

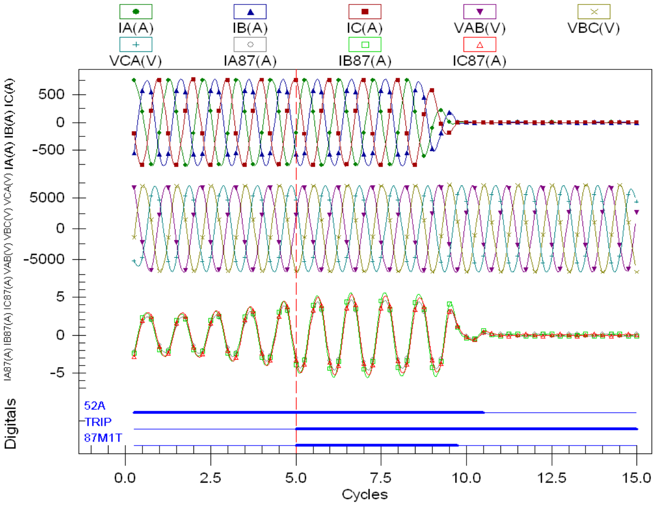

Fig. 9. Filtered event report of a differential trip

In addition, the raw, unfiltered event data are shown in Fig. 10. We can see how the relay digital filtering processed the distorted current signals.

As an initial response, both the motor and relay were tested. The relay tested within the manufacturer-specified tolerances, and the motor showed no signs of insulation degradation. What was causing the differential current to flow?

After testing, authorization was given to attempt another motor start, with personnel monitoring the machine to react should any problems arise. The motor tripped again during starting on differential.

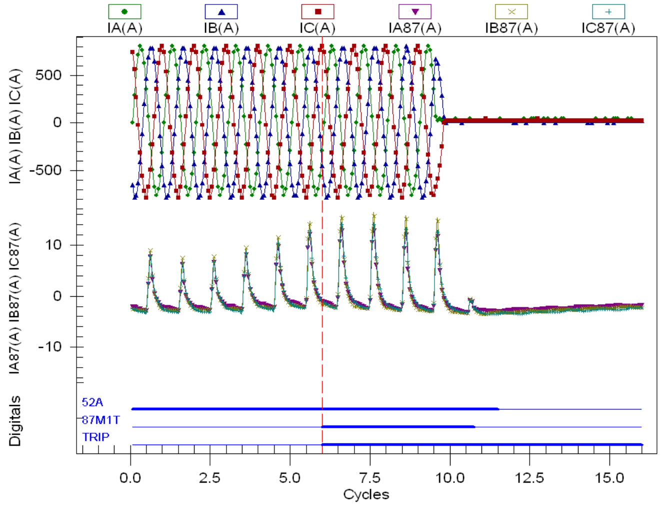

Fig. 10. Raw event report of a differential trip

When the relay and primary equipment are tested and appear to be functioning as expected, the next logical place to check is the secondary wiring. After the insulation to ground on the secondary wiring was checked, two wires were found to have developed short circuits to ground. The locations of the ground faults are shown in Fig. 11. Both were located in the metallic conduit between the switchgear and the motor location. All wiring in this metallic conduit was replaced.

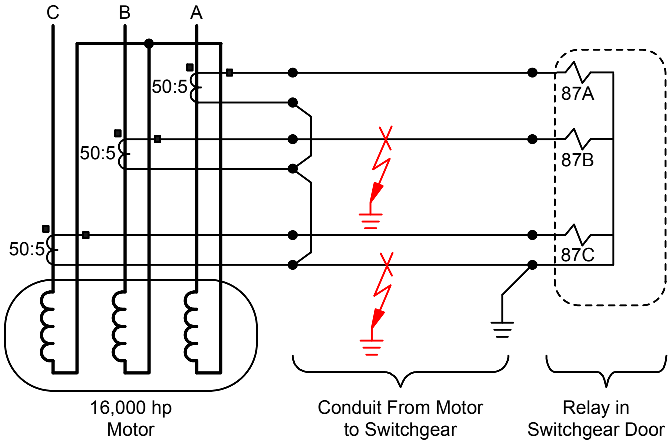

Fig. 11. Simplified three-line diagram with short-circuit locations shown

After correcting the issues with the secondary wiring, the motor was started with no resulting trip. The oscillograph from the successful start is shown in Fig. 12. Note that the differential current is greatly reduced, now less than 0.5 A secondary.

CT circuits should only be grounded at one location. Additional grounding points can sometimes be the result of mistakes missed at commissioning. In this particular case, the problems appeared after the motor had been installed for some time, and an event in the conduit between the motor and the switchgear where the relay was mounted resulted in multiple grounds on the CT circuit.

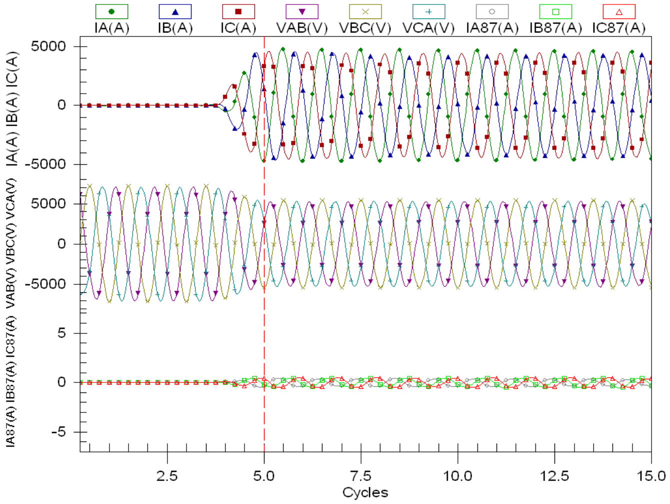

Fig. 12. Filtered event report from a successful start

V. Event 4: Load Profile Data Help Find RTD Problem

In May 2011, a motor began alarming on a high winding resistance temperature detector (RTD) temperature. This particular motor was not set to trip on RTD temperatures but just to alarm operators. The alarm was coming in intermittently. The microprocessor-based relay that the RTDs were connected to had RTD-failure features to detect open- or short-circuited RTDs. These features did not provide any indication of a problem.

After the initial findings, a load profiling feature was enabled in the microprocessor-based relay. This feature allows analog points such as the individual RTD temperatures to be stored periodically in the relay over time. The RTD temperatures were recorded at 5-minute intervals over approximately a 3-day period. The results for the RTD temperatures are shown in Fig. 13.

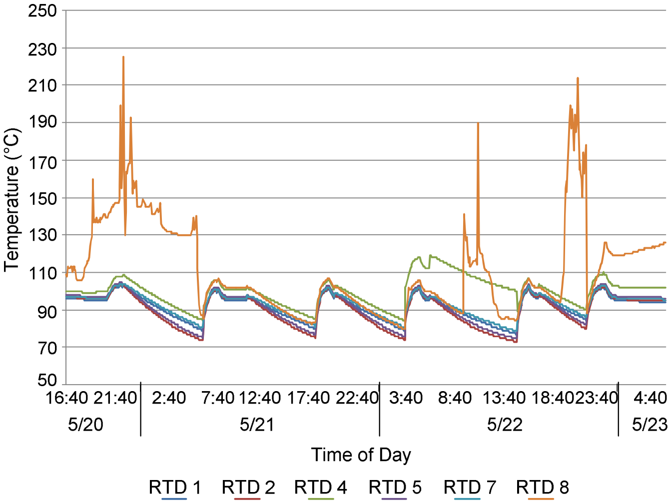

Fig. 13. RTD temperature versus time

We notice that RTDs 1 through 7 trend together and match reasonably well. However, RTD 8 exhibits erratic behavior at various points in the 3-day period. The temperature increases in RTD 8 alone.

After further investigation, a loose connection on the RTD 8 circuit was found. This particular relay RTD diagnostic algorithm declares an open circuit when the measured temperature is above 250°C. Because the connection was not a true open circuit but simply a loose wire, the impedance (and hence temperature) never exceeded the threshold.

This event highlights why RTD voting is often employed when RTD measurements are used to trip. In this particular case, the relaying scheme alarmed as it should have and the RTD problem with RTD 8 was correctly identified after troubleshooting. Using features beyond event reports and motor start reports, such as load profiling or trending, can save troubleshooting time and capture important information.

VI. Event 5: Full Phase Differential Trip During Starting

In May 2011, a 6,000 hp motor protected by several relays, including a differential relay, started successfully. However, the differential relay indicated a TRIP target. Upon further review of the relay data, it appeared that the differential element asserted. If the differential relay indicated a trip, why did the breaker not open immediately? Also, why did the differential element assert in the first place when the motor continued to operate after the relay operation with no visible, audible, or measurable damage?

The oscillograph from the filtered event report is shown in Fig. 14. Notice how the ground currents are not sinusoidal and decay throughout the event report. Whenever we see ground current that decays, it is an indication that CTs may be saturating.

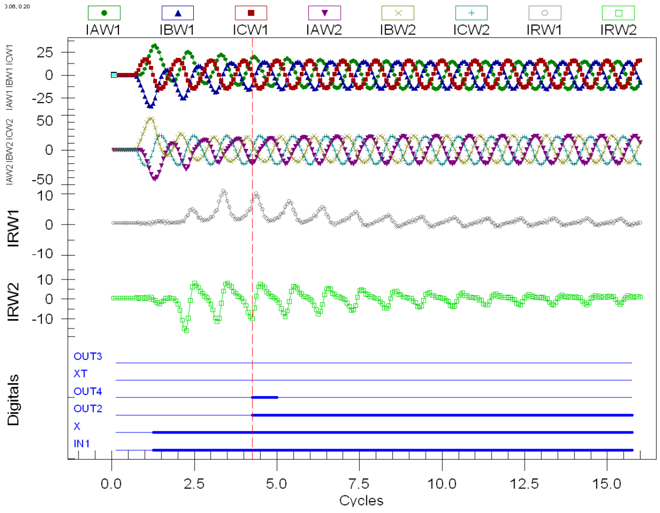

Fig. 14. Filtered event report of the phase differential trip

Because we have the *raw* event reports, we can import the data into a mathematical analysis tool for a better look at the data to help validate any theories we may have.

Because the CT ratios are different for Winding 1 and Winding 2, comparing the secondary currents that are plotted in the event reports is not as obvious as looking at the primary currents. We would expect the primary currents to be exactly the same in magnitude during a motor start, only 180 degrees out of phase. We can adjust the plots for the Winding 2 currents by inverting the values (multiplying by –1) to account for this 180-degree phase shift that is due to the CT polarities going into the differential relay. So for the plots shown in Fig. 15, Fig. 16, and Fig. 17 (A-, B-, and C-phase respectively), we would expect to see the Winding 1 and Winding 2 currents plotting right on top of one another.

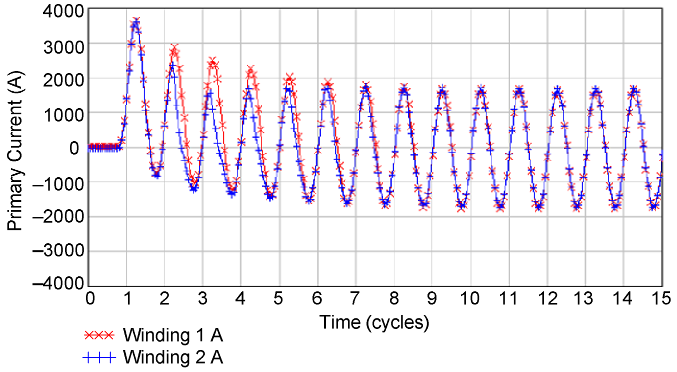

Fig. 15. A-phase Winding 1 and Winding 2 currents

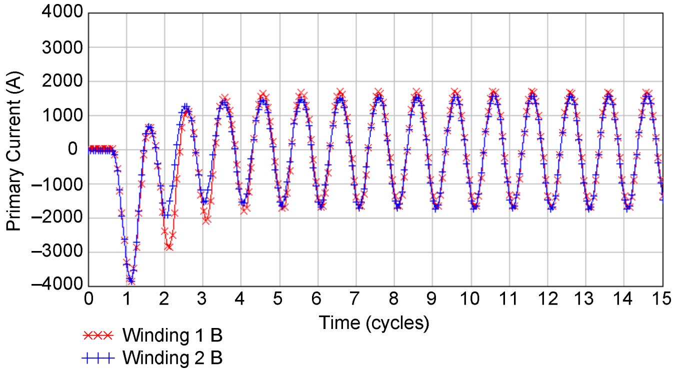

Fig. 16. B-phase Winding 1 and Winding 2 currents

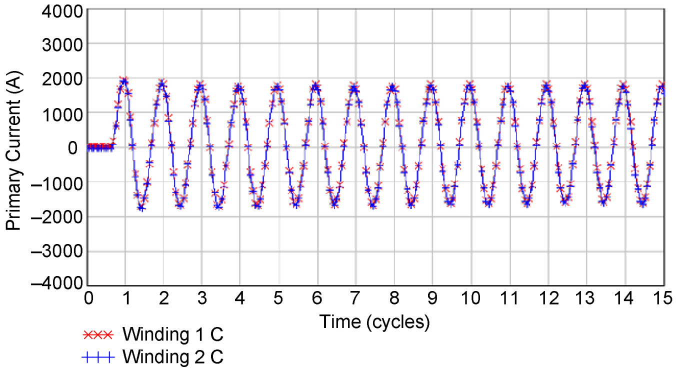

Fig. 17. C-phase Winding 1 and Winding 2 currents

Note that for the C-phase currents, the Winding 1 current and Winding 2 current in Fig. 17 almost match. However, for A-phase and B-phase in Fig. 15 and Fig. 16, we notice that the Winding 2 currents experience saturation. The two sets of CTs did not perform equally. And for this reason, self-balancing differential protection is generally the preferred method when possible, as discussed in Section IV.

When applying full phase differential protection, matching the CTs (ratio, ANSI rating, and even saturation curves) is another method that can be used to help minimize the risk that one set of CTs will perform differently than the other.

However, in this particular case, the CTs were already installed and could not realistically be changed until a scheduled outage.

How can we make an adjustment to the settings to prevent the differential element from tripping during starting? Adjustments to the relay settings can be made with relative ease until changes to one or both sets of CTs can be made.

A. Relay Settings Solution #1: Add Time Delay

One option is to add a time delay. This is performed in the logic already programmed into the relay:

X = IN1
MTU3 = 87R*XT + 87U
TXPU = 600.000
TXDO = 0.000

Essentially, differential protection is blocked until the XT timer times out. Input 1 asserts shortly after a start, and then XT has a built-in time delay of 600 cycles (or 10 seconds). So effectively, we block differential protection for 10 seconds after starting. This explains why the TRIP3 bit did not assert for this event, even though the 87R element asserted. There are two problems, or deficiencies, with these settings. The first problem is that we block the differential relay during starting. While this ensures security, it compromises dependability. Should we attempt to start the motor while it is faulted, the differential element will be blocked for 10 seconds. This may be acceptable if backup protection is in place to provide high-speed tripping of severe or catastrophic machine faults. The second problem is that 87R is included in the MTU1 trip equation. Although this trip logic is not set to assert an output contact and trip any breakers, it does result in the relay targeting, which can be confusing.

B. Relay Settings Solution #2: Decrease Relay Sensitivity

Another option is to desensitize the relay. We can do this by adjusting the slope settings. Fig. 18 shows the simulated operate and restraint currents for the differential element with the settings as they were in the relay at the time of this event for the A-phase currents. Note that this particular relay has a dual-slope characteristic.

The measured operate and restraint currents shown in Fig. 18 cross the trip threshold. The settings were SLP1 at 35 percent, SLP2 at 75 percent, and IRS1 at 3 per unit. If we adjust the settings so that SLP2 equals 75 percent and IRS1 equals 1.8 per unit, the relay will restrain. Fig. 19 shows the relay response with both the original and new threshold settings.

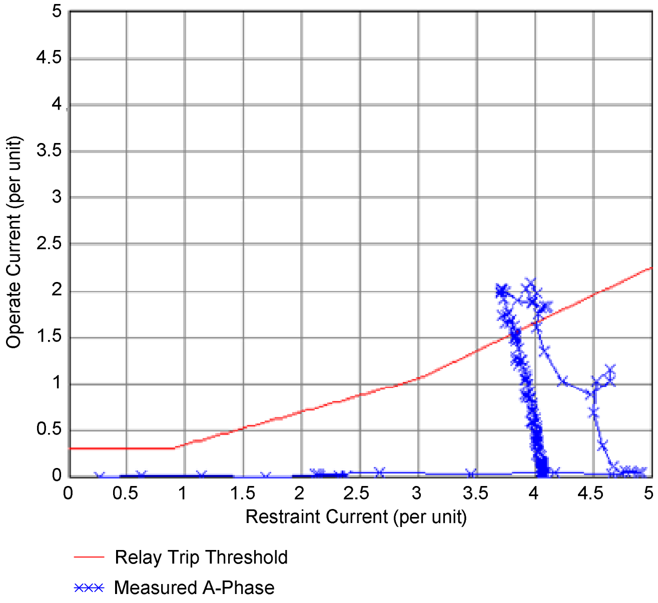

Fig. 18. Relay trip threshold and measured current with the original settings

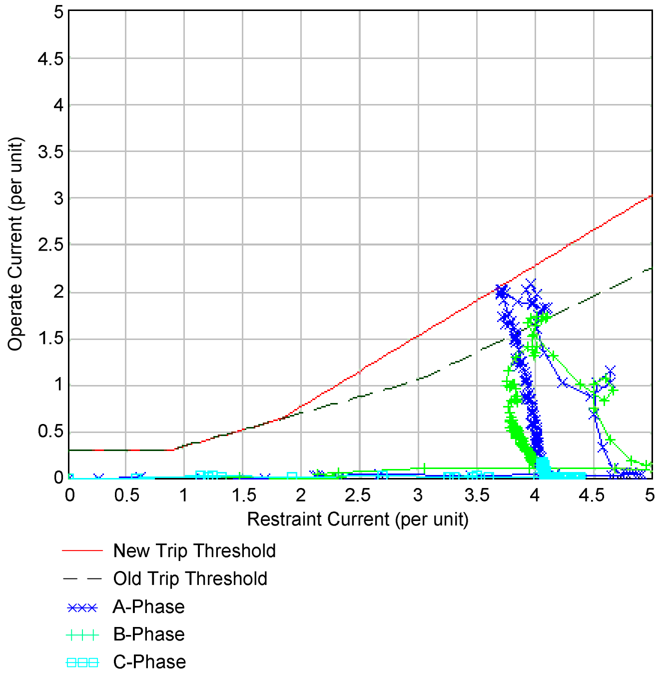

Fig. 19. Relay trip threshold and measured current with the original and new settings

To further prove that the settings adjustment will work, the relay events were played back into the relay with the settings adjusted using a test set with the capability to replay Common Format for Transient Data Exchange (COMTRADE) events. Fig. 20 is the oscillograph from this test with the updated slope settings.

The ultimate solution for this particular problem is to replace both CTs during the next scheduled outage so that they have identical CT ratios, ANSI ratings, and saturation characteristics. In the meantime, the slope settings were adjusted to ensure security during starting and to avoid the nuisance targeting that was a result of the previous timer scheme.

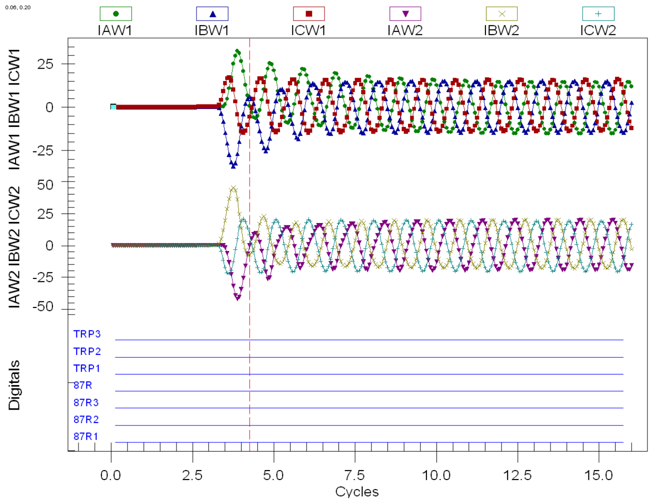

Fig. 20. Raw event report from the replayed event with the new settings

VII. EVENT 6: SYNCHRONOUS MOTOR TRIPS ON LOSS OF FIELD

In July 2011, a 25,000 hp synchronous motor was tripped by a loss-of-field relay. The motor was in service when an adjacent motor was started. The connections were as shown in Fig. 21.

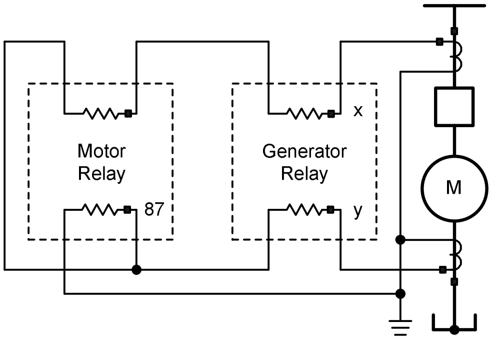

Fig. 21. 25,000 hp synchronous motor one-line diagram

As is common for synchronous motor installations, a generator relay was installed in parallel with the main motor protection relay to provide field-related protection. At the time of the start, the generator relay tripped the synchronous motor on a loss-of-field element. The event report from the trip is shown in Fig. 22.

The motor has a manual voltage regulator that was set to operate near unity power factor. Fig. 23 and Fig. 24 show the phasor relations prior to and during the adjacent motor start, respectively.

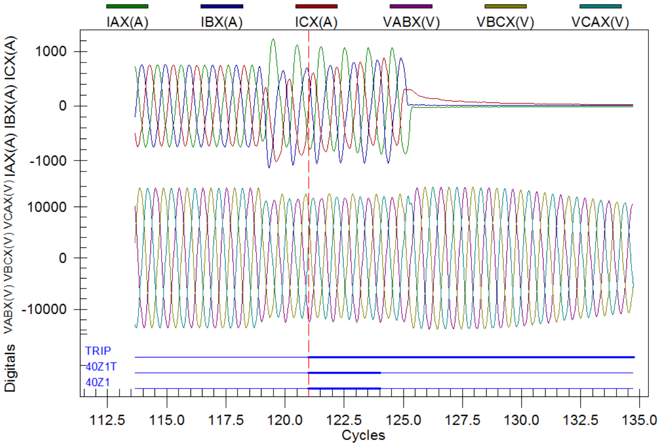

Fig. 22. Loss-of-field trip

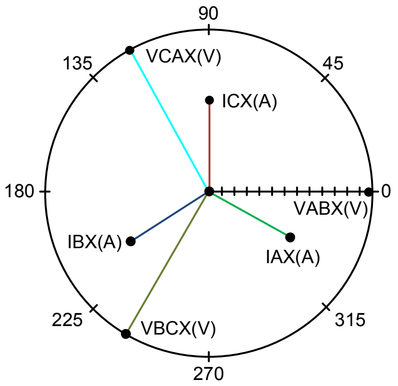

Fig. 23. Normal load phasors

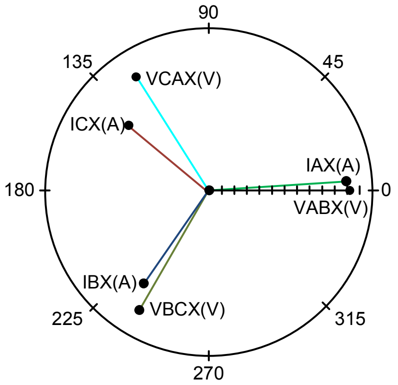

Fig. 24. Loss-of-field event phasors

By design, a generator relay defines positive power (both real and reactive) to be out of the generator. As can be seen in Fig. 23 and Fig. 24, the relay is calculating forward power, indicating that power is flowing into the system. However, because the relay is applied to a motor, we know that the opposite is true, leading to the conclusion that the CTs should be connected with the reverse polarity.

Fig. 24 also indicates that VARs are flowing into the machine, which appears to be a loss-of-field condition. However, during the start of the adjacent motor, the bus voltage dropped. Because VARs flow toward the lower voltage, they are actually flowing out of the motor. Therefore, the VARs are actually flowing out of the machine, but the relay thinks they are flowing into the machine.

The solution to the problem is that the generator relay is expecting both CTs to be connected with opposite polarity to this installation. Reversing the polarity of both sets of CTs causes the relay to correctly read the current values and prevents operation of the loss-of-field relay if these circumstances occurred again.

Therefore, when applying a generator relay for synchronous motor protection, it is important for the user to carefully analyze how the relay is designed to operate and the conventions used in it. This ensures that the relay is installed and set properly and thus functions correctly during operation.

VIII. EVENT 7: SELF-CLEARING FAULT TRIPS MOTOR PROTECTION RELAYS

In January 2011, a 14,000 hp induced draft (ID) fan motor tripped on two separate protective relays. Relay A, which was connected to the feeder breaker CTs, declared an instantaneous ground fault. Relay B, which was connected to a flux-balancing CT for stator differential protection, also tripped. The motor is connected ungrounded wye. Fig. 25 shows the unfiltered fault record captured by Relay A.

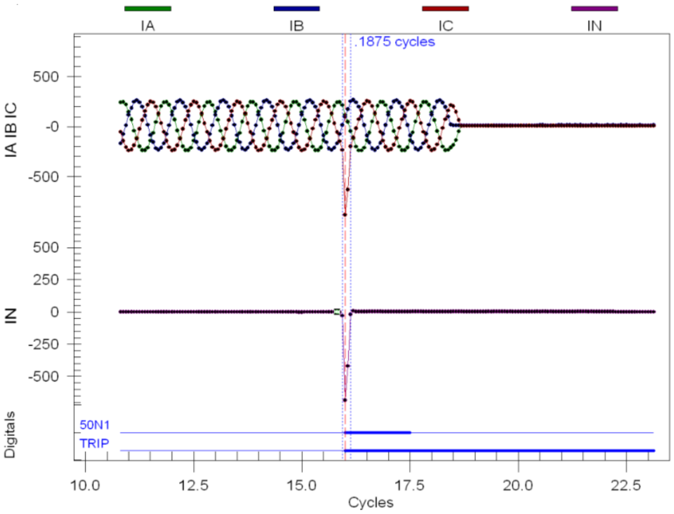

Fig. 25. Relay A event capture

The 50N element, which called for the trip, was set to 400 A primary. The event indicates a spike of about 1,248 A (peak) for a very short duration. It is the short duration of fault current that is puzzling. In general, once a fault starts, it does not finish on its own, and the opening of a breaker is required to clear the fault. While the breaker did open 2.67 cycles after the spike, the fault extinguishes prior to the opening of the breaker.

Fig. 26 shows a portion of the unfiltered event captured by Relay B. Again, we can see that the C-phase currents (dashed line) spike to about 1,200 A (peak). In addition to the C-phase current, we also have the C-phase differential current, which is the current from the flux-balancing CTs located in the junction box of the motor. The C-phase differential current also shows a very large and abrupt increase in current.

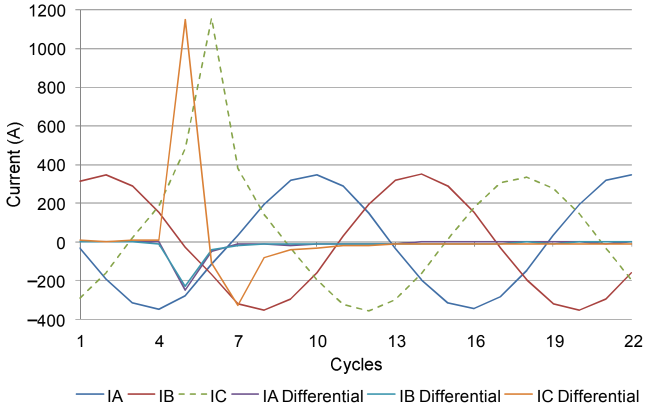

Fig. 26. Relay B event capture

Some of the questions we may ask after viewing these data include: Is this a legitimate system event? Was it a fault? If so, where is this fault located and how did it extinguish itself?

As mentioned earlier, it is extremely rare for a fault to extinguish itself. At first glance, it may be easy to dismiss this as a possible relay error. Digital relays perform the same routine repeatedly at the same intervals of time. Relay A samples the sinusoids at a rate of 16 times per power system cycle, or 960 Hz. Relay B samples the sinusoids at a rate of 12 times per power system cycle, or 720 Hz. Each relay must sample every value correctly for the relay to determine correct operation. It may be easy to assume that the relay got one of the millions of samples that it takes per day wrong, leading to the misoperation. However, there are multiple items to keep in mind that challenge this theory, including the following:

- Digital relays have numerous safeguards to prevent erroneous data from occurring, including relay self-tests.
- For this particular event, Fig. 27 shows that two sequential measurements on C-phase of Relay A (each dot is a sample) are very high compared to pre- and post-event data. This further supports that the relay is in fact measuring a real event.
- Not only is the spike seen on C-phase, but it is also seen at the same time on the IN channel, which is a separate analog channel that is measured by the relay. Also, the magnitudes are similar.

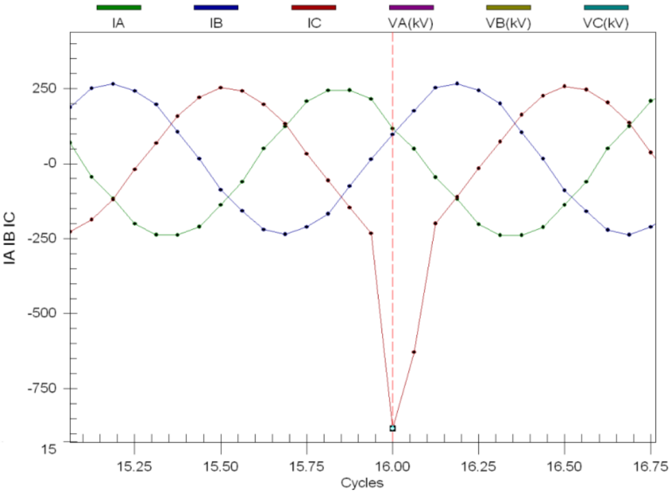

Fig. 27. Zoomed Relay A event capture

Based on these data alone, we can confidently say that this was a legitimate system event. The fact that two relays operated and generated events also verifies that we had a system event.

Now that we are confident that something did in fact happen on the system, the next step is to make sure it was an actual fault and not faulty wiring that led to an erroneous value. In this case, we have data from the flux-balancing CTs for the differential, CTs on the feeder, and a flux-balancing CT for the neutral protection. They all report a very similar waveform shape (a short-duration spike) and similar peak magnitudes. Also, the differential CTs show the fault on C-phase as do the load breaker CTs. So we have enough supporting data present to say with certainty that there was a legitimate fault in the motor protection zone that led to the relay trip. This motor should *not* go back in service until we take a look inside to see what the problem may be. If we ignored these events and put the motor back in service, we would run the risk of a second event that might severely damage the motor.

Once the motor was taken out of service, the search began to visually inspect it for signs of a fault. The bell ends were removed on-site for a visual inspection of the stator winding. A burn mark was found in the motor end box near the neutral point of the stator. No other damage was seen. A burn mark does not explain elevated fault current seen by the relays because a fault to ground at the neutral point of the motor would produce no fault current. For reference, it was found through system models that a bolted phase-to-ground fault at the incoming phase terminals of the motor produces 1,200 A of root-mean-square (rms) fault current. We see about 883 A rms during the 0.1875 cycles the fault is present. Based on this information, the burn mark cannot be the only trouble spot in the motor. The burn mark only represents the path the arc took to get to ground; the source of the burn mark has yet to be found.

The motor was shipped to the manufacturer for closer inspection. It was carefully taken apart, and extensive tests were performed. High-potential tests on the windings showed no apparent issues with the winding. Fig. 28 shows a picture of the motor lying on its side, viewed from the nondrive end.

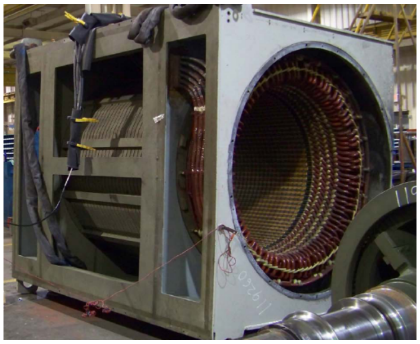

Fig. 28. 14,000 hp ID fan motor

Based on the fault current values seen during the event, closer inspection was given to the source side of the stator winding. This includes the junction box where the phases are landed on the motor terminals. The two conductors in the foreground are paralleled neutral conducts, and these show a sign of possible arcing (see Fig. 29). The two paralleled conductors just behind are the C-phase incoming conductors.

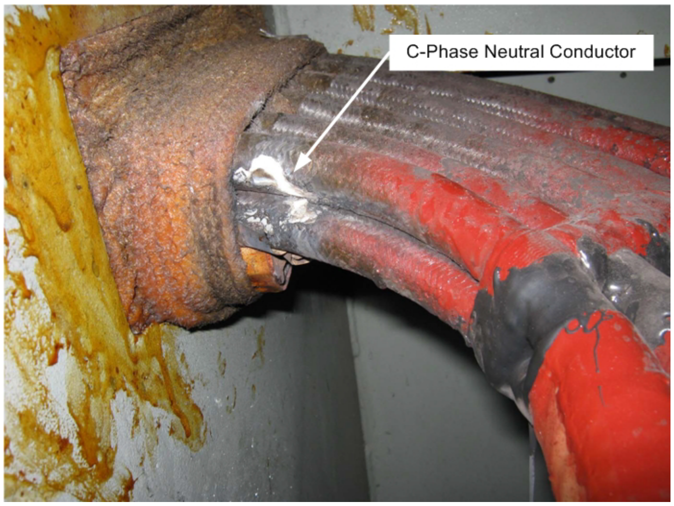

Fig. 29. Side view of the incoming and neutral conductors

Closer inspection was required to see if there was some arcing on the incoming phases. This physical evidence of a fault is very near the differential flux-balancing CT and at a point where the neutral and source to the stator are very close to each other. Fig. 30 shows a top view of the conductors.

Once the external arcing was seen on the neutral, the wrapping around the incoming C-phase conductors was removed to reveal the silicon jacket. This revealed apparent tracking from a fault and showed the silicon jacket eroding. Based on the length and trajectory of the marks, it is apparent that moisture ingress led to the breakdown of insulating material. Fig. 31 shows the tracking marks in the incoming C-phase line.

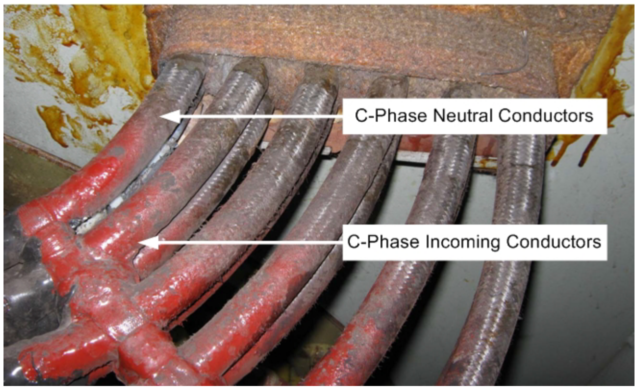

Fig. 30. Top view of the incoming and neutral conductors

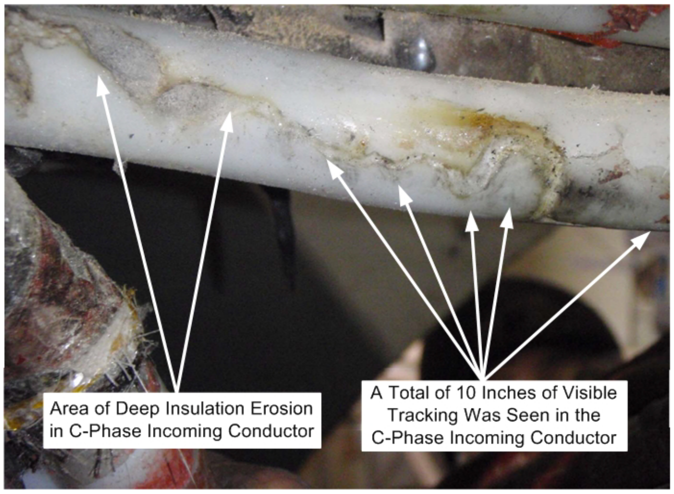

Fig. 31. C-phase incoming conductor damage

At this point, we have clearly found an insulation breakdown on the C-phase incoming conductors and tracking on the neutral conductor. However, a connection between the incoming C-phase and neutral would not produce fault currents but a motor unbalance condition. What about that burn mark that was found on-site?

Fig. 32 shows a very tiny burn mark that is very close to the neutral and C-phase tracking. This is the path for C-phase to ground and led to the large amount of current seen.

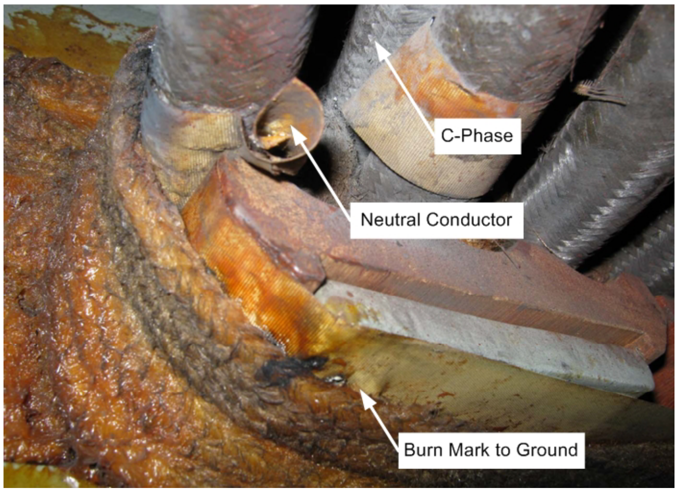

Fig. 32. Ground point

This particular fan was located between two areas with large temperature differences that led to condensation forming in the motor. This condensation gathered at the bottom of the motor housing and found a way to seep into the conductors, which eventually broke down the insulation. With the insulation breakdown and a supply of water running near the C-phase conductor, the dielectric strength between C-phase and ground broke down and allowed a temporary flashover. Fig. 33 shows an electrical diagram of the fault.

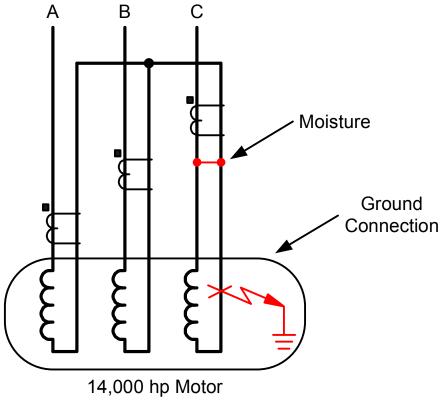

Fig. 33. Electrical representation of the fault

Because of the speed, sensitivity, and event reporting features of the relays, the fault was detected and cleared very quickly with evidence that a problem occurred. If this had been ignored, the next fault may have been permanent and severely damaged the motor. By analyzing and trusting the event report data, we were able to repair the motor at a minimal cost.

IX. CONCLUSION

Since the invention of the motor 180 years ago, we have been using this great tool in numerous applications. Today, ac motors are critical to the operation of power, industrial, and manufacturing plants. A false trip or, worse, the failure of a motor can halt a major process, costing thousands or even millions of dollars in lost revenue and environmental fines.

Therefore, as discussed in this paper, it is essential that the event report data provided by microprocessor-based motor protection relays be analyzed in detail to determine root cause for each operation. This should be done regardless of whether company policy is to automatically replace a failed motor.

This paper presents several real-world events to illustrate the lessons that can be learned from the stories told by event data. Protection schemes and operating practices can be improved based on these lessons to reduce outages and damages. This makes operations safer and more reliable, leading to less downtime and lost revenue.

X. ACKNOWLEDGMENT

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XII. BIOGRAPHIES

Derrick Haas graduated from Texas A&M University in 2002 with a BSEE. He worked as a distribution engineer for CenterPoint Energy in Houston, Texas, from 2002 to 2006. In April 2006, Derrick joined Schweitzer Engineering Laboratories, Inc., where he works as a field application engineer. He is a member of IEEE.

Jason Young graduated from the University of Waterloo in 2006 with a BASc in Electrical Engineering. In 2004, he joined Ontario Power Generation as a protection and control engineering intern. He also worked as a planning technician intern for Hydro One Networks. He joined Schweitzer Engineering Laboratories, Inc. in 2006, where he serves as a field application engineer.

Ryan McDaniel earned his BS in Computer Engineering from Ohio Northern University in 2002. In 1999, Ryan was hired by American Electric Power (AEP) as a relay technician, where he commissioned protective systems. In 2002, Ryan began working in the Station Projects Engineering group as a protection and control engineer. His responsibilities in this position included protection and control design for substation, distribution, and transmission equipment as well as coordination studies for the AEP system. In 2005, Ryan joined Schweitzer Engineering Laboratories, Inc. and is currently a field application engineer. His responsibilities include providing application support and technical training for protective relay users. Ryan is a registered professional engineer in the state of Illinois and a member of IEEE.

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