Using High-Resolution Oscillography to Improve the Performance of Controlled Switching for Transformers

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***Abstract*—Energization of power transformers at a random point-on-wave (uncontrolled energization) can result in inrush currents that far exceed the full-load rating of the transformer. High inrush current can result in power quality issues and induce unnecessary stress on connected equipment. In contrast, controlled switching, in which the breaker is closed at a point-on-wave chosen to minimize the inrush current, greatly reduces the inrush current and its negative effects.**

This paper describes the design and commissioning of a controlled switching scheme to energize and de-energize a 485 MVA, 220/18 kV transformer. Energization of this transformer frequently resulted in a large reactive current draw from the power grid. The poor power quality was adversely affecting equipment in the adjacent power station and transmission yard. It was not unusual for energization events to cause flickers and brownouts. Excessive noise could sometimes be heard for several minutes from this transformer and sympathetically from other transformers already in operation at the nearby power station, signaling long-lasting negative effects from the initial inrush.

The paper explores several controlled switching schemes and describes the one chosen for this application. It discusses the design and commissioning process and highlights the use of high-resolution oscillography to supplement breaker timing tests to obtain a critical breaker advance-time setting for the scheme. The results show that by using a controlled switching device and fine-tuning its breaker advance-time setting, inrush currents exceeding 6 pu have been reduced to less than 0.2 pu.

I. Introduction

Huntly Power Station was originally built with four 250 MVA steam turbines to produce ~1,000 MW of energy for the New Zealand electric power system. In 2006, the station was augmented with a single-axis gas turbine generator (G5) rated at 475 MVA. It was connected to the grid by a 485 MVA 220/18 kV delta-wye step-up transformer (T500). Various switching arrangements allowed the local station supply to be derived from the 220 kV grid via the generator transformer, from the local supply of the adjacent power station, or from the G5 gas turbine generator.

Failure of the existing controller required the energization of the T500 generator transformer from the 220 kV grid via a manual close bypassing the controller. The large inrush currents from these random energizations resulted in brownouts and voltage sag events. Sympathetic inrush caused by T500 on the adjacent Huntly generator transformers could frequently be heard for many minutes after some closing attempts.

This paper discusses the design and commissioning of a replacement system for the failed point-on-wave control of the 220 kV circuit breaker connecting T500 to the 220 kV grid. It shows that using oscillography to fine-tune the opening and closing times of each breaker pole can greatly reduce the magnetizing inrush. When a transformer is de-energized, residual flux remains due to the hysteresis characteristics of the core material. If the transformer is re-energized at a random instant of time, the core may saturate, resulting in an inrush current several times the nominal transformer rating. Energizing the transformer when the prospective flux from the source voltage matches the residual flux virtually eliminates any inrush current [1] [2] [3] [4].

Controlled switching devices (CSDs) have been successfully applied to reduce transformer inrush [1] [2] [3] [4]. Present CSD technology uses one of the following two methods:

1. Voltage integration is used to compute the residual flux in the transformer core. Then, a controlled close is performed such that the prospective flux created by the applied voltage is equal to the residual flux in the core [1] [2] [4]. The use of this method requires accurate measurement of the transformer winding voltages and is difficult to achieve using a capacitive voltage transformer (CVT).
2. The transformer is treated as a reactor and controlled closing is applied assuming that the residual flux is close to zero [2] [3]. Unlike the previous method, voltage measurements on the transformer winding are not required and the controlled closing is performed at a system voltage maximum. The performance of this method is expected to be superior to random switching but may be inferior to the voltage integration method.

II. Application Considerations for Controlled Switching Scheme

The goal of the system design was to provide a controlled switching scheme for the 220 kV circuit breaker associated with T500. Normal system operation is to energize the 18 kV system from the 220 kV grid via the T500 circuit breaker (CB52 in Fig. 1). This is sometimes referred to as “back livening.” The generator is synchronized to the 18 kV bus via the generator circuit breaker (52G). An existing synchronism check scheme was retained for CB52 for occasionally synchronizing to the grid.

Many controllers apply a voltage integration technique to estimate the level of residual flux and adjust the closing times of each pole accordingly. However, for this application (as is often the case for high-voltage systems) only CVTs were available for voltage measurement on the transformer winding. As such, the alternate method that assumes minimal residual flux in the core prior to closing was chosen. If upon de-energization there is residual flux, the transformer could still saturate when it is re-energized.

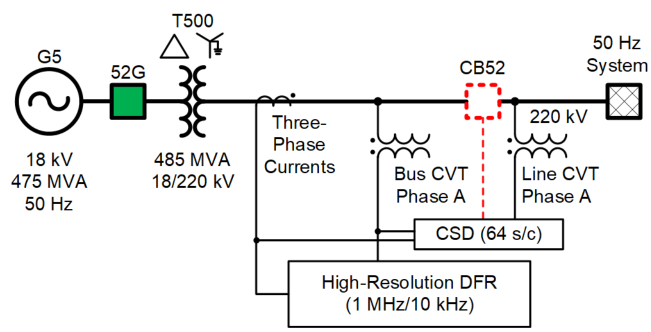

Fig. 1. System one-line diagram for transformer controlled switching application

For three single-phase transformers, the method can be achieved by closing at the transformers' respective voltage maximums. If the transformers have magnetically dependent cores [3] [4], energization of the first pole creates a flux that appears in the other two phases. If the first phase is closed at a voltage maximum, the other two phases should be closed one-fourth of a power system cycle later (or in half-cycle increments thereafter) [3]. Table I depicts the controlled switching angles and associated delays with respect to a voltage zero crossing on the R phase for this scheme (50 Hz system) [3].

TABLE I
RECOMMENDED CLOSE AND OPEN TIMES FOR A GROUNDED DELTA-WYE TRANSFORMER AFTER AN R-PHASE VOLTAGE ZERO CROSSING [3]

Pole	Closing Angle	Closing Time (ms)	Opening Angle	Opening Time (ms)
R	90°	5.00	90°	5.00
Y	180°	10.00	210°	11.67
B	180°	10.00	120°	6.67

The final advance-time settings for the controller need to account for the total delays in operating the circuit breaker, including the measurement and processing time of the CSD, the charging of the trip and close coils, and the travel time of the breaker poles (mechanical operating time). These factors were accounted for during site testing where the circuit breaker mechanical operating times (both open and close) were measured. The average operating times were divided into half-cycles to isolate the remainder, which was subtracted from the timers used in the controller. The resulting times were used for the first close and open operations during commissioning.

Another phenomenon to account for that cannot be measured directly is the circuit breaker electrical closing and opening time. As the breaker poles close, the dielectric medium (e.g., vacuum or SF6) breaks down and begins to conduct. The moment of conduction corresponds to the circuit breaker electrical closing time and depends on the voltage across the breaker poles, the dielectric properties, and the distance between the poles. Ideally, conduction should begin at a voltage maximum, corresponding to a flux of zero. This is also applicable during circuit breaker opening: current ceases to flow when the breaker poles are separated by enough distance or a zero crossing occurs. During commissioning, the authors compensated for this parameter by using oscillography from a high-resolution (1 MHz) digital fault recorder (DFR).

The CSD in this application uses a single-phase voltage as a reference to initiate a controlled open or close command at the point-on-wave angles provided in Table I [3]. A secondary injection test set and a controller connected to a dummy circuit breaker were used to determine the timings for the initial scheme. The opening and closing times were programmed and tested assuming zero delay for the operation of each breaker pole. Field testing provided the mechanical operating times for each pole, which provided the initial commissioning circuit breaker advance-time settings.

III. CONTROLLED CLOSING PERFORMANCE

To aid the commissioning process, a DFR with high-resolution oscillography [4] was used to fine-tune the CSD timings. Oscillography reports of 64 samples per cycle (s/c) from the CSD and 10 kHz and 1 MHz resolutions from the DFR were used to confirm the operations and to fine-tune the switching process, which otherwise would not have been an option.

A. Controlled Close 1

The parameters of the CSD were set to correspond to the opening and closing times in Table I and were compensated with the breaker pole mechanical operating times measured during site testing. The event captured from the first close, shown in Fig. 2, has the characteristics of a transformer energization event: a decaying dc offset waveform with a peak current of 1.3 kA and noticeable dwell times (flat regions).

Fig. 3 shows the first few milliseconds of the close with 1 MHz and 10 kHz resolutions. Ideally, Pole A would close 5 ms after the R-phase voltage (VAS) zero crossing, followed by Poles B and C after another 5 ms.

The transient currents and voltages of the 1 MHz resolution report clearly show the instants that each pole closed. Although 1 pu inrush is a good result, it is obvious that the pole close timing could be improved. Closer inspection of the 1 MHz oscillography in Fig. 4 revealed the timing adjustments that were necessary for all three poles.

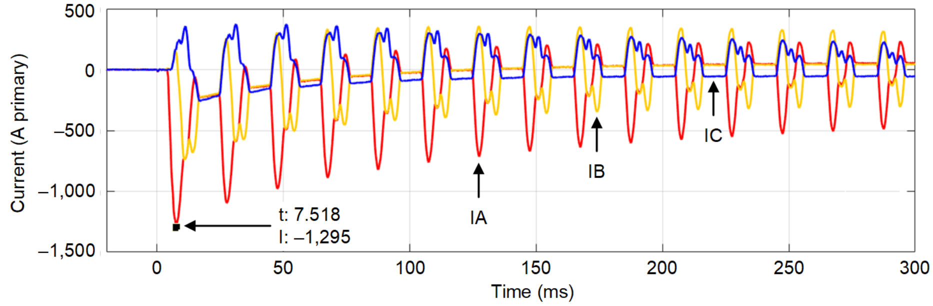

Fig. 2. Initial controlled close inrush currents measured at 64 s/c

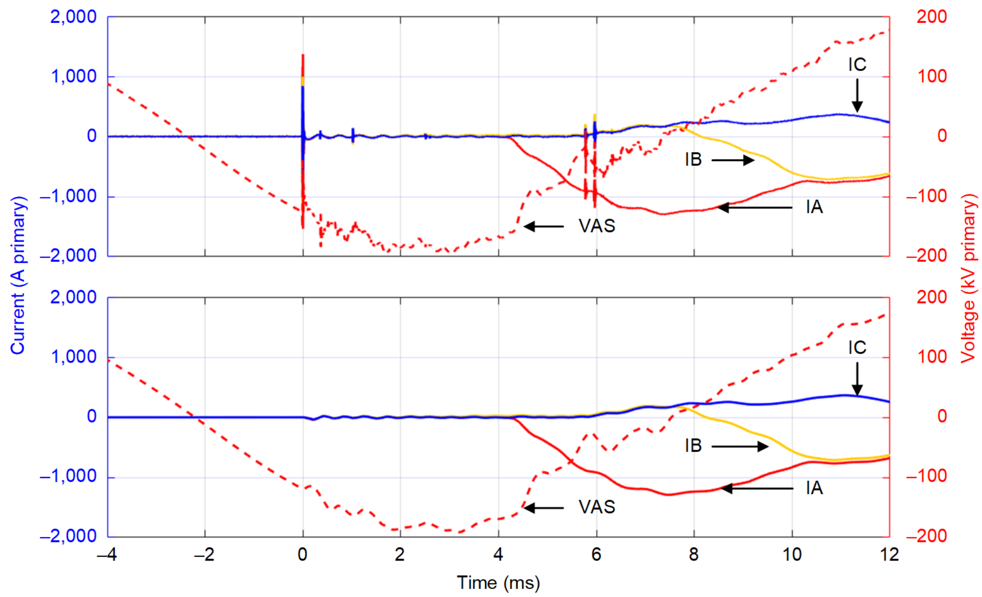

Fig. 3. Poles closing (currents and voltages during inrush) at 1 MHz (top) and 10 kHz (bottom) resolutions

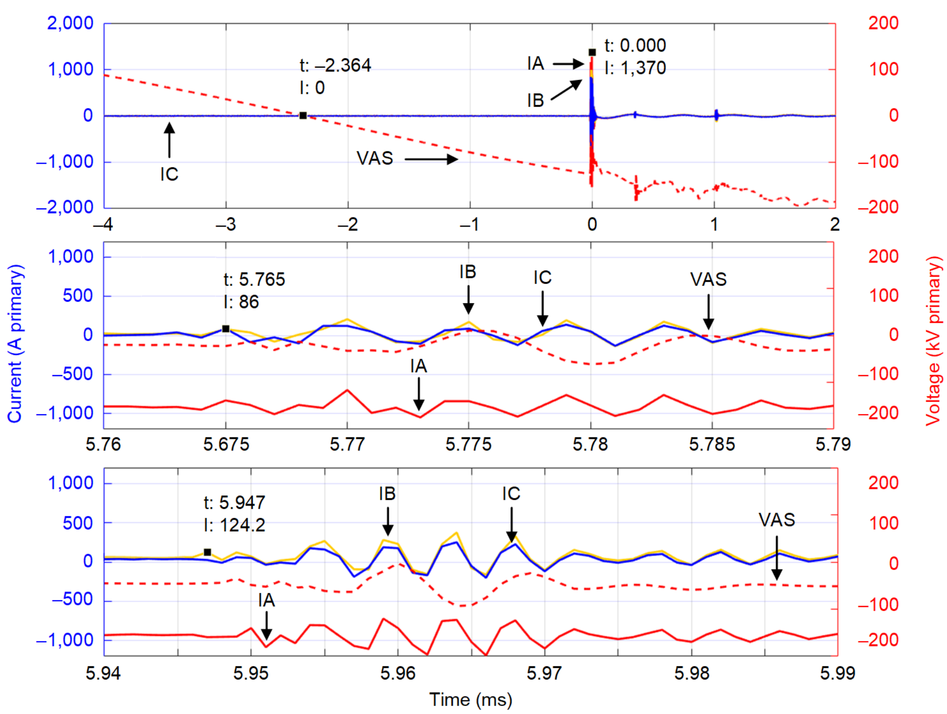

Fig. 4. Details of first pole (a), second pole (b), and third pole (c) closing

Pole A appears to have closed 2.364 ms after the VAS zero crossing (Fig. 4a). This allowed the CSD parameters to be delayed by (5 – 2.364) = 2.636 ms for the close of Pole A. Poles B and C closed around the same time, as intended by the CSD parameters. To determine which pole closed first and at what time requires a closer look at the 1 MHz record at t = 5.77 ms and t = 5.96 ms, as shown in Fig. 4b and Fig. 4c respectively.

Fig. 4c shows the Pole B currents diverging a bit earlier and further than those of Poles C and A. This indicates that Pole B might have closed last (5.947 ms). Fig. 4b shows that the Pole C currents seem to diverge a bit more than the Pole B currents, indicating that Pole C might have closed second (5.765 ms). Poles B and C closed more slowly than expected, and Pole A was slowed by 2.636 ms. This required the close times for Poles B and C to be delayed by (2.636 – 0.947) = 1.689 ms (Fig. 4c) and (2.636 – 0.765) = 1.871 ms (Fig. 4b), respectively.

Note that the order of pole closing is not definitive. In hindsight, it might have been better to stagger the close of the subsequent poles to obtain the electrical closing times with more confidence.

The current waveforms in the 64 s/c (Fig. 2) and 10 kHz events (Fig. 3b) did not provide any information for the second (Fig. 4b) or third pole closures (Fig. 4c), but they did provide some information for the first pole closure. This is shown in Fig. 5. The greater the resolution, the easier it is to determine the closing time accurately. Note that the 10 kHz and 64 s/c event records are delayed in both the currents and voltages compared with the 1 MHz event. This can be explained by signal processing delays, which are not expected to cause an issue when comparing currents and voltages with the same sampling rate.

Finally, Fig. 5 shows high-frequency transients 1.025 ms after the electrical close of Pole A. This appears to be due to the mechanical closing of Pole A, which corresponds to the values obtained from circuit breaker tests onsite.

B. Controlled Close 2

Fig. 6 shows the result of the closing attempts after the timing adjustments described above. Although the close timing has improved, the inrush current unexpectedly increased. Although surprising, the behavior is related to the transformer de-energization, as described in Section IV.

C. Controlled Closes 3 and 4

Another close was performed using the same parameters as Closing 2. This time, the inrush current reduced significantly to a peak value of 160 A (see Fig. 7a). To confirm that the results were consistent, a final close was performed (see Fig. 7b). During commissioning, there were no further switching operations.

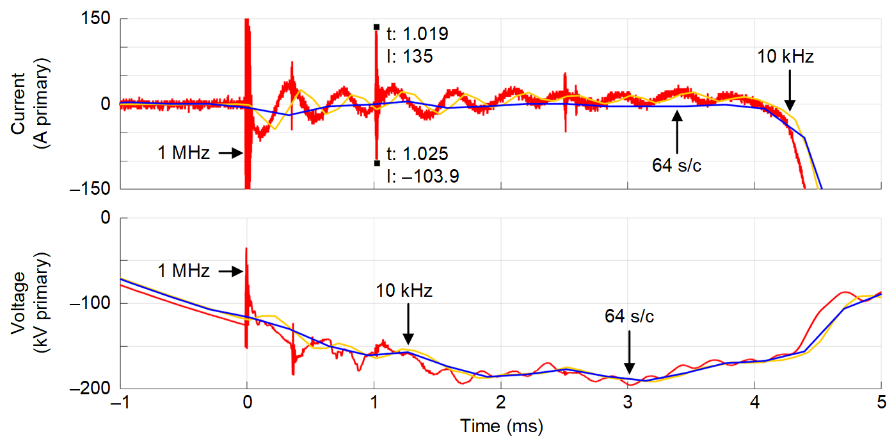

Fig. 5. Currents and voltages at different sampling rates during the initial pole close

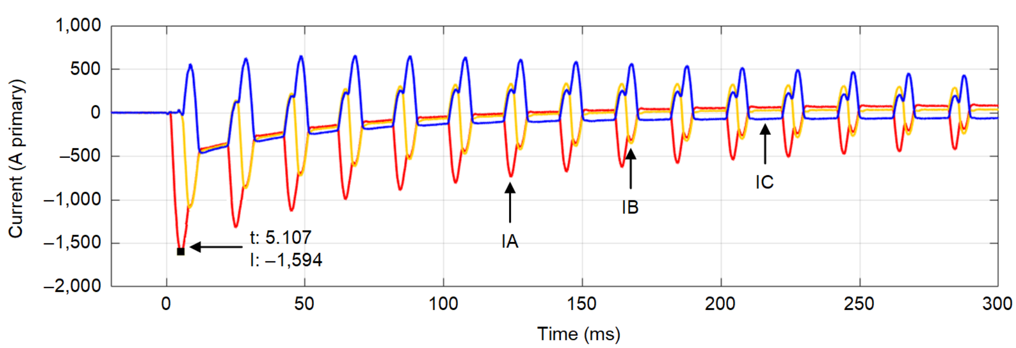

Fig. 6. Controlled closing with tuned parameters (no improvement)

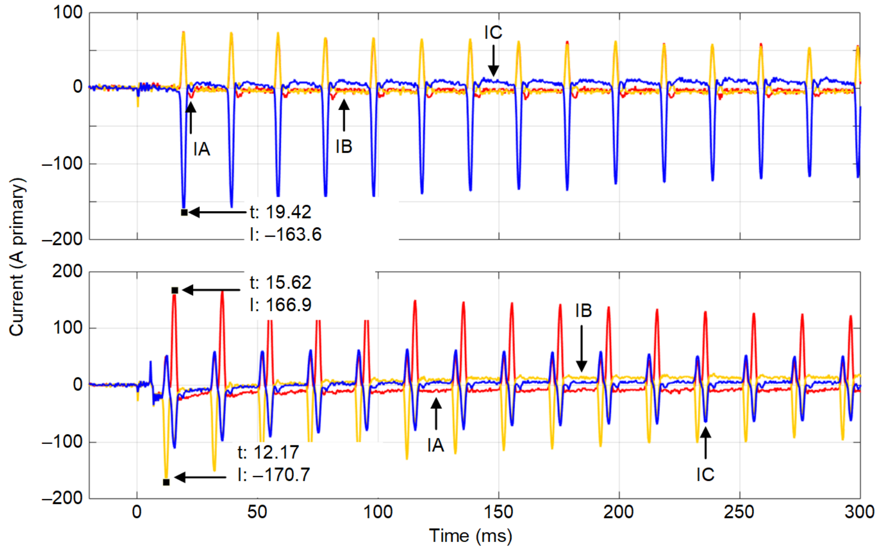

Fig. 7. Controlled closing attempts with tuned CSD parameters (substantial improvement)

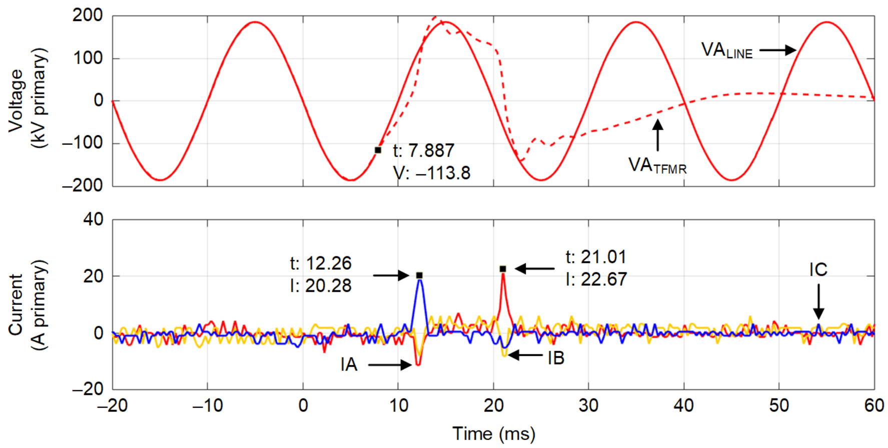

Fig. 8. Voltages and currents during controlled opening without tuned parameters (64 s/c)

IV. Effect of Controlled Opening on Switching Performance

As observed in the previous section, the second controlled close attempt (Fig. 6) with tuned parameters resulted in a peak inrush current of 1.6 kA, even higher than the 1.3 kA peak current in the initial attempt (Fig. 2). The two subsequent attempts resulted in substantial reductions to 160 A (Fig. 7). Explaining this behavior requires a close examination of the oscillography recorded during de-energization.

A. Controlled Open 1

The high-resolution DFR did not generate oscillography for Controlled Open 1, which followed Controlled Close 1. However, the CSD was wired to measure Pole A voltage on both the transformer and line sides of the circuit breaker and generated the oscillography shown in Fig. 8. This allowed the opening parameters of the CSD to be tuned.

The Pole A voltages start diverging at t = 7.89 ms after the voltage zero crossing, indicating an electrical opening of Pole A. An error of 2.89 ms, compared to the intended 5 ms, provided the information required to tune the CSD. The voltage was approximately –0.62 pu instead of the intended –1 pu (or +1 pu).

A large current transient is evident in Fig. 8 on Pole C at 12.26 ms, followed by another on Pole A at 21.01 ms. Normally, one would consider these currents to be due to the opening of the breaker poles. However, given that they were so far away (16.01 ms) from the intended operation, they could not be used to tune the opening parameters.

Unfortunately, the CSD only had single-phase voltage measurements from both the line- and transformer-side CVTs, which allowed the tuning of only one pole. However, given that the three poles exhibited similar mechanical operating times, they were adjusted by the same duration. The CVT transient on Pole A confirmed the initial assumption that the use of voltage integration methods would result in poor controlled switching performance.

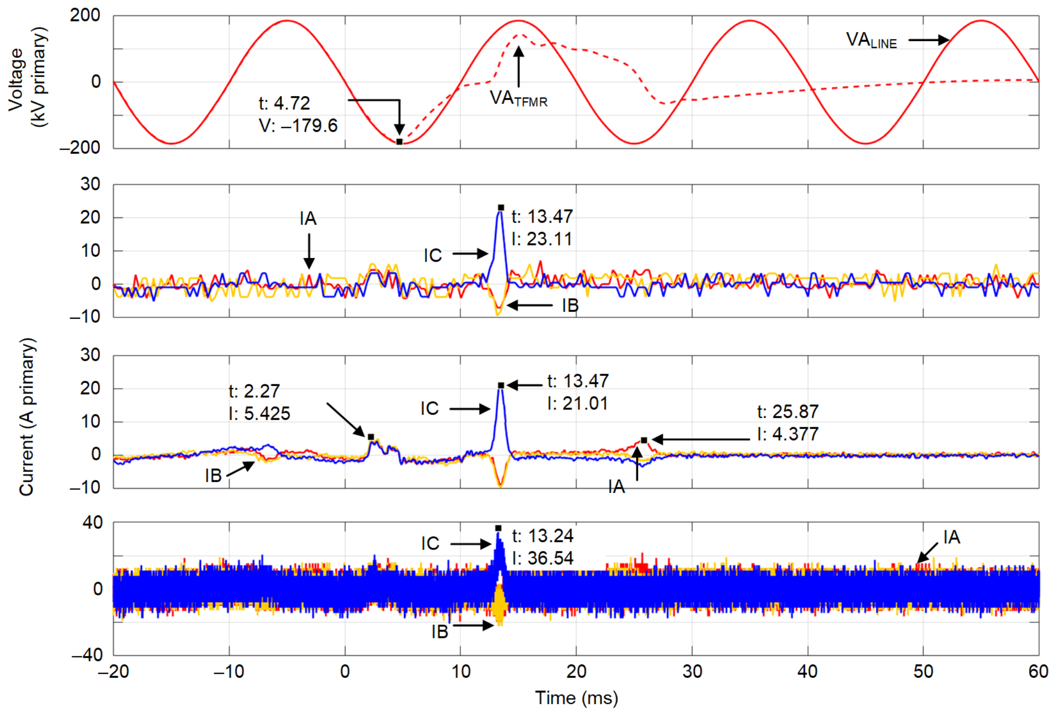

Fig. 9. Tuned controlled opening 64 s/c voltages (a), 64 s/c currents (b), 10 kHz currents (c), and 1 MHz currents (d)

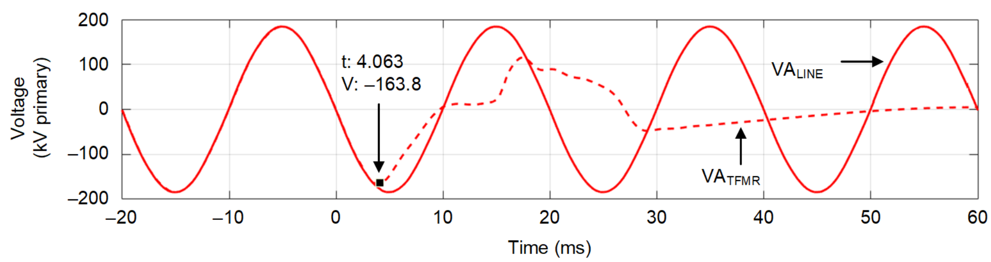

Fig. 10. Voltages (64 s/c) for the final controlled open

B. Controlled Opens 2 and 3

Controlled Open 2 occurred after Controlled Close 2, which occurred after the CSD parameters had been changed. The oscillography from both the CSD and the DFR are shown in Fig. 9. The voltages in Fig. 9a show that the Pole A tuning worked because the opening occurs near the negative voltage maximum (–0.98 pu).

The currents at 10 kHz (Fig. 9c) provide clearer information than the two other resolutions. The 64 s/c resolution does not show the three current disturbances clearly, and the 1 MHz oscillography has too much noise. The current disturbance at 2.27 ms (Fig. 9c) was likely caused by the mechanical opening of the pole, and the voltage divergence (Fig. 9a) appears to correspond to the electrical opening at 4.72 ms, which is approximately where it should be (5 ms from Table I). The other current disturbances were significantly further away than expected and, hence, had to be ignored.

The performance of the final Controlled Open 3 was confirmed, as shown in Fig. 10, as being close to expectations (–0.89 pu). Since commissioning, there have been no further operations of Circuit Breaker CB52, limiting further analysis.

V. Summary of Controlled Switching Performance

The performance of the controlled switching is summarized in Table II. The inrush was reduced from greater than 6 pu to 0.72 pu (1.3 kA peak) by using controlled switching without any tuning. Tuning of the parameters resulted in a further reduction to 0.09 pu (160 A peak).

TABLE II
OVERALL PERFORMANCE OF CONTROLLED SWITCHING

Event	CSD Tuning	Notes
Controlled Close 1 (Fig. 2–Fig. 5)	Untuned	1.3 kA peak (0.72 pu), moderate inrush
Controlled Open 1 (Fig. 8)	Untuned	Interruption at voltage = –0.62 pu
Controlled Close 2 (Fig. 6)	Tuned	1.6 kA peak (0.89 pu), moderate inrush
Controlled Open 2 (Fig. 9)	Tuned	Interruption at voltage = –0.98 pu
Controlled Close 3 (Fig. 7a)	Tuned	160 A peak (0.09 pu), low inrush
Controlled Open 3 (Fig. 10)	Tuned	Interruption at voltage = –0.89 pu
Controlled Close 4 (Fig. 7b)	Tuned	170 A peak (0.09 pu), low inrush

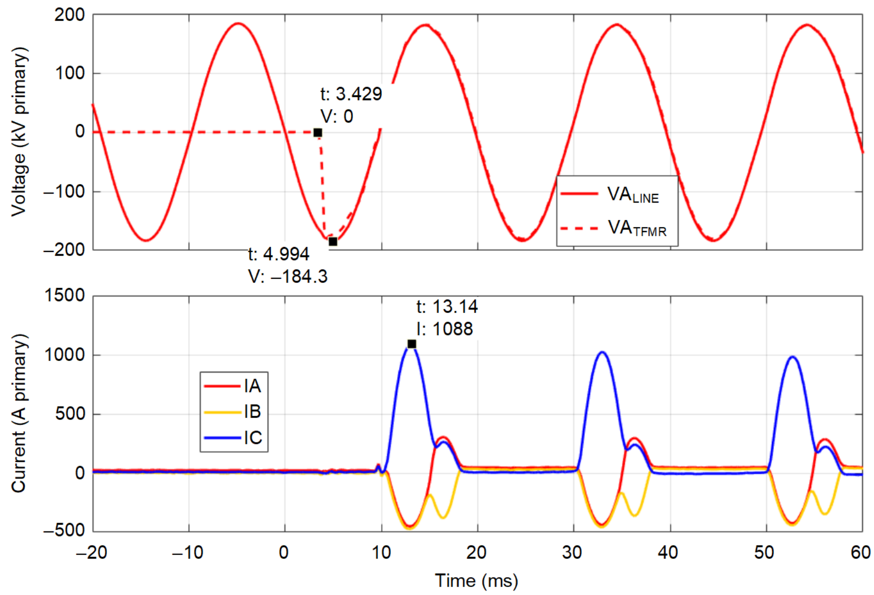

Fig. 11. Controlled close one year later

The following reasons summarize how this excellent performance was achieved:

- The controlled closing parameters were tuned using high-resolution oscillography. The 1 MHz oscillography outperformed the 10 kHz and 64 s/c by showing the closing of the second and third poles and by showing the electrical operating time in relation to the mechanical operating time (prestrike time).
- Table I was used to tune the controlled switching process by relying on the voltage information available at 64 s/c [3].
- Controlled Close 2 still exhibited a substantial amount of inrush, likely because the controlled opening prior to it was still not tuned. Thereafter, subsequent controlled closing attempts demonstrated a significant improvement in the amount of inrush.
- Tuning of the controlled opening was performed by using the only available voltage measurement.
- The 10 kHz oscillography provided a large amount of information on the currents during opening. However, this information was not used to tune the opening process because the current transients were far from the intended operation time.

For this application, not all voltage measurements were wired to the CSD and DFR. Having all voltage measurements wired would have provided additional information to allow better tuning of the CSD parameters.

To make more effective use of the oscillography, it would have been beneficial to intentionally stagger the close of the poles. This would ensure that the poles would close at approximately the same point-on-wave and not interfere with the tuning process, as was the case in Fig. 4.

VI. Performance After One Year

The unit transformer was de-energized for a planned maintenance outage approximately one year after the new scheme was commissioned. Increased confidence had caused the switching and outage requirements to be reduced, significantly reducing the required outage time. There was no longer a requirement by the transmission operator to energize from a station 80 km away.

When the unit was de-energized, an error in the switching procedure meant the transformer was isolated via an uncontrolled open of a three-pole circuit breaker. Subsequently, the only records captured were from the close operation. The controlled close produced an inrush current of ~0.6 pu, more than the expected 0.09 pu if the close followed a controlled open. Regardless, it was still a significant improvement over the 6 pu that had been seen over the years from random close operations. Fig. 11 shows that the close timing was approximately 1.5 ms before a voltage maximum.

VII. Conclusion

This paper discusses the design and commissioning of a replacement system for the point-on-wave control of a 220 kV circuit breaker energizing a 485 MVA transformer. Failure of the original controller required the transformer to be manually closed, which resulted in large inrush currents, brownouts, voltage sag events, and sympathetic inrush of adjacent transformers that could be heard for many minutes after some closing attempts.

A new scheme was designed and commissioned to control both the closing and opening timings for each circuit breaker pole. Only CVTs were available on the 220 kV system, hence the new scheme consisted of fixed points on the waves. During the commissioning process, high-resolution oscillography (1 MHz, 10 kHz, and 64 s/c) was used to tune the parameters of the CSD. The 1 MHz oscillography provided the highest amount of information during the controlled closing. Despite the tuning, the initial inrush record demonstrated an increased inrush current, followed by a reduction for subsequent events. Some unexpected behavior in the currents during opening could not be explained.

Analysis of the event records after the commissioning explained the initial increase in the inrush current despite controller parameter tuning. Both controlled opening and closing worked together to reduce inrush current significantly based on the strategy from [3].

Fine-tuning the parameters of the CSD by observing the oscillographic records substantially reduced the magnetizing inrush currents from over 6 pu to 0.1 pu. This demonstrates that adequate controlled switching performance can be obtained by combining the controlled opening and closing processes and tuning the parameters using high-resolution oscillography without the use of voltage integration techniques.

VIII. References

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IX. Biographies

Vetti Bala is a principal control system engineer with Genesis Energy, in New Zealand. He is a C&I engineer with over 20 years of experience in the power generation sector, with the greater focus on asset management of electrical power systems. He has always ensured a timely life cycle management of the critical assets including generator protection, excitation, governor, and DCS control systems.

Brett Hampson is a senior application engineer with Schweitzer Engineering Laboratories, Inc. He is an electrical engineer with over 15 years of experience in the installation, testing, design, and management of electrical power and control systems. His experience includes both managing and participating in the review, design, manufacture, installation, and commissioning of several electric power generation and distribution systems; protection systems, safety analysis of work systems, as well as extensive experience in construction, including managing his own electrical contracting company.

Ritwik Chowdhury received his bachelor of engineering degree from the University of British Columbia and his master of engineering degree from the University of Toronto. He joined Schweitzer Engineering Laboratories, Inc. in 2012, where he has worked as an application engineer and presently works as a lead engineer in research and development. Ritwik holds two patents and has authored over a dozen technical papers in the area of power system protection and controlled switching. He is a member of the rotating machinery protection and relaying practices subcommittees of the IEEE PSRC committee and a registered professional engineer in the province of Ontario.

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