Field Experience With Ultra-High-Speed Protection, Traveling-Wave Fault Locating, and Circuit Breaker Reignition Detection on a 220 kV Line in the Kalahari Basin

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***Abstract*—This paper provides valuable information about field experience acquired by NamPower, in Namibia, Africa. NamPower installed ultra-high-speed (UHS) relays to monitor a 220 kV, 113.6 km overhead line between the Omburu and Khan substations. UHS relays use traveling-wave-based (TW-based) and incremental-quantity-based principles to provide line protection. UHS relays include TW-based fault-locating (TWFL) methods to locate faults with high accuracy, and they also include MHz recording capability that can be used to detect high-frequency power system events like reignition in circuit breakers. This line was selected by NamPower to evaluate UHS protection and TWFL technology and to compare fault-clearing time and fault location accuracy with existing conventional line protection.**

Elements and schemes based on transient phenomena are now available in microprocessor-based relays and are being applied in electric power system protection schemes. This paper shares a vivid example, experience, and perspective using event analysis, which includes the use of Bewley diagrams to show the time-space relationship of TWs. The TW phenomenon, known for decades, is gaining popularity for UHS protection and accurate fault locating. The paper describes NamPower's experience by analyzing the performance of the UHS line relay for a C-phase-to-ground fault on the line, highlighting the following:

- **Performance of UHS protection**
- **Accurate double-ended TWFL results**
- **Fault-clearing time**
- **Post-fault arcing and circuit breaker reignition**

I. Introduction

NamPower is Namibia's national power utility, originally known as South West Africa Water and Electricity Corporation (SWAWEK). Key to SWAWEK's success was the effective development of the hydropower station (the Ruacana Scheme with a capacity of 240 MW) and the establishment of a transmission system for the distribution of electricity through the country's central districts to Windhoek. In its 32-year history, SWAWEK has made valuable contributions to the country's economic development. In July 1996, SWAWEK became NamPower. Today, NamPower's 34,000 km transmission and distribution network is one of the longest networks in the world. The transmission network includes transmission lines at voltage levels from 66 kV ac to 400 kV ac and 350 kV high-voltage direct current (HVDC).

This paper begins with an overview of the NamPower system and their line protection philosophy, and then it provides a brief introduction to protection elements and schemes that operate using incremental quantities and traveling waves. The paper then discusses NamPower's experience with fast relay operating time, fault-clearing time, ultra-high-speed (UHS) protection performance, accurate fault locating, and observations from ultra-high-resolution transient records. The field experience focuses on observations and experience gained from an internal C-phase-to-ground fault on the 220 kV Omburu-Khan 1 line that occurred on February 4, 2020, with UHS relays applied at both line terminals. The analysis highlights the performance of UHS line protection compared to existing phasor-based protective relays, while reviewing the results of the double-ended traveling-wave-based fault-locating (TWFL) method. The paper also presents observations of post-fault arcing and circuit breaker reignition visible in the 1 MHz sampling event records.

II. The NamPower System

NamPower owns and operates three power stations with the combined installed capacity of 459.50 MW. The following power stations are the main sources of local power generation capacity in the country:

- 347 MW Ruacana hydroelectric power station in the Kunene region
- 90 MW Van Eck coal-fired power station outside of Windhoek
- 22.5 MW Anixas diesel-powered power station at Walvis Bay

NamPower owns a world-class transmission system and a network of 66 kV to 400 kV of overhead lines spanning a distance of more than 11,704 km (shown in Fig. 1). Continuous investments are made to strengthen and keep the national grid in its best condition to ensure an efficient, reliable, and effective network with minimal disruptions. In addition to these lines, NamPower's asset base includes 156 transmission substations and 92 distribution substations with a total transformer capacity of 8,978 MVA, along with specialized HVDC and SVC devices.

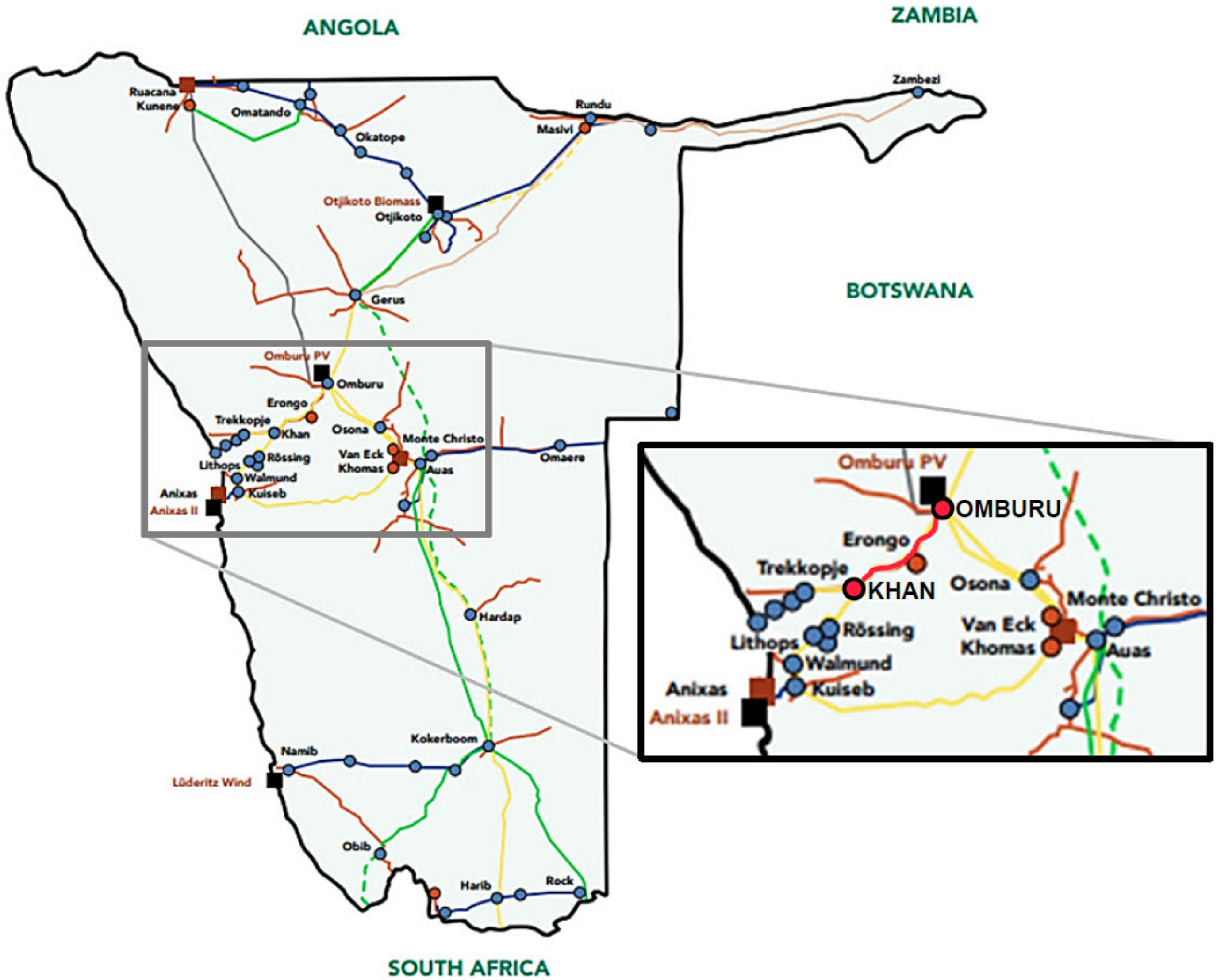

Fig. 1. NamPower transmission network (inset), showing a zoomed-in view of the 220 kV Omburu-Khan transmission line corridor [1].

Two 220 kV 113.6 km overhead lines (Line 1 and Line 2) connect the Omburu and Khan terminals. These are major transmission lines in NamPower's transmission network and pass over difficult inaccessible terrain in the Kalahari Basin. Fig. 1 shows the NamPower transmission network and a zoomed-in view of the Omburu-Khan 1 line.

A. 220 kV Omburu-Khan 1 Transmission Line

The Omburu-Khan 1 transmission line (shown in Fig. 1) is a critical line in the well-maintained NamPower electric power system. Sustained faults on either of these lines means loss of electric power service to thousands of customers and critical mining industry loads around the Khan substation.

Fig. 2 shows the one-line diagram of the 220 kV Omburu-Khan 1 transmission line. Four bus-reactors, a filter bank, and a static VAR compensator are at the 330/220/66 kV Omburu substation on the 220 kV bus. A 220 kV filter bank is at the 220/66 kV Khan substation. The 220 kV buses at both Omburu and Khan substation are a double-bus (not shown in Fig. 2) single-breaker scheme. Terminal equipment is listed in Table I, and line data are listed in Table II.

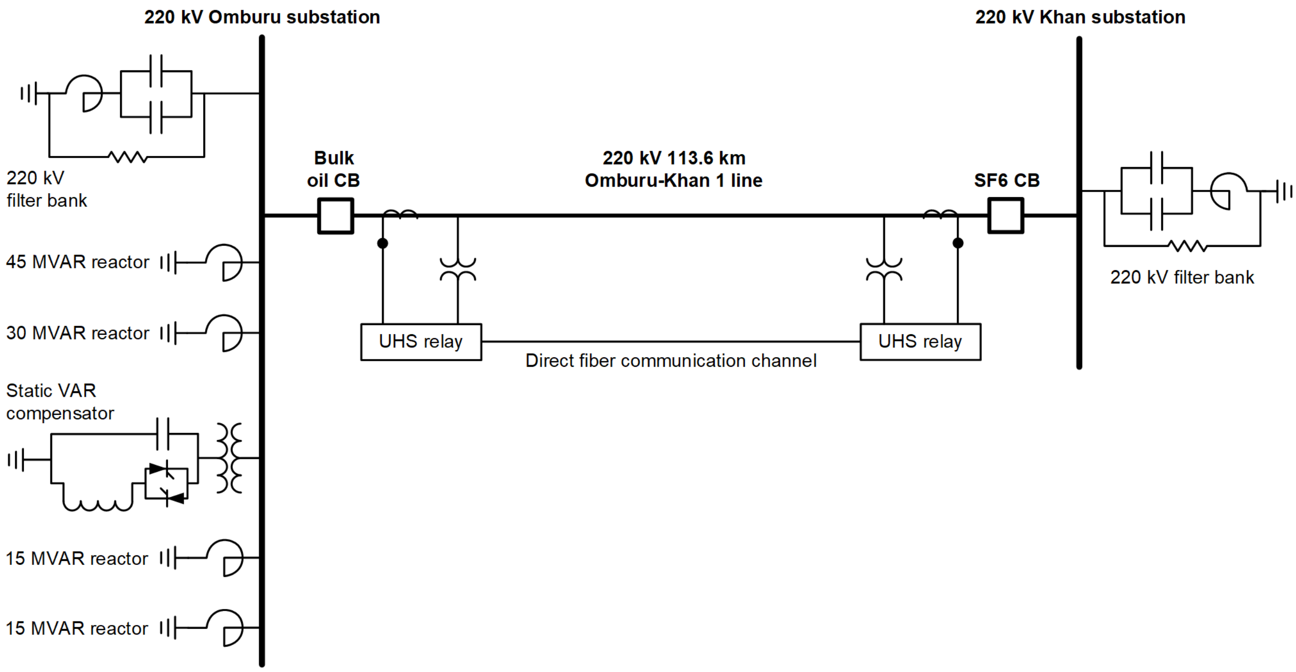

Fig. 2. 220 kV, 113.6 km Omburu-Khan 1 line one-line diagram.

TABLE I
TERMINAL EQUIPMENT

Equipment	**Omburu**	**Khan**
Line-to-Line Voltage	220 kV	220 kV
220 kV Outgoing Lines From Terminal	5	5
Current Transformer	Ratio: 800/1 A Class: TPS $I_m \leq 150$ mA $R_{CT} \leq 3.2\ \Omega$	Ratio: 800/1 A Class: TPS $I_m \leq 150$ mA $R_{CT} \leq 3.2\ \Omega$
Line CCVT	Y-Connected Ratio: 220 kV/110 V Class: 3P Burden: 100 VA	Y-Connected Ratio: 220 kV/110 V Class: 3P Burden: 100 VA
Circuit Breaker	Type: Bulk Oil Circuit Breaker Short Circuit Breaking Current: 30.3 kA for 3 s	Type: SF6 Circuit Breaker Short Circuit Breaking Current: 40 kA for 3 s

TABLE II
LINE DATA

Parameter	**Value**
Source Impedance at Omburu (Z_{SO})	36.97 Ω
Source Impedance at Khan (Z_{SK})	49.95 Ω
Positive-Sequence Line Impedance (Primary)	$46.925\ \Omega \angle 77.78°$
Zero-Sequence Line Impedance (Primary)	$164.575\ \Omega \angle 75.41°$
Line Length	113.6 km
Traveling-Wave Line Propagation Time (TWLPT)	386.66 µs
Line Voltage	220 kV
CCVT Rating	220 kV/110 V Line-to-Line
CTR at Khan	800:1 A
CTR at Omburu	800:1 A

B. *Line Protection on the Omburu-Khan 1 Line*

Per the NamPower line protection standards, existing line protection on the Omburu-Khan 1 line uses phasor-based line current differential (87L) and step distance (21) protection, in conjunction with a permissive overreaching transfer trip (POTT) scheme. Fault locating is based on the single-ended impedance-based method.

The 87L scheme uses phase, negative-sequence, and ground elements. The differential relays perform identical line current differential calculations in a peer-to-peer architecture using the direct fiber communication between Omburu and Khan. The phase current differential pickup is set up to 1.2 pu with or without line-charging-current compensation, and negative sequence and ground differential protection pickup levels are set between 0.1 and 0.15 pu. The distance protection practice at NamPower is to set four distance zones, using Mho elements for phase faults and quadrilateral elements for ground faults. The POTT scheme uses the overreaching distance elements. The Zone 1 distance reach is set at 80 percent of the line impedance and is set to trip instantaneously. The Zone 2 reach is set to 120 percent of the line impedance, reaching beyond the remote bus from both Omburu and Khan terminals and is set with a delay of 400 ms. Zone 3 is set as reverse, with the reach set to 45 percent; it is used for blocking and weak infeed schemes. Zone 4 is set to the same reach as Zone 2, but with a much longer operating time between 1 and 3 s; it serves as a remote breaker failure backup. For distance accelerated tripping, NamPower uses the POTT scheme over the power line carrier (PLC) or optical ground wire (OPGW) fiber-optic channel. The direct transfer trip (DTT) scheme is also used to send a direct trip to the remote end in case of local breaker failure. The weak infeed scheme is also implemented on radial lines or lines with weak terminals. All Zone 1 faults initiate autoreclosing; Zone 2 elements can only initiate autoreclosing if a permissive trip signal is received from the remote end. Zone 4 trips result in a lockout of the autoreclosing function. Negative- and zero-sequence-based directional overcurrent elements are used as backup protection to detect phase and ground faults.

The line has coupling-capacitor voltage transformers (CCVTs) at each end of the line. In general, phasor-based line protection relays applied with CCVTs are prone to overreaching and face challenges in accuracy of operation [2]. The presence of voltage and power quality improvement equipment, like bus reactors, static VAR compensators, and filter banks at either end of the line challenge the operation of phasor-based distance protection elements and the accuracy of impedance-based fault locating [3]. NamPower wanted to improve fault-clearing times and the accuracy of locating faults, so when they learned of the new technology available with UHS relays, they decided to evaluate these relays and install a pair of UHS relays to monitor the Omburu-Khan 1 transmission line.

III. UHS Protection and Traveling-Wave Fault Locating

UHS relays [4] include the TW-based differential (TW87) scheme, the TW-based directional (TW32) element, the incremental-quantity-based distance (TD21) element, and the incremental-quantity-based directional (TD32) element. UHS relays include TWFL methods to locate faults with a high level of accuracy. The ability of UHS relays to provide transient recording at a 1 MHz sampling rate and 18-bit resolution allows analysis of high-frequency power system events, including breaker reignition. These capabilities are unavailable in existing conventional microprocessor-based line protective relays.

A. *TW-Based Line Protection: TW87 and TW32*

The UHS protective relays in the pilot installation included a TW-based directional (TW32) element and a TW-based differential (TW87) scheme. References [5] and [6] discuss TW-based protection principles and their field performance in detail. The nature of current and voltage TWs for different fault conditions is summarized in this section and aids in basic TW analysis.

For an internal fault on the line, the first current TWs detected at the local and remote line terminals have the same polarity and are separated by less than the TWLPT. TWLPT is the one-way end-to-end TW travel time of the transmission line. TWLPT is a configuration setting required by the UHS relays. The accuracy of the TWLPT setting is critical for the security of the TW87 protection scheme and for the accuracy of the TWFL methods. TWLPT is measured by using the transient record captured during a line energization test, as recommended in [7].

When the fault is external to the line, the first current TWs detected by the local and remote line terminals have opposite polarities and are separated by exactly the TWLPT. This is the fundamental principle of the TW87 scheme. The TW87 scheme requires that the UHS relays at each line terminal exchange measurements of the local voltage and current signals sampled at 1 MHz using the dedicated fiber-optic channel. With the dedicated fiber-optic channel connected, the relays time-synchronize data over the channel and do not rely on an external time source. Additional implementation details of the TW87 scheme in UHS relays are available in [4].

The polarities of the first voltage and current TWs that arrive at one terminal after a fault occurs indicate the direction of the fault. When the fault is in the forward direction, the voltage TW and current TW have opposite polarities; for a reverse fault, the voltage TW and current TW have the same polarity. This fundamental principle forms the basis of TW32 element. The TW32 element in the UHS relay is used only for fast keying of the POTT scheme and is not intended for direct tripping of circuit breakers. Additional implementation details of the TW32 element and POTT scheme in the UHS relay are available in [4].

B. Incremental-Quantity-Based Protection: TD21 and TD32

The UHS protective relays included protection elements that use voltage and current incremental quantities, which are the differences between a present instantaneous sample and a one-cycle-old sample. The incremental quantities contain the pure fault voltage and current information and exclude any pre-fault load information [2]. These signals are filtered with a low-pass filter and then applied to directional and distance elements. The relay calculates incremental voltage and incremental replica currents for six measurement loops [4].

The TD21 element is a fast-underreaching Zone 1 distance element used for instantaneous tripping. This element calculates the incremental voltage change at the reach point and compares it with the pre-fault voltage at the same reach point. For an in-zone fault within the reach point, the calculated incremental voltage change at the reach point will be greater than the pre-fault reach point voltage. For a fault beyond the reach point (outside the zone of protection), the calculated incremental voltage change at the reach point will be less than the pre-fault reach point voltage [4].

The TD32 element provides a fast, secure, and dependable directional indication. This element is used as part of a POTT scheme and is not intended for direct tripping of circuit breakers. The TD32 element calculates the operating torque as a product of sign-inverted incremental loop voltage and incremental replica loop current. It also calculates the forward and reverse restraining torques based on the incremental replica loop current and relay settings for the forward/reverse impedance thresholds. For a forward fault, the incremental loop voltage and incremental replica loop current have opposite polarities, which results in a positive torque, and then TD32F declares forward direction. For a reverse fault, the incremental loop voltage and incremental replica loop current have the same polarity, which results in a negative torque, and then TD32R declares reverse direction. The calculated torques are integrated and the operating torque is compared with the restraining torques. Reference [4] discusses the TD32 element in detail.

C. TWFL

Faults on transmission lines generate TWs that propagate from the location of the fault to the line terminals. The fault location can be calculated based on the TW arrival times, the line length (LL), and the TWLPT. TWFL is widely popular with transmission system operators, largely due to its field-proven track record with reported errors being within one tower span (300 m or 1,000 ft) on average, regardless of LL. The accuracy of impedance-based fault-locating methods is approximately 0.5 to 2 percent of LL for the double-ended method and 2 to 5 percent of LL for the single-ended method [8]. For a 100 km transmission line, a ±1 percent error requires inspection of the likely 2 km section (about seven towers). The UHS relays applied in this pilot application include the following methods:

- Single-ended traveling-wave-based fault-locating (SETWFL)
- Double-ended traveling-wave-based fault locating (DETWFL)
- Single-ended impedance-based fault-locating (SEZFL)
- Double-ended impedance-based fault-locating (DEZFL)

The DETWFL method uses the arrival times for the initial TW at both terminals, along with the LL and the TWLPT, to calculate the fault location. Obtaining the time stamp of the arrival time of the initial TW at each terminal can be achieved by various means, as described in [9]. In this pilot application, a direct fiber-optic connection was available between the Omburu and Khan line terminals and was used for the DETWFL method. The general equation used to calculate DETWFL results is shown in (1). M is the calculated fault location, t_L is the arrival time of the initial TW at the local terminal, and t_R is the arrival time of the initial TW at the remote terminal.

$$M = \frac{LL}{2} \bullet \left(1 + \frac{t_L - t_R}{TWLPT}\right) \quad (1)$$

The UHS relays in this pilot application were also capable of compensating (1) by using (2) and the TW current transformer (CT) cable propagation time setting (TWCPT) in each relay to increase the accuracy of DETWFL by compensating for the time delay that is introduced by the cables between the CTs and the relay. The compensation is not needed if both relays use CT cables with the same propagation time (similar cable types with similar lengths). The fault locator adjusts for the associated time delay by backdating the initial TW time stamps at both terminals [9].

$$M = \frac{LL}{2} \bullet \left(1 + \frac{(t_L - t_R) - (TWCPT_L - TWCPT_R)}{TWLPT}\right) \quad (2)$$

The UHS relays also provide a calculated fault location using the SETWFL method. This is particularly useful when dedicated point-to-point direct fiber-optic (or IEEE C37.94 multiplexed communications with submicrosecond time-synchronized relays) is unavailable for a given application, a single relay is installed on a radial line, or the fiber-optic channel used for relay-to-relay communications is temporarily out of service.

D. Transient Recording

The UHS relay provides transient recording functionality with two types of records:

- Ultra-high-resolution record containing voltages and currents (megahertz record [MHR], 1 MHz sampling).
- High-resolution record containing voltages and currents, derived protection quantities, and all digital bits (time-domain record [TDR], 10 kHz sampling).

Both types of records are stored in IEEE C37.111-2013 COMTRADE format. As per this format, both the MHR and TDR IEEE COMTRADE records are comprised of three files: configuration (CFG) file, data (DAT) file, and header (HDR) file. The three-letter abbreviations serve as the file extension type. The CFG file describes the content of the DAT file, the DAT file contains the values for each input channel for each sample in the record, and the HDR file contains relay settings and event-related analog quantities (such as pre-fault and fault voltages and currents, fault type and location, etc.), which are helpful when analyzing power system events and relay operations [4] [9].

Fig. 3 shows the part of the HDR file that contains the fault location information. This is available in the HDR files of both the MHR and TDR IEEE COMTRADE records [4] [9].

```
[Fault_Location]
SE_TW_Location1
SE_TW_Location2
SE_TW_Location3
SE_TW_Location4
DE_TW_Location
SE_Z-Based_Location
DE_Z-Based_Location
First_TW_Time_Local
First_TW_Time_Remote
```

Fig. 3. Part of the IEEE COMTRADE header file containing fault location information.

The fields in Fig. 3 are described as follows:

- SE_TW_Location ($n = 1, 2, 3, 4$) are the fault locations from the SETWFL method.
- DE_TW_Location is the fault location from the DETWFL method.
- SE_Z-Based_Location is the fault location from the SEZFL method.
- DE_Z-Based_Location is the fault location from the DEZFL method.
- First_TW_Time_Local is the time stamp of the first local TW, compensated by the CT cable delay.
- First_TW_Time_Remote is the time stamp of the first remote TW, compensated by the CT cable delay.

Event analysis software [10] enables the user to open the MHR IEEE COMTRADE records and plot the voltage and current signals, obtain phase TWs, obtain modal TWs (zero, alpha, and beta Clarke components) for manual analysis, and apply time cursors that replicate the interpolation method used by the UHS relays to obtain the TW arrival time with submicrosecond accuracy [8], as shown in Section IV of this paper. The time stamp of the initial TW at each terminal may be obtained by opening the corresponding MHR IEEE COMTRADE records in the event analysis software, plotting the appropriate modal TW signal according to the fault type, and sliding the time cursor to line up with the peak of the initial TW. It is important to note that this time stamp does not include compensation for the TW CT cable delay. The event analysis software also provides the ability to plot and analyze Bewley diagrams. When time-synchronized MHR IEEE COMTRADE records from the UHS relays at each terminal of the line are opened in a single session of the event analysis software, the software allows the user to plot the Bewley diagram and automatically align the local and remote TW peaks to display the fault location relative to either terminal of the line (see Fig. 12).

IV. Field Experience

On February 4, 2020, a C-phase-to-ground fault was recorded by the UHS relays monitoring the Omburu-Khan 1 line. This was the first fault on the line following the installation of the UHS relays. For the analysis of this fault, transient records were retrieved from the UHS relays at both terminals.

A. *Fault-Clearing Time*

Fault-clearing time (FCT) is well defined in Section III (Part A) of [11]. At Omburu, the existing phasor-based underreaching Zone 1 distance element (Z1T in Fig. 4) operated in 13.87 ms for this fault and issued a C-phase single-pole trip to the breaker. The bulk oil circuit breaker at Omburu took 63 ms to clear the fault, for a total FCT of 76.87 ms (see Fig. 4).

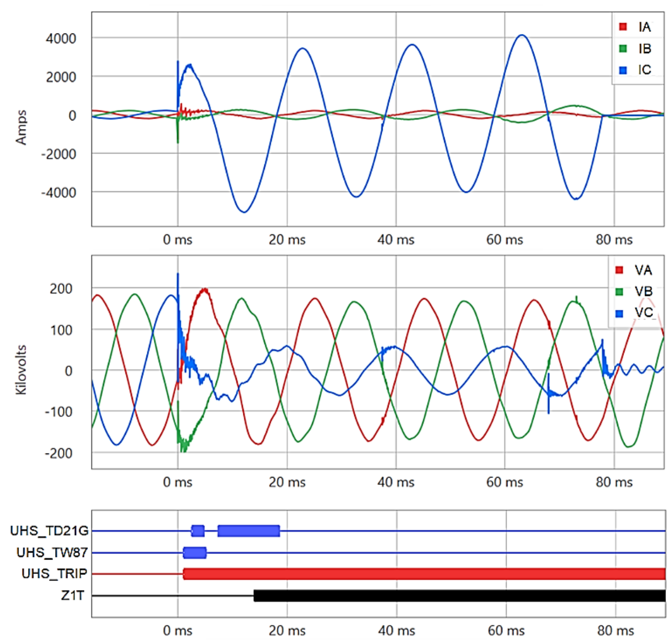

Fig. 4. Transient record oscillography and performance of UHS relay and phasor-based distance protection at Omburu terminal.

At Khan, the existing phasor-based underreaching Zone 1 distance element operated (Z1T in Fig. 5) in 35 ms, and the SF6 circuit breaker opened in another 23.7 ms. The total FCT was 58.7 ms (see Fig. 5). In comparison to the operating time of the phasor-based relays, the UHS relays operated almost 13 ms faster at Omburu and nearly 34 ms faster at Khan.

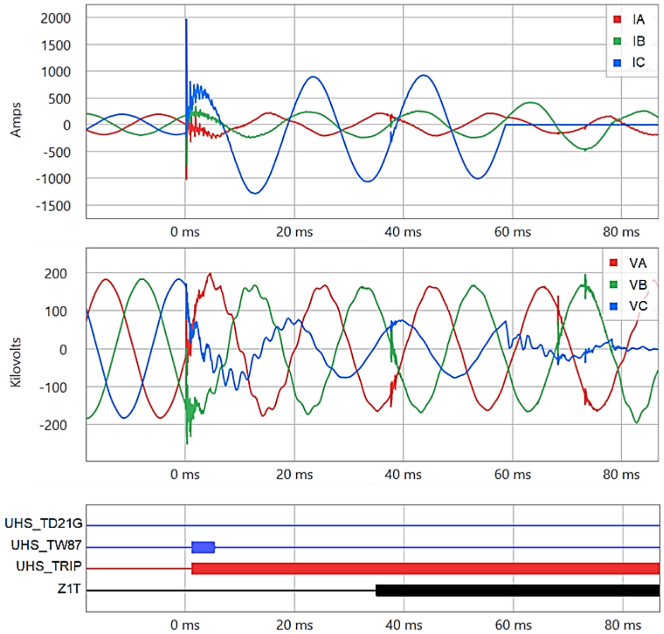

Fig. 5. Transient record oscillography and performance of UHS relay and phasor-based distance protection at Khan terminal.

The UHS relays were not wired to trip the circuit breaker during the pilot installation; however, UHS relays are now wired for tripping (fault-clearing) to improve FCT over the existing phasor-based protective relays, as shown in Table III.

TABLE III
FCT COMPARISON

Equipment	**Omburu**	**Khan**
Circuit Breaker	Type: Bulk Oil Circuit Breaker Short Circuit Breaking Current: 30.3 kA for 3 s	Type: SF6 Circuit Breaker Short Circuit Breaking Current: 40 kA for 3 s
Existing Phasor-Based Relay Operate Time (ms)	13.87	35
Breaker Trip Time (ms)	63	23.7
FCT (ms)	76.87	58.7
UHS Relay Operate Time (ms)	1.092	1.05
UHS FCT (ms)	64.092	24.75
FCT Difference (ms)	12.778*	33.95*
Percentage Reduction	16.6%	57.8%

*Note: FCT reduction time expected to be 20 ms (1 cycle at 50 Hz) as is typically observed for UHS FCT [12].

It is significant to note that the Khan terminal has a fast SF6 circuit breaker. 30 ms (1.5 cycles at 50 Hz or 25 ms at 60 Hz) FCTs are generally expected and observed with UHS protection and 2-cycle SF6 circuit breakers.

B. TW87 Scheme Performance

Line energization tests were performed during commissioning, and the TWLPT for the 220 kV Omburu-Khan 1 line was measured to be 386.66 µs. In this application of UHS relays, the relay-to-relay communication was established via a dedicated point-to-point fiber-optic channel. Reference [4] describes the relevance of TWLPT and direct fiber communications to the TW87 scheme. The TW87 scheme compares timing, polarities, and magnitudes of current TWs at both line terminals. The TW87 scheme asserted in less than 1.1 ms at the Omburu terminal and in less than 1.3 ms at the Khan terminal (as shown in Fig. 6). The first TWs arriving to the two terminals are of the same polarity (as observed in Fig. 13), and the time difference of 239.422 µs is less than the TWLPT, which is the signature of an internal fault.

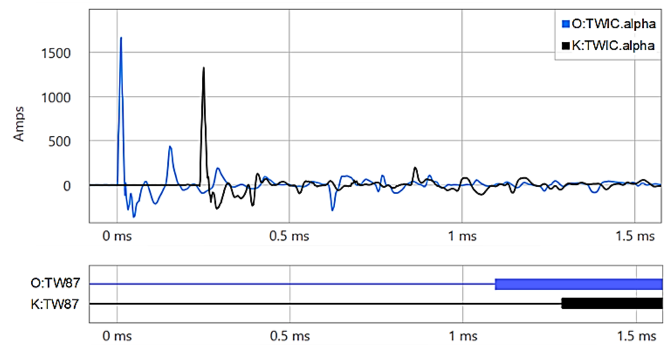

Fig. 6. C-phase alpha-mode current TWs and operation of the TW87 scheme at the Omburu (O) and Khan (K) terminals.

C. TW32 Element Performance

Theoretically, a wide-bandwidth (high-fidelity) voltage transformer is ideal to measure voltage TWs. However, in most cases, the UHS relays can measure the first voltage TW even with a CCVT because of interwinding capacitance across the step-down transformer and the interturn capacitance across the CCVT tuning reactor [7]. This voltage TW measurement is not accurate in terms of voltage TW magnitude, but it is accurate in terms of the arrival time and polarity, which is sufficient for the TW32 element. With CCVTs at either end of the line, we observed that the TW32 element declared the fault to be forward (TW32F asserted) in less than 100 µs at Omburu and Khan terminals. Remember that the opposite polarities of TW currents and TW voltages indicate a forward event from both terminals, as highlighted in Fig. 7 and Fig. 8.

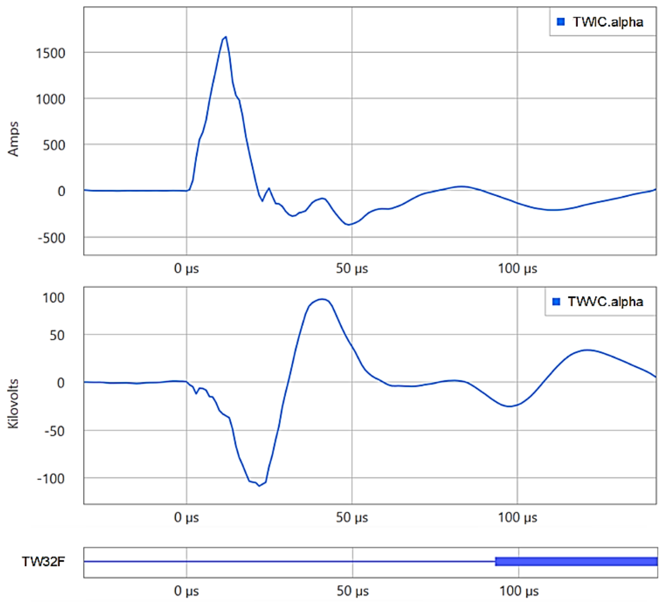

Fig. 7. C-phase alpha-mode current and voltage TWs and operation of the TW32 element at the Omburu terminal.

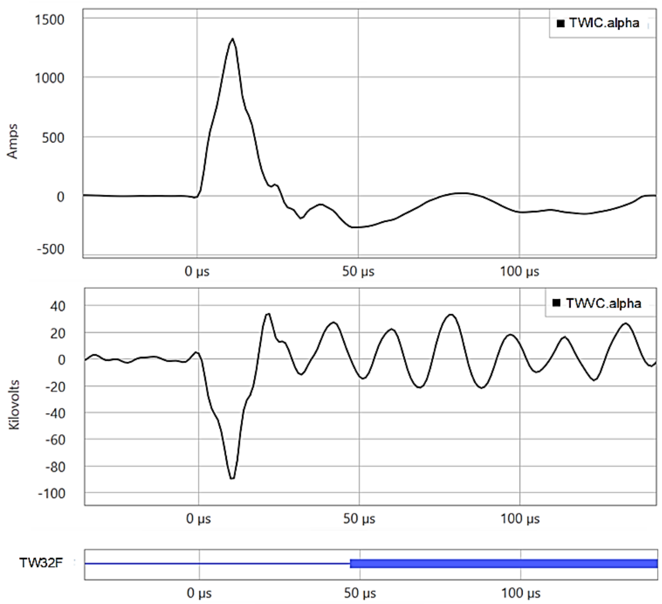

Fig. 8. C-phase alpha-mode current and voltage TWs and operation of the TW32 element at the Khan terminal.

Although the POTT scheme was not enabled at the time of this fault, NamPower was interested in the performance of the TW32 element as part of their consideration for enabling the POTT scheme with keying of the permissive trip signal from the TW32 element in the future.

D. *TD21 Element Performance*

The fault was detected as a Zone 1 C-phase-to-ground fault by the TD21 element (TD21G) at Omburu. With the TD21G reach set at 70 percent and the fault located at 19 percent of the line (21.629/113.60 km), the fault is well within the Zone 1 element reach and operated in 2.59 ms (Fig. 9). From the Khan terminal, the fault located at 81 percent (1–0.19 pu) was beyond the 70 percent reach of the TD21G element; therefore, the TD21 restrained from operating.

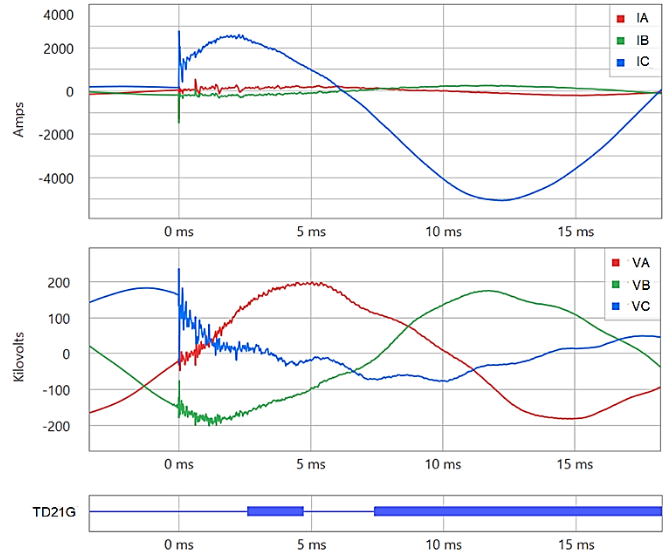

Fig. 9. Current and voltage captured by the UHS relay at Omburu and operation of the TD21 ground (TD21G) element.

E. *TD32 Element Performance*

The incremental-quantity directional (TD32) element operated and detected the fault as forward (TD32F) in both relays. The TD32F digital logic asserted in 1.09 ms at Omburu (shown in Fig. 10) and in 1.15 ms at Khan (shown in Fig. 11). In Fig. 10 and Fig. 11, the incremental-quantity replica loop current is opposite in polarity to the incremental quantity loop voltage. The incremental-quantity replica current for the C-phase-to-ground loop can be calculated using custom calculations in the event analysis software (DIZCG = DIZC – DIZ0) [4].

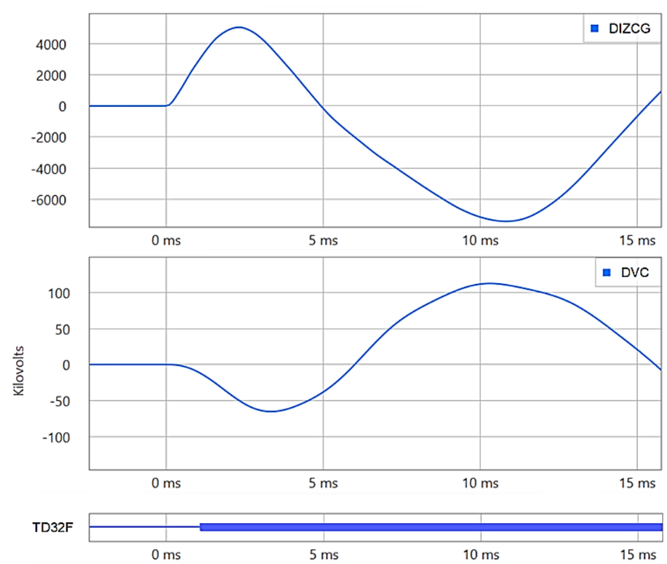

Fig. 10. Incremental-quantity replica loop current and incremental-quantity loop voltage captured by the UHS relay at Omburu and operation of the TD32 element.

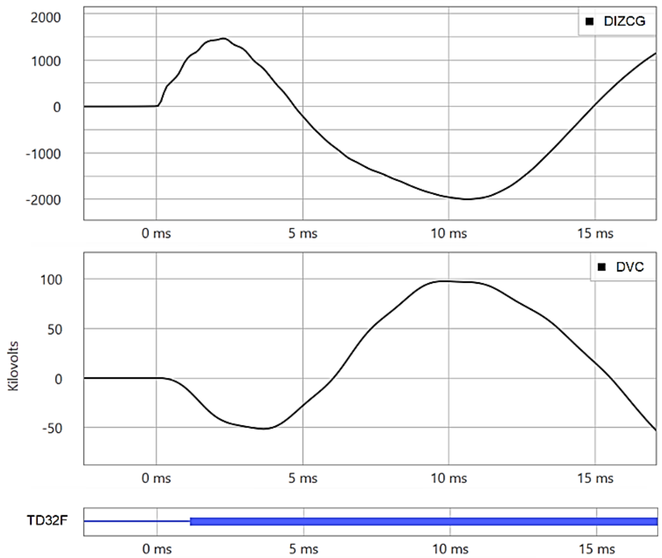

Fig. 11. Incremental-quantity replica loop current and voltage captured by the UHS relay at Khan and operation of the TD32 element.

F. DETWFL

The direct fiber-optic channel is used to exchange 1 MHz sampled voltages and currents between the relays. Each UHS relay time-stamps the arrival of the first TW associated with the local currents and received remote currents. With the arrival time of the initial TW at the local and remote terminals known, each UHS relay automatically calculates the fault location using the DETWFL method by applying the TW arrival times, along with relay settings for LL and TWLPT, in (1). The Bewley diagram in Fig. 12 shows the C-phase TW alpha mode currents from the Omburu and Khan terminals. The Bewley diagram provides a visualization of the TWs for the fault and allows for verification of the DETWFL result. Since the UHS relays at Omburu and Khan terminals have identical cables with identical lengths from the CTs, the TWCPT compensation was unnecessary, and (1) is used to explain results.

The UHS relays located the fault at 21.629 km from Omburu and 91.971 km from Khan. Fig. 13 displays the C-phase alpha mode current TWs captured by the UHS relays at the Omburu and Khan terminals and shows the relative arrival time difference of 239.422 µs between the first TWs at each terminal. It also shows that the initial TWs that arrived at each terminal have the same polarity (positive) and are separated by less than the TWLPT for this line (386.66 µs).

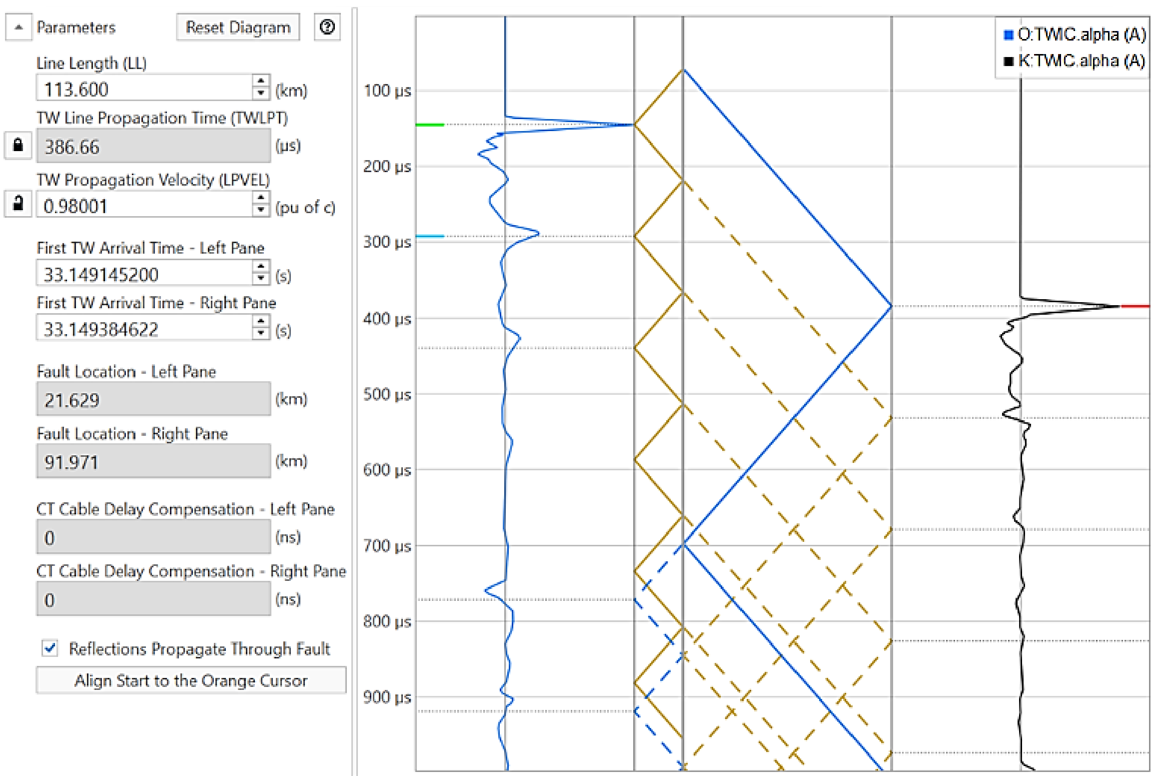

Fig. 12. Bewley diagram showing C-phase alpha-mode current TWs for the Omburu (O) and Khan (K) terminals.

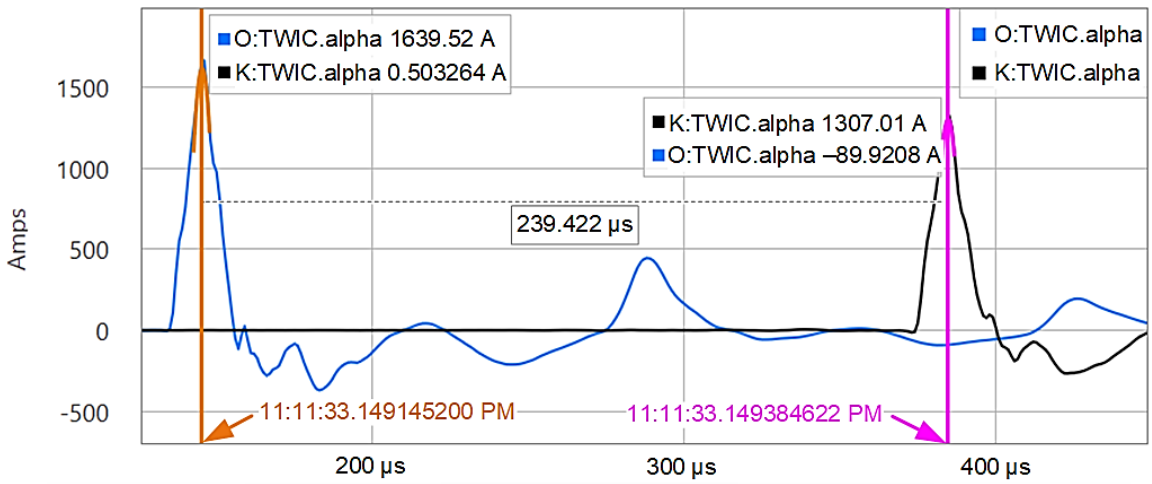

Fig. 13. C-phase alpha-mode current TWs captured by the UHS relays at Omburu (O) and Khan (K), showing the difference in arrival times of the initial TW at each terminal.

The time stamps for the initial TW that arrived at each terminal can also be confirmed from the fault location information in the HDR file of the MHR or TDR IEEE COMTRADE records from either terminal. Fig. 14 shows the fault location information in the HDR file from the UHS relay at Omburu.

```
[Fault_Location]
SE_TW_Location1,"21.047(km)"
SE_TW_Location2,"$$$$$$$(km)"
SE_TW_Location3,"$$$$$$$(km)"
SE_TW_Location4,"$$$$$$$(km)"
DE_TW_Location,"21.629(km)"
SE_Z-Based_Location,"24.638(km)"
DE_Z-Based_Location,"18.768(km)"
First_TW_Time_Local,"2020/02/04,06:11:33.149145200"
First_TW_Time_Remote,"2020/02/04,06:11:33.149384622"
```

Fig. 14. Fault location information in the Omburu UHS relay HDR file.

The information in Fig. 14 confirms that the relay automatically calculated the fault location using the DETWFL method (DE_TW_Location is 21.629 km). This result can also be verified manually by using the time difference in arrival times of the initial TW at each terminal. This can be obtained by either plotting the analog TW signals in the event analysis software (as shown in Fig. 13) or by using the "First_TW_Time_Local" and "First_TW_Time_Remote" values from the HDR file (as shown in Fig. 14) in (1). The fault location from Omburu and Khan, is calculated using (3) and (4), respectively:

$$M_{\text{Omburu}} = \frac{113.6 \text{ km}}{2} \cdot \left(1 + \frac{-239.422 \text{ µs}}{386.66 \text{ µs}}\right) = 21.629 \text{ km} \quad (3)$$

$$M_{\text{Khan}} = \frac{113.6 \text{ km}}{2} \cdot \left(1 + \frac{239.422 \text{ µs}}{386.66 \text{ µs}}\right) = 92.971 \text{ km} \quad (4)$$

Field observation confirmed that the fault location was accurate.

V. Post-Fault Arcing and Breaker Reignition Observed in 1 MHz Transient Records

While reviewing the fault current profile of the C-phase from both terminals and comparing them, we observed that there are two additional instances when TWs were launched before the fault was cleared (see Fig. 15).

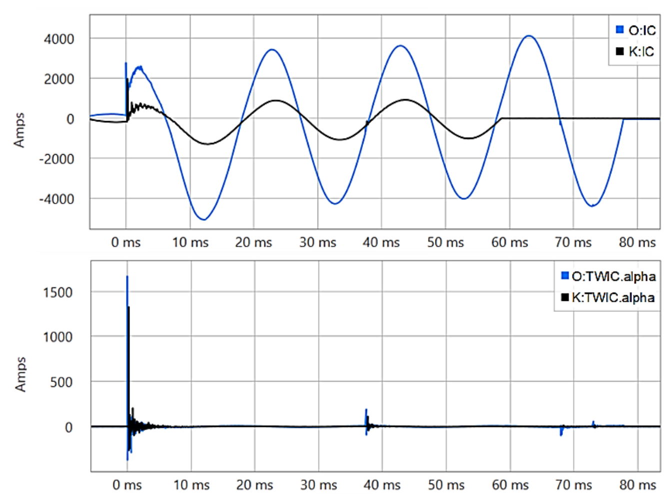

Fig. 15. Measured C-phase currents and alpha-mode TWs observed by the UHS relays at Omburu (O) and Khan (K), showing additional disturbances following the fault initiation.

The first instance (shown in Fig. 15) at 37.5 ms after the fault initiated is when a second arcing fault occurred at the same fault location and TWs were received at Omburu and Khan. Multiple reflections between the fault location and each line terminal can be seen for this instance. A zoomed-in view of the C-phase alpha-mode current TWs is shown in Fig. 16. This disturbance occurred 2 cycles before the Omburu breaker opened and 1 cycle before the Khan breaker opened, and it launched TWs that arrived at the Omburu terminal 237.398 µs before arriving at the Khan terminal. Additionally, both of the initial TWs that arrived at the line terminals have positive polarity. These observations confirm that the disturbance is internal to the line and confirm the recurrence of a fault that originated at or close to the same location as the initial fault.

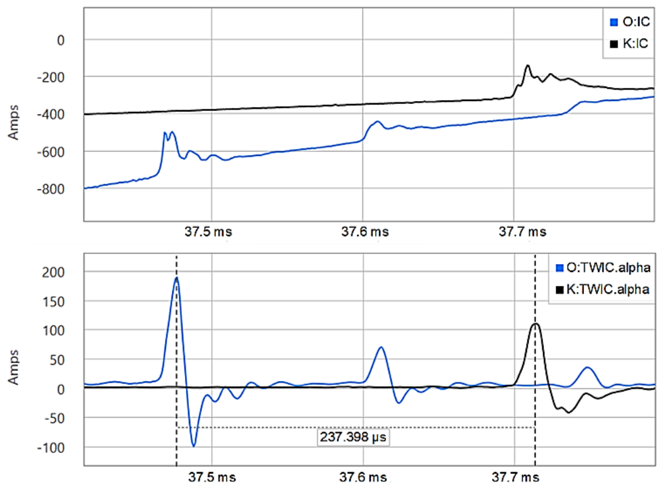

Fig. 16. C-phase alpha-mode current TWs that arrived at Omburu (O) and Khan (K) after being launched by a second arcing fault at the same fault location.

The second instance is observed 68 ms after the first fault initiated, when a clear reignition of the C-phase current is observed 108 µs after an interruption at the previous current zero-crossing. The TWs launched at Omburu reflected from the fault and hit the open breaker at the Khan terminal. The details of these observations are shown in Fig. 17 and Fig. 18. By using the MHR (1 MHz sampling) IEEE COMTRADE record data, the UHS relays can also reveal transient phenomena, like breaker reignition. The relay can be used in a system to automatically detect, log, record, and alarm for breaker reignition detection [13]. Since circuit breakers interrupt fault current at the zero-crossing of the fault current, a reignition is likely to occur within 90 electrical degrees or less than 5 ms (for a 50 Hz system) of the zero-crossing. When a breaker reignition occurs, traveling waves are launched towards the fault location, which is still fully ionized, and then they travel to the remote terminal of the line. These TW reflections can be observed in the MHR IEEE COMTRADE record. This phenomenon caused a half-cycle delay while clearing the fault at Omburu.

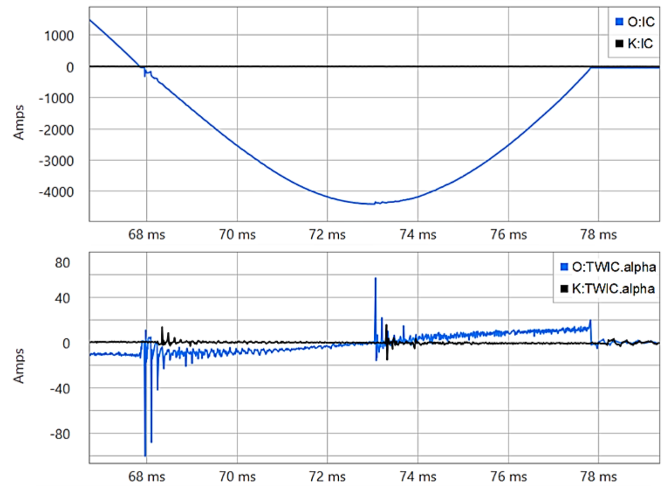

Fig. 17. C-phase currents and alpha-mode TWs at Omburu (O) and Khan (K) showing breaker reignition that delayed fault clearing by a half cycle.

As observed in Fig. 18, the difference in time between the TW launched at Omburu during the breaker reignition and received at Khan is 375.574 µs, which is very close to the TWLPT value.

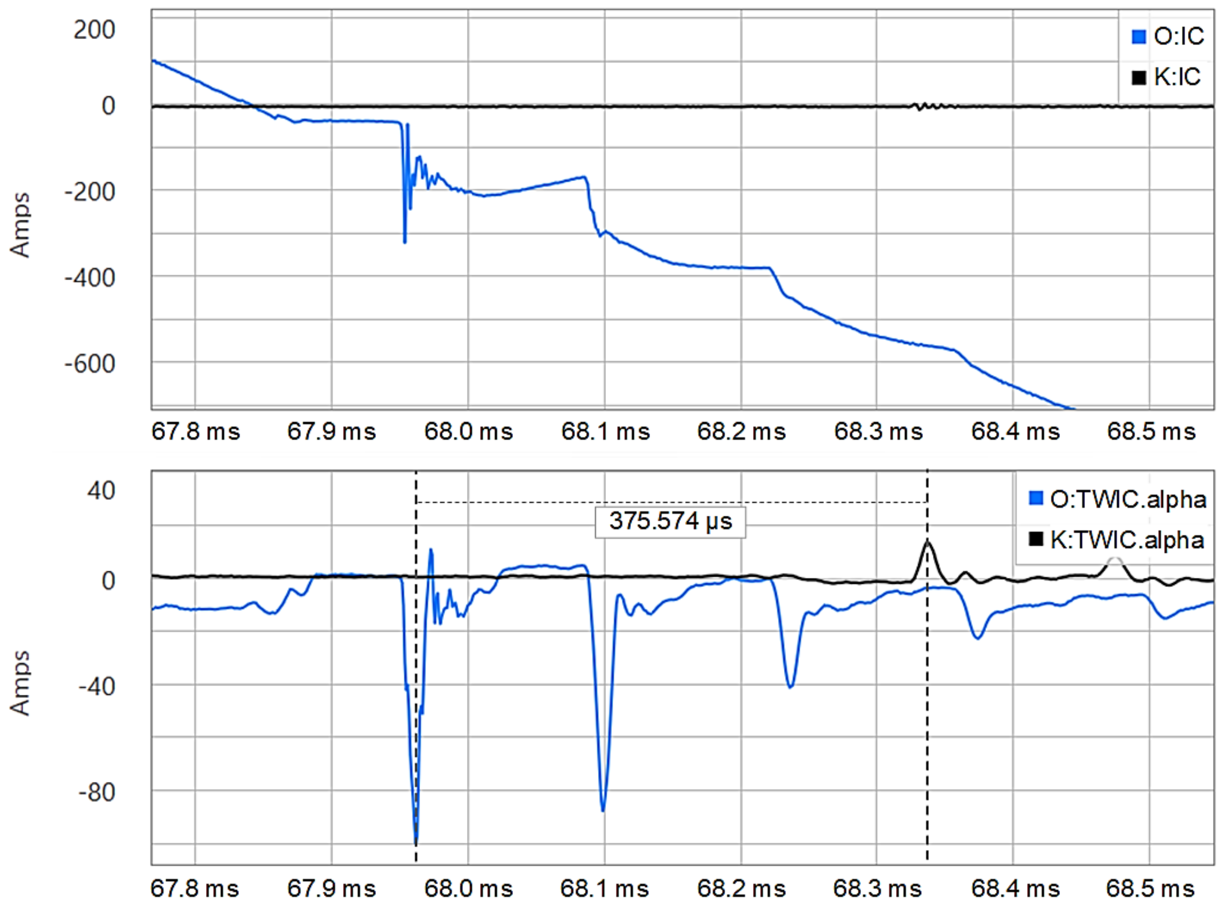

Fig. 18. Magnified view of C-phase current and alpha-mode TWs at Omburu (O) and Khan (K), showing breaker reignition shortly after a current zero-crossing and resulting in TWs traveling from Omburu and Khan.

VI. Conclusion

The use of TWs in line protective relays for UHS protection and accurate fault locating is gaining popularity. UHS relays with 1 MHz transient recording capabilities are providing valuable insights into power system operation. The field experience, observations, and lessons learned are similar and repeat those reported and documented by other users of UHS relays. UHS relays and the 20 ms (1 cycle at 50 Hz) reduction in fault-clearing time (FCT) enables NamPower to improve power system transient stability margins, gain insight into equipment health, and take preventive action to reduce equipment wear. This insightful experience has ultimately endowed NamPower with the tools to proactively investigate and address potential problems, such as dielectric strength and quenching capability of the breaker, before they turn catastrophic [13]. With UHS relays, NamPower has the potential to further improve the reliability and availability indices of the transmission network to an unprecedented level.

VII. References

[1] NamPower, “NamPower Annual Report 2020,” 2020, Available: https://www.nampower.com.na/public/docs/annual-reports/NamPower%20Annual%20Report%202020.pdf

[2] E. Schweitzer, III, B. Kasztenny, A. Guzmán, V. Skendzic, and V. Mynam, “Speed of Line Protection – Can We Break Free of Phasor Limitations?” proceedings of the 41st Annual Western Protective Relay Conference, Spokane, WA, October 2014.

[3] F. Albasri, T. Sidhu, and R. Varma, “Performance Comparison of Distance Protection Schemes for Shunt-FACTS Compensated Transmission Lines,” *IEEE Transactions on Power Delivery*, Vol. 22, Issue 4, October 2007.

[4] SEL-T400L Time-Domain Line Protection Instruction Manual. Available: selinc.com/products/T400L/docs/

[5] E. Schweitzer, III, B. Kasztenny, and V. Mynam, “Performance of Time-Domain Line Protection Elements on Real-World Faults,” proceedings of the 42nd Annual Western Protective Relay Conference, Spokane, WA, October 2015.

[6] A. Guzmán, V. Mynam, V. Skendzic, J. Eternod, and R. Morales, “Directional Elements – How Fast Can They Be?” proceedings of the 44th Annual Western Protective Relay Conference, Spokane, WA, October 2017.

[7] B. Kasztenny, A. Guzmán, N. Fischer, V. Mynam, and D. Taylor, "Practical Setting Considerations for Protective Relays That Use Incremental Quantities and Traveling Waves," proceedings of the 43rd Annual Western Protective Relay Conference, Spokane, WA, October 2016.

[8] A. Guzmán, B. Kasztenny, Y. Tong, and V. Mynam, "Accurate and Economical Traveling-Wave Fault Locating Without Communications," proceedings of the 44th Annual Western Protective Relay Conference, Spokane, WA, October 2017.

[9] D. Corton, J. Melado, J. Cruz. Y. Korkmaz, G. Patti, and G. Smelich, "Double-Ended Traveling-Wave Fault Locating Without Relay-to-Relay Communications," proceedings of 74th Annual Conference for Protective Relay Engineers Virtual Format, March 2021.

[10] SYNCHROWAVE Event Software Instruction Manual. Available: selinc.com/products/5601-2/docs/.

[11] B. Kasztenny and J. Rostron, "Circuit breaker ratings – A primer for protection engineers," proceedings of the 71st Annual Conference for Protective Relay Engineers.

[12] Field Experiences With Traveling-Wave Protection and Fault Locating Available: selinc.com/TW-Field-Experiences.

[13] J Matsuoka, "Use of a Protective Relay for Breaker Reignition Detection," proceedings of the 46th Annual Western Protective Relay Conference, Spokane, WA, October 2019.

VIII. Biographies

Frans Shanyata is a senior engineer at Namibia Power Corporation (NamPower). He is currently leading a team of protection engineers within NamPower. As a team leader responsible for the protection of the NamPower transmission grid, his primary functions are in PAC schemes design, protection IED configuration and testing, and substation SCD files development. He is also responsible for transmission grid fault studies and analysis. He is a registered PE with the engineering council of Namibia. In 2010, Frans received his BE in electrical engineering; in 2012, he received his ME in high voltage engineering and electrical physics from Kazan State Power Engineering University. He has been working for NamPower in the same field since 2013. He is also involved in CIGRE B5 working groups.

Sthitaprajnyan Sharma received his BE in electrical engineering from Utkal University in 2006 and post-graduate diploma in international business from the Indian Institute of Foreign Trade in 2016. He has worked as a power system design engineer at SPML Infra Limited and as a protection engineer at ABB. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2011 as a field application engineer and is currently working as an application engineering manager. He is involved in the training, technical support, and commissioning of protection and control solutions for generation, transmission, distribution, and industrial applications. He is an IEEE Power & Energy Society member since 2020 and a member of IET, UK. He is a registered Professional Engineer with the Engineering Council of South Africa.

Deon Joubert is the regional technical manager for Schweitzer Engineering Laboratories, Inc. (SEL), responsible for technical solutions and business development. He has 34 years of electric power engineering experience in transmission and distribution systems. In 1987, Deon graduated from Vaal University of Technology in heavy current electrical engineering. He was a senior design engineer in transmission design at Eskom (South Africa's national utility), developing feeder, bus zone, and transformer system designs. In 2000, he joined SEL as an international power system protection application engineer. In 2002, he transitioned to the role of regional manager and established the SEL office in South Africa for sales and customer services in the African region. He is a senior member of the South African Institute of Electrical Engineers and registered as a Professional Engineering Technologist with Engineering Council of South Africa. He is a member of the CIGRE Study Committee B5 Protection and Automation working group.

Richard Kirby is a senior product sales manager at Schweitzer Engineering Laboratories, Inc. (SEL) in Houston, Texas. His current focus is ultra-high-speed transmission line protection technology. He is a registered Professional Engineer in Arkansas, Louisiana, Michigan, Oklahoma, and Texas. He has 28 years of diverse electric power engineering experience. He received a BS in engineering from Oral Roberts University in 1992, and he earned his Master of Engineering in electric power from Rensselaer Polytechnic Institute in Troy, New York in 1995. He is an IEEE Power & Energy Society and Industrial Applications Society senior member.

Greg Smelich earned a BS in Mathematical Science and an MS in Electrical Engineering in 2008 and 2011, respectively, from Montana Tech of the University of Montana. Greg then began his career at Schweitzer Engineering Laboratories, Inc. (SEL) as a protection application engineer, where he helped customers apply SEL products through training and technical support, presented product demonstrations, worked on application guides and technical papers, and participated in industry conferences and seminars. In 2016, Greg made the transition to the SEL research and development group as a product engineer, where he now helps guide product development, training, and technical support related to time-domain technology. He has been a certified SEL University instructor since 2011 and an IEEE member since 2010. Greg is a registered PE in the state of Washington.

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