Analysis of a Misoperation at Murray, KY Due to Zero Sequence Mutual Coupling

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***Abstract*—This paper presents an event which occurred on the TVA power system at the Murray, KY 161kV switching station on October 25th, 2022. This event includes a single misoperation of a 161 kV transmission line protection package. As a result of this event, the 161 kV line terminal was tripped erroneously for a fault outside of its protective zone due to a phase-to-ground fault on an adjacent 500kV line. This misoperation will be evaluated and described in detail, including mitigations planned. The impact of zero sequence mutual coupling as applied to this event will be examined, including how the maximum zero-sequence current for the 161 kV terminal occurred for faults at the 500 kV level. This paper will also seek to address how common short circuit macros used to aid in the evaluation of maximum short circuit current can overlook possible maximums induced by faults on mutually coupled lines.**

***Index Terms*—Event Analysis, Misoperation, Zero Sequence Mutual Coupling**

I. Introduction

A basic objective of power system protection is selectivity, or relay coordination, where selectivity is defined by maximum continuity of service with minimum system disconnection. For protective elements which may respond to conditions outside of their primary zone of protection, it is the duty of the protection engineer to ensure selectivity or proper relay coordination. Said coordination may be achieved by setting protective elements such that they are incapable of responding to conditions outside of their primary zone of protection and/or such that they operate as fast as possible for faults within their primary zone of protection but display delayed operation for faults beyond their primary zone of protection [1].

On October 25th, 2022, TVA experienced a single line-to-ground fault on its Cumberland Fossil Plant to Marshall 500kV line, which resulted in the operation of a protective element on TVA's Murray to Marshall 161kV line via an instantaneous ground overcurrent element at Murray on the Marshall 161kV line terminal. The operation of this protective element, in turn, resulted in the operation of the local line breaker at Murray. The initial intent of this element was to underreach the remote line terminal at Marshall for all fault conditions which may influence the element, thus ensuring operation for faults only in the primary zone of protection, and operate the local line breaker with no intentional delay. However, as indicated by the operation, this element was set inadequately and was able to respond to external events resulting in a misoperation of the Murray 161kV line terminal. Thus displaying a lack of selectivity for a protective element on the TVA system.

II. System Overview

The Cumberland Fossil Plant to Marshall 500kV line (L6073) and the Murray to Marshall 161kV (L5033) line are approximately 78 and 33 mile long transmission lines, respectively, which are joined at Marshall by a 500kV:161kV:13.2kV Wye-Wye-Delta transformer bank. The following Fig. 1 shows a simplified single line diagram of the system under consideration. It should be noted that Marshall 500kV substation is a 3 position ring bus with breaker 5074 being shared between the Cumberland and Shawnee 500kV transmission lines. Prior to the occurrence of the event under study, breaker 5074 at the Marshall 500kV substation was open.

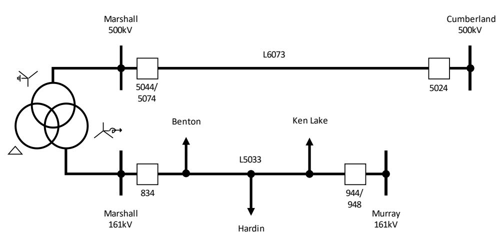

Fig. 1. Simplified system single line

The Cumberland to Marshall 500kV line originates from the Cumberland 500kV Fossil Plant where it runs west from Cumberland City, TN then north into Kentucky for approximately 46 miles where it enters a right-of-way shared by the Murray to Marshall 161kV line. The Murray to Marshall 161kV line enters this same right-of-way approximately 1.3 miles out of Murray. These two transmission lines then continue their runs for approximately 32 miles, sharing a right-of-way but not sharing structures, until their eventual termination at TVA's Marshall 500kV substation.

Fig. 2. Shared right-of-way

Sharing of this right-of-way results in a significant amount of mutual coupling between the two lines for the majority of their remaining 32 mile runs. In total, 31.2 miles of line are coupled. Mutual coupling records sourced from TVA's transmission line data is shown below in Table I. Note that the zero-sequence impedance of the Murray to Marshall 161kV line is 73.133∠74° Ω. Using Carson's formula to find the total mutual impedance in primary Ohms, we find that the mutual impedance between the two lines is approximately 38.9% of the zero-sequence line impedance of the Murray to Marshall 161kV line. Though this is not near the upper limit of percent mutual impedance, generally regarded to be near 70%, this is a significant amount of mutual coupling.

TABLE I
MUTUAL COUPLING RECORDS

From Bus	To Bus	Segment Length	Coupled Length	From B-factor	To B-factor	Z Mutual (% on 100MVA)
Marshall	Benton	14.69	14.50	0.0088	0.9959	0.7995+j1.1803
Benton	Hardin	5.98	5.98	0	1	0.4223+j0.6332
Hardin	Ken Lake	1.17	1.17	0	1	0.0815+j0.1226
Ken Lake	Murray	10.88	9.53	0	0.8759	0.6681+j1.0033
Total		32.72mi	31.18mi	0.0040	0.9529	1.971+j2.939

At present, the Cumberland FP to Marshall 500kV line is protected by a redundant dual pilot scheme where the primary and secondary relays are operating in a permissive overreaching transfer trip (POTT) scheme. The Murray to Marshall 161kV line is protected by a redundant single pilot scheme where the primary relays are operating in a directional comparison blocking (DCB) scheme and the secondary relays are operating in a step distance (SD) scheme. It is worth noting that, at the time of this event, the DCB scheme on the Murray to Marshall 161kV line was disabled, effectively resulting in the line being protected by a redundant SD scheme.

Note that, for ground protection, all relays operating in a pilot scheme provide pilot ground protection via mho ground distance and definite ground time-overcurrent elements. All relays also provide ground protection via SD elements: instantaneous ground distance, instantaneous ground overcurrent, and ground time-overcurrent elements. All terminals use negative-sequence directional elements for polarization of the ground overcurrent elements. The following analysis will reveal that, in the face of a ground fault on the Cumberland FP to Marshall 500kV line, protective setting inadequacy resulted in a loss of selectivity and a misoperation of the Murray to Marshall 161kV line.

III. SEQUENCE OF EVENTS

At approximately 13:47:00 on October 25th, 2022, a B-phase line-to-ground fault developed on the Cumberland FP to Marshall 500kV line. As a result of this fault, the following sequence of operations took place as recorded by TVA's SCADA SOE shown in Fig. 3.

Time	Milliseconds	Alarm Name	Alarm
10/25/2022 13:47:00	377	CUMBERLD PCB 5024	Trip
10/25/2022 13:47:00	423	MARSHALL PCB 5044 (CUMBERLAND XFMR)	Trip
10/25/2022 13:47:00	637	MURRAY PCB 948	Trip
10/25/2022 13:47:00	817	MURRAY PCB 944	Trip
10/25/2022 13:47:01	317	MURRAY PCB 944	Close
10/25/2022 13:47:06	647	MURRAY PCB 948	Close
10/25/2022 13:47:17	460	MARSHALL PCB 5044 (CUMBERLAND XFMR)	Close
10/25/2022 13:50:35	610	CUMBERLD PCB 5024	Close

Fig. 3. TVA SCADA SOE Report.

As can be seen, upon development of the fault, TVA reported four simultaneous operations: Cumberland 500kV breaker 5024 trip, Marshall 500kV breaker 5044 trip, Murray 161kV breaker 948 trip, and Murray 161kV breaker 944 trip. Post fault, TVA experienced successful automatic reclose of Murray 161kV breaker 948, Murray 161kV breaker 944, and Marshall 500kV breaker 5044. Cumberland 500kV breaker 5024 was later closed by dispatching.

With the fault being located on the Cumberland FP to Marshall 500kV line, it is expected that protection on the Cumberland FP to Marshall 500kV line would operate to extinguish the fault. However, with no fault present on the Murray to Marshall 161kV line, we should not have expected operation of Murray 161kV breakers 948 and 944.

An event report recorded by the A-set relay at Cumberland Fossil Plant is shown in Fig. 4, where the time axis is at zero just prior to the relay operation. It can be seen that, at -12.47ms on the orange cursor, the b-phase current begins to increase in magnitude as compared to the a-phase and c-phase currents. Approximately 0.75 cycles later, the relay picks up both zones 1 and 2 ground distance elements and, zone 1 being set to operate a trip command with no intentional time delay, sends a trip command to the local breaker 5024 which opens 2.4 cycles later.

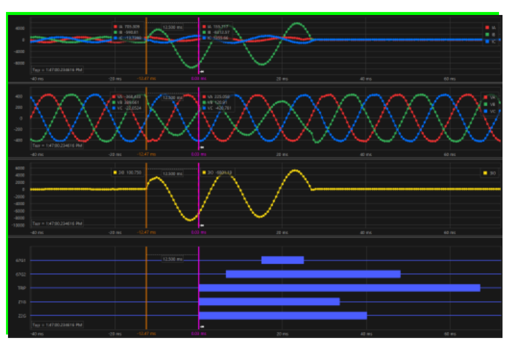

Fig. 4. Cumberland 500kV event report.

In comparison to the above, the event report shown in Fig. 5 is from the A-set relay at the Marshall 500kV terminal. Like its counterpart, this relay first picks up zone 2 and zone 1 ground distance elements where, zone 1 being an instantaneous element, it promptly sends a trip signal to the local breakers. This occurs about 0.50 cycles after fault inception. Again, approximately 2.4 cycles later, the local breaker 5044 opens.

Fig. 5. Marshall 500kV event report.

To this point, the two operations at Cumberland 500kV and Marshall 500kV are expected. The Cumberland FP to Marshall 500kV line has experienced a b-phase line-to-ground fault which fell within each terminal's zone 1 ground distance element. At both terminals, these elements were set to trip with no intentional time delay and, as such, resulted in operation of the closed breakers at each terminal thus extinguishing the fault. The following operation, however, was not expected.

The event report in Fig. 6 came from the A-set relay at the Murray 161kV terminal. Though there was no fault recorded on the Murray to Marshall 161kV line, at the same time the b-phase line-to-ground fault developed on the Cumberland FP to Marshall 500kV line, the Murray 161kV terminal experienced high magnitudes of near pure zero-sequence current. This resulted in pickup of the ground overcurrent element which was set to operate with no intentional time delay. As a result, a trip signal initiated and approximately 3 cycles later breakers 944 and 984 at Murray 161kV were opened.

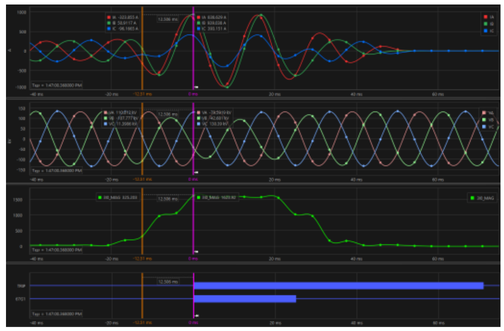

Fig. 6. Murray 161kV event report.

IV. Investigation and Findings

As mentioned previously, the relaying on the Murray 161kV terminal operated incorrectly via its instantaneous ground overcurrent element. At the time this event occurred, the element had been set per TVA philosophy: the pickup was based on the maximum current seen for an external, remote bus fault, under common N-1 contingencies including remote ground sources or mutually coupled parallel lines out-of-service. This approach resulted in an instantaneous ground overcurrent setting of 1400 A primary. However, from the Murray event report in Fig. 6, at the time the instantaneous ground overcurrent element picked up and initiated a trip sequence, the Murray A set relay was measuring 1624 A primary of zero-sequence current or 116% of the relay setting.

Post-event investigation revealed the fault was likely the result of a buildup of bird residue on structure 229 of the Cumberland FP to Marshall 500kV line. This structure is just before the line enters the right-of-way with the Murray to Marshall 161kV line, approximately 59% from Cumberland 500kV. As shown in Fig. 7, plotting this fault in Computer Aided Protection Engineering (CAPE) with a 1.0 pu system voltage and all-ties-closed, we see a zero-sequence current of 1636 A primary sourced to the relaying on the Murray 161 kV terminal. This is within 1% of our measured event current.

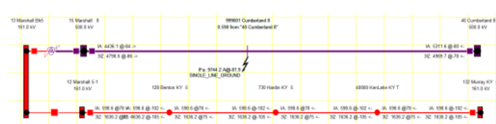

Fig. 7. CAPE simulation of fault condition.

The configuration of our system resembles that of Configuration 1 as described by Thompson [SEL paper]. In this configuration, two mutually coupled, parallel lines share a zero-sequence path at one end of the lines but are electrically isolated at the other either by a natural configuration or by a portion of the system such as a breaker opening or some other form of disconnect. In our case, the Wye-Wye bank acts a

Commented [PDG1]: Considering impedance of XFMR bank and line to fault location, may be considered configuration 2. Systems "appear" to be electrically isolated due to large impedance between relay location and fault location.

direct connection between the Marshall 161kV and Marshall 500kV buses in the zero-sequence network. In this configuration, based on the ground sources involved, location of the fault, and strength of mutual coupling, overcurrent elements may be put at risk of overreaching or underreaching their setpoints when not based on faults on mutually coupled lines. This is the case here.

In Fig. 8, the same fault is re-plotted as above without the influence of mutual coupling, only 58 A primary of zero-sequence current flow through the Murray 161kV terminal. This indicates that the vast majority of our available zero-sequence current is the result of mutual coupling between the two transmission lines.

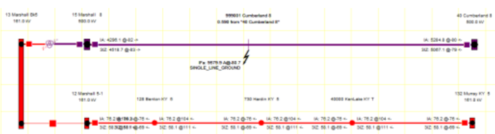

Fig. 8. CAPE simulation of fault condition neglecting mutual coupling.

V. Conclusion

VI. Acknowledgements

References

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