Pinhook 500kV Transformer Neutral CT Saturation

Russell W. Patterson
Tennessee Valley Authority

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Abstract

This paper discusses the saturation of a 500kV neutral CT upon energization of a 1300MVA transformer bank. The event resulted in the misoperation of a restricted earth fault element protecting the bank and capacitor bank protection on grounded wye capacitor banks in the surrounding system remote from this station. The merits of the simple directional overcurrent restricted earth fault scheme will be discussed as well as the analysis of the capacitor bank protection misoperations.

Introduction

On May 31, 2003 TVA energized the 1300MVA Pinhook bank from the 500kV side with the 161kV breakers open and 13kV tertiary winding unloaded. The bank tripped by 500kV winding restricted earth fault (REF) protection located in the B-set microprocessor transformer protection relay. On a subsequent energization of the bank, 161kV capacitor banks remote from this station misoperated by solid-state residual overcurrent protection (SFC relays).

Figure 1 below shows the transformer bank configuration and the secondary CT wiring to one of the microprocessor bank protection relays. Dual primary bank protection relays are used and both A and B set relays are wired identical but from different CT windings with the exception of the neutral CTs (one per neutral).

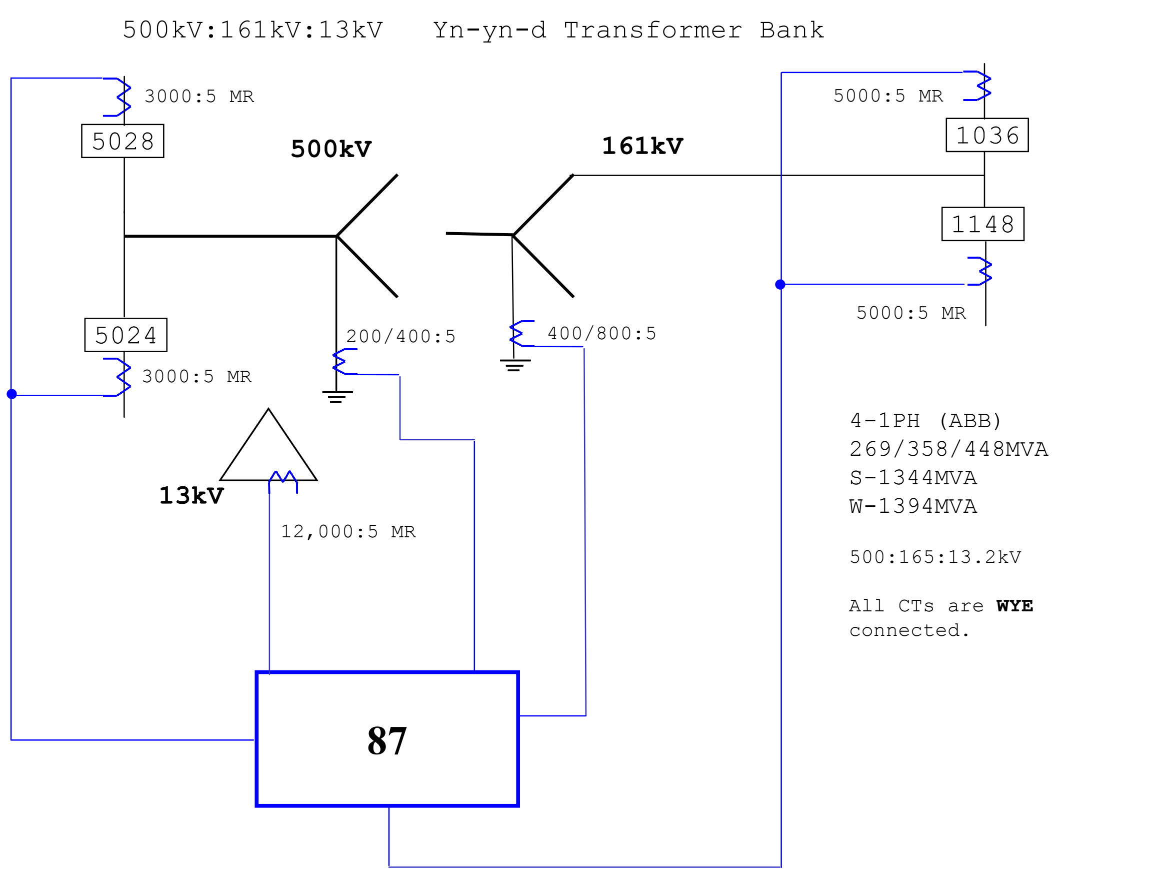

Figure 1. One-line of Pinhook bank differential protection circuit.

Neutral CT Saturation

Figure 2 shows the 500kV currents during the May 31, 2003 energization of the Pinhook bank. B-phase has a large DC offset and the CT experiences some degree of saturation as can be seen by the inrush current waveform transitioning below the axis. The 500kV neutral CT experiences significant saturation around the 200ms point.

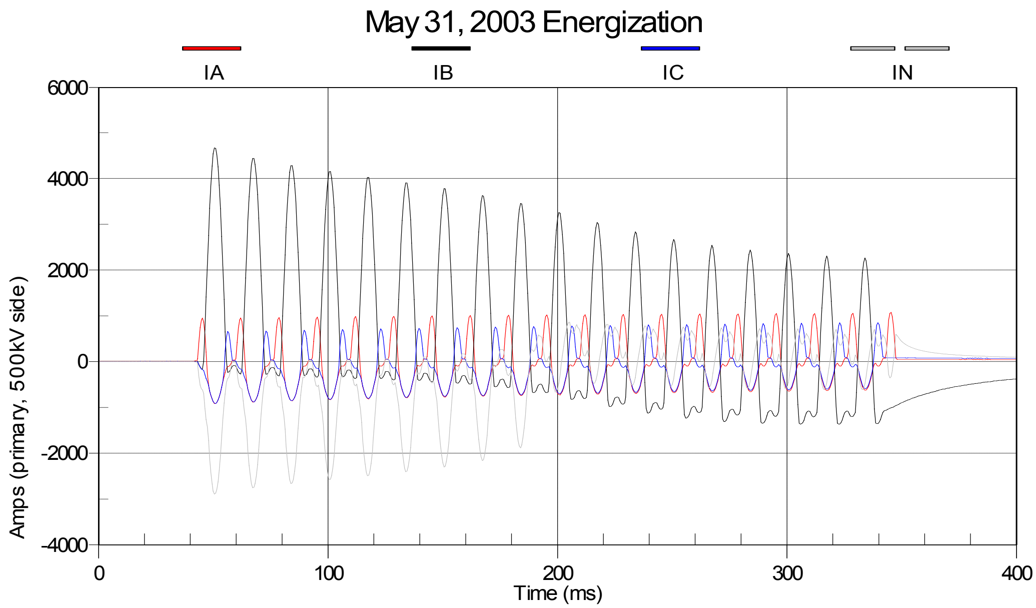

Figure 2. 500kV Phase Currents and 500kV Neutral Current.

Figure 3 below shows the 500kV neutral current along with the 500kV residual of the phase currents. Initially all CTs reproduce well but around the 200mS point the neutral CT experiences heavy saturation. The 500kV neutral CT is a 25kV, 200/400:5 (set on 400:5), T200 on full winding, T90 on tap, type KOR-15.

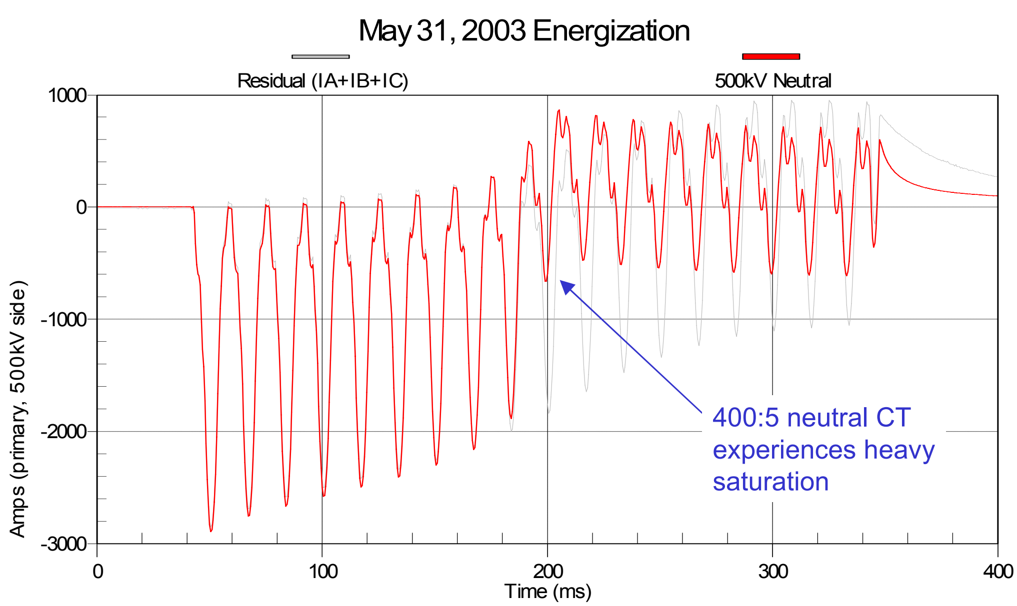

Figure 3. 500kV Neutral CT Saturation.

Affect on a Restricted Earth Fault Protection Element

Figure 4 shows the differential current resulting between the 500kV residual and 500kV neutral CT currents.

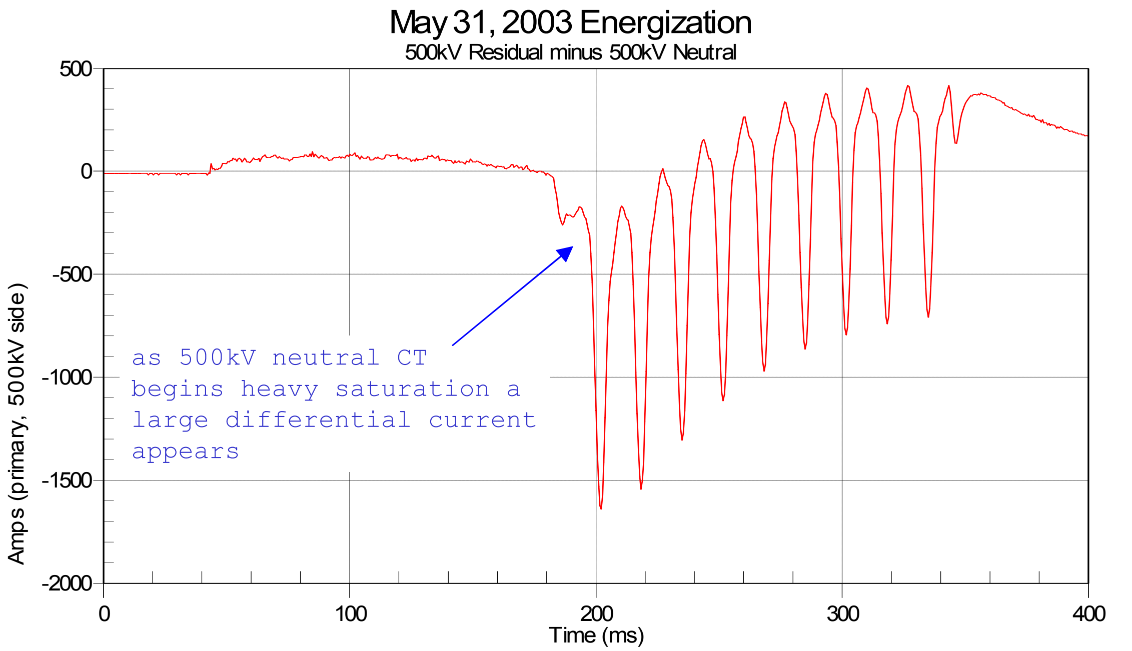

Figure 4. <u>500kV Ground Differential Current</u>.

The B-set transformer differential relay has an REF element that is implemented as a traditional differential element with slope. When the 500kV neutral CT saturated it produced a large REF differential current (Figure 4) causing this differential element to pickup. After a 6 cycle delay it tripped. The 500kV breaker disconnects the transformer bank 2 cycles later.

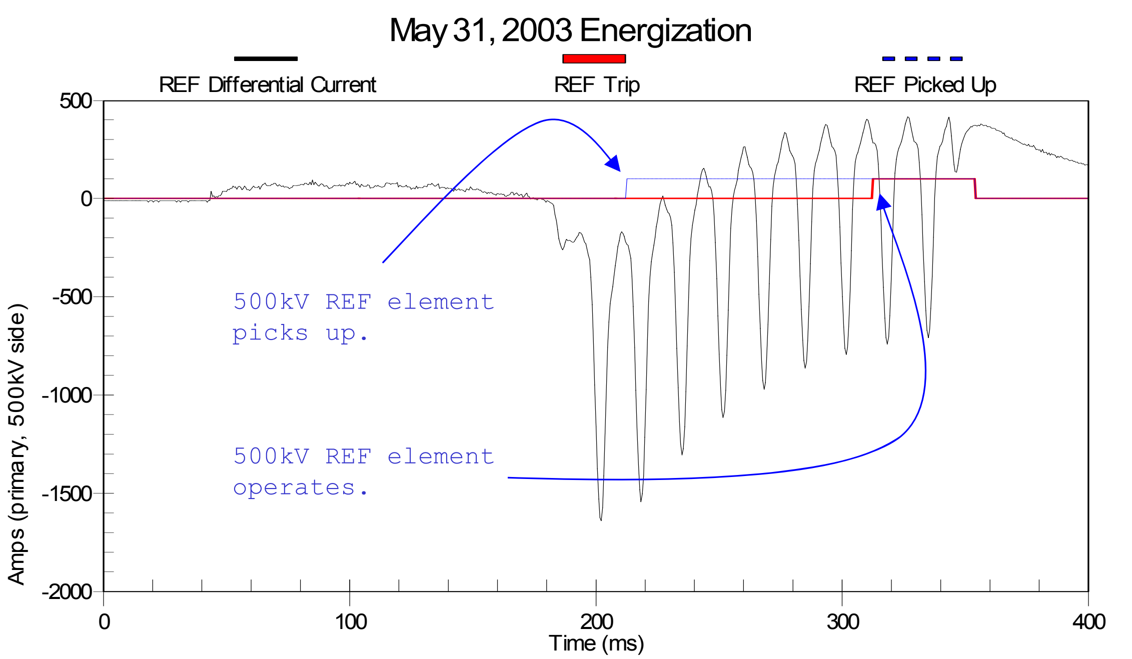

Figure 5. <u>B-set transformer relay initiates a trip</u>.

The B-set relay was running an early version of the relay vendor's firmware which included a default slope setting of 10%. Subsequent versions of the firmware had a default slope of 40% as well as other enhancements to make the REF element more secure.

The A-set relay implemented REF protection using a simple directional overcurrent principle[2] that is simple, secure and reliable. This method compares an operate quantity (residual of 500kV phase currents) with a polarizing quantity (500kV neutral current). The element won't allow operation unless the two currents are within 90° of each other and are of sufficient magnitude. The CT currents are wired to the relay such that normally these two currents are 180° out-of-phase with each other. Even under heavy saturation the two currents cannot migrate to within 90° of each other. Figure 6 shows a phasor plot of the two currents fundamental components before and after the 200ms point where heavy saturation starts.

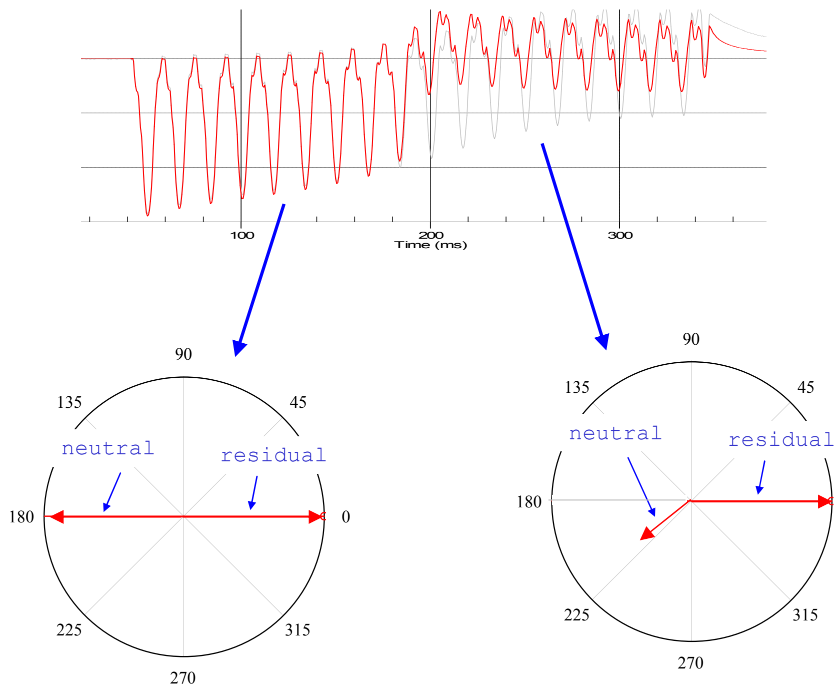

Figure 6. Fundamental phasors before and during saturation.

Even under heavy saturation the neutral current doesn't shift more than 45° leading from its previous position of 180°. The simple directional current approach to REF protection won't allow operation unless the two currents are within 90° of each other. This method appears very secure against misoperation due to neutral CT saturation.

Misoperation of Area Capacitor Banks

The May 31, 2003 bank energization only lasted about 16 cycles before the REF misoperation tripped off the bank. On June 11, 2003 the bank was energized for a second time. This time the REF problems in the B-set relay had been overcome and the bank remained energized. Subsequent to this bank energization three area 161kV capacitor banks misoperated by SFC (obsolete static type) residual overcurrent relays.

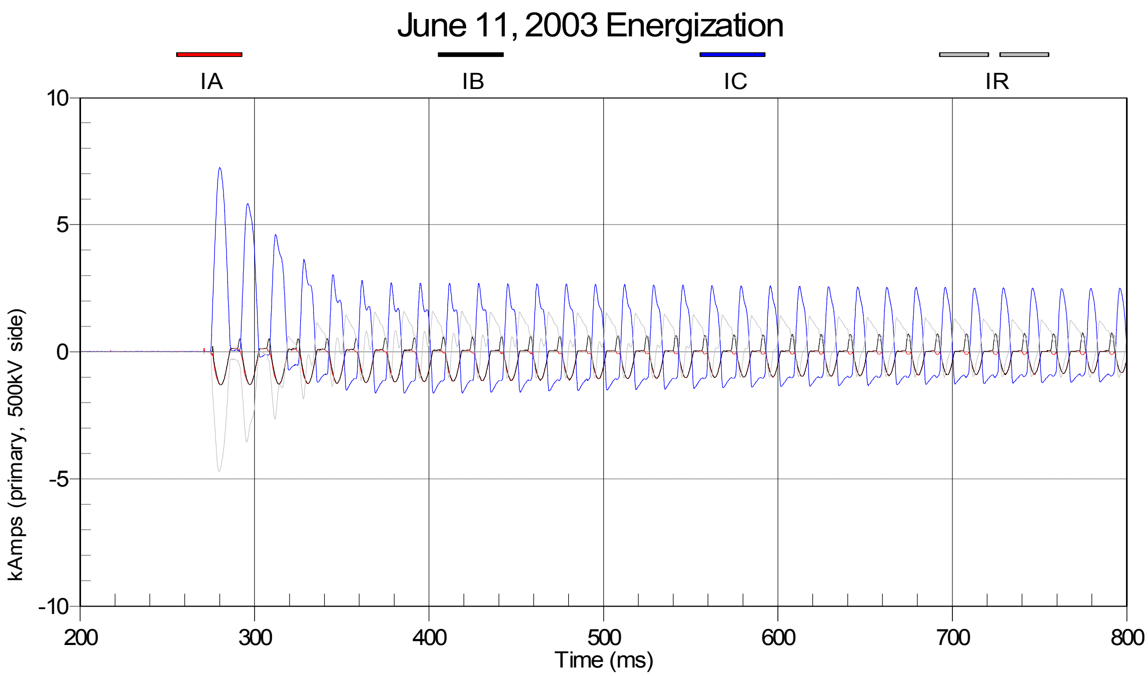

Figure 7. June 11 Energization of Pinhook Bank.

The energization of the large Pinhook transformer bank was a significant unbalanced condition applied to the power system. The large currents in the transformer neutral were reflected in area 161kV capacitor bank neutrals. A sensitive residual overcurrent relay (SFC) applied on these capacitor banks misoperated for these currents. The SFC relay is a solid-state relay that operates on a true RMS value. TVA field test personnel have tested the SFC relay to ascertain its frequency performance[1]. The relay was tested up to the 14th harmonic and was shown to have a flat frequency response. (i.e., the relay operates the same when it sees 5A at 840Hz as it does for 5A at 60Hz). Reference 1 describes misoperations of the SFC during geomagnetic storm events.

The SFC was wired to see capacitor bank residual current and was set low (20-30A primary). It was supervised by a 3V0 relay designed to block its operation during normal system ground faults while allowing its operation for capacitor bank unbalance. The capacitor banks were excellent sinks for the inrush neutral current and the supervising relays were set based on system fault studies such that they did not pickup during this event. Note that these currents flowing in the capacitor bank neutrals would have been predominately 2nd harmonic. This is contrary to what we usually think flows in neutrals. For balanced harmonics (symmetrically created across all three phases) only triplen (3^{rd}, 6^{th}, 9^{th} etc.) harmonics flow in the capacitor bank neutrals[3]. But, transformer energization is not a symmetrical event as is clearly seen by the 500kV residual current present during energization (Figure 8).

SCADA Sequence of Event data during the June 11 Energization:

- 13:39:11 Pinhook 500/161kV intertie bank energized at 500kV
- 13:39:13 Smyrna 161kV cap bank trips by SFC ground relay
- 13:39:17 McMinnville 161kV cap bank trips by SFC ground relay
- 13:39:18 Murfreesboro 161kV cap bank trips by SFC ground relay

Note: Wilson 161kV cap bank likely did not trip because it was tagged out.

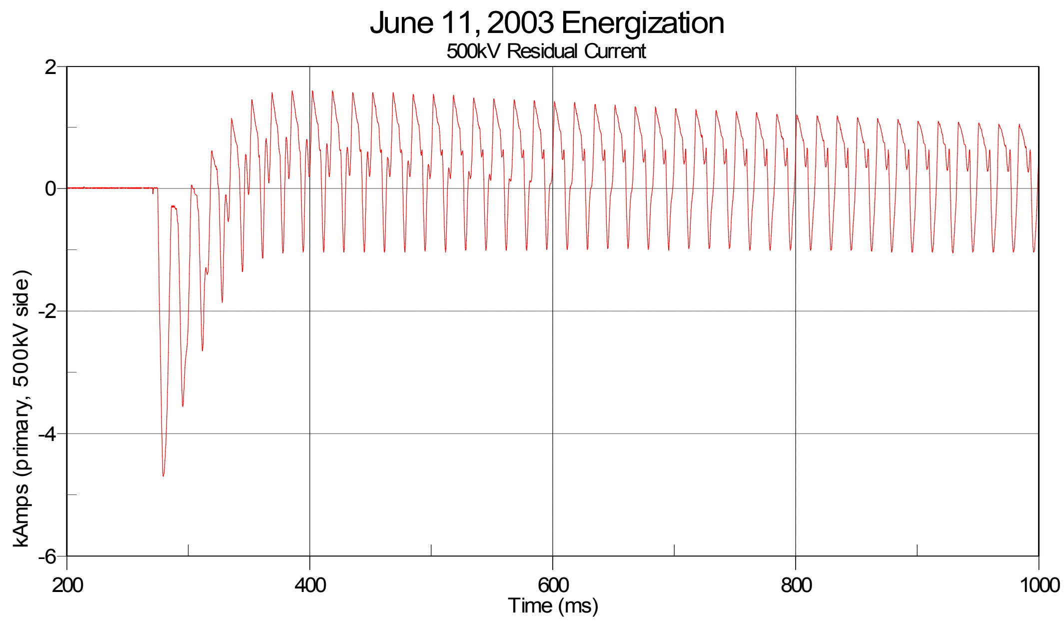

Figure 8. Residual current present during June 11th energization.

The bank was energized a third time on June 12, 2003 with a similar result. The bank stayed in and, once again, three area 161kV capacitor banks (two new ones this time) misoperated by SFC relay. The following is a quote from our Transmission Operator disturbance log: "1819: The Franklin 161-kV, Smyrna 161-kV and Murfreesboro 161-kV capacitor banks were interrupted by ground relay action. This interruption coincides with energizing the Pin Hook 500/161/13-kV transformer. Cause is under investigation."

The SFC relay is poorly suited to protection of a capacitor bank for 60Hz fault duty. Capacitor banks are excellent sinks for harmonic energy. TVA has experienced significant simultaneous loss of 161kV capacitor banks (up to 800MVAR) due to misoperations of SFC relays during geomagnetic events[1]. The geomagnetically induced currents (GIC) caused half-cycle saturation of 500kV transformers with the resulting harmonic currents finding a path down the capacitor bank neutrals. TVA has also experienced misoperation of an SFC residually connected relay protecting a 161kV capacitor bank when an electrically nearby 500kV transformer bank was energized with one phase on the wrong tap[1].

To preclude the chances of significant loss of 161kV capacitor banks these relays have been replaced with microprocessor relays that operate on the fundamental (60Hz) component only.

Summary

- The simple directional overcurrent approach to Restricted Earth Fault (REF) protection provides excellent security during neutral CT saturation.
- Harmonic currents other than triplen (3rd, 6th, 9th, etc.) can flow in capacitor bank neutrals if they are generated asymmetrically in the power system (such as during a transformer energization).
- History repeats itself. The GIC events of July 15, 2000 uncovered a susceptibility to misoperation of SFC relays that resurfaced when the large Pinhook transformer bank was energized.

References

1. Patterson, R.W., "Mathcad Analysis of Davidson Capacitor Bank Misoperation", paper presented to the 2001 Georgia Tech Fault and Disturbance Analysis Conference. Available at http://webpages.charter.net/rwpatterson357/

2. IEEE Standard C37.91-2000 "IEEE Guide for Protective Relay Applications to Power Transformers"

3. Sankaran, C., "Effects of Harmonics on Power Systems - Part I". EC&M, October 1995. pp. 33-42

4. IEEE Standard C37.110-1996 "Guide for the Application of Current Transformers Used for Protective Relaying Purposes."

5. Walter A. Elmore, "Protective Relaying Theory and Application". ABB. pp. 80-81.

Software

TOP – The Output Processor. TOP reads data from a variety of sources and transforms it into high quality graphics for inclusion in reports and documents. TOP was developed by Electrotek Concepts® to visualize data from a variety of simulation and measurement programs. It can be freely obtained at the following website: http://www.pqsoft.com/TOP/index.htm

Biographical Sketch

Russell W. Patterson is Manager of System Protection & Analysis for the Tennessee Valley Authority (TVA, www.tva.gov) in Chattanooga, Tennessee. Prior to this he was manager of TVA's Advanced Network Applications group where he was responsible for the maintenace and expansion of the state estimators used by TVA. As Manager of System Protection & Analysis he is responsible for the setting of all protective relays in the TVA transmission system and at Hydro, Fossil and Nuclear generating plants. He is responsible for ensuring that TVA's protective relays maximize the reliability and security of the transmission system. This includes setting and ensuring the proper application and development of protection philosophy for the TVA. Prior to this role Russell was a Project Specialist in System Protection & Analysis and was TVA's Power Quality Manager responsible for field and customer support on PQ related issues and disturbances. Russell has performed transient simulations using EMTP for breaker Transient Recovery Voltage (TRV) studies including recommending mitigation techniques. Russell is an active member of the IEEE Power System Relaying Committee (PSRC) and a prior member of the Protection & Controls Subcommittee of the Southeastern Electric Reliability Council (SERC). Mr. Patterson earned the B.S.E.E. from the Mississippi State University in 1991. Russell is a registered professional engineer in the state of Tennessee and is a Senior Member of IEEE. Russell's website is http://webpages.charter.net/rwpatterson357/ and he can be e-mailed at rwpatterson@tva.gov.