Negative Sequence Voltage Relay Misoperations Due to Cable and Transformer Energization Transients

M. B. Marz
Senior Member, IEEE

V. Skendzic
Member, IEEE

Cooper Power Systems
Thomas A. Edison Technical Center
Franksville, WI 53126 USA

Abstract - **Transient waveform distortion can affect protective relay performance and cause relay misoperations. Present standards do not require most relays to be tested for distortion sensitivity. This paper examines a case where a negative sequence voltage relay misoperated because of the transients developed during cable and transformer energizations at an industrial location with suspected harmonic voltage distortion. The design characteristics that make many relays sensitive to transient and harmonic distortion are discussed. The real time power system simulations and harmonic sensitivity tests used to evaluate and prevent further relay misoperations are described.**

Keywords: Transient Analysis, Relays, Harmonics.

I. INTRODUCTION

The effect of transient and harmonic distortion on protective relay operation has been discussed in the literature [1-4], but most of this work has dealt with relay operation in the laboratory rather than on actual power systems. This paper describes an industrial system where switching transients and background harmonics combined to cause negative sequence voltage relay misoperation during cable and transformer energizations. This case emphasizes the importance of understanding the consequences of negative sequence relay sensitivity to transient and harmonic distortion.

Transient and harmonic analysis including real time transient simulations, system frequency response simulations, and relay harmonic sensitivity testing were performed to study the relay misoperations. A feasible solution was determined and is being implemented. The analysis and solution techniques described in this paper can be used to analyze and solve similar problems.

II. RELAY DISTORTION SENSITIVITY

Protective relay response to transient and harmonic distortion varies greatly among relays designed to have the same response to undistorted fundamental frequency waveforms. This can be true not only for relays built by different manufacturers, but also for relays of different vintage made by the same manufacturer [5]. Because of this, it is impossible to make specific statements about relay distortion sensitivity and the study of distortion related relay problems is most accurate when based on actual network conditions and the actual protective devices applied [6-7]. Some general observations that can be made about relay distortion sensitivity are discussed below.

A. Electromechanical Relays

The induction disk based timing or integration devices used in electromechanical relays tend to be affected by distorted waveforms. The disk operating torque is typically created by a flux in quadrature with the current. This flux is developed by phase shifting components within the relay that are optimized for the system's fundamental frequency. Operation is less efficient at other frequencies. This reduces relay sensitivity and increases operating time. Counteracting this phenomena is the fact that induction disk speed increases with frequency. The comparator set point can also vary with temperature or other environmental effects.

Another effect experienced by electromechanical relays is hysteresis in the magnetic comparator circuit. Because of this hysteresis the value necessary to cause a relay to operate (begin timing) may be significantly higher than the value required to release (stop timing) and prevent the relay from tripping (timing out).

B. Solid State Relays

Solid state relays can be designed to respond to input waveform peak value, average value, or rms value. While these responses are tested to be accurate when monitoring fundamental waveforms, they may not be accurate when monitoring distorted waveforms. Digital relays, unlike electromechanical relays, can also be subject to discretization and aliasing errors. Even if a signal is accurately digitized, a relay's sensitivity to harmonics will depend on the performance of the signal processing algorithm used.

Solid state comparator circuits are virtually free of hysteresis effects, unless this function is intentionally added as a part of the design. This means that in most cases a solid state relay's operation and release values will be identical. Aside from the fact that hysteresis is not a problem with solid state relays, digital relays are not inherently more immune to distortion than electromechanical relays.

C. Distortion Effects on Tested Relay Operation

Three relays were tested as part of this study, the electromechanical relay that misoperated in the field and two potential solid state replacements. Although the relays were all of different designs, they were all negative sequence voltage relays and used similar methods of calculating negative sequence voltage. Each relay used a PT connection designed to block zero sequence voltages. The relays then used circuits similar to those described in [8] to rotate and sum the input voltages to calculate negative sequence voltage. The circuits used resistors and inductors or capacitors. These elements are designed to perform accurate phase rotation at 60 Hz. Any deviation from this frequency will cause phasor rotation and sequence calculation errors.

The solid state relays tested for this study were each equipped with low pass filters. These filters are designed to minimize the effects of harmonics and transients. Because they are of low pass design, they are more effective at higher frequencies. The electromechanical relay was not equipped with any filtering.

In addition to the sequence calculation errors caused by the frequency of the transients, the fact that transient voltages are rarely balanced on all three phases may also cause the relay to interpretate a transient as a negative sequence voltage. Misinterpretation of transients by relays is usually controlled by setting the relay time delay to a value long enough to allow transients to damp out, but short enough to insure that actual events of concern will not cause equipment damage.

III. THE CASE UNDER CONSIDERATION

A portion of the system where the relay misoperations occurred is shown in Fig. 1. The 13.8 kV industrial load is fed from a 230 kV system through parallel 1 km overhead lines and 2 km underground cables. Two 230/69 kV transformers feed a cable with 27 km and 28 km segments. This cable energizes two 75 MVA 69/13.8 kV transformers. Relay misoperations preventing cable and transformer energization have occurred when the 27 and 28 km cable segments and 69/13.8 kV transformers were individually energized.

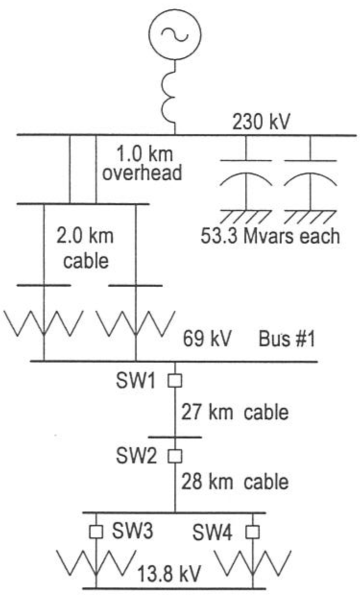

Fig. 1. *Area Where Relay Misoperations Occurred*

A. Symptoms

Relay misoperations were first experienced when the 27 km 69 kV cable was energized. The 27/47 (undervoltage/phase sequence voltage) relay misoperation caused breaker SW1 to remove the cable from service several seconds after it was energized. After increasing the time dial setting failed to prevent tripping, the phase sequence voltage relay function was disabled. The undervoltage relay function did not cause the circuit to trip out during energization, but removing the phase sequence voltage relay disabled motor protection during single phasing events.

Substantial distortion was monitored during both cable and transformer energization events (Fig. 2). The highest and longest lasting (several seconds) distortion was monitored when the second 69/13.8 kV transformer was energized. Less distortion was present when the first transformer was energized. The least and shortest duration distortion (several cycles) was present when each of the cable segments were energized. The switching events with the highest and longest lasting distortion were correlated with increased probability of relay misoperation.

In addition to the transient distortion present during energization, steady state harmonics were also a concern. The source of these harmonics was suspected to be other industrial loads connected to the 230 kV system. Although it is unusual to have significant harmonics at such a high voltage level, the size of nearby industrial loads and distance from strong sources made harmonics a concern.

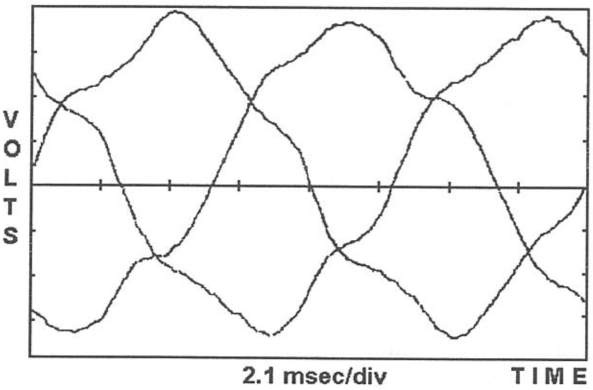

Fig. 2. *69 kV Bus #1 Voltage During Second Transformer Energization (Close SW4)*

B. Initial Analysis

There was some initial concern that the relay misoperations were caused by coupling between the cable and a relay pilot wire. This was investigated and discounted as a source of the relay misoperations.

Since the industrial area where the relay misoperations occurred was suspected of having significant background harmonics, having the harmonic producers apply filters was initially considered as a part of the solution. Because of political and economic considerations, however, detailed information on harmonic sources was not available. Without this information, efforts to mitigate the harmonics to acceptable levels would be futile. Instead effort was concentrated on identifying the exact cause of the relay misoperations and determining feasible solutions.

IV. ANALYSIS

Three types of analysis designed to understand and correct the problems being experienced were performed. After identifying the primary misoperation mechanism of the existing electromechanical relay the same set of tests was extended to two solid state relays selected as potential replacements.

The first analysis used real time transient simulations performed on a transient network analyzer (TNA) with relay settings and connections as they were at the time of misoperation.

The second analysis used harmonic frequency scans to determine which system configurations might result in steady state harmonic or transient resonances.

Finally, harmonic sensitivity tests of both the electromechanical and solid state relays were conducted to pinpoint the exact sensitivity of tested relays to distorted waveforms.

A. Transient Simulations

To confirm energizing transients were the cause of the electromechanical relay misoperations, one of the misoperating relays was connected to a TNA model of the system. The TNA voltage corresponding to individual relay locations was amplified and fed to the relay under test in real time. The system voltage and relay outputs were recorded on an external digital event recorder.

The electromechanical relay was set to operate for a 5% line-to-neutral negative sequence voltage. Simulations were performed with 0, 53.3 and 106.6 Mvars of capacitance at the 230 kV bus and under strong and weak system conditions. Weak system conditions were simulated by reducing the 230 kV bus short circuit capability to the level available with a key 230 kV line out of service. The model included transformer saturation and was able to capture voltage magnification effects observed in the field. In order to obtain a statistical distribution of system behavior with respect to the energization closing angle, each simulation case included 100 individual runs with statistically varying closing angles.

Transient simulations revealed frequent relay negative sequence element activations. Most of these events were of short duration and failed to cause the relay to time out and activate the trip contacts. More negative sequence element operations were observed during weak system conditions than during strong system conditions. During cable energization, the negative sequence relay element was activated in 68-82% of the weak system and 52-77% of the strong system energizations simulated. The exact percentages depend upon the number of 230 kV capacitors in service. None of the cable switching events lasted long enough to cause the timer to time out (relay trip).

During transformer energization the negative sequence relay element was activated in 89-98% of the weak system and 91-96% of the strong system energizations simulated. Again, the exact percentages depend upon the number of 230 kV capacitors in service. Unlike cable energization, transformer energization resulted in transients lasting long enough to cause the negative sequence element to latch up. This was followed by a relay timer time out (trip) in 20% of the cases simulated.

Transformer energization not only resulted in more negative sequence element operations than cable energization, but also caused relay misoperations, indicating that the transients were of longer duration. A sample of the voltage transients simulated on the 69 kV winding during energization of the second 69/13.8 kV transformer is shown in Fig. 3. This transient is sufficient to cause the electromechanical relay to begin operating, but not sufficient to cause it to time out and cause a trip.

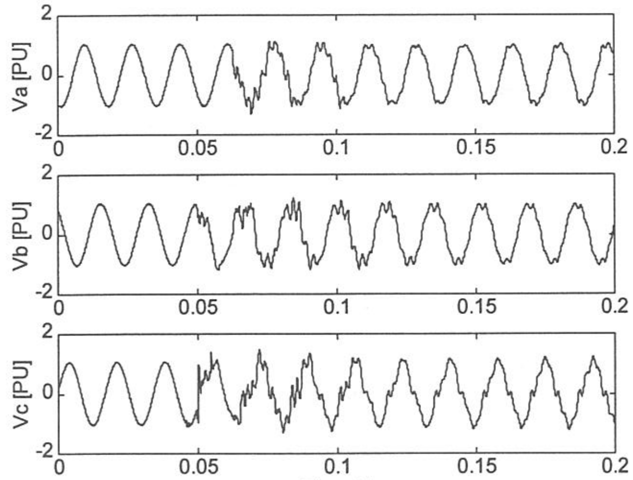

Fig. 3. *69 kV Voltage Transient During 69/13.8 kV Transformer Energization*

An analysis of the transients in Fig. 3 revealed that the predominant frequency of the transient was 420 Hz, the 7th harmonic (Fig. 4).

Because the level of background harmonics was unknown, initially none were simulated. When approximately 2% background harmonics were simulated, they prevented the electromechanical relay negative sequence element contacts from releasing. This caused additional trip operations during both transformer and cable energization events.

The above simulations were repeated with a solid state relay in place of the electromechanical relay. The first solid state relay tested was set to its most sensitive settings, 2% negative sequence voltage and 4 cycles time delay. Even with these severe settings, the device did not misoperate for any of the line energization events and for a maximum of 4% of the transformer energization events. Increasing the time delay to 64 cycles eliminated all trip operations.

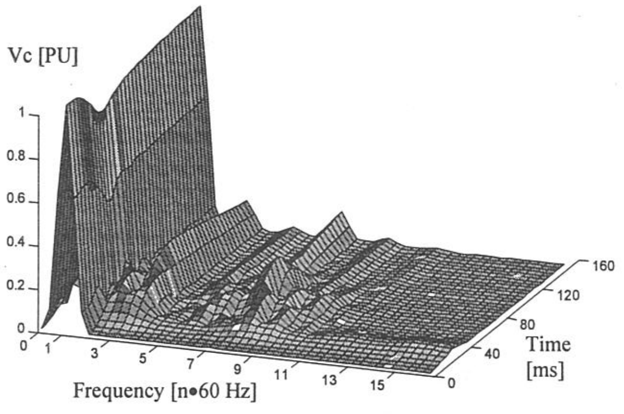

Fig. 4. *Analysis of the Transformer Energization Transient Shown in Fig. 3*

Comparable results were obtained when a second solid state relay was tested. Because both solid state relays are equipped with low pass filters, both solid state relays are much less sensitive to distortion than their electromechanical counterpart.

B. System Frequency Scans

Because no information on nearby harmonic sources was available, frequency scans were performed using a digital model to obtain some information on the harmonic impedance characteristics of the system.

The first frequency scans were conducted on a small model representing the system in Fig. 1. A harmonic current source was placed at the load end of the element being energized or at the 230 kV bus. Simulations were performed with one or both cable segments in service and with one or both of the 69/13.8 kV transformers in service. Different system strengths were also simulated.

An approximately third harmonic resonance appeared on most frequency scans, regardless of the system configuration simulated. This is of minimal concern if the third harmonic distortion is balanced as both the electromechanical and the solid state relays were found to be insensitive to zero sequence harmonics. A seventh harmonic resonance appeared when the second cable segment was modeled. This is the frequency that was excited by the transformer energization transient simulations. No additional resonant frequencies were observed when the two transformers were modeled

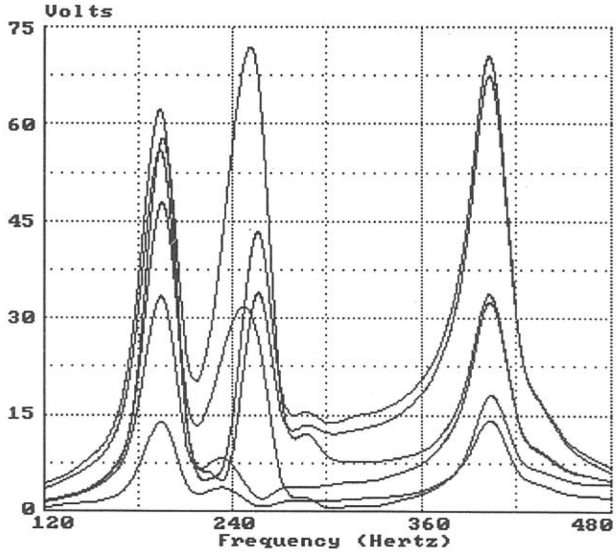

Fig. 5. *Large Model Frequency Scan Results*

A larger model simulating much of the 230 kV and 115 kV systems near the industrial plant was assembled. When frequency scans were performed on this model a near 4th harmonic resonance appeared (Fig. 5). Each of these resonances represent a frequency that may be excited by cable or transformer energization transients.

In all of the frequency scan simulations performed, the effect of increasing system strength was to slightly increase the existing resonant frequencies. The strongest system configuration increased each resonance frequency by about 60 Hz (one harmonic).

C. Relay Harmonic Sensitivity Tests

In spite of the problems associated with relating relay harmonic sensitivity testing to real world situations, it was decided that such tests would provide a general idea of a relay's sensitivity to distortion. We tested the relays using three phase 120 volt 60 Hz waveforms. Individual harmonics were superimposed on all three phases with the appropriate phase relationship consistent with balanced harmonic distortion. Triplen harmonics (3rd, 6th, 9th, etc.) were in phase (0 degrees) on all three phases, positive sequence harmonics (4th, 7th, 10th, etc.) were given phase angles of 0, -120, and +120 degrees, and negative sequence harmonics (2nd, 5th, 8th, etc.) were given phase angles of 0, 120, and -120 degrees. Because of the frequency dependence of the negative sequence detection networks used in each of the relays, the importance of the angles associated with the positive and negative sequence harmonics is debatable. Harmonic voltage distortion levels at the relay inputs were measured throughout the study.

Tests were conducted for a variety of relay settings. The most obvious difference between the electromechanical and solid state relays tested was that the operating (timer on) and release (timer off) values were vastly different for the electromechanical relay being tested. Whenever a relay negative sequence relay element operates, it must first time out before it will cause a breaker to trip. If the condition causing the operation ceases, the relay will release, begin resetting itself, and not cause a breaker operation. For the solid state relays tested, the operation and release values were identical.

The harmonic sensitivity of the relays tested is shown in Table 1. The electromechanical relay was tested with a negative sequence voltage setting of 5%. The solid state relays were tested with multiple negative sequence voltage settings. All of the relays successfully blocked zero sequence harmonics before the voltages were subjected to negative sequence voltage calculation circuit. This makes the negative sequence voltage calculation circuit simpler [8]. The electromechanical relay was less sensitive to lower frequency negative sequence voltages and higher frequency positive sequence voltages. Overall, however, the sensitivity of the relay to harmonic distortion did not significantly decrease with frequency.

The solid state relays, which were each equipped with low pass filters were also more sensitive to lower frequency harmonics. The relays were also more sensitive to harmonics at lower settings. The solid state relays were virtually immune to any harmonics above the 8th, especially for higher relay settings.

In most cases, the electromechanical relay tested would not release (stop timing) until a harmonic level approximately one fifth of the operation (start timing) level occurred. For example, if it took a 10% harmonic voltage distortion to cause the relay contacts to operate, the contacts would not release until the harmonic voltage distortion was below 2%. With this relay in service, a 10% distortion caused by an inrush transient could cause the relay timer to begin operating. Even if the transient distortion disappears before the relay could time out, background harmonics of 2% would be sufficient to hold the comparator circuit active and cause the relay to trip.

TABLE 1

RELAY HARMONIC SENSITIVITIES (EMR - ELECTROMECHANICAL RELAY, SSR - SOLID STATE RELAY, * >24%)

Harmonic #	Frequency Hz	Sequence +/-/0	EMR Operate 5% setting	EMR Release 5% setting	SSR #1 2% setting	SSR #2 2% setting	SSR #2 4% setting	SSR #2 6% Setting
2	120	negative	6.2%	0.9%	9.0%	1.6%	3.9%	6.3%
4	240	positive	12.8%	2.8%	*	9.2%	20.8%	*
5	300	negative	7.8%	1.6%	*	5.6%	12.0%	19.3%
7	420	positive	10.9%	1.5%	*	21.5%	*	*
8	480	negative	8.2%	1.1%	*	19.3%	*	*
10	600	positive	10.1%	1.9%	*	*	*	*
13	780	positive	9.7%	1.9%	*	*	*	*
14	840	negative	8.5%	1.1%	*	*	*	*
16	960	positive	9.7%	1.5%	*	*	*	*
17	1020	negative	8.5%	1.5%	*	*	*	*

V. PROBLEM SOLUTION

The analysis performed as part of this study determined that the relay misoperations that occurred during cable and transformer energization were the result of relay sensitivity to transients and harmonic distortion. It was determined that the relay negative sequence voltage contacts operated because of transient distortion during energization operations and that they failed to release due to background harmonics or prolonged transients during transformer energization. The background harmonics, while not severe enough to cause relay operation themselves, were severe enough to prevent timer release once operation had begun.

Analysis of alternative relays, ones equipped with low pass filters and using solid state rather than electromechanical technology (to avoid hyterisis effects), indicated that the alternative relays tested were much less sensitive to distortion. The low pass filters minimized the effects of system resonances, higher frequency transients and harmonic distortion. Another advantage of the solid state relays is that because hysteresis is not a problem, their operating and release levels under distorted conditions are identical. This study has resulted in the replacement of the misoperating electromechanical relays with solid state relays that are less sensitive to transient and steady state voltage distortion.

VI. CONCLUSIONS

Relay sensitivity to transient and harmonic waveform distortion can cause relay misoperations, even when no other distortion related problems are evident. Because of the variety of relays available and the many types of distortion on power systems, no universal conclusions regarding electromechanical and solid state relay distortion sensitivity can be made. Solid state relays equipped with filters were determined to be preferable under the conditions of this case study. The best method of testing relay response to a given condition is to simulate that condition, including the actual relay to be utilized. As detailed digital models of relays that accurately simulate distortion effects are difficult to obtain, testing using the actual relay hardware is preferable.

VII. REFERENCES

[1] H. Barchetti, N. Korponay, and A. Mosbeck, "Behavior of Current Transformers, Relays, and Protective Devices Subjected to Transients," *CIGRE Report*, 31-06, 1968.

[2] W. F. Horton and S. Goldberg, "The Effect of Harmonics on the Operating Points of Electromechanical Relays," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-104, No. 5, May 1985, pp. 1178-1188.

[3] A. A. Girgis, J. W. Nims, J. Jacomino, J. G. Dalton, and A. Bishop, "Effect of Voltage Harmonics on the Operation of Solid State Relays in Industrial Applications," *IEEE Transactions on Industry Applications*, Vol. IAS-28, No. 5, September/October 1992, pp. 1166-1173.

[4] W. A. Elmore, C. A. Kramer, and S. E. Zocholl, "Effect of Waveform Distortion on Protective Relays," *IEEE Transactions on Industry Applications*, Vol. IAS-29, No. 2, March/April 1993, pp. 404-411.

[5] J. F. Fuller, E. F. Fuchs, and D. J. Roesler, "Influence of Harmonics on Power Distribution System Protection," *IEEE Transactions on Power Delivery*, Vol. 3, No. 2, April 1988, pp. 549-557.

[6] IEEE Power System Relaying Committee, "The Impact of Sine-Wave Distortions on Protective Relays," *IEEE Transactions on Industry Applications*, Vol. IA-20, No. 2, March/April 1984, pp. 335-343.

[7] M. Okamura, F. Andow, I. Mitani, Y. Okita, and M. Masui, "Development of New Relays with Significantly improved Performance Against Badly Distorted Transient Waveforms," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-99, No. 4, July/August 1980, pp. 1426-1436.

[8] C. F. Wagner and R. D. Evans, *Symmetrical Components*, McGraw-Hill Book Company, New York, 1933.

VIII. BIOGRAPHIES

Michael Blase Marz received his BSEE from the University of Notre Dame in 1983, MSEE from Purdue University in 1984, and MBA from the University of Minnesota in 1989. From 1984 to 1989 he was an engineer in the System Planning and Operations departments of Minnesota Power in Duluth. In 1989, he joined the Systems Engineering Group of Cooper Power Systems where he is now a Staff Engineer at the Thomas A. Edison Technical Center in Franksville, WI. He is a registered Professional Engineer in the state of Minnesota.

Veselin Skendzic received his BSEE from the University of Split in Croatia in 1983, MSEE from University of Zagreb in Croatia 1990, and Ph.D. from Texas A&M University in 1994. In 1994, he joined the Systems Engineering Group of Cooper Power Systems where he is now a Staff Engineer at the Thomas A. Edison Technical Center in Franksville, WI.