Five-Wire Distribution System Demonstration Project

Tom A. Short, *Senior Member, IEEE*, James R. Stewart, *Fellow, IEEE*, David R. Smith, *Fellow, IEEE*, James O'Brien, *Member, IEEE*, and Kenneth Hampton

***Abstract*—During this demonstration project, an overhead portion of a four-wire power distribution circuit was converted to a five-wire system. The fifth wire is an isolated neutral that carries all of the unbalanced return current. The measurements suggested that a ground relay could be set much lower on a five-wire system than a comparable four-wire system for improved high-impedance fault detection. Stray voltage was also much lower when the circuit was operated as a five-wire configuration. Magnetic fields were generally lower on the five-wire circuit than at the same locations during four-wire operation. Conversion of an existing four-wire system to a five-wire system presented several unique concerns including fifth-wire placement, crew safety and operations, and how to interface the five-wire system with the existing four-wire distribution system.**

***Index Terms*—Grounding, high-impedance faults, magnetic fields, power distribution, stray voltage.**

I. Introduction

A FOUR-WIRE multigrounded distribution system is the predominant system used in North America. One of the features of a four-wire design is that unbalanced load current can return in the earth. The presence of ground current results in the drawbacks that high-impedance faults are difficult to detect, stray voltages can be caused, and magnetic fields are higher. Other types of distribution designs have been proposed to address these concerns including three-wire designs [1].

The five-wire design is a new approach that may reduce stray voltage and magnetic fields and also make high-impedance faults more easily detectable [2]–[5]. The fifth wire is an isolated neutral that carries all of the unbalanced return current (see Fig. 1). Under normal conditions, the five-wire design operates very similar to the four-wire design with one major exception: all the return current is confined to the neutral that is isolated from ground. The multigrounded ground wire continues to perform the safety functions associated with a multi-grounded system.

The purpose of this study was to simulate, construct, and monitor a five-wire distribution system over a two-year period. The first year of the two-year monitoring period involved extensive monitoring of an existing four-wire system. After completion of the first year of monitoring, the four-wire system was converted to a five-wire system, and another year of monitoring was performed.

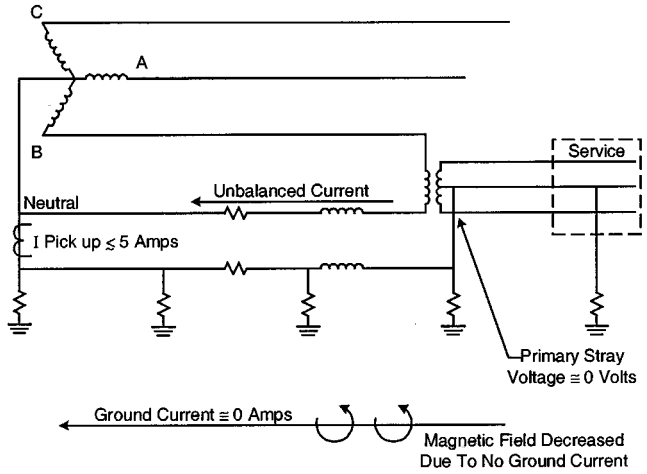


Fig. 1. Five-wire distribution system.

II. Design and Construction

A 12.47-kV three-phase wye distribution system circuit in South Cooperstown, New York was chosen as the five-wire demonstration site. The circuit consists of approximately ten to thirteen kilometers of overhead line. Most of the line is of armless construction, with some cross-arm construction scattered throughout the system. Approximately four kilometers of the South Cooperstown circuit was converted to a five-wire configuration as shown in Fig. 2. Fig. 3 shows a typical pole converted to the five-wire configuration. The two-bushing transformer has an arrester on both bushings, and one bushing is attached to the fifth wire.

The fifth wire was added, and the existing multigrounded neutral was used as a safety ground. During the project, terminology was an ongoing source of confusion. Technically, the isolated wire carrying the unbalance current is the neutral wire. This was very confusing for the line crews who associate the neutral with the wire that became the safety ground. Referring to the ungrounded neutral as the "fifth wire" was understood by all parties.

Five recorders that captured trend data and fault data were located on the circuit. One was in the substation, one was at the substation exit riser pole, and three recorders were at various locations on the circuit.

The demonstration project line was converted for approximately 20% of the new construction cost. Five-wire construc-

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T. A. Short was with Power Technologies, Inc., Schenectady, NY 12301 USA. He is now with EPRI PEAC, Schenectady, NY 12301 USA (e-mail: t.short@ieee.org).

J. R. Stewart is a Consultant, Schenectady, NY (e-mail: jr.stewart@ieee.org).

D. R. Smith is with Power Technologies, Inc., Wilmerding, PA 15148 USA (e-mail: drsmith_pti@compuserve.com).

J. O'Brien and K. Hampton are with NYSEG, Binghamton, NY 13902 USA (e-mail: jdobrien@nyseg.com; klhampton@nyseg.com).

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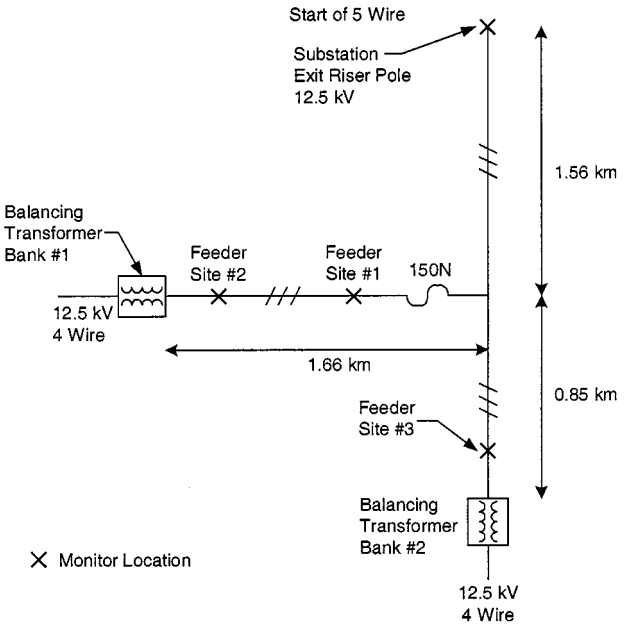


Fig. 2. Five-wire portion of the South Cooperstown test circuit.



Fig. 3. Five-wire pole with a single-phase transformer.

tion costs can vary significantly depending on particular circuit characteristics and utility work practices. Broad estimates of construction costs for three-phase construction are 10% to 20% higher than four-wire costs for new construction while an upgrade on existing circuits may be 20% to 40% of the installed cost (on overhead circuits). Single-phase new construction may

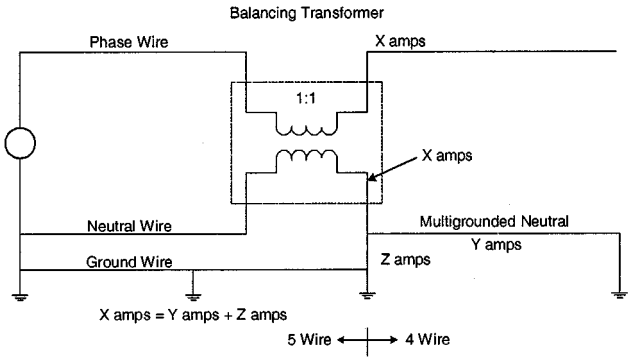


Fig. 4. Single-phase balancing transformer used to interface a four-wire circuit to a five-wire circuit.

cost 20% to 30% more while an upgrade might be 30% to 50% of the installed cost.

Conversion of the existing four-wire system to a five-wire system presented several unique concerns for the line crews. Given the design of the test distribution circuit, the fifth wire was placed on standoffs in the neutral position on the pole, opposite from the system ground. The extra pole loading was considered in the conversion.

Under faults or an open neutral condition, the fifth wire (the neutral) can rise to several thousand volts. Because of this, the fifth wire was treated as a live conductor as the following.

1) Fiberglass standoffs were used to maintain clearance between the ground wire and the fifth wire.
2) A warning tag was installed at each standoff indicating that this conductor was isolated from earth and should not be used for earth reference.
3) Line crews used gloving appropriate for 15-kV-class operation when working on this wire. This safety precaution was taken in case the fifth wire were to open or there was a fault on the line while line mechanics were working on the fifth wire.
4) Insulate “tree wire” was used for the conductor (covered conductors).
5) All lead wires connecting the transformer bushings to the neutral wire were treated as live conductors. Where needed, insulated standoffs or insulators were used to route jumpers around transformers or other objects.

The line was converted to five-wire construction starting at the riser pole directly outside of the substation. Balancing transformer banks were used in the conversion where the five-wire section reverted back into the existing four-wire system. The balancing transformer is a 1 : 1 current transformer placed inline with the phase and neutral wires (see Fig. 4). Balancing transformers have been suggested as a means of reducing ground currents [6], and they have been used for many years on electrical railroad systems to keep unbalanced currents out of the ground.

Under normal operation a balancing transformer forces the phase current and neutral return current to sum to zero and prevents return current from returning to the source via the ground wire path. It also provides for detection of an open neutral upstream on the five-wire section of line. An isolation transformer could have provided these objectives; however, given the characteristics of the test circuit, fuse coordination

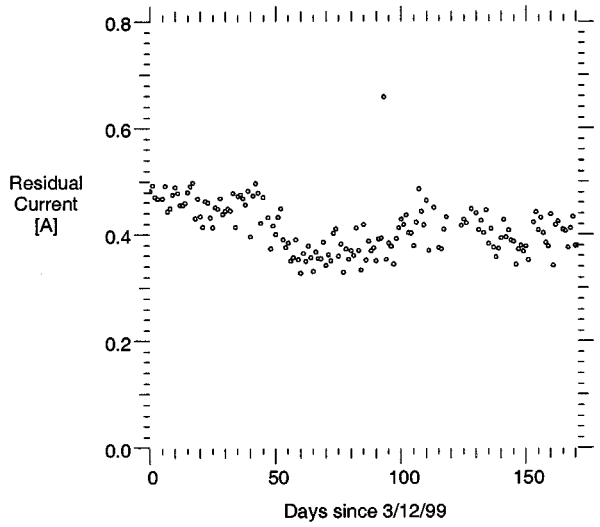


Fig. 5. Maximum daily residual current on the metering-class CTs at the substation exit riser pole during five-wire operation.

could not be achieved. Since the balancing transformer represents much lower impedance, this method of isolation was used. An isolation transformer must transfer all of the power magnetically. A balancing transformer only has to transform enough power to supply the circuit unbalance. Because a balancing transformer is a lower-rated unit, it will be lighter and less expensive than an isolation transformer.

III. High-Impedance Fault Detection

One of the main benefits of a five-wire system is a more sensitive detection of high-impedance faults. In a traditional four-wire system, high-impedance faults are very difficult to detect. On the South Cooperstown circuit, the pickup of the ground current relay is set at 120 A. High-impedance faults are much less than this. A five-wire system allows much greater ground fault sensitivity because all of the unbalanced current returns through the neutral, and a negligible amount flows in the ground.

Sensitive ground fault detection can be done by measuring the *residual* current at the substation exit riser pole (the start of the five-wire circuit). The *residual* current is the summation of the current in the phase conductors and the neutral conductor. Under normal conditions the residual current should be zero. If a phase conductor comes into contact with the earth, the current in the high-impedance fault will show up on the residual measurement.

The residual current was measured with metering CTs installed near the substation exit riser pole. The residual current on the metering class CTs has been below 0.7 A since they were installed in March 1999 as shown in Fig. 5.

As a general practice, a high-impedance detection relay would be a time-overcurrent relay set so that it takes a relatively long time to trip (at least 1 s), so it would not trip on inrush events. The time delay and the reset characteristics of the sensitive ground fault relay should also allow for the reclose characteristics of downstream devices.

The pickup of a ground relay is usually set at least two times higher than the normal peak current seen by the relay. For the case of the residual connection, more conservatism would be warranted. The metering CT residual measurements had a peak of 0.7 A. A relay pickup of 5 A would have a small chance of false trips. This compares to a ground relay pickup setting on the four-wire system that is generally in the range of 100 to 300 A.

Because the likelihood of an actual high-impedance fault during the monitoring period was very small (none occurred), a test was performed that mimics a high-impedance fault. To simulate a high-impedance fault on the five-wire circuit, a transformer was connected from the phase conductor to the ground wire (all other single-phase transformers were connected between a phase and the neutral/fifth wire). The load placed on the secondary of the test transformer was a heater with several resistive elements to simulate different high-impedance fault currents (from 0.5 to 3 A on the primary). When the heater was switched on, the residual current was detected at the substation riser pole for currents under one amp. Fig. 6 shows an example of a test where the recorder at the substation riser pole detected the turn on and turn off of the heater. Simulated faults down to 1 A were successfully detected on all three phases.

IV. Stray Voltages

During the monitoring periods, the stray voltage in the five-wire configuration was about 40% lower than the four-wire configuration as shown in Table I. During four-wire operation, the stray voltage tracked feeder currents and during five-wire operation, there was less correlation between primary current and stray voltage as shown in Fig. 7.

The stray voltage performance of the five-wire circuit with large unbalance was demonstrated by staged tests done on the circuit. An existing 1000-kVA floating-wye delta transformer bank was converted to an open-wye open-delta configuration. The open-wye open-delta configuration is known for causing large ground currents. Table II shows stray voltages during four-wire and five-wire operation where 50 A of unbalance current was injected by the transformer bank conversion. The stray voltages were much lower during five-wire operation.

V. Magnetic Fields

Spot measurements at various locations were done for magnetic fields during four-wire and five-wire operation. During five-wire operation, the magnetic fields were generally lower. At most locations, the magnetic fields were generally 10% to 50% lower than at the same locations during four-wire operation. Because the South Cooperstown circuit had relatively balanced currents during the monitoring, the small level of improvement was expected.

The performance of the five-wire circuit with a large unbalance on it was better illustrated by a staged conversion test done on the circuit. During one of the tests, over 80 A of return current was forced into the ground (the unbalance current for the entire circuit was normally around 15 A). During these tests, the magnetic fields at all locations were much lower during the five-wire configuration than the four-wire configuration as illustrated in Fig. 8. At the location in Fig. 8, the biggest difference in magnetic fields was near a buried phone cable.

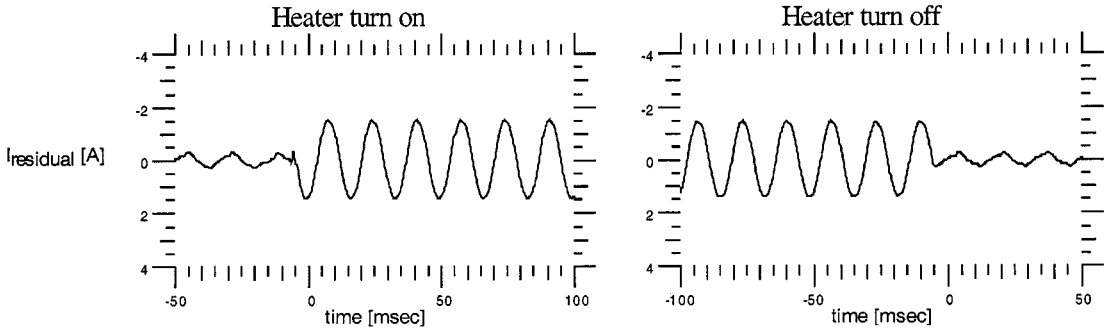


Fig. 6. Example of the heater element being turned on and turned off as recorded at the riser pole.

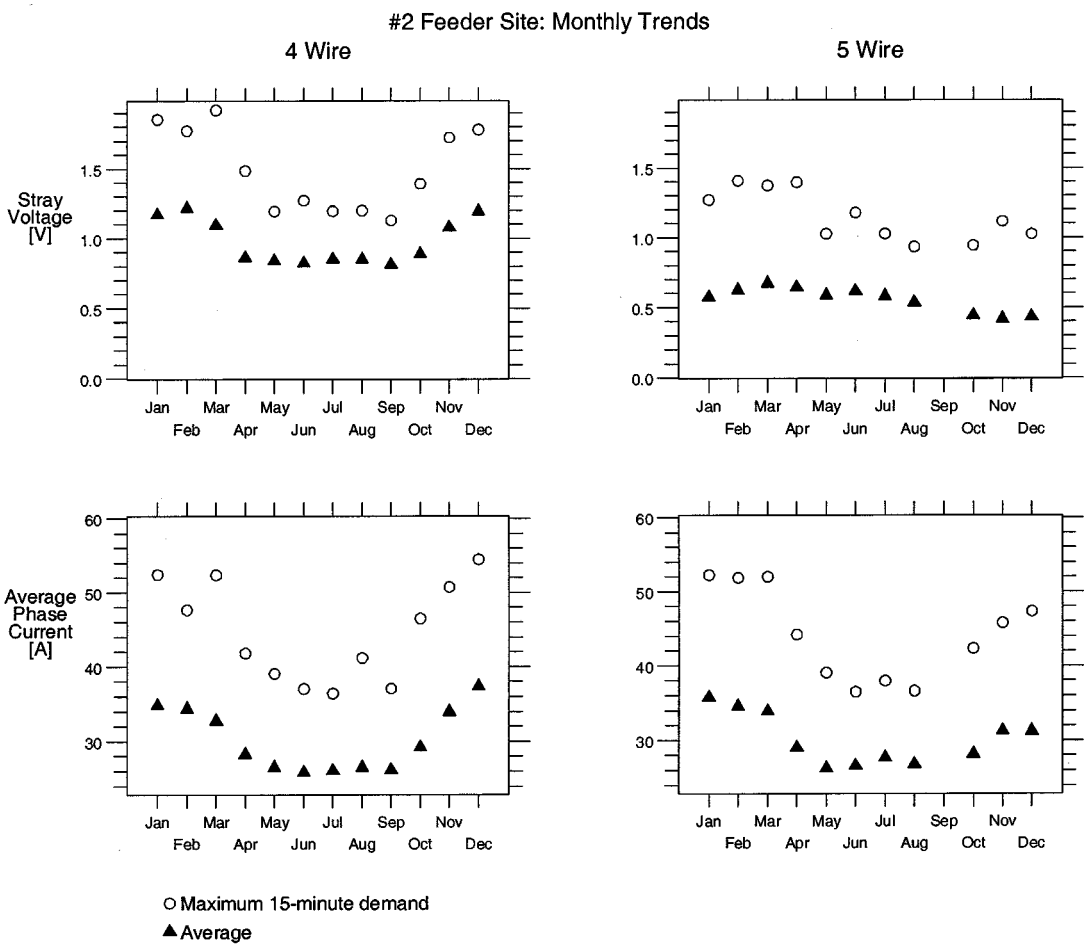


Fig. 7. Monthly stray voltage comparison at feeder site #2.

TABLE II
STRAY VOLTAGES DURING THE 8/24/99 TEST WITH THE PHOENIX MILLS STEP BANK CONVERTED TO AN OPEN-WYE OPEN-DELTA CONFIGURATION [STRAY VOLTAGES ARE IN RMS VOLTS]

	Substation Exit Riser Pole	Shed	Feeder Site #3	Phoenix Mills Step Bank
distance from sub	0 km	0.8 km	2.2 km	2.3 km
4 wire	1.7 V	0.44 V	3.75 V	11.00 V
5 wire	1.4 V	0.35 V	0.68 V	0.71 V

VI. RESPONSE TO FAULTS

No faults were measured on the five-wire portion of the circuit during the monitoring period. The weather during the summer of the five-wire monitoring period was unusually stable. A few faults were measured on the four-wire portion of the circuit downstream of the balancing transformers. This provided a good test of the balancing transformers' characteristics. One of the key reasons why balancing transformers were used as the interconnection is that they introduce less impedance on the line for downstream faults. For large faults, the balancing transformers saturated. Fig. 9 shows the most significant

TABLE I
AVERAGE STRAY VOLTAGE COMPARING FIVE-WIRE OPERATION TO FOUR-WIRE OPERATION [VOLTS]

	Substation Exit Riser Pole	Feeder Site #1	Feeder Site #2
4 wire	1.81	0.29	0.97
5 wire	1.11	0.13	0.56

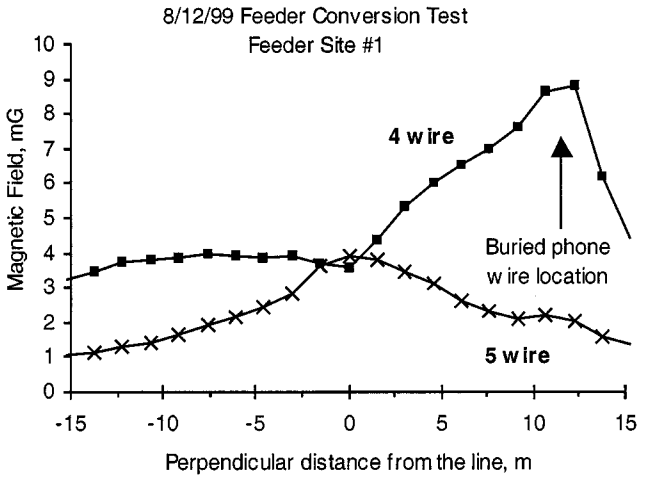


Fig. 8. Magnetic field profile near the #1 feeder site during the 8/12/99 conversion test where the 1000-kVA Fly Creek bank is converted to open-wye open-delta configuration.

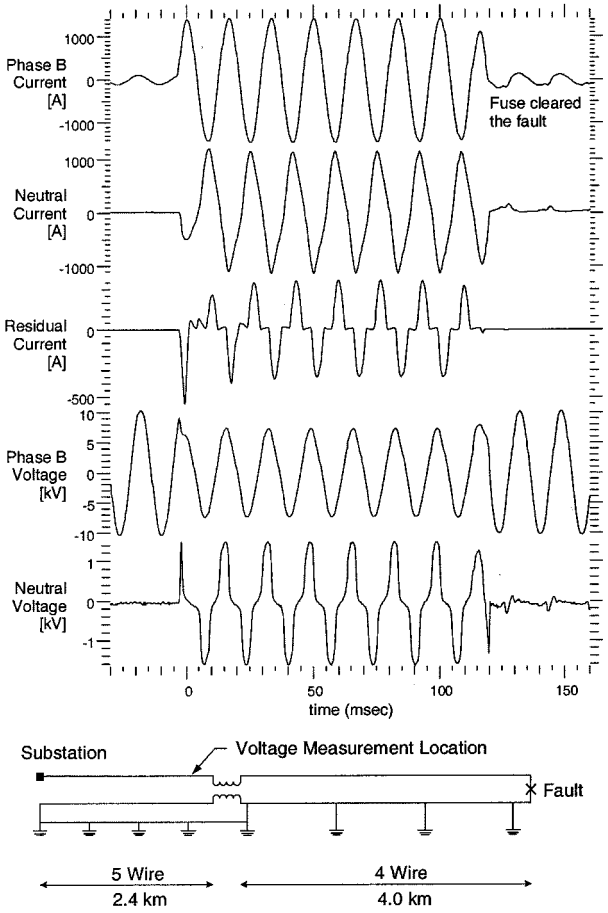


Fig. 9. Single-phase fault on May 18, 1999.

signals for a fault on May 18, 1999 when a contractor dug into a cable on a fused tap on the four-wire system. The fuse on the tap operated to clear the fault. The balancing transformers went into saturation and allowed the return current to flow to ground. The neutral voltage at feeder site #3 (which is close to the balancing transformers) is highly distorted. The residual current at the substation riser pole is also highly distorted. The neutral current is somewhat distorted. The distortion is normal, and this operation is what is expected for faults downstream of the balancing transformer.

Near the end of the project, a 1000-A, 0.95-s fault damaged one of the balancing transformers causing an open circuit. A line crew had to close the shorting switches on the balancing transformers to restore service to downstream customers.

An inspection of the damaged balancing transformer revealed that a 15-cm portion of a 12 AWG lead from the H1 bushing to the transformer coil was melted away. In effect, this lead acted as a fuse. Temperature calculations confirm the 12 AWG conductor would not have been able to withstand the through fault. The event points out that it is critical that the balancing transformers meet the fault current specified. The fault specification for this transformer was 3000 A for 1 s, but it was not met in this case.

VII. CONCLUSIONS

The main conclusion of the five-wire demonstration project is that the five-wire system improved performance for high-impedance faults, stray voltages, and magnetic fields relative to a four-wire system:

High-impedance faults can be detected more easily on a five-wire system. High-impedance faults as low as 5 A may be detected on a five-wire system.

Stray voltages are much less on a pure five-wire system than on a four-wire system. If only a portion of a circuit is converted to a five-wire system, end effects will impact the system's ability to control stray voltage. Some of the unbalanced return current in the four-wire system may return via the ground wire in the five-wire system causing stray voltage on the five-wire portion.

Magnetic fields are lower on the five-wire system. This is especially true when the overhead line is near conducting objects in the ground like buried phone wires or water pipes.

Balancing transformers are an effective way of conversion from a five-wire system to a four-wire system. A balancing transformer offers lower impedance that helps with overcurrent coordination. A balancing transformer will also provide some protection for an open neutral condition.

The fifth wire (the neutral) should be treated as an energized conductor and installed as such. Surge arresters of the same rating as the phase arrester should be mounted on the neutral bushings of all transformers.

Crew practices are important when considering a five-wire system. The location of the neutral and its insulation require proper attention. Initial installations should have the fifth wire labeled to warn crews that it is not to be treated as a grounded conductor.

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REFERENCES

[1] J. J. Burke, "Controlling magnetic fields in the distribution system," *Transmiss. Distribut.*, pp. 24–27, Dec. 1991.

[2] P. B. Stecuik, J. J. Burke, D. C. Weiler, and W. S. Sears, "Five-wire distribution system design," EPRI White Paper, August 20, 1993.

[3] P. B. Stecuik and J. J. Burke, "Philosophies of overcurrent protection for a five-wire distribution system," in *Proc. Transmiss. Distribut. Conf. Expo.*, Los Angeles, CA, Sept. 16–20, 1996, Panel Session Paper.

[4] R. G. Reed and L. D. Hall, "Method and apparatus using a five-wire network for distribution of electrical power," U.S. patent 5 793 593, 1998.

[5] EPRI, *Five-Wire Distribution System Demonstration Project*. Palo Alto, CA, ESEERCO, New York, NY, NYSERDA, Albany, NY: EPRI, 2000.

[6] H. Hofmann and G. Preston, "Reduction of stray currents and magnetic fields from single-phase power distribution systems," *IEEE Trans. Power Delivery*, vol. 10, pp. 1112–1118, Apr. 1995.

Tom A. Short (S'89–M'90–SM'98) received the M.S.E.E. degree from Montana State University, Bozman, in 1990.

He has been with Power Technologies, Inc., Schenectady, NY, since 1990. He has been involved in several monitoring projects on distribution systems. He has performed lightning protection, voltage sag, flicker, capacitor application, and load flow analysis studies as well as a variety of other modeling studies on distribution circuits. In 2000, he joined the Schenectady, NY, office of EPRI PEAC.

James R. Stewart (S'69–M'74–SM'79–F'88) received the B.S., M.S., and Ph.D. degrees from Syracuse University, Syracuse, NY.

After working for Niagara Mohawk Power Corporation, he worked for 25 years at Power Technologies, Inc., Schenectady, NY, performing various transmission and distribution related projects. Research areas included compact high voltage transmission lines, high phase order transmission lines, electric and magnetic fields from power facilities, and five-wire distribution.

Dr. Stewart is a Registered Professional Engineer in New York.

David R. Smith (M'72–SM'85–F'01) received the B.S.E.E. degree from Pennsylvania State University, State College, PA, and the M.S.E.E. degree from the University of Pittsburgh, Pittsburgh, PA, in 1963 and 1968, respectively.

From 1963–1988, he was with the Westinghouse Electric Corporation, Burr Ridge, IL, and since then with Power Technologies, Inc, Schenectady, NY. His areas of interest are power distribution system analysis, simulation, equipment application, and failure investigations. He is a co-holder of four patents.

Dr. Smith is a Registered Professional Engineer in Pennsylvania.

James O'Brien (M'98) received the B.S.E.E. and M.S.E.E. degrees from Clarkson University, Potsdam, NY, and the M.B.A. degree from Colorado State University, Fort Collins, CO.

He has been with NYSEG, Binghamton, NY, since 1989. He has been involved in various distribution engineering design projects, studies, and operation functions at NYSEG.

Kenneth Hampton received the B.S.E.E. degree from Pennsylvania State University, State College, PA.

He has been with NYSEG since 1986. He has been involved in specifying and applying distribution class equipment, performing stray voltage, ferroresonance and RI/TVI investigations and mitigative measures, and conducted various R&D projects.