AUTOTRANSFORMERS FOR SUPPLYING PORTABLE MINING EQUIPMENT

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ABSTRACT

Power center manufacturers are using autotransformers to provide second utilization voltages and to derive system neutrals on the secondaries of ungrounded two winding transformers. The neutral is high resistance grounded and is intended to provide system grounding for all connected loads. A laboratory model for the different circuit configurations was used to determine if ground fault protection was provided. These configurations were analyzed and evaluated to determine if a safety problem existed. This paper discusses limitations on the use of autotransformers for establishing system grounding and the inherent hazards associated with their application.

INTRODUCTION

The economic advantage of buying reconditioned face equipment, such as roof bolters, shuttle cars, drills, etc., has created a demand for a power center that can supply more than one level of alternating voltage. Power center manufacturers normally meet this demand by building equipment with two isolated secondary windings. However, when remanufactured power centers are required to supply dual voltages, manufacturers are using a combination of the existing secondary winding and adding an autotransformer for the second output voltage. These units can supply any two of the most common voltages: either 480, 600 or 995 Vac.

The use of a dual voltage transformer installation that uses an autotransformer to provide a second voltage, is a practice used quite extensively in industries other than mining. Of course, the major differences between mining and other industries is that mining equipment and loads are not fixed in permanent locations. Trailing cables that connect the power center to portable and mobile equipment frequently experience insulation failures. The number of ground faults on these circuits are more numerous than installations using raceway and stationary load designs. Lethal voltages created by ground faults cannot be allowed to persist on the frames of equipment. This becomes critical because miners are always in contact with the equipment during operation.

With this in mind, Federal Regulations for certain underground mines require that all three phase circuits that originate underground, have a direct or derived neutral that is high resistance grounded and provided with ground fault protection. These requirements, combined with the need for a dual voltage power center, created a unit that utilizes an autotransformer in conjunction with a standard two winding step-down transformer.

This paper is a result of a request from the enforcement branch of the Mine Safety and Health Administration. Questions about the suitability of the autotransformer for deriving a system neutral, any limitations created by various connections of secondary loads, and the ability to supply zero sequence current during a ground fault were investigated.

LITERATURE REVIEW

Autotransformers have been used by the utility industry for many years. Boyajian[1] states that autotransformers are superior to standard transformers in terms of: lower cost, greater efficiency, better regulation, smaller size and smaller exciting current. A regular two winding transformer requires all the kVA to be transformed from the primary to the secondary through the magnetic circuit, while an autotransformer requires only a fraction of the total kVA transformed with the balance transferred conductively.[2]

The relationship of the autotransformer rating to the output power is shown in equation 1 as the ratio of the lower voltage to higher voltage.

$$\frac{Rating}{Output} = 1 - \frac{E_2}{E_1} \qquad (1)$$

where: E_1 = higher voltage

E_2 = lower voltage

A general rule of thumb for sizing an autotransformer is that the percentage kVA (power) transformed is equal to the percentage of the output voltage.[1] For example, an autotransformer that is used to supply 600 Vac to a 100 kVA load, is connected to a 480 Vac circuit. The voltage ratio, from equation (1), will be 1-(480/600) or 20 percent. The minimum size of the autotransformer can now be calculated as 100 kVA x 0.2 or 20 kVA. The 20 kVA is the amount of power transformed magnetically and 80 kVA is transferred conductively.

Stigant[3] states that when the voltage transformation ratio, E_1/E_2, exceeds two, the cost efficiency that warranted their application originally is not feasible.

The following is a summary of disadvantages as stated by Boyajian[1], Kosow[2], and Stigant[3]:

1) The effective percent impedance of the autotransformer is equal to the product of the ratio of equation 1 and the percent impedance of a standard isolation transformer. This reduced percent impedance increases the short-circuit current by the inverse ratio of equation 1 and the mechanical stresses caused by the short-circuit are increased by the square of this inverse ratio. Using the

previous example, a 0.2 ratio would equal a short-circuit current increase of 5 times (1 divided by 0.2), and the mechanical stresses would increase by 25 times (5 squared).

2) Normally, transformers are not designed to withstand the higher mechanical stresses caused by the increase in short circuit current. Extensive damage could be expected when an autotransformer is subjected to a short-circuit, especially when the system impedance is very low (stiff system). An increase in autotransformer reactance or system reactance can be used to limit short-circuit current to a safe value for the autotransformer.

3) The internal terminations of the autotransformer are required to carry large values of current during normal operation. The high efficiency of the unit is due to the majority of load current transferred conductively through the main transformer winding. These terminations or junctions may become hot spots which can develop into an open circuit. This allows the input voltage to be imposed on the autotransformer output. If a voltage raising unit is used, the lower voltage would appear on the autotransformer output. Conversely, with a voltage lowering unit, a higher voltage would appear on the autotransformer output.

LABORATORY TESTS

The typical dual voltage power center schematic is shown in figure 1. The secondary windings of the power transformer were connected in delta and furnish 480 volts.

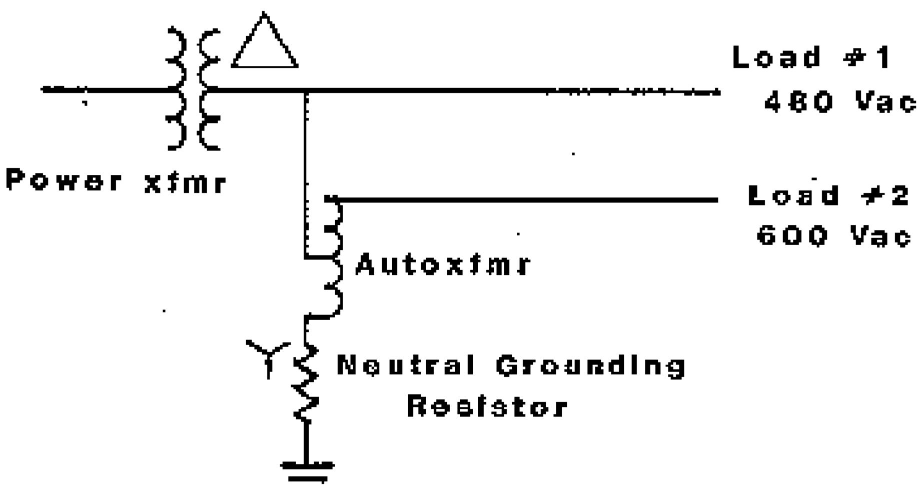

Figure 1. Typical Transformer Connections

The autotransformer windings were connected in wye for 550 volts. The neutral point of the autotransformer was grounded through a 25 ampere resistor. Laboratory tests measured the amount of ground fault current that flowed when ground faults were intentionally created at various locations in either the 480 or 550 volt circuits. To provide a consistent baseline, phase 'A' was chosen to be grounded in all ground fault tests. These tests included ground faults with all circuit loads connected and variations of loads connected or removed.

A. <u>Test Circuit</u>

Power into the laboratory was supplied from a 500kVA, 480 Volt, three phase power transformer as shown in figure 2. Power to the test circuit was controlled through a motor starter (motor contactor/circuit breaker/disconnect unit).

The test circuit consisted of three, single-phase, 37.5kVA, power transformers connected delta-delta with a 480 to 480 Vac voltage ratio. A 10 ampere molded case circuit breaker, CB-1, was connected to the secondary to protect and isolate load #1. Load #1 was a 7.5 horsepower motor running unloaded. Between the secondary winding and CB-1 was another connection to CB-2. This 25 ampere molded case circuit breaker was used to protect and isolate the autotransformer. A wye connected, three-phase ganged, variable autotransformer was rated 27.2 kVA at a maximum of 560 volts. The output of the autotransformer was set at 550 volts and a 25 ampere molded case circuit breaker, CB-3, was used to protect and isolate load #2. Load #2 utilized a noninductive load (power resistors). The resistors were used due to the unavailability of a 550 motor.

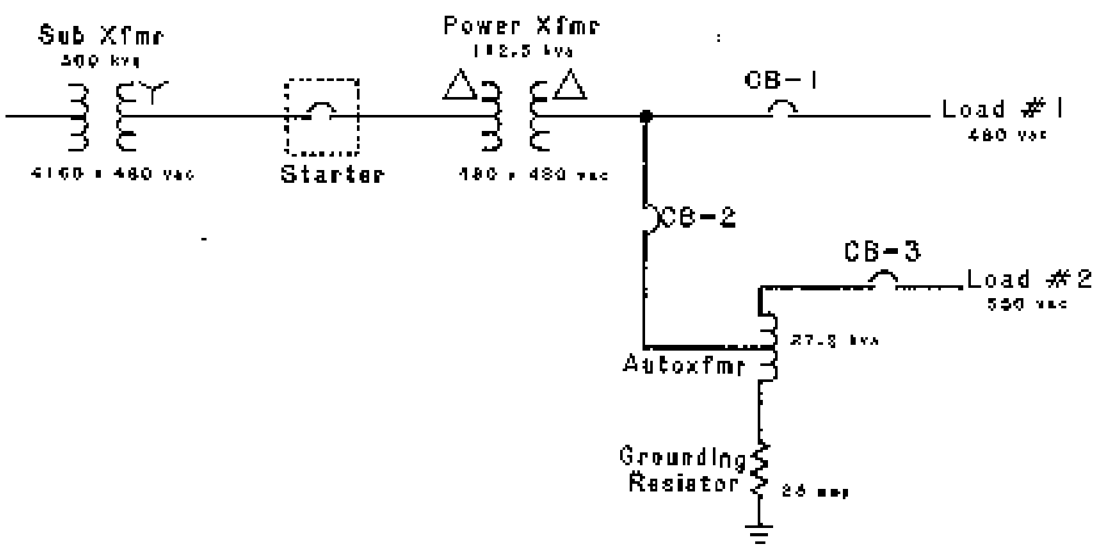

Figure 2. Test Circuit

The neutral point of the autotransformer was tied to ground through a 25 ampere grounding resistor. All equipment frames were interconnected with #12 AWG copper wire and connected to the earth side of the grounding resistor. All power wiring to the loads used three conductor unshielded #12 AWG, S.O. cable, and #10 AWG, 7 strand insulated conductors for transformer/circuit breaker wiring.

Intentional ground faults were created at different points in the test circuit. The initiation of the fault was through a 30 ampere motor contactor which had a 120 Vac coil for remote control. One lead from the contactor was connected to the phase conductor and the other was tied to the ground side of the neutral grounding resistor. Table #1 summarizes the laboratory tests performed.

B. Instrumentation

A Nicolet[1] digital two channel recording oscilloscope was used to capture and save the desired voltage and current waveforms. Voltage was recorded with the aid of times 100 probe and currents were recorded with Pearson[1] precision current transformers which generated a 10 millivolt signal for every ampere of current. The captured signals were analyzed with a laboratory microprocessor that computed "rms" values and produced hardcopy printouts of the waveforms.

C. Test Results

A variety of tests were conducted to determine the circuit characteristics during inrush (start-up), full load, and ground fault conditions. Additional tests were conducted to determine the autotransformer characteristics. The unregulated incoming voltage was well over 500 volts, and is shown in the motor and autotransformer voltage values. The output of the autotransformer was adjusted for 550 volts. In the following tables, all values are rounded off for ease of discussion.

[1]Use of manufacturers' or trade names is for identification purposes only and does not imply endorsement by the Mine Safety and Health Administration.

Test	Type	Energized Load or C.B. Status	Fault Location (See Note)
A, B	Inrush Current Testing	#1, #3	-
C	Full Load Testing	#1, #3	-
D	Full Load Testing	#1	-
E	Full Load Testing	#1, #2, #3	-
F, R, BB	Ground Fault	#1, #2, #3	#1, #2, #3
G, S, CC	Ground Fault	CB-1 Open	#1, #2, #3
H, T, DD	Ground Fault	CB-2 Open	#1, #2, #3
J, U, EE	Ground Fault	CB-2 Open	#1, #2, #3
K, V, FF	Ground Fault	CB-2 ϕ A Open	#1, #2, #3
L, W, GG	Ground Fault	CB-2 ϕ B Open	#1, #2, #3
M, X, HH	Ground Fault	CB-2 ϕ C Open	#1, #2, #3
N, Y, JJ	Ground Fault	CB-2 ϕ A & ϕ B Open	#1, #2, #3
P, Z, KK	Ground Fault	CB-2 ϕ B & ϕ C Open	#1, #2, #3
Q, AA, LL	Ground Fault	CB-2 ϕ C & ϕ A Open	#1, #2, #3
MM	Autoxfmr Testing	#2	-
NN, PP	Autoxfmr Testing	#1, #2, #3	#2, #1
NOTE: #1 - Motor, #2 - Resistor, #3 - Autotransformer			

Table I. Laboratory Tests Summary

1) <u>Inrush Tests</u>: The inrush tests are shown in table I as ‘A’ and ‘B’. Table II is a summary of the results. Test ‘A’ was the autotransformer inrush test and test ‘B’ the motor inrush tests.

Test	Motor		Autotransformer	
	Amps	Volts	Amps	Volts
A	--	--	62	508
B	69	509	--	--

Table II. Inrush Current Tests Summary

2) <u>Full Load Tests</u>: The full load tests are listed as tests ‘C’, ‘D’ and ‘E’. The first test, ‘C’ was with the motor and autotransformer energized. The next test, ‘D’, was with the autotransformer and resistor load energized. The final test, ‘E’, had all loads energized. Table III summarizes the results of these tests.

Test	Motor		Autotransformers		Resistor	
	Amps	Volts	Amps	Volts	Amps	Volts
C	6.1	530	0.5	529	--	--
D	--	--	2.1	528	1.9	545
E	5.8	528	2.1	529	1.9	546

Table III. Full Load Tests Summary

3) Ground Fault Tests: The ground fault tests are divided into three basic groups: a ground fault at phase 'A' on the motor (Table IV), the resistor (Table V), and the autotransformer (Table VI). Within these three groups, isolation of loads or single phasing conditions were created. Ground faults on phase 'A' at the motor are listed as tests 'F' through 'Q'. Ground faults at the resistor load are shown as test 'R' through 'AA'. Finally, ground faults at the autotransformer are listed as tests 'BB' through 'LL'.

Test	Power Transformer				Autotransformer				Resistor				Grounding Resistor		C.B.# Open
	Amps			Volts	Amps			Volts	Amps			Volts			
	ϕA	ϕB	ϕC	ϕB-ϕC	ϕA	ϕB	ϕC	ϕB-ϕC	ϕA	ϕB	ϕC	ϕB-ϕC	Amps	Volts	
F	--	10	25	516	19	3	21	529	--	--	--	535	21	206	--
G	--	--	--	---	2	2	2	---	--	--	--	---	0	---	1
H	--	--	--	---	0	0	0	---	--	--	--	---	0	---	2
J	--	--	--	---	0	2	19	---	--	--	--	---	17	---	3
K	--	--	--	---	0	3	17	---	--	--	--	---	19	---	2ϕA
L	--	--	--	---	2	0	16	---	--	--	--	---	14	---	2ϕB
M	--	--	--	---	1	15	0	---	--	--	--	---	14	---	2ϕC
N	--	--	--	---	0	0	15	---	--	--	--	---	14	---	2ϕA&B
P	--	--	--	---	0	0	0	---	--	--	--	---	0	---	2ϕB&C
Q	--	--	--	---	0	13	0	---	--	--	--	---	13	---	2ϕC&A

Table IV. Ground Fault Tests Summary - Phase A Grounded at Motor

Test	Power Transformer				Autotransformer				Resistor				Grounding Resistor		C.B.# Open
	Amps			Volts	Amps			Volts	Amps			Volts			
	ϕA	ϕB	ϕC	ϕB-ϕC	ϕA	ϕB	ϕC	ϕB-ϕC	ϕA	ϕB	ϕC	ϕB-ϕC	Amps	Volts	
R	--	9	27	521	23	4	23	522	--	--	--	522	22	217	--
S	--	--	--	---	18	3	18	---	--	--	--	---	16	---	1
T	--	--	--	---	0	0	0	---	--	--	--	---	0	---	2
U	--	--	--	---	0	0	0	---	--	--	--	---	0	---	3
V	--	--	--	---	0	2	2	---	--	--	--	---	0	---	2ϕA
W	--	--	--	---	15	0	15	---	--	--	--	---	14	---	2ϕB
X	--	--	--	---	19	19	0	---	--	--	--	---	18	---	2ϕC
Y	--	--	--	---	0	0	0	---	--	--	--	---	0	---	2ϕA&B
Z	--	--	--	---	0	0	0	---	--	--	--	---	0	---	2ϕB&C
AA	--	--	--	---	0	0	0	---	--	--	--	---	0	---	2ϕC&A

Table V. Ground Fault Tests Summary - Phase A Grounded at Resistor Load

Test	Power Transformer				Autotransformer				Motor		Resistor	Grounding Resistor		C.B.# Open
	Amps			Volts	Amps			Volts	Volts	Amps	Amps			
	ϕA	ϕB	ϕC	ϕB-ϕC	ϕA	ϕB	ϕC	ϕB-ϕC	ϕB-ϕC	ϕA	ϕA	Amps	Volts	
BB	26	--	--	522	22	3	22	515	526	6	2	20	201	--
CC	--	--	--	---	17	3	17	---	---	--	--	16	---	1
DD	--	--	--	---	0	0	0	---	---	--	--	0	---	2
EE	--	--	--	---	16	2	17	---	---	--	--	16	---	3
FF	--	--	--	---	0	2	2	---	---	--	--	0	---	2ϕA
GG	--	--	--	---	14	0	16	---	---	--	--	14	---	2ϕB
HH	--	--	--	---	14	14	0	---	---	--	--	14	---	2ϕC
JJ	--	--	--	---	0	0	0	---	---	--	--	0	---	2ϕA&B
KK	--	--	--	---	0	0	0	---	---	--	--	0	---	2ϕB&C
LL	--	--	--	---	0	0	0	---	---	--	--	0	---	2ϕC&A

Table VI. Ground Fault Tests Summary - Phase A Grounded at Autotransformer

4) Autotransformer Tests: The autotransformer tests duplicated previous test set-ups, with the current and voltage sensors located at the autotransformer input and common leads. The results are listed in table VII, and labeled as tests ‘MM’, ‘NN’ and ‘PP’. The first test, ‘MM’ was conducted with the motor disconnected. Tests ‘NN’ and ‘PP’ were with all loads connected and a ground fault created at the resistor and motor respectively.

Test	Autotransformer Amps Input			Autotransformer Amps Common			Volts Input to Common	Volts Input to Resistor Load	Location of Ground Fault
	φA	φB	φC	φA	φB	φC	φA	φA	φA
MM	1	.2	.2	.05	.05	.05	339	1	--
NN	23	34	2	.07	.2	2.1	20	.5	Resistor
							φA - φB	φB - φC	
PP	2	.3	2	.01	.2	2	51	51	Motor

Table VII. Autotransformer Test Summary

D) Analysis

In the four groups of tests conducted, the ground fault tests were the major concern. The inrush and full load tests established benchmarks of normal operation. The autotransformer tests demonstrated the dynamics of the unit during various circuit conditions.

Acceptable values for ground fault protection normally are based on 50% of the neutral grounding resistor rating.[4] In this specific case, all ground fault current values that exceed 12.5 amperes were considered sufficient for proper protection.

The first series of ground fault tests require grounding phase ‘A’ of the motor. In reviewing table IV, the value of ground fault current measured at the grounding resistor, ranged from 0 to 21 amperes. All values over 12.5 amperes were eliminated, with only the values in tests ‘G’, ‘H’, and ‘P’ remaining. The second series of ground fault tests, require grounding phase ‘A’ of the resistor load. A review of table V indicates four of the ten tests exceed 12.5 amperes. The remaining six tests: ‘T’, ‘U’, ‘V’, ‘Y’, ‘Z’, and ‘AA’ were zero. The final series of ground fault tests involve grounding phase ‘A’ of the autotransformer. Of the ten tests listed n table VI, five were over 12.5 amperes and five were under. The five tests under are: ‘DD’, ‘FF’, ‘JJ’, ‘KK’, and ‘LL’.

A review of the previously discussed conditions, where ground fault current did not flow, was evaluated to determine whether a safety hazard exists. Even though ground current is absent when any energized phase conductor comes in contact with earth it can create a shock hazard. The hazard exist when the ground path is completed by a person coming in contact with the frame (ground) of an energized unit of equipment. If a potential is absent, such as when a circuit breaker or fuse opens, a shock hazard does not exist.

The conditions described in the preceding analysis are summarized in table VIII. Only the conditions described in tests ‘H’, ‘P’, ‘Z’, and ‘KK’ are considered to be an electrical hazard. Figures 3, 4, 5, and 6 show a diagram of these tests.

Test	ϕA-Fault Location	C.B.# Open	Electrical Hazard Exists
G	Motor	CB-1	No
H	Motor	CB-2	Yes
P	Motor	CB-2ϕB&C	Yes
T	Resistor	CB-2	No
U	Resistor	CB-3	No
V	Resistor	CB-2ϕA	No
Y	Resistor	CB-2ϕA&B	No
Z	Resistor	CB-2ϕB&C	Yes
AA	Resistor	CB-2ϕC&A	No
DD	Autoxfmr	CB-2	No
FF	Autoxfmr	CB-2ϕA	No
JJ	Autoxfmr	CB-2ϕA&B	No
KK	Autoxfmr	CB-2ϕB&C	Yes
LL	Autoxfmr	CB-2ϕC&A	No

Table VII. Electrical Hazards Summary - when Ground Fault Current Does Not Flow

The analysis of the laboratory tests indicate there are situations that can be hazardous to personnel, when a grounded phase condition exists without ground fault current flowing.

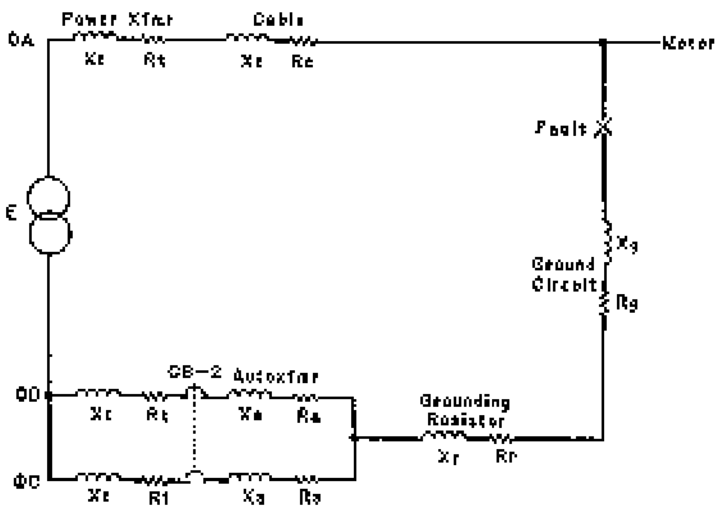

Figure 3. Impedance Diagram - Ground Fault at Motor with CB-2 Open

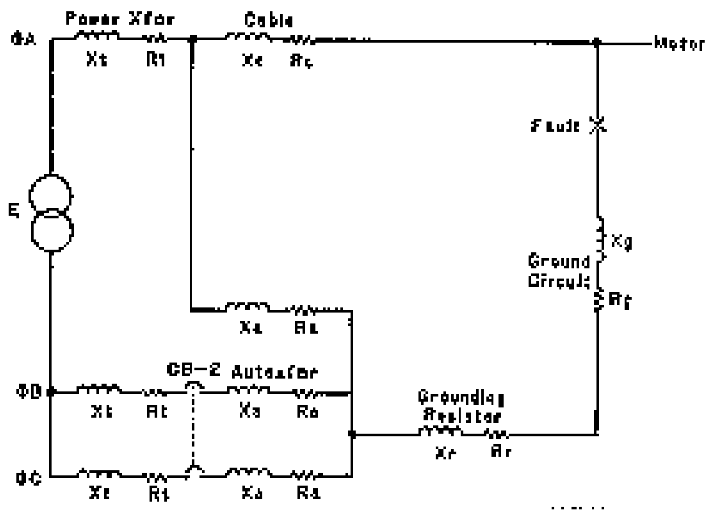

Figure 4. Impedance Diagram - Ground Fault at Motor
with CB-2, Phase B & C Open

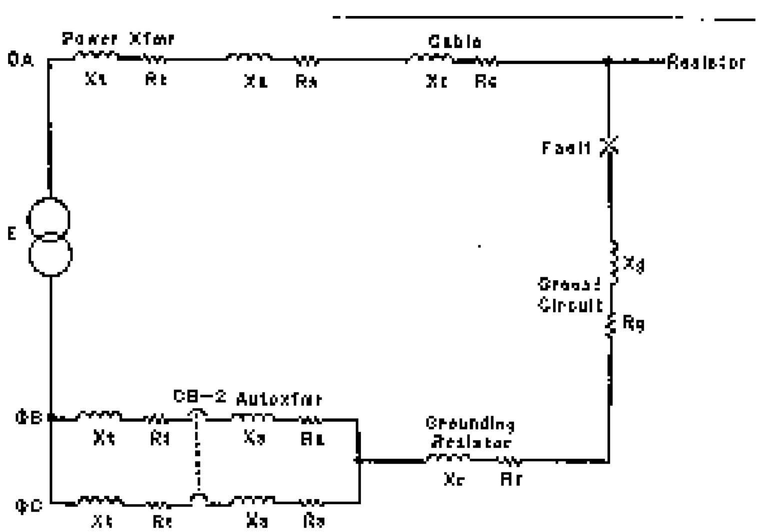

Figure 5. Impedance Diagram - Ground Fault at Resistor
Load with CB-2, Phase B & C Open

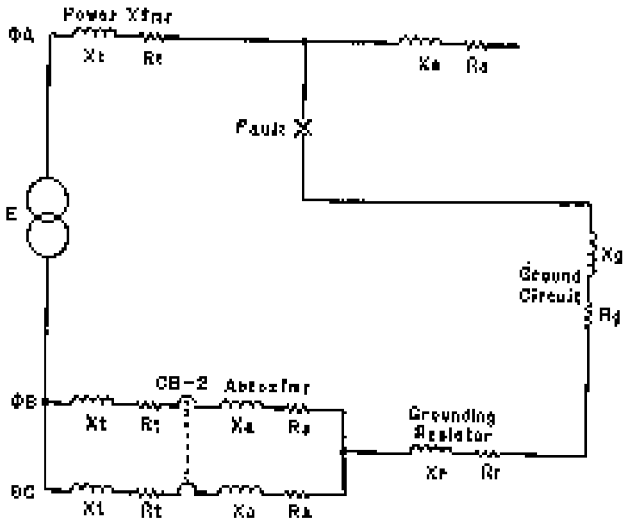

Figure 6. Impedance Diagram - Ground Fault at
Autotransformer with CB-2, Phase B & C Open

CONCLUSIONS

The laboratory testing of the autotransformer connections to the secondary of a step-down isolation power transformer indicate that ground current will flow when certain conditions are present. As expected, the path of ground fault current will flow through the grounding conductor and the neutral grounding resistor. The current distribution through the autotransformer was present in all phases except the phase that was faulted or open. Finally, the fault current at the secondary windings of the power transformer was distributed through the ungrounded phases.

Ground fault current will not flow when unique conditions occur in the autotransformer circuit. The opening of a line fuse or a circuit breaker can isolate fault current from the secondary winding of the power transformer. This was evident by the test results which list four conditions that were considered hazardous. In each case the input lead to the autotransformer was opened. When ground faults did occur, the current path was through the autotransformer. A fuse placed in the autotransformer input was equivalent to fusing a ground wire. Protecting the autotransformer against short-circuits and overloads is needed, but, overcurrent devices should not be placed in the input to the autotransformer unless all secondary output feeders from the power center are opened simultaneously. One way this can be accomplished is by using a three phase circuit interrupter in the power transformer output, with an undervoltage release energized from the autotransformer output. When a ground fault causes the input to the autotransformer to open, power to all secondary loads would then be interrupted.

Also, the higher short-circuit currents associated with an autotransformer could cause a winding of termination to open and again prevent ground fault current from flowing. In addition to blocking ground fault current, an open winding in the autotransformer will force the voltage of the power transformer output onto the autotransformer output. This can result in an increase or decrease in voltage and effect the insulation rating of the power center. An increase in voltage could overstress the power center insulation. Therefore, the insulation rating of the power center should be based on the highest secondary output voltage of the power center. Unfortunately, this does not solve the problem with connecting receptacle and cables loads. Any load rated for the normal autotransformer circuit voltage could be connected. An open circuit in the autotransformer windings could impose a higher voltage on the load. This in turn, could cause the insulation of the cable or motor to breakdown and create a shock hazard.

Therefore, all autotransformer applications should use the voltage increasing scheme. An open winding would result in a lower voltage output and will not exceed the insulation rating of the cable or load.

As previously discussed, autotransformers can supply a second voltage to power the section mining equipment. They can be used efficiently and safely when properly applied. The key to their safe use is to eliminate any hazards created when abnormal conditions occur. The need for maintaining the integrity of the autotransformer an dits connection to the power transformer secondary is critical for their safe use in the mining environment. With proper design and maintenance, autotransformers can safely be used in the mining community.

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