# ANALYSIS OF A DC-TO-FRAME FAULT ON AN AC/DC SHUTTLE CAR

by

Arlie B. Massey, Stefan E. Gawel and John M. Mesina

U.S. Department of Labor
Mine Safety and Health Administration
Approval and Certification Center
Triadelphia, West Virginia.

Abstract An Investigation was conducted to determine electrical behavior when a dc-to-frame ground fault occurs on the secondary side of au AC/DC shuffle car which utilizes an auto-transformer fed SCR package and an SCR drive for the traction motors. Ten different ground wire devices from five manufacturers and eight sizes of neutral ground resistors were used during testing. Fault voltage and current data were recorded at low and high tramming speeds and at locked rotor. Harmonic analysis of the fault signals revealed that the 180 Hz signal of the SCR drive produced the major portion of the fault current and voltage drop across the ground wire device. A simplified equivalent circuit describing the electrical fault was derived. A series L-C circuit (notch fi1ter), resonant at 180 Hz was fabricated and placed across each of the ground wire devices to determine if the filter would simultaneously reduce frame-to-ground fault voltage and increase the total current flow to enhance ground fault detection capabilities. This paper presents the findings of this investigation.

## I. INTRODUCTION

The Approval and Certification Center (A&CC) was alerted to a shock problem by Mr. Terrance Dinkel [1], in which a maintenance worker was shocked while troubleshooting an AC/DC shuffle ear. The machine utilized dc traction motors controlled by SCR drives which were supplied power through an auto-transformer. The machine involved had been blocked and the traction motors were being operated for trouble shooting purposes. A report provided to the A&CC included an analysis in which the waveform of the fault voltage its generating mechanism and pertinent machine electrical parameters were estimated.

*The* A&CC performed an analysis *[2] based* on the fault waveform and circuit parameters obtained from Mr. Dinkel memorandum. The results indicated that the current levels did not constitute a hazard to mining personnel. However, the calculated touch potential and body cm-rent levels exceeded the 0.5 mA rms perception level for 60 Hz current. Therefore, a detailed investigation into the exact nature of the fault and possible means for resolving the. situation was nndertaken.

## II. TECHNICAL APPROACH

Because of the unavailability of the specific shuttle car, all field tests were conducted on two AC/DC machines obtained for this purpose. The testing was conducted at a rebuild facility capable of providing a mine duty power cinder. The shuttle cam chosen uilize similar circuitry for the SCR traction drives as the machine involved in the incident. The test circuit used for the field tests is shown in Figure 1.

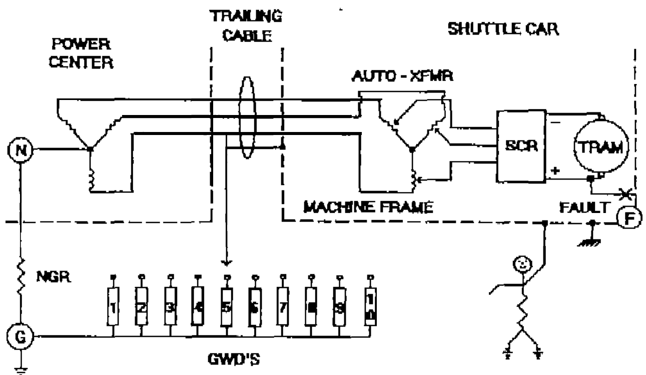


**Figure 1. Test circuit for field trials.**

Eight separate values of neutral grounding resistors (NGRs) and ten inductive type ground wire devices (GWDS) were used during testing. The shuttle cars were isolated from all earth return paths and voltage measurements with respect to time were recorded during simulated low and high speed tramming and locked rotor for fault and no fault conditions. The measurements were taken from the grounded side of the

NGR to the shuttle car frame to the load side of the GWD and to the power center transformer neutral.

Laboratory tests were performed at the A&CC High Voltage Power Laboratory. These tests were conducted to determine the electrical characteristics of the GWDs while subjected to a combination of both ac and dc currents. AU field and laboratory measurements were recorded on magnetic media using a Nicolet Model 4094 Oscilloscope and cross checked using a Hewlett Packard Model 3478A (true rms) digital multimeter. The test instruments were isolated from power system ground by isolation transformers. The data obtained were translated to an IBM ASCII text file format using a program called VU-Petit (Version 1,2) for later Fourier and computer analysis.

## III. DISCUSSION

Data from the laboratory and field tests were organized and analyzed in an attempt to define an equivalent circuit for the dc-to-frame ground fault.

### A. Field Trial 1

Data recorded during field trial #1 revealed that the fault voltage waveforms were a mixture of dc and multiple harmonics of 60 Hz. Figure 2 shows the frame to neutral harmonics during the fault.

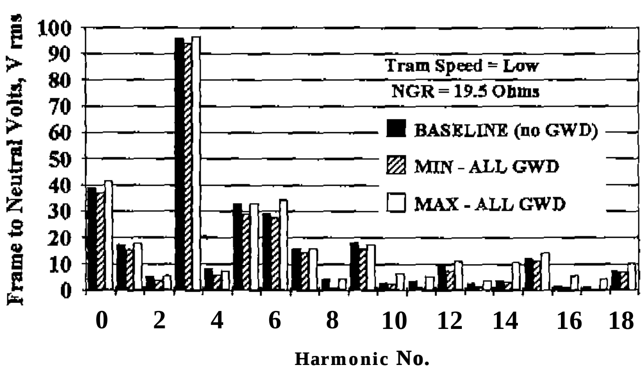


**Figure 2. Frame to neutral voltage in dc to frame fault**

Fault voltage measurements further revealed that the frame-to-ground (FTG) fault voltage was essentially equal to the GWD-in-ground voltage (See Figure 3) and that the fault voltages at low (L) speeds were much larger than at high (H) speeds (See Figure 4). As a result the analysis concentrated on low speed trammming conditions.

Fourier analyses conducted on the low speed steady state voltage waveforms showed that the major portion of the cm-rent and voltage across the GWDs was 180 Hz (See Figures 5a and 5b).

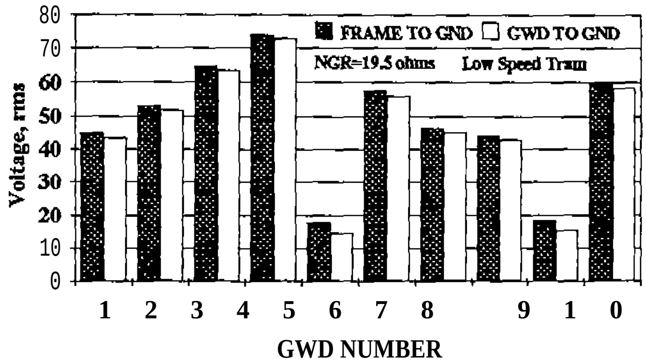


**Figure 3. Comparison of fault voltages.**

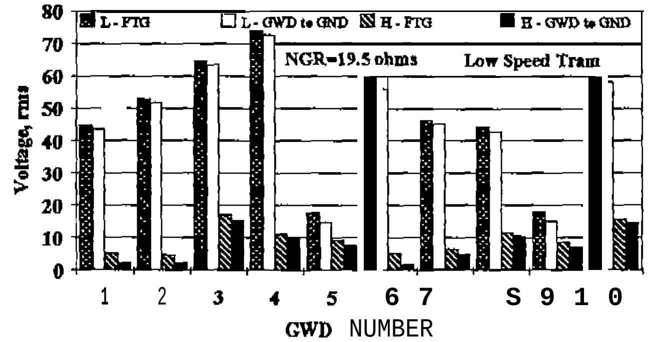


Figure 4. Low/high speed **frame/GWD to** ground fault **voltages.**

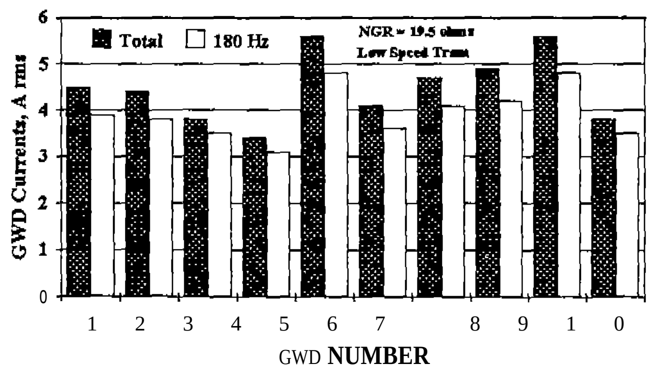


**Figure 5a. GWD 180 Hz and total voltages.**

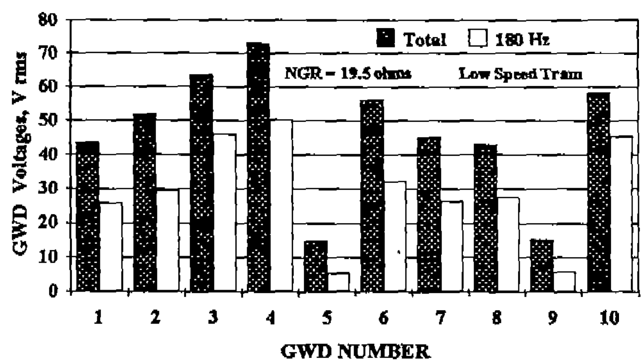


**Figure 5b. GWD 180 Hz and total currents.**

Figure 5a shows that the 180 Hz voltage was never less than 55 percent of the total voltage for eight of ten GWD's Figure 5b shows that the 180 Hz current was never less than 83 percent of the total current.

*1) Simplified Equivalent Fault Circuit:* In addition to the measurements with a GWD in the circuit "baseline" (without GWD) data,were recognized using a 19.5 and a 71.19 ohm NGR. The baseline data were used to derive a 3rd harmonic Thevenin equivalent circuit for the fault source (i.e. "ideal" dc and ac voltage generators in series with an internal resistance and reactance). Figure 6 shows the 180 Hz fault source $V_{fn}$ above the terminals N (neutral) and F (flame ground).

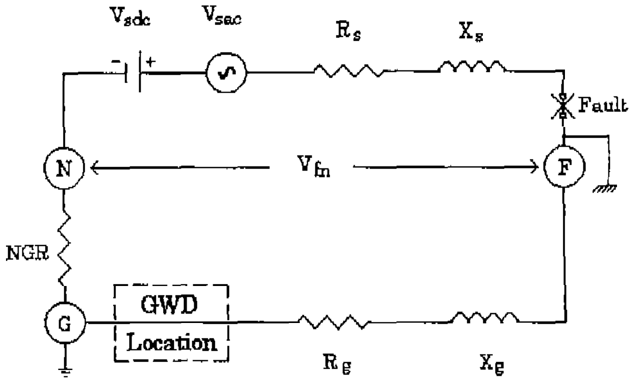


***Figure 6.*** **Simplified equivalent circuit.**

Figure 7 shows how $V_{fn}$ typically appears with and without a GWD in the circuit. For comparison the GWD's effect on the frame-to-ground fault voltage is shown in Figure 8. The prominence of the 180 Hz component is evident from Figures 2,7 and 8.

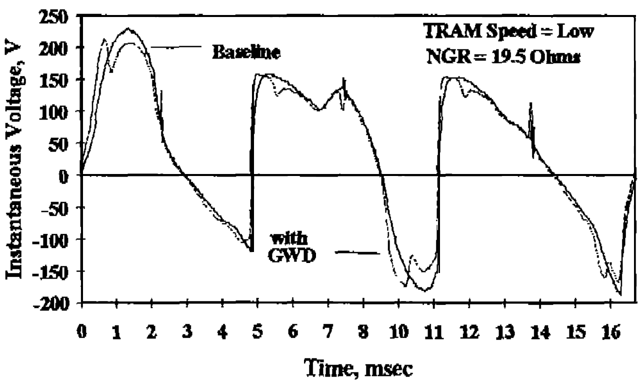


**Figure 7. Frame to neutral fault voltage.**

The rms voltage and current values for dc and 3rd harmonic of the baseline fault voltage were used to calculate the dc voltage and 180 Hz parameters of the equivalent circuit They are: $V_{sdc}$ = 40.1 V dc $V_{sac}$ = 100.0 V rms; $R_s$ = 0.59 ohms; $X_s$ = 3.6 ohms. For the 500 ft. #5 AWG ground conductor: $R_g$= 0.2 ohms; $X_g$ = 0.019 ohms. It should be noted that $R_g$, $R_s$, $X_g$ and $X_s$ are assumed to be current independent for the calculations.

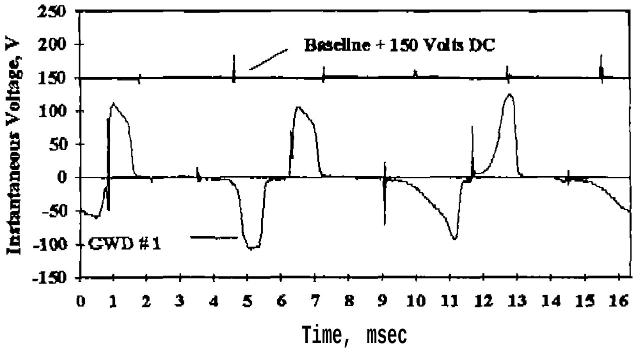


Figure 8. Frame to ground waveforms - with and w/out GWD; low tram speed NGR = 19.5 Ohms.

2) *Characterizing the GWDS:* To enable use of the simplified equivalent circuit the GWD parameters at the frequency of interese (180 Hz) must be placed in series with R and $X_g$ of the ground conductor (See Figure 6). Since the dc resistance of each GWD is only a few milliohms, it was ignored. The pertinent GWD parameters are its 180 Hz resistance, Rae, and its 180 Hz reactance, X. A Fourier analyses of the GWD voltages and currents includes the phase angle, P. If the same time internal is analyzed for both current and voltage Rac and X can be calculated from the Fourier coefficient Figure 9 shows the relationship between the impedance ac resistance inductance and phase angle as the dc and 180 Hz current increases.

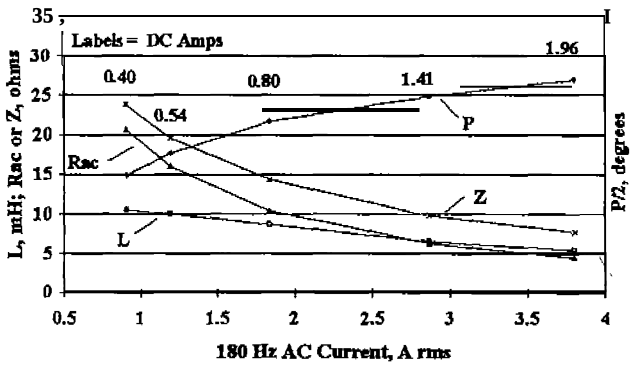


**Figure 9. 180 Hz characteristics GWD #2, field trial I.**

*Note* that the phase angle (P), ac resistance (Rac), inductance (L) and impedance (Z) all vary with the combined magnitude of dc and 180 Hz currents. Although not shown in Figure 9, these parameters also vary with frequency. A comparison of Figures 9 and 10 reveals the effect of frequency on the ac resistance. At 0.90 amps, 180 Hz (leftmost point on Fig. 9} Rac of the GWD is 20.7 ohms while at 0.81 amps, 60 Hz (rightmost point on Fig. 10) Rac is only 0.91 ohms.

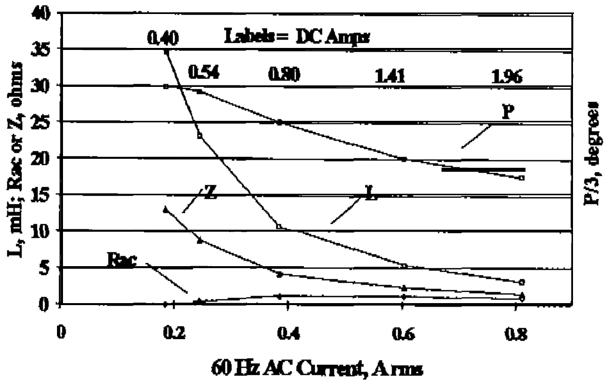


Figure 10. 60 Hz Characteristics - GWD #2, field trial 1.

3) *Testing the Simplified Equivilent Circuit:* The third harmonic equivalent circuit maybe tested to learn how closely the voltages and currents calculated using the circuit approach the actual *total* voltages and currents. Using values from Figure 9 at the maximum current point (where $I_{dc}$ = 1.96 A dc, $I_{ac}$ (180 Hz) = 3.80 A rms, Rac = 4.57 Ohms and L = 5.6 mH for which X = 6.30 ohms) and the source and ground wire parameters cited following Figure 7, calculation yields $I_{dc}$ = 1.98 A dc $I_{ac}$ = 3.74 A rms and frame to ground fault voltage = 29.6 V rms.

Calculating the resultant of the dc and 180 Hz currents yields 4.2 A rms versus 4.4 A rms for the measured total value. This is an error of -4.5 percent Thus calculations from the equivalent circuit closely approximated the 180 Hz (3.74 VS. 3.80) and total (4.2 vs. 4.4) rms values of currents through the GWD. However, the circuit did not adequately approximate the total flame-to-ground voltage; compare the calculated 29.6 V rms (which is accurate for 180 Hz) versus the measured total 53.1 V rms. It should be noted that a worst case estimate of the total voltage may be obtained by dividing the calculated 180 Hz voltage (29.6) by the least voltage ratio of 180 Hz to total (0.55). The result for this example is 53.8 V rms versus 53.1 actual.

## B. Laboratory Measurements

***1) Harmonic Distribution Influence on GWD Parameters:*** The Rac and X parameters were also measured in the laboratory at 60 Hz and 180 Hz with and WithOut injected dc current for the low-voltage *GWDs* only (# 2,6,7, and 8). Figures 11 and 12 are plOtS of the inductance L and Rac versus 180 Hz current calculated from GWD #2 laboratory data

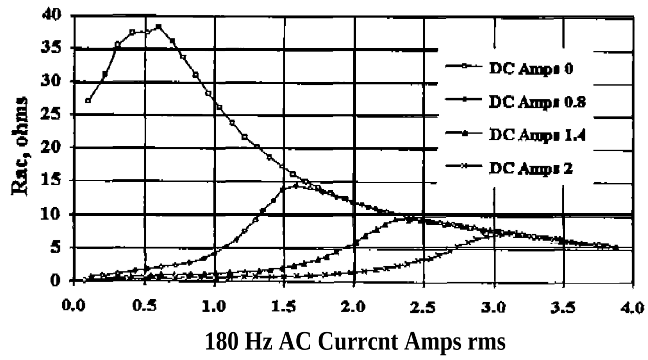


**Figure** 11. **AC and dc current effect on 180 Hz resiatance - GWD** #2.

Similar **type** results were obtained at 60 Hz for all the GWDs tested. Comparing the data from Figure 9 to Figures 11 and 12 reveals that Rac and X values differ significantly for the same values of dc and 180 Hz currents. For example at the end points where the dc current was 1.99 Amps in the laboratory versus 1.% Amps during field Trial 1, Rac was 5.7 ohms in the laboratory while only 4.7 ohms in field Trial 1. At the same points, X was 7.98 ohms from the laboratory data, but only 6.30 ohms in field Trial 1. The only essential difference between field Trial 1 data and the laboratory data is the frequency distribution of the sources.

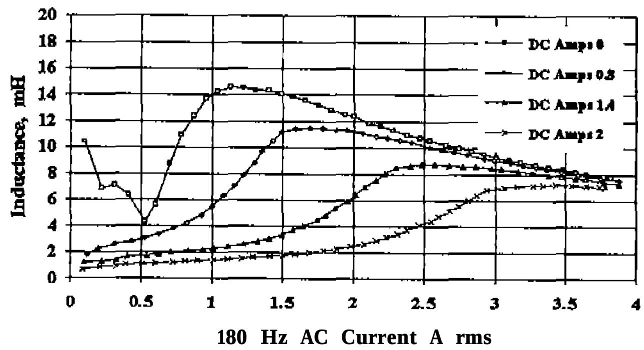


Figure 12. AC and dc current effect on 180 Hz inductance - GWD #2.

It can also be shown from Figures 11, 12, 13, and 14 that at low value of ac current the presence of dc current reduces both the GWD'S inductance and Rac. It follows that should a dc-to-frame fault go undetected, induced 60 Hz currents will not be as limited as when the fault is not present. Furthermore, when **two machines** come in contact and a dc-to-frame ground fault exists, the fault current adds to the induced current and a more energetic intermachine arc ([3], [4], [5]) may occur when the machines separate.

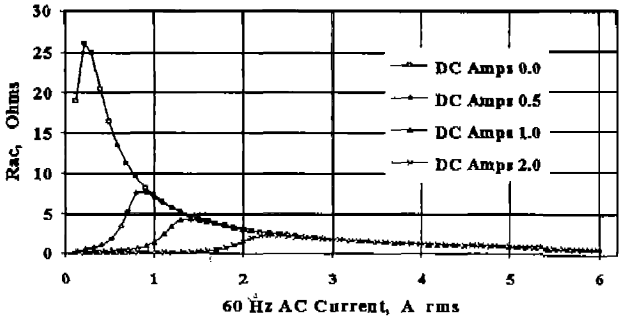


**Figure 13. DC current effect on 60 Hz resistance, GWD #2.**

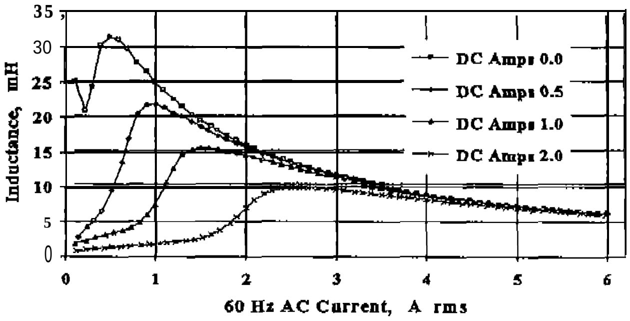


**Figure 14. DC current effect on 60 Hz inductance, GWD #2.**

C. **Follow-up from Field Trial 1 and Laboratory Tests**

***1) The Notch Filter:*** **Analyses** of field Trial 1 and laboratory data pointed to a possible means for reducing the frame-to-ground fault voltage while simultaneously improving the detectability of the fault It appeared that a series resonant (notch filter) circuit, sharply tuned to 180 Hz, placed in parallel with the GWD would increase the total ground wire current, while simultaneously decreasing the fault voltage between the machine. frame and ground- The assumption here is that the induced ground wire current of concern to intermachine arcing is essentially 60 Hz and practically devoid of 180 Hz current. Sharp 180 Hz tuning is necessary to mininmize reducing the 60 Hz impedance of the GWD. Lack of such sharp tuning will tend to negate the GWD's ability to suppress intermachine arcing resulting from induced 60 Hz currents. Sharp tuning 19 also necessary for effective performance of GWDs with respect to ground wire monitor signals.

**D.** Field Trial 2

A second field trial was needed to validate the assumption that the induced ground wire current is essentially 60 Hz and devoid of 180 Hz. **A form of notch filter was constructed by wiring a *780* microfarad** capacitor in series with GWD #9. GWD #9 provided **the** 1 mH inductance necessary (along with the capacitor) to obtain the 180 Hz resonance. Plots of the 60 Hz and 180 Hz inductance for GWD #9 versus 60 Hz and 180 Hz currents, as measured from Trial 1 data are shown in Figure 15. Note that unlike the variable 60 Hz inductance the 180 Hz inductance remains relatively constant at about 1 mH m spite of the combined ac and dc currents.

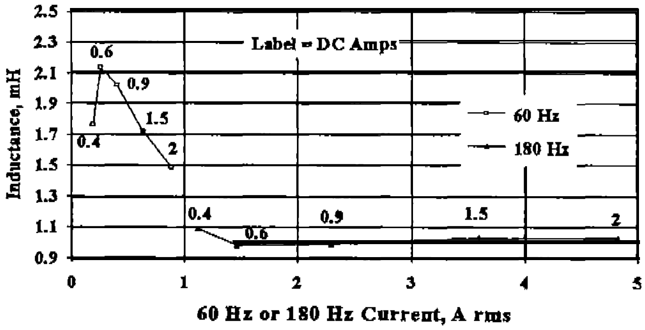


**Figure 15. GWD #9 characteristics -field trial 1.**

Comparing the frame-to-ground voltages and currents measured during a dc-to-frame fault with and without the notch filter for locked rotor and low speed conditions verified that the filter reduced the fault voltage magnitudes while increasing the total ground wire current Figures 16 and 17 show the low speed case.

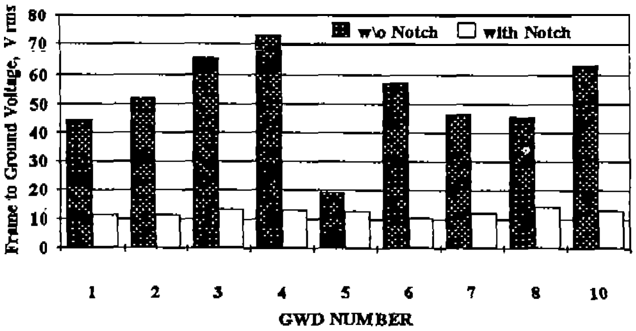


**Figure 16. Notch filter effect on fault voltage at low Speed; NGR = 18.19 0hms.**

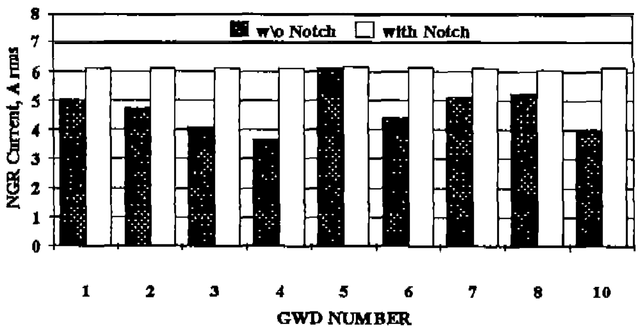


**Figure 17. Notch filter effect on NGR fault current at low speed; NGR = 18.19 ohms.**

This alone does not demonstrate the frequency selectivity of the notch filter, since a resistor in parallel with the GWDs would also decrease fault voltage and increase the current. Figure 18 (which is for (HVD #2 only but which is typical) reveals that the 180 Hz signal is treated selectively. The selectivity is not as good as desired for frequencies above 180 Hz but the 21:1 reduction of the 180 Hz frame potential is good.

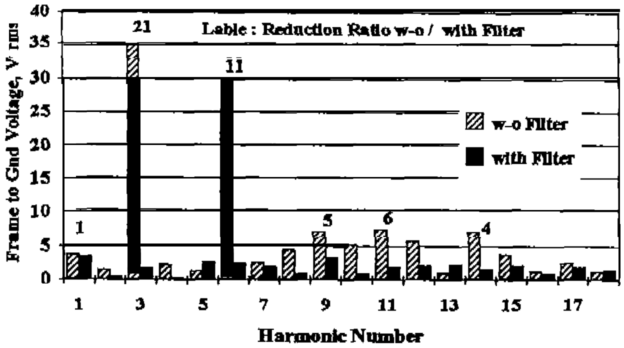


**Figure 18. Notch filter effect GWD #2; locked rotor; NCR = 18.19 Ohms.**

The other task planned for the second field trial was to measure the harmonic distribution of the voltage induced in the ground wire. If induced currents flowing in the ground wire contained a significant portion of the third harmonic (180 Hz), then the notch filter concept would reduce the GWD's effectiveness as an intermachine arc suppressor. The voltage was measured between the machine’s frame and ground without any fault present- Figure 19 shows the frequency distribution of this voltage. This distribution shows that the amount of 180 Hz present is small compared to the 60 Hz component.

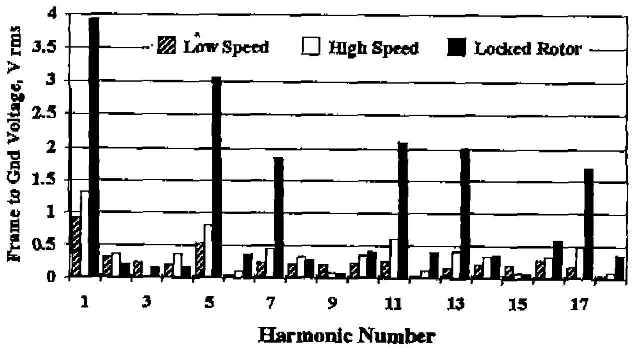


**Figure 19. Open circuit induced voltage harmonic distribution.**

**E. Shock Potential Analysis**

*1)* ***Calculations to Determine the Degree of Hazard:*** Tests performed during this investigation clearly demonstrate that the major portion of the shock potential reported is 180 Hz The path for fault current flow is through the auto-transformer which feeds the SCR package. The worst case frame-to-ground voltage recorded during testing was 74 V rms total for GWD #4. A Fourier analysis of this voltage reveals that 0.23 volts is dc, 1.64 volts is 60 Hz and 50.34 volts is 180 Hz. Currents slightly above the perception threshold may cause injury as a result of the startle reaction. However, more important is the degree of hazard of the frame-to-ground voltage as a shock potential. Since the 180 Hz component is large compared to the dc and 60 Hz it will be assumed for calculation purposes that the shock experienced is comprised entirely of the 180 Hz If a conservative body resistance of 500 ohms is assumed, the calcualted 180 Hz current through the body is 101 milliamperes.

Based on work performed by Dalziel [6], the current-time formula for lethal shock at 60 Hz is

$$I = (116 \text{ to } 185) / \sqrt{t}$$

**where I = current in milliamperes,**

**and t = time in seconds**

which is applicable within the range of 0.008 to 5.0 seconds. The equation is also applicable to 180 Hz. Solving this equation for t, during 116 in the numerator (for a 110 pound person), shows that the person must be in contact with the faulted frame for a period exceeding 1.31 seconds . A more reasonable value of body resistance is 1000 ohms which would further reduce the current to approximately 51 milliamperes. This requires the 110 pound person to be **in contact for over** 5 seconds. Berstein [7] identifies 50 mA as a safe current level for durations longer than 2 seconds.

**IV. Conclusion**

Several methods have been identified which minimize the magnitude and time duration of dc to frame shock potential on thse types of equipment:

1. Utilize a ground fault detection system to detect the current and trip a circuit breaker (either on-board the machine or the power tatter) which deenergizes the faulted circuit;
2. Replace the inductive type GWDs with diode type GWD's (in some applications other factors may render this an impractical solution);
3. Install a properly designed 180 Hz notch filter across the inductive type GWDs.

To adequately demonstrate that the notch filter concept is an across-the-board solution, an evaluation of induced currents is required on a variety of mining industry trailing cables.

Replacing the auto-transformer with a double wound (isolating type) transformer eliminates the path for fault current flow and therefore eliminates the continuous dc to frame fault shock potential entirely. Replacing the auto-transformer on present equipment may not be practical because of space limitations.

Each of these methods should be thoroughly examined to determine the best solution for each situation However, the goal in all cases is to repair the fault condition.

## V. RECOMMENDATIONS

It is recommended that de-to-frame ground faults not be permitted to exist on the frames of equipment Regardless of the method chosen to detect the condition, all sources of ground wire fault current should be repaired. Future machine designs should include methods to minimize the occurrence and duration of voltage potentials on the frames of machines with auto-transformer fed SCR drives.

## REFERENCES


1. Dinkel, Terrance Memorandum to Ronald Schell, Frank Delimba and Robert Dalzell October 24, 1990.

2. Klouse, Kenneth P., Memorandum to James K. Oakes, November 14, 1990.

3. West Virginia University, Evaluation and Mitigation of Inductive Interference Problems in Portable Power Cables, NTIS PB-230 972, July, 1973,235 pp.

4. U.S. Patent No. 3,855,501, Thomas L. Agnew, "Multiple Vehicle Spark Elimination System for Explosive Atmospheres", December 17,1974.

5. West Virginia University, Evacuation and Mitigation of Inductive Interference Problems in Portable Power Cables, NTIS PB-246 386, August 1975, 170 pp.

6. Dalziel, C. F. and W. R Lee. Reevaluation of lethal Electric Current. IEEE Trans. and Ind Gen. Appl., V. lGA-4, No. 5, 1968, pp. 467-476.

7. Bernstein Theodore, "Safety Criteria For Intended Or Expected Non-lethal Electrical Shocks", Proceedings of the 1st International Symposium on Electrical Shock Safety Criteria, 1985, Pergamon Press, pp. 283 -293.