Compatibility Between GFCI Breakers and Household Adjustable Speed Drives

Jonathan Kimball
Senior Member, IEEE
Missouri University of Science and Technology
Rolla, MO 65409
kimballjw@mst.edu

Jordan Henry
Student Member, IEEE
Missouri University of Science and Technology
Rolla, MO 65409
jmhyxc@mst.edu

***Abstract*—As manufacturers find more applications for adjustable speed drives (ASDs) in household appliances, ground fault circuit interrupter (GFCI) compatibility becomes crucial. As compared to industrial applications, the GFCI thresholds for residential applications are much lower. This work explores the compatibility issues that arise for a 1.5 hp (1.1 kW) ASD intended for use in a hot tub or spa. The experimental frequency response of a commonly-used GFCI breaker is compared to the common-mode current of a commercially-available ASD. To enhance compatibility, the input filter needs to be changed to reduce capacitance to earth.**

***Index Terms*—adjustable speed drive, ground fault circuit interrupter, electromagnetic compatibility**

I. Introduction

Adjustable speed drive (ASD) technology has matured to the point where residential applications are cost-effective. For example, ASDs are widely available for high-end heating, ventilation, and air-conditioning (HVAC) applications, where they are used for the same reasons as in industrial HVAC systems [1]. A growing application is in hot tubs and spas. Conventional hot tub pumps use fixed-speed or multiple-speed motors. ASDs provide greater user comfort and convenience.

Unfortunately, ASDs present significant challenges in a residential power system. Electromagnetic interference (EMI) concerns require significant filtering on the input lines. Generally, EMI requirements for residential installations [2, 3] are more stringent than for industrial or commercial installations. A second challenge is ground fault circuit interrupter (GFCI) compatibility. While permanently-installed HVAC systems do not require GFCI protection, hot tubs and spas do require GFCIs for personnel safety [4], as do cord-connected appliances used in wet locations.

The US standard for GFCI breakers [5] only specifies performance at 60 Hz. A typical breaker, though, will respond to ground current at other frequencies in some undefined manner. In the following section, experimental determination of GFCI frequency response is discussed. Next, experimental determination of the ground current in a typical ASD is discussed and compared to the GFCI. Finally, a mitigation method is described.

The objective is to ensure that the ASD does not inadvertently trip the GFCI. Previously, GFCI breakers have been tested for their immunity to fast transients [6], such as those typical on the power grid. In the present work, the concern is ground currents at frequencies related to either the input rectifier (harmonics of the line frequency, 60 Hz) or the output bridge (harmonics of the pulsewidth modulation (PWM) frequency, 10 kHz). Although GFCI compatibility is related to the issues that occur in ground fault detection of high-resistance ground systems [7], the problems in a residential application are distinct. The fault current levels are much lower, and the system has a low-resistance ground that is used for EMI purposes.

II. GFCI Frequency Response

To explore compatibility, the first step was to determine the frequency response of a GFCI breaker. Since most equipment that would use an ASD requires permanent wiring, a panel breaker was evaluated, rather than a GFCI outlet. For this project, a Square D HOM120GFIC 20 A breaker was tested. Fig. 1 shows a photograph of a disassembled breaker, and Fig. 2 shows the essential circuit schematic. The circuit that senses ground current and actuates the breaker is unknown, but may use an integrated circuit such as an LM1851 from National Semiconductor, or perhaps an application specific integrated circuit (ASIC).

The circuit has two main subcircuits, power and detection. The power supply derives from the 120 V input and is used both to power the detection subcircuit and to power the actuator. The detection subcircuit uses a current transformer (CT) to detect common-mode current. The CT encloses both the line and neutral conductors that serve the load, but not the

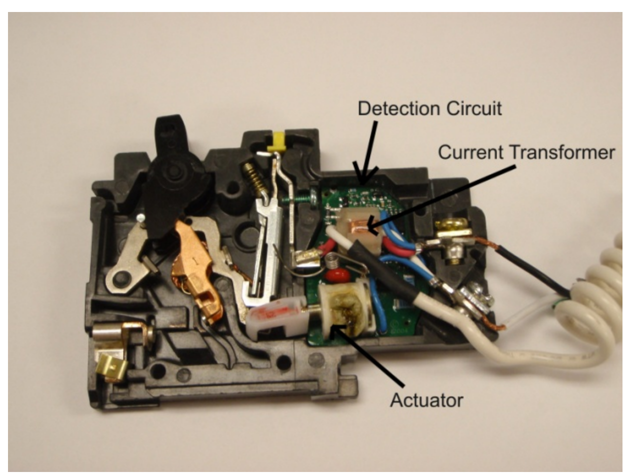

Fig. 1. Disassembled GFCI breaker with key components labeled.

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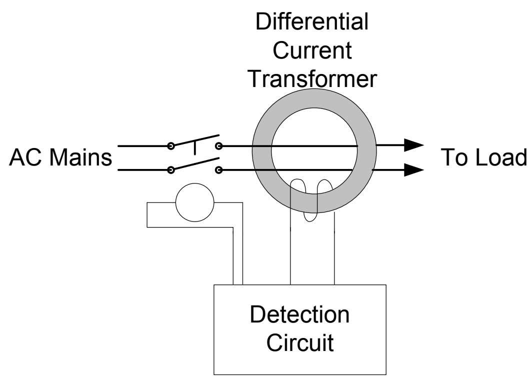

Fig. 2. Conceptual schematic of typical GFCI breaker.

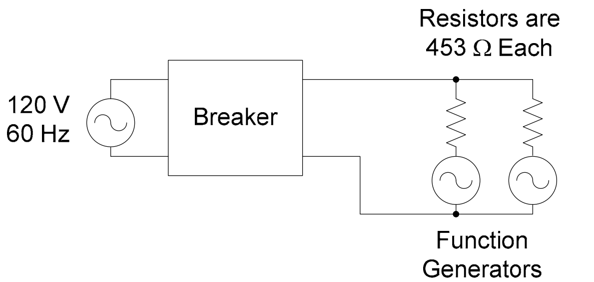

Fig. 3. Schematic of test fixture. Wires were connected so that the imposed current appears as common-mode current.

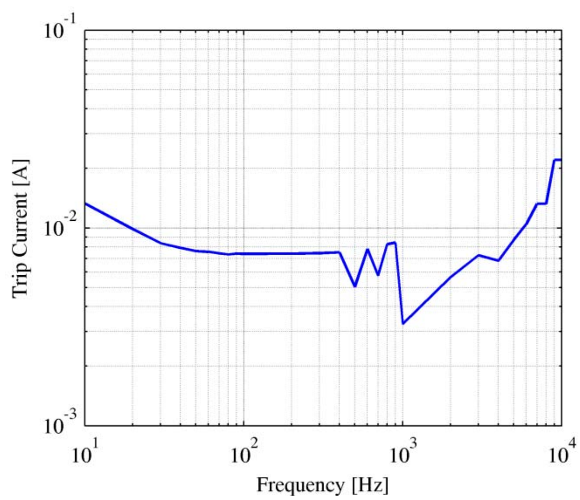

Fig. 4. Trip curve for GFCI with single-frequency current injection.

ground. So, any current the CT senses could be causing a shock hazard. When a ground fault is detected, a solenoid trips the breaker.

Frequency dependence enters the circuit both through the CT and through the sensing circuit. CTs have a natural high-pass filter characteristic due to non-ideal magnetic materials with finite permeability. One would expect the current needed to trip the breaker to increase at low frequencies as the CT's transfer function rolls off. At high frequencies, one

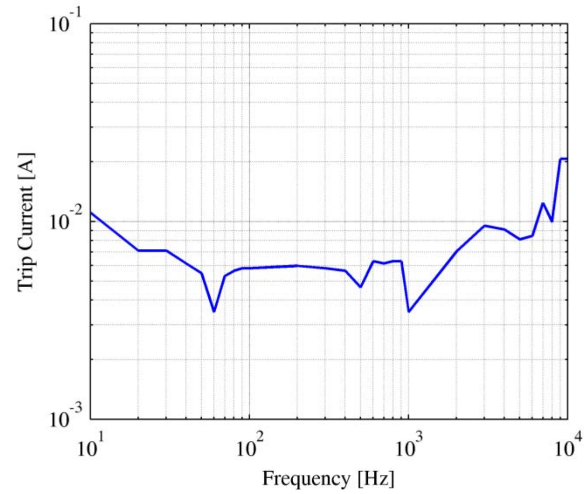

Fig. 5. Breaker trip curve with a baseline of 3.5 mA at 60 Hz, in addition to this injected current.

would expect the threshold to change due to analog or digital filtering in the detection subcircuit.

Since the detection circuit is unknown, the trip threshold was determined experimentally. The breaker's circuitry and actuator were powered with 120 V at 60 Hz from a conventional outlet. A Tektronix AFG3102 function generator with resistive load was used to inject current into the sensing circuit, as shown in Fig. 3. Fig. 3 also shows a second function generator that was used to evaluate the interaction between multiple frequency components (see below). The function generator was set to each of several frequencies, with an initial output level of 0 V. The voltage was gradually increased until the breaker tripped. The voltage was verified with a Tektronix TDS2024 oscilloscope, and the current was calculated from voltage and resistance.

Fig. 4 shows the basic frequency response of the GFCI breaker. Notice the flat response from about 50 Hz to 400 Hz. Below 50 Hz, the increased trip level may be attributed to the high-pass characteristic of the CT. The steep drop at 1 kHz could be a concern for some ASDs with low switching frequencies. Above 10 kHz, the breaker never tripped despite high ground currents (in excess of 20 mA). The increase at low frequency is presumably related to the transfer function of the CT.

Fig. 5 shows the frequency response of the GFCI breaker with an extra 60 Hz component. One function generator was set to supply 3.5 mA at 60 Hz (approximately half of the trip threshold) while the other function generator was swept as before. The only significant interaction occurred at 60 Hz, where the two current sources added up to the same threshold as in Fig. 4. The conclusion is that the controller is nearly linear and reacts to frequency components individually. Compatibility can be determined by comparing individual frequency components of common-mode current to the trip curve of Fig. 4.

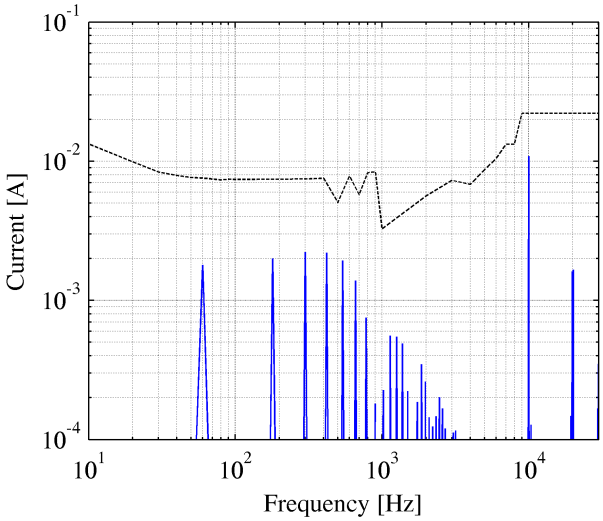

Fig. 5. ASD common-mode current (blue, solid, lower curve) with GFCI trip curve (black, dashed, upper curve)—as originally constructed.

III. ASD Testing and Compatibility

A fast Fourier transform (FFT) of the common-mode current of an ASD is shown in Fig. 5. The common-mode current increases with load, particularly the odd harmonics of the line frequency, so this test was performed under heavy load. Superimposed on Fig. 5 is the breaker trip curve from Fig. 4. All current components are below the trip curve. However, the ASD frequently trips the GFCI during start-up. Presumably, one or more of the frequency components increases transiently and trips the breaker.

The ASD front-end includes a two-stage EMI filter, shown schematically in Fig. 6. According to FCC regulations [3], this device is a class B digital device (marketed for use in a residential environment) and is an unintentional radiator.

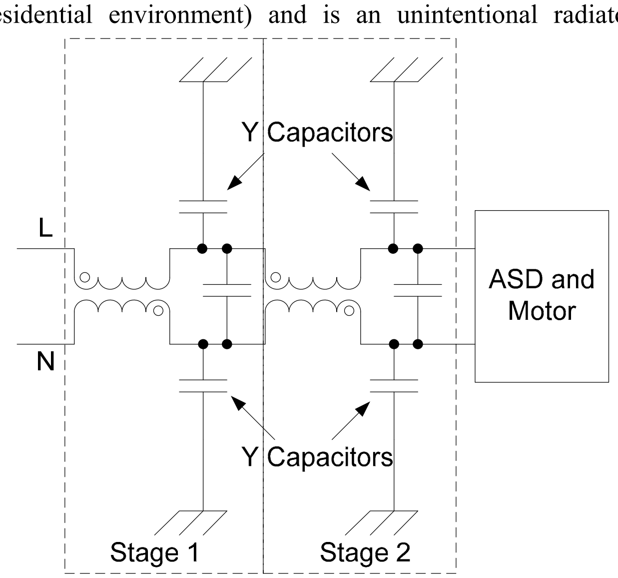

Fig. 6. Simplified schematic of input EMI filter.

Regulations limit the conducted and radiated emissions over a wide frequency range. Radiated emissions may be reduced by a suitable enclosure. Conducted emissions are reduced by a filter of the type shown in Fig. 6. Each stage includes a common-mode choke, an X capacitor (connected line-to-neutral), and two Y capacitors (connected from each live conductor to earth).

A significant fraction of the common-mode current of Fig. 5 results from the EMI filter, so a minor modification is needed. Figs. 7-8 show the common-mode current for two different options: either remove the Y capacitors of the first stage or the Y capacitors of the second stage. In either case, the common-mode current decreases. The change at the line frequency is minimal, but the change at harmonics past the seventh is substantial. Fig. 9 shows all three options—as designed ("factory"), with the first stage Y capacitors removed, and with the second stage Y capacitors removed.

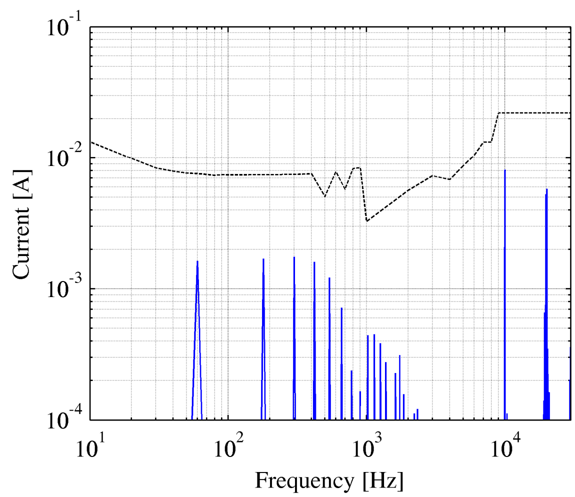

Fig. 7. As in Fig. 5, but with Y capacitors of first stage removed.

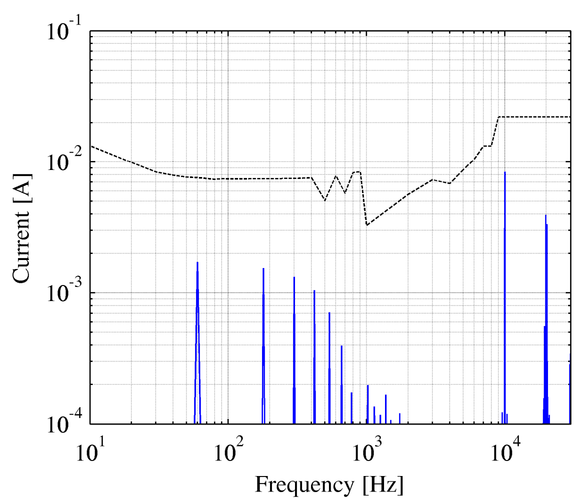

Fig. 8. As in Fig. 5, but with Y capacitors of second stage removed.

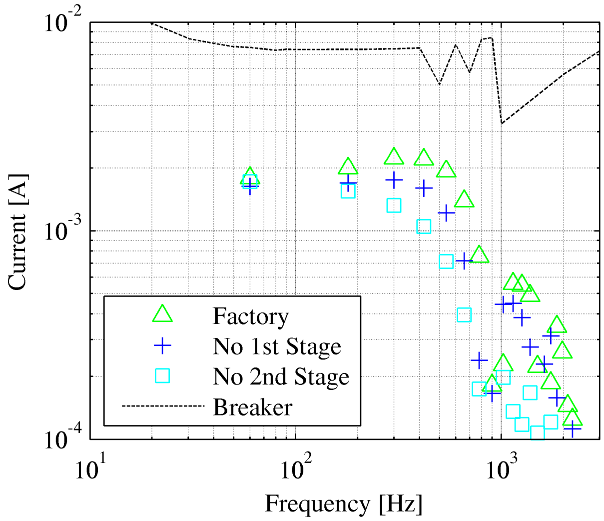

Fig. 9. Comparison of magnitudes of common-mode currents at line harmonics for the three options.

Removing the second stage Y capacitors is marginally preferable.

The conducted emissions of a class B unintentional radiator are restricted for the frequency range of 150 kHz to 30 MHz, as shown in Section 15.107 of [3]. The purpose of the two-stage filter is to mitigate the emissions over this frequency range. Preliminary test results showed that removing the second stage Y capacitors did not measurably increase the emissions over this frequency range. In fact, at frequencies below 1 MHz, the emissions decreased by 2-3 dB when the Y capacitors were removed. Apparently, one stage of common-mode filtering is sufficient and differential-mode emissions dominate. Removing the Y capacitors does not change the differential-mode filtering.

The radiated emissions of a class B unintentional radiator are restricted for the frequency range of 30 MHz to 960 MHz, and beyond, where the EMI filter in question has little impact. Similarly, conducted emissions of an unintentional radiator are unregulated below 150 kHz, where PWM harmonics are significant.

IV. Conclusions

The relationship between EMI compliance and GFCI compatibility was explored for an adjustable-speed drive designed for residential use. A GFCI breaker was tested to find its threshold current over a range of frequencies. The common-mode current of an ASD was measured and compared against the GFCI threshold. Reducing the amount of EMI filtering decreases common-mode current components at the odd harmonics of the line frequency, up to about 2 kHz, and improves GFCI compatibility. Preliminary EMI testing showed that there was no measurable impact on conducted emissions when the second stage Y capacitors were removed.

V. Acknowledgments

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VI. References

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