Littelfuse Startco
SE-701 Ground Fault Monitor
With
Variable Frequency Drive

Test Report

by

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Executive Summary

Littelfuse Startco has conducted witness testing of the SE-701 Ground-Fault Monitor. The SE-701 was tested for use upstream (line side) of a variable-frequency drive (VFD) to verify its ability to detect a ground fault downstream (load side) of the VFD.

The test system included of a 3-phase source connected to a delta-wye transformer. The transformer-secondary neutral was connected to a 200-ohm neutral-grounding resistor. The 480-V three-phase output of the transformer was connected to a VFD which was used to drive a small motor. The transformer-to-VFD connection, VFD-to-motor connection, and neutral-grounding-resistor connection were monitored using SE-701 Ground-Fault Monitors and EFCT-1 Current Transformers. The connection diagram is shown in Fig. 1.

To configure the VFD for the testing, it was necessary to remove or disconnect various phase-to-ground capacitors because they were not rated for line-to-line voltage which is present during a bolted ground fault on a resistance-grounded system. The removal of these capacitors was not in the manual included with the drive; instructions were obtained from the manufacturer's technical support group.

This test shows that an SE-701 at each of the CT locations is capable of detecting a ground fault on the VFD-to-motor connection. Therefore, in VFD applications it is recommended that the CT and SE-701 be located upstream of the drive—this connection will detect a ground fault in the supply cable to the VFD, in the VFD, and downstream of the VFD.

Additional testing was also performed to evaluate the performance of the SE-701 with ground faults of various currents at other locations in the system.

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Introduction

The microprocessor-based SE-701 uses an external zero-sequence current transformer (CT) and selectable DFT or peak-detection algorithms to detect ground-fault current. This testing was completed to verify the ability of the SE-701 to detect a ground fault downstream of a VFD with the CT located upstream of the drive.

The tests were performed at the Littelfuse Startco facility in Saskatoon, Canada.

A test circuit was devised to allow the SE-701 to be tested at several locations in the circuit and under various operating conditions. Testing was done with a variable-resistance ground-fault placed on the drive connection to the motor, at the VFD dc bus, and at the supply transformer-secondary terminals. The tests involved varying the drive output frequency such that a frequency response for the SE-701 could be observed for frequencies up to 60 Hz. Frequencies above 60 Hz were not tested, as the response of the SE-701 peak filter is the same from 60 to above 400 Hz. As frequencies this high are uncommon in industrial applications, testing was deemed unnecessary.

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Background

Test Circuit

The test circuit was a test-bench version of a typical industrial VFD installation, with the addition of ground-fault relays. The circuit was connected as shown in Fig. 1.

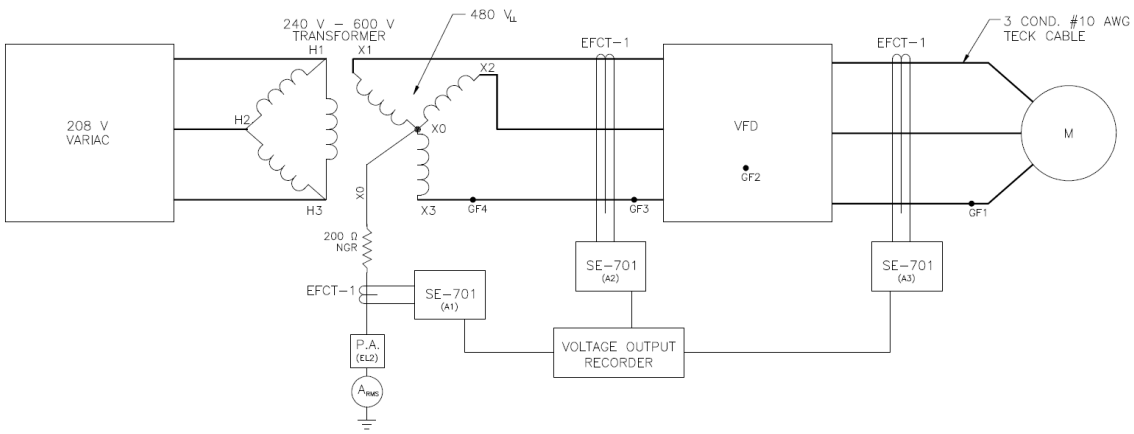

Figure 1. Circuit Schematic

The test circuit included a three-phase variable-voltage ac input, connected to a delta-wye 240:600-V, 3-kVA step-up transformer. Utilizing the variable-voltage input, the transformer was configured for 480-Vac line-to-line at the wye secondary. See Fig.2.

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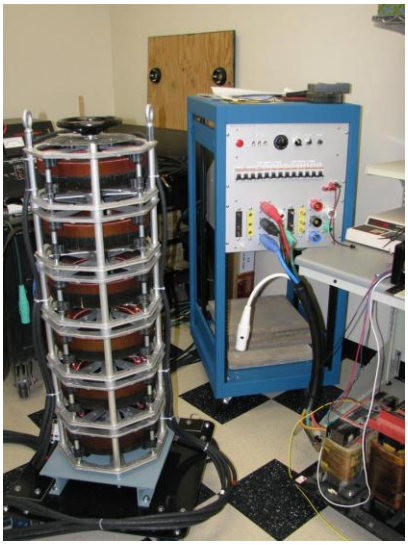

Figure 2. Incoming power supply

The transformer neutral was connected to a 200-ohm neutral-grounding resistor (NGR) in series with a power analyzer and a root-mean-square (RMS) ammeter. This circuit passed through an EFCT-1 zero-sequence current transformer which was connected to an SE-701 Ground-Fault Monitor (analog output A1). See Fig.3.

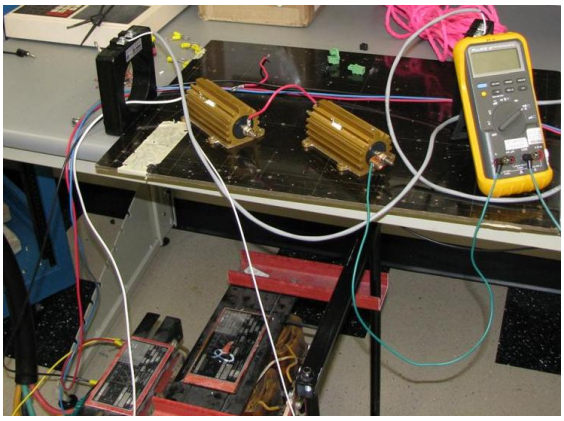

Figure 3. Transformer, NGR, and RMS Ammeter

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The transformer secondary was connected to the VFD. The output of the VFD was connected to 100 feet of 3C#10 Teck cable, which was connected to a ½ hp three-phase motor. The circuits from the transformer to the VFD and the VFD to the motor passed through EFCT-1 zero-sequence current transformers which were connected to SE-701 Ground-Fault monitors (analog outputs A2 and A3). See Fig. 4.

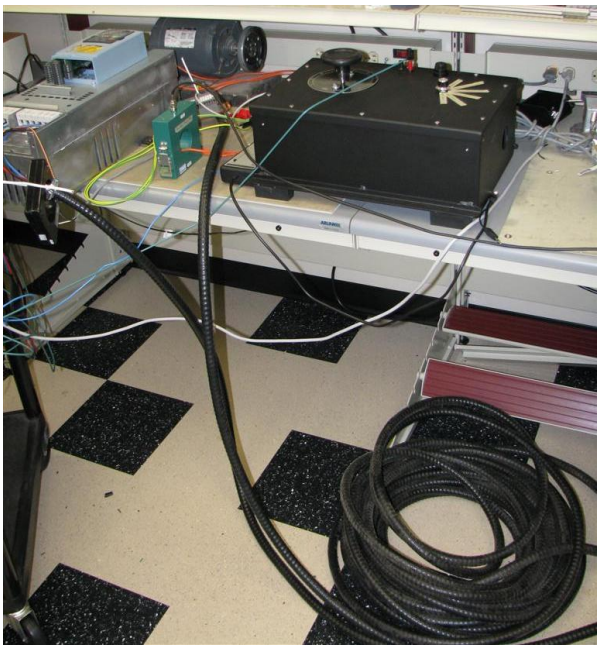

Figure 4. VFD, Teck Cable, Variable Resistor and Motor

Ground-Fault Apparatus

A variable-resistance ground-fault apparatus was used to place a ground-fault on the system. The schematic of the apparatus circuit is shown in Fig.5.

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The apparatus consisted of a variable resistance with a 0 to 2850 ohm range connected in series with a power analyzer and an RMS ammeter. The variable resistance can be comprised of the following components to achieve desired resistance values:

(5) – 470 ohm resistors
(1) – 500 ohm rheostat

One end of the apparatus was connected through a push-button switch to one phase of the power circuit and the other was connected to ground to simulate a ground fault of various resistances. See Figs. 5 and 6. With a line-to-ground voltage of 277 V, this apparatus allowed a ground-fault-current range from 1.385 A using only the NGR to 91 mA with all resistors connected and the rheostat set to 500 ohms.

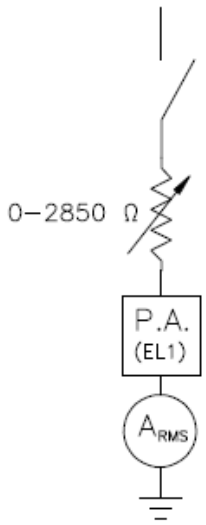

Figure 5. Ground-Fault Apparatus Schematic

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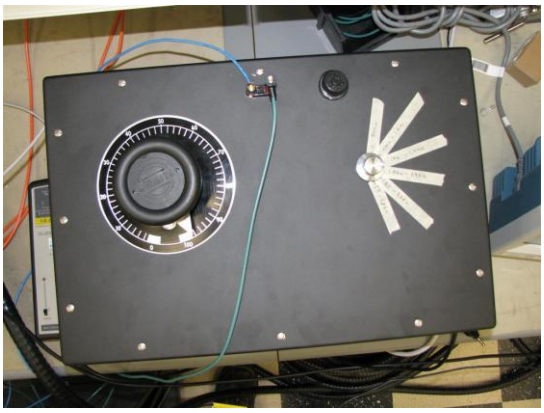

Figure 6. Variable Ground-Fault Resistor

Ground connections for ammeters and motor chassis bond were connected to a ground point on the VFD chassis. The VFD chassis was connected to the building ground, as shown in Figs. 7 and 8.

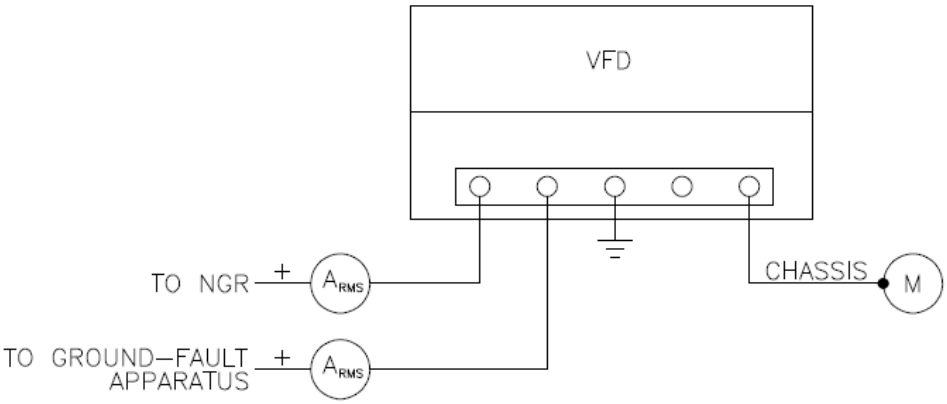

Figure 7. Grounding Diagram

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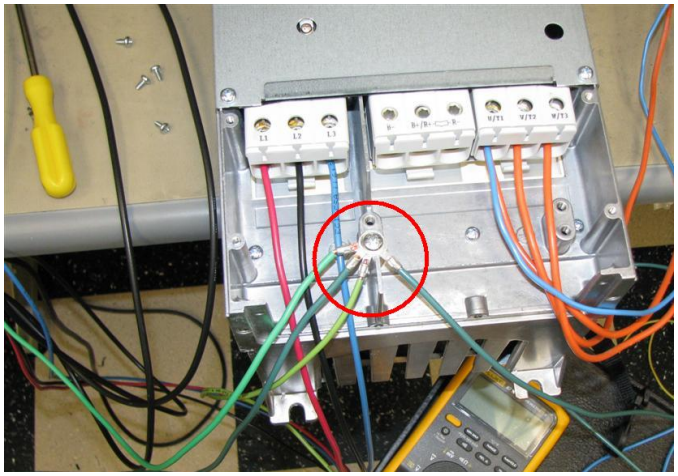

Figure 8. Ground Connections at VFD Chassis

Equipment

The equipment used during the test is listed in Table 1.

Variac	Superior Electric Variable Autotransformer A219111-008
Current Transformers	EFCT-1, 5:0.05-A, 82 mm ID
Transformer	Hammond 240:600V 3kVA Transformer
NGR	Dale RH-250 250 W 100 Ohm Resistor (x2)
Ammeters	Fluke 87, Fluke 87 V
Voltage Output Recorder	HIOKI 8808 Memory HiCorder
Power Analyzer	Yokogawa WT500 Power Analyzer
Motor	Westinghouse FD78 ½ HP 3-Phase Motor
Cable	100 ft 3C#10 TECK
Variable Frequency Drive	480 V 3-Phase 20 HP

Table 1. Equipment List

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Figure 9. Connected Test Circuit

Controllable Variables

In order to simulate the power system and provide valid results, the test circuit was able to simulate a variety of conditions. There were several controllable parameters which are listed in Table 2.

Variables	Settings
Output Frequency of VFD	0 – 320 Hz (0.01 Hz increments)
Ground-Fault Resistance	0 – 2850 Ohms
SE-701 Filter Selection	Fixed or Variable Frequency
SE-701 Trip Level	5 mA – 4.95 A (5 mA increments, 1 – 99%)
Fault location	Upstream or Downstream of VFD, VFD dc bus, and supply-transformer termination.

Table 2. Controllable Test Parameters

Data

In order to analyze the operation of the system, data was collected from the RMS ammeters, power analyzer, and oscilloscope as well as the SE-701 Ground-Fault Monitor trip and analog outputs. This data will verify the ability of an SE-701 to operate correctly in a VFD application.

Procedure

Measurements

Measurements were recorded from the two RMS ammeters and the outputs of the three SE-701 monitors. The SE-701 analog output is a 0-5 V voltage output linearly representing the 0-100% rating of CT-primary current. When connected to an EFCT-1, the analog-output scaling is 1 mV per 1 mA of measured current.

Non-filtered and filtered ground-fault (EL1) and NGR (EL2) currents and voltages were measured by the power analyzer. See Figs 1 and 5. The power analyzer has an internal selectable 500 Hz low-pass filter. Application of the filter was necessary as the unfiltered signals contained large amounts of noise, making waveforms difficult to visualize. This is seen in an example ground-fault with a 1-A fault current at 10-Hz fundamental frequency. See Figs. 10 and 11.

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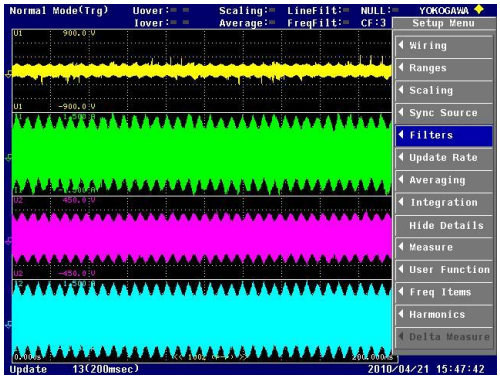

Figure 10. 10 Hz 1 A Fault, wide band

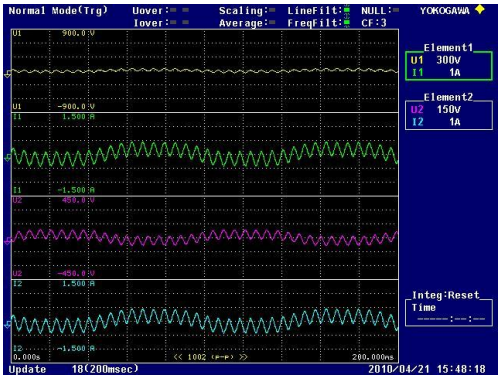

Figure 11. 10 Hz 1 A Fault, 500 Hz Filter

From top to bottom, the waveforms are; line-to-ground voltage, ground-fault current, NGR voltage, and NGR current.

Initial Test

An initial test with the VFD operating at 60 Hz was completed. This test was repeated using both SE-701 fixed frequency (DFT) and variable frequency (peak-detection) filters. A downstream ground fault was applied to the system (point GF1 in Fig.1.) and all three SE-701 Ground-Fault Monitors tripped, with very similar analog-output values as shown in Table 3.

Frequency	Filter Setting	NGR Current (mA)			Fault Current (mA)			SE-701 Analog Output (mV) Load-Side Fault		
		Fluke 87	EL2	EL2 NF	Fluke 87	EL1	EL1 NF	A1	A2	A3
60	DFT	326	254		316	255		251	251	243
60	PEAK	295	247	296	280	247	294	264	268	263

Table 3. Initial Test, Load-Side Fault, 60 Hz

The unfiltered currents measured by the power analyzer, EL2 NF and EL1 NF, are similar to the values of the Fluke RMS meters, while the power analyzer filtered values, EL2 and EL1, are similar to the SE-701 analog output values. The waveforms in Figs. 12 and 13 were captured for the filtered and unfiltered fault currents from the power analyzer.

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It can be seen from the waveform captures that the fault current contains many harmonic components. With the 500 Hz filter applied, a 180-Hz ripple current can be seen superimposed over the 60-Hz drive output. This 180-Hz ripple current was observed in all subsequent tests at various output frequencies.

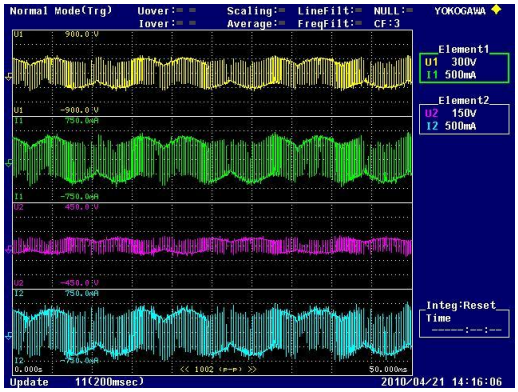

Figure 12. 60 Hz 300 mA Fault, wide-band Filter

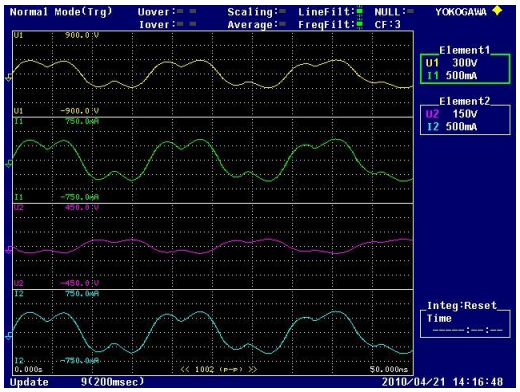

Figure 13. 60 Hz 300 mA Fault, 500 Hz Filter

Variable-Frequency Testing

Tests performed using various frequencies generated by the VFD were completed using both the DFT and peak-detection filters to demonstrate SE-701 performance with each filter when monitoring a system with frequencies within the range of 10 to 60 Hz. In these tests, all three SE-701 monitors were set to trip at 5%, corresponding to a ground-fault current of 250 mA. At the selected frequencies, the fault current was increased until all three SE-701 units tripped; the current values at the trip point were recorded. See Table 4.

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Frequency	Filter Setting	NGR Current (mA)			Fault Current (mA)			SE-701 Analog Output (mV) Load-Side Fault		
		Fluke 87	EL2	EL2 NF	Fluke 87	EL1	EL1 NF	A1	A2	A3
60	DFT	326	254		316	255		251	251	243
50	DFT	375	259	375	364	258	373	260	260	260
40	DFT	537	305	537	513	302	535	270	270	270
30	DFT	760	337	763	735	337	762	330	330	300
25	DFT	945	365	945	910	360	943	340	340	318
20	DFT	For a 1-A fault, trip setting must be 4% (200 mA) to cause a trip.								
10	DFT	For a 1-A fault, trip setting must be 1% (50 mA) to cause a trip.								
60	PEAK	295	247	296	280	247	294	264	268	263
50	PEAK	317	219	318	299	219	315	268	265	253
40	PEAK	371	208	371	353	208	369	268	268	258
30	PEAK	453	202	452	432	202	452	260	260	270
20	PEAK	700	223	699	670	224	696	325	312	312
10	PEAK	1030	224	1030	1000	224	1030	400	400	380

Table 4. Variable-Frequency Tests

Using the 200 ohm NGR, it was not possible to generate a ground-fault current large enough to trip an SE-701 below 20 Hz with the DFT filter selected and the pick-up set to 5% (250 mA). Using a fault current of 1.0 A it was possible to trip the SE-701's with the DFT filter selected, with settings of 4% (200 mA) and 1% (50 mA) for frequencies of 20 Hz and 10 Hz, respectively.

DC Bus Fault Testing

The ability to detect an internal dc-bus fault was tested. The voltage of the bus without a fault applied was first observed and recorded. See Fig. 14. With no fault applied, a 180 Hz ripple voltage can be seen on the bus. This waveform was also found on the negative DC bus.

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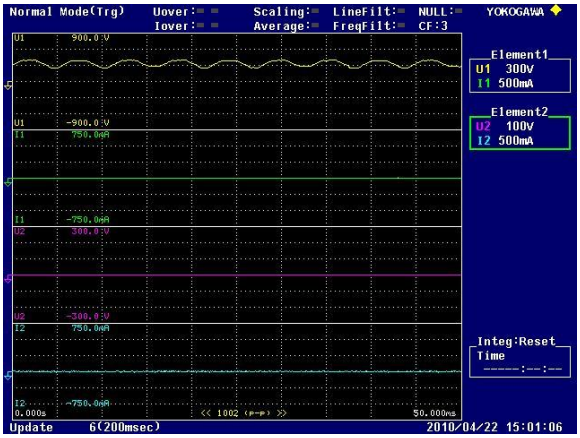

Figure 14. Positive DC Bus to Ground Voltage, No Fault

With a 500 mA fault applied to the negative bus (point GF2 in Fig. 1.) the following waveforms were recorded.

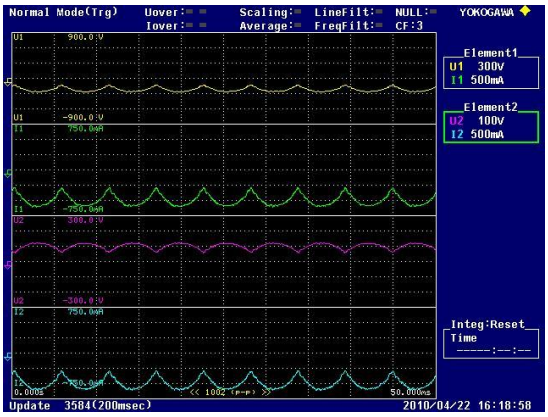

Figure 15. Negative DC Bus 500mA fault

The ripple current is in the fault as well as through the NGR, with a sizeable DC offset. Fault data is shown in Table 5.

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TEST	Filter Setting	NGR Current (mA)		Fault Current (mA)		SE-701 Analog Output (mV)	
		AC	DC	AC	DC	A1	A2
+DC Bus Fault	PEAK	50	273	50	273	70	70
						Trips with 100 mA Setting	
+DC Bus Fault	PEAK	91	500	91	500	108	108
						Trips with 150 mA Setting	
-DC Bus Fault	PEAK	90	-497	90	-497	107	107
						Trips with 150 mA Setting	

Table 5. DC Bus Fault Data

A spectrum analysis of the negative DC bus fault yielded the output shown in Figs. 16 and 17.

Figure 16. Negative DC Bus Harmonics Graph

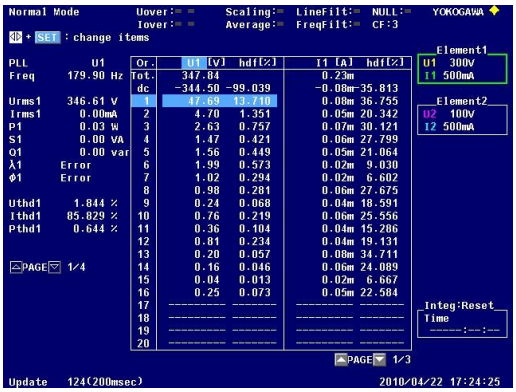

Figure 17. Negative DC Bus Harmonics Data

The 180 Hz component of fault current is 13.7% of the total fault current.

Upstream Fault Testing

This test was performed with a ground fault placed at the input of the drive (point GF3 in Fig.1.). This was done to show that the SE-701 (A1) monitoring the input to the drive as well as the SE-701 (A2) on the NGR would trip and the SE-701 monitoring the drive-to-motor connection would not trip. The trip levels of A1

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and A2 were set to 5% (250 mA) and A3 was set to 1% (50 mA.) Currents were recorded at the point where both A1 and A2 had functioned at each frequency.

Frequency	Filter Setting	SE-701 #1 Measuring NGR Current			SE-701 #2 Measuring GF Current on Input of Drive			SE-701 #3
		NGR Current	Fault Current	A1	NGR Current	Fault Current	A2	A3
		No Fault Outputs, Drive ON.		92			92	74
60	PEAK	249	236	238	258	246	241	81
50	PEAK	251	236	239	259	245	238	80
40	PEAK	252	237	239	260	245	237	73
30	PEAK	251	237	240	259	245	238	80
20	PEAK	252	237	241	258	243	240	77
10	PEAK	253	237	237	262	247	244	76

Table 6. Fault Testing at VFD Input

While A3 shows values of over 50 mV, it did not trip during any of the tests.

The test was then repeated with the fault located upstream of SE-701 A2 (point GF4 in Fig.1). SE-701's A2 and A3 were set to 1% (50 mA), while A1 was set at 5% (250 mA). The ground-fault current was gradually increased until A1 tripped at each frequency.

Frequency	Filter Setting	SE-701 #1 Measuring NGR Current			SE-701 #2	SE-701 #3
		NGR Current	Fault Current	A1	A2	A3
		No Fault Outputs, Drive ON.		92	92	74
60	PEAK	251	238	241	95	80
50	PEAK	252	237	239	91	77
40	PEAK	251	236	240	94	77
30	PEAK	252	237	238	90	80
20	PEAK	252	237	239	91	80
10	PEAK	253	238	239	92	77

Table 7. Fault testing upstream of A2

Regardless of frequency, A1 would trip while A2 and A3 would not.

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Fault Current and Line-Side Leakage

A comparison of the line-side leakage relative to fault current was completed in order to see what affect fault current has on leakage on the line side of the drive. This test was used to simulate a fault upstream of the line feeding the drive. In this test a ground fault was placed at the transformer secondary terminals (point GF4 in Fig. 1.), with varying current and the output of the SE-701 (A2) on the VFD input was recorded. See Table 8.

System Fault Current (mA)	Analog Output of SE-701	
	Min	Max
0	71	90
100	70	93
200	68	81
300	71	97
400	70	96
500	90	112
600	79	113
700	84	116
800	83	124
900	87	106
1000	85	107

Table 8. Upstream Fault Current and SE-701 Output

The SE-701 was set at 50mA and in all cases did not trip.

Analysis

Initial Test Results

The initial test proved the capability of the SE-701 to detect a ground fault located on the load side of a VFD, with a zero-sequence CT located at any of three different positions in the circuit.

The SE-701's monitoring the line side of the VFD, the load side of the VFD and the NGR showed nearly identical outputs. These outputs were very similar to the

ones measured by the power analyzer with the 500 Hz low-pass filter selected. Testing with both DFT and peak filters yielded similar values with the drive output at 60 Hz. It can be seen during the peak-filter test that the current detected by the RMS ammeters is similar to the current measured by the power analyzer with no filter selected; both include all frequencies present in the current signal.

This test has proven that zero-sequence currents on the load side of a VFD are not isolated from the line side of the VFD. The zero-sequence current is equally detectable by an EFCT-1 at the NGR, the VFD line side, and the load side.

Variable-Frequency Results

Testing of the SE-701 at various fault frequencies was completed using both the DFT and peak filter selection of the SE-701. The results show that the bandwidth of the DFT filter is too narrow to be used in VFD applications in which the VFD operates below 50 Hz. The peak filter is a better choice in this type of application—its wider filter bandwidth allows the SE-701 to detect frequencies below 50 Hz. Even with the peak detection filter, frequencies below 50 Hz are attenuated. This frequency response is shown in Fig. 18.

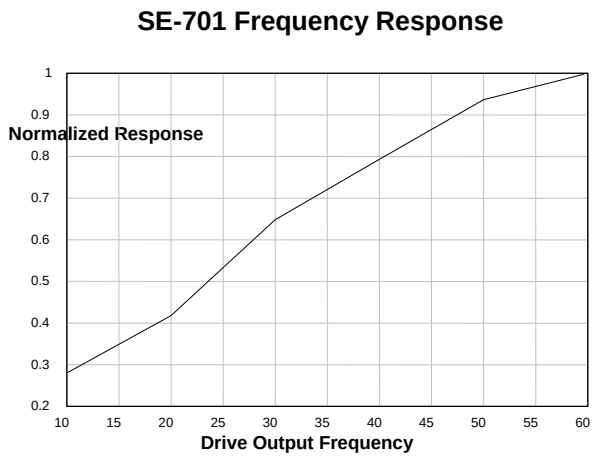

Figure 18. SE-701 Frequency Response, Peak Detection Filter

From Fig. 18 a recommended setting for the SE-701 can be calculated based on the lowest expected operational frequency. This setting can be found by multiplying the desired trip level by the normalized response value at the lowest expected operational frequency.

Recommended setting = (desired trip level) x (response @ lowest frequency)

For instance, if a 1,000-mA RMS trip level is desired and the VFD will be operating at 40 Hz, the recommended SE-701 setting is 1,000 mA x 0.8 = 800 mA, or 16%.

DC Bus Fault Results

When a fault was placed on the VFD DC bus, the fault current had a predominant DC component with a smaller 180 Hz AC component as well as some harmonics of 180 Hz. The 180-Hz component is created by the VFD's full-wave rectifier "front end". A current transformer is unable to detect the DC component of the

fault; however because of the sizeable 180-Hz component, it is possible for an SE-701 to detect this type of fault.

The DC fault spectrum analysis in Fig. 17. shows the 180 Hz amounts to 10-15% of the fault. Therefore, if it is desired to have an SE-701 trip on a DC-bus fault it is recommended that the pickup level be set to 10% of the NGR let-through current. (This assumes that the measured-feeder charging current is less than 10% of the NGR let-through current, or the SE-701 could sympathetic trip when a ground fault occurs elsewhere on the system.)

Upstream Fault Results

When a fault is located upstream of the monitoring EFCT-1, the SE-701 does not trip. This shows that the SE-701 does not detect an upstream fault. The SE-701's which were downstream of the fault were set to their lowest setting of 1%, corresponding to a 50 mA trip level. While it was noticed that the outputs of the SE-701 showed levels of up to 95 mV, the relays did not trip, and this is the desired response.

Fault-Current and Line-Side-Leakage Results

With a ground fault located upstream, a CT measures the charging current of the feeder downstream. This test was performed to determine what affect upstream-fault magnitude has on the measured charging current.

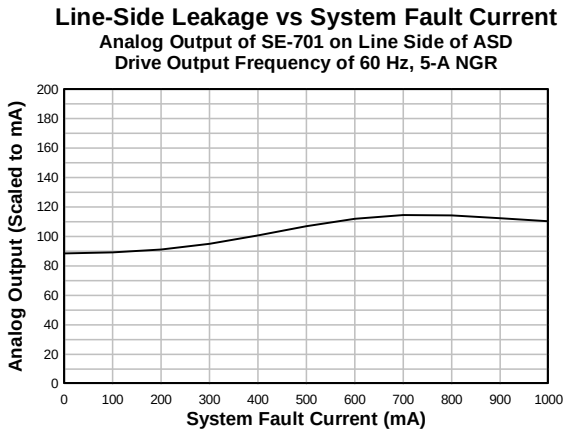

Figure 19. Line-Side Leakage vs System Fault Current

As can be seen in Fig. 19, an increase in upstream fault current has only a very slight effect on the level of charging current. The increase in charging current was not substantial enough to trip an SE-701.

Limitations

As these tests were conducted under lab settings, they were created to best simulate systems in the field. However, it is impossible to create a direct analogue to applications in the field. During these tests the system was operated with only one VFD fed by a dedicated input. The ½ hp motor was unloaded, and the NGR of 200 ohms limited the current of the fault to 1.38 A. These tests were performed over the course of two days at room temperature, in an indoor lab and therefore cannot simulate all possible conditions that may be experienced in a field application over a long period of time.

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Conclusion

Each SE-701, one each upstream and downstream of the VFD and one at the NGR, measured an equal amount of VFD-frequency zero-sequence current when a ground-fault was applied on the load side of the VFD. This proves that the VFD does not isolate zero-sequence current, and that an SE-701 placed at the line or load side of the drive will detect the same amount of zero-sequence current. An SE-701 placed upstream of a VFD is capable of monitoring the feeder, VFD, and the load downstream of the CT.

When an SE-701 is used in a variable-frequency application, use the peak (variable-frequency) filter selection. This selection has a wider pass band and less attenuation at frequencies below 60 Hz. When used in these applications, a lower trip setting for the lower frequencies can be required due to the SE-701 frequency response. The lowest operating frequency expected should be considered and the normalized pick-up value from Fig. 18 should be used to calculate the appropriate trip level.

A DC bus fault can be detected by an SE-701 monitoring upstream of the VFD. The DC component is not detected, but the 180 Hz ripple current can be. The 180 Hz component is roughly 10-15% of the total fault current. Therefore, it is necessary to have the SE-701 set at a level of roughly 10% of the NGR let-through current in order to detect a DC bus fault. (The reduction in setting applies at this location only. Monitors upstream and on the NGR may require a higher setting as they will measure accumulated system harmonics.)

When a fault is located upstream of a monitoring CT, the current is not detected by that SE-701. This shows that if a fault is located on the line side of, or inside of a VFD, with an SE-701 connected on the load side of the drive, the fault is not detected.

The effects of fault-current magnitude with a fault at the transformer terminals were examined. This showed that when a fault is upstream of the CT, such as on another drive fed by the same feeder, that the SE-701's will not trip. The change in charging current was minimal and the SE-701's did not trip.