Lowering the Limits for Earth-Fault Detection

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Abstract—**Current flowing to earth has only two paths—it can flow to earth through an earth fault, and it can flow to earth through distributed capacitance. Current flowing to earth through distributed capacitance can cause sympathetic tripping during an earth fault and it can cause nuisance tripping during normal operation. If the earth-fault trip level is high enough to eliminate sympathetic tripping, nuisance tripping due to unbalanced and harmonic capacitive current is usually not a problem. However, if sympathetic tripping is not a concern and earth-fault trip levels are lowered, nuisance tripping can become a problem that worsens with the increased use of adjustable-speed drives. This paper discusses the sources of current flowing to earth that are not the result of an earth fault, and it shows how a digital filter tuned to the fundamental component of earth-fault current can provide lower trip levels without nuisance tripping.**

The limit to practical low-level earth-fault protection in industrial electrical systems is a function of physical parameters. Current sensing is the best method to detect and locate earth faults; however, system capacitance, unbalanced loads, current-sensor limitations, and harmonics affect current measurement and limit the lower level of practical earth-fault detection. Earthed systems are presumed in the following discussion on limiting factors and the techniques that can be implemented to mitigate them.

Fig. 1 illustrates that each phase in a distribution system has capacitance to earth. Phase-to-earth capacitance is distributed throughout the electrical system, but it can be modeled as a "lumped" value, as

shown in the figure. When the system is energized, capacitive current will flow from each phase to earth. The extent to which this capacitive current affects earth-fault detection will be discussed in some detail.

Charging current is defined as the current that flows to earth when one phase of an unearthed system is faulted to earth, as measured by the ammeter causing the fault in Fig. 2. Charging current can cause sympathetic earth-fault tripping in the unfaulted feeders of a multiple-feeder system. As Fig. 3 shows, core-balance current transformers (CT's) on unfaulted feeders detect the charging current of their respective feeders. The CT on the faulted feeder detects the vector sum of the charging currents of the unfaulted feeders and the current in the impedance-earthing device. To avoid sympathetic tripping, the earth-fault current pickup level must be set above the largest feeder's charging current. To detect high-impedance faults and provide machine-winding protection, the earth-fault current pickup level should be less than 20% of the prospective earth-fault current. The pickup level of all system earth-fault protection devices should be the same, and coordination should be accomplished by varying trip delay times.

Unbalance in the phase-to-earth capacitances ($Xc \neq Xb \neq Xa$) illustrated in Fig. 1 will result in a steady-state zero-sequence current. One source of unbalance is geometric asymmetry with respect to the phase conductors and earth. In a balanced system, phase capacitive currents add to zero. In an unbalanced system, the sum of the capacitive currents is not zero and it can be detected by a core-balance current transformer. This current to earth is not the result of an earth fault but it can cause nuisance earth-fault tripping. Transposing phases in long feeders can reduce capacitance unbalance.
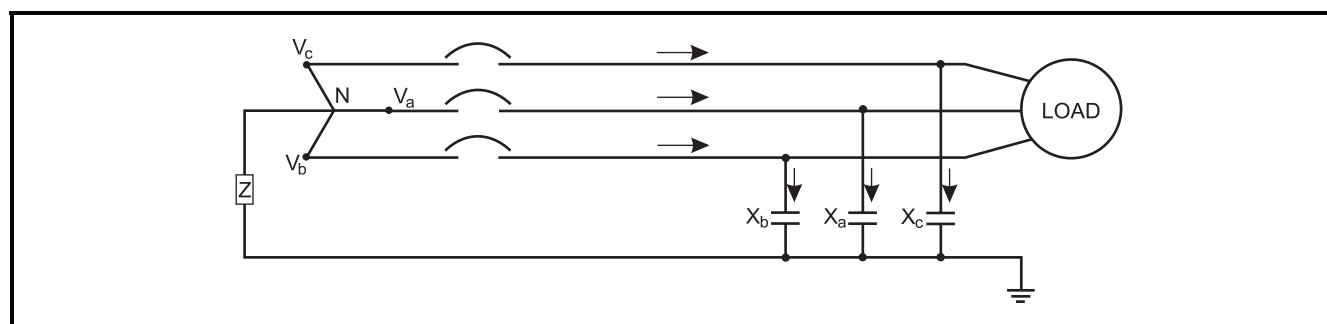

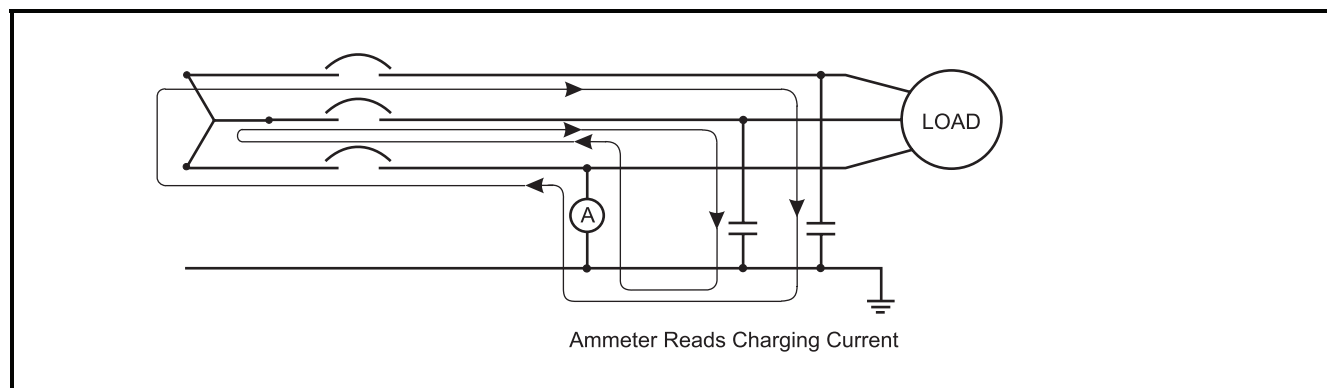FIGURE 1. 3-Phase System Showing Phase-to-Earth Capacitance.
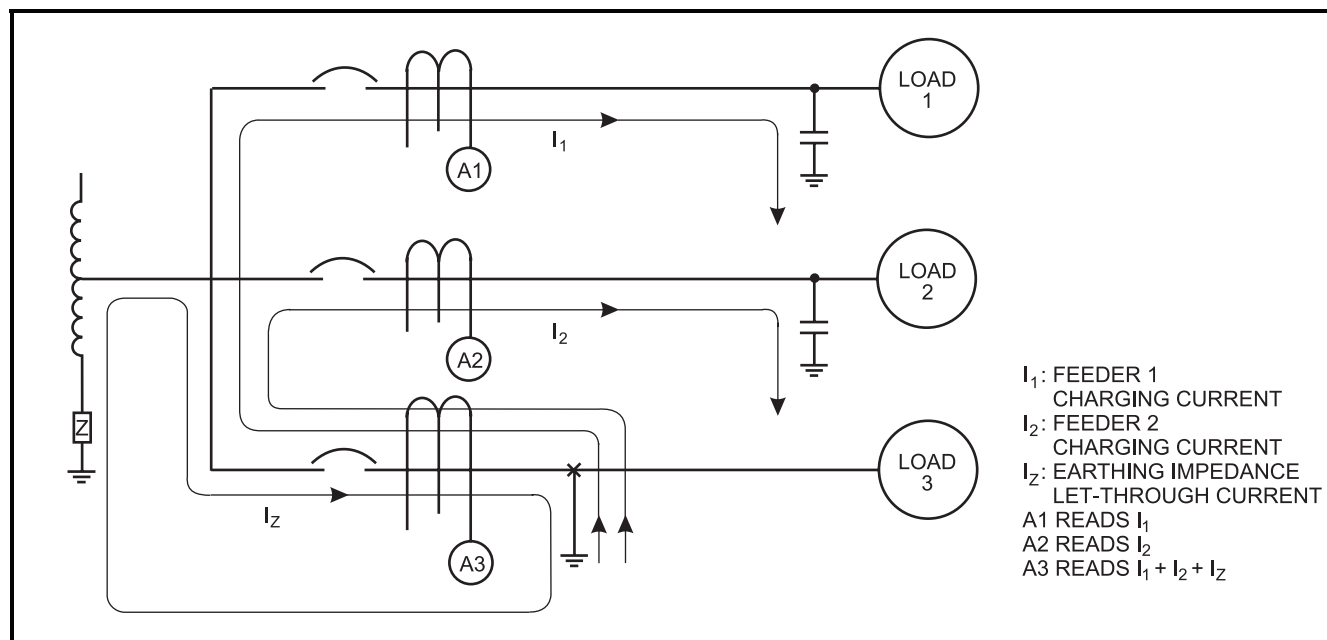
FIGURE 2. Definition of Charging Current.

I_1: FEEDER 1
CHARGING CURRENT
I_2: FEEDER 2
CHARGING CURRENT
I_Z: EARTHING IMPEDANCE
LET-THROUGH CURRENT
A1 READS I_1
A2 READS I_2
A3 READS $I_1 + I_2 + I_Z$

FIGURE 3. Multiple-Feeder Earthed System with an Earth Fault.

Phase-voltage unbalance (Fig. 1: Van≠Vbn≠Vcn) has the same effect as unbalanced phase capacitance. Voltage unbalance forces capacitive current to be unbalanced, and the resultant can be detected by a core-balance current transformer.   Unbalanced voltage from the electrical utility may be the result of unbalanced single-phase loads. Voltage unbalance combined with capacitance unbalance may increase capacitive current unbalance, and this current can cause nuisance earth-fault-protection trips.

It is important to note that unbalanced load currents do not cause nuisance earth-fault trips. If there is no leakage to earth, unbalanced load currents add to zero and do not cause an output from a core-balance CT.

When a motor is started across-the-line, the inrush current can have a dc-offset component that can cause an output from a core-balance current transformer. Transient characteristics are unpredictable because the switch can close at any point in the electrical cycle.   Transient conditions typically last less than 100 ms and nuisance earth-fault trips can be avoided by setting a longer trip delay time or by using a digital filter to reject the dc component.

All current transformers, including the window-type core-balance CT's used to detect earth-fault (zero-sequence) current have practical limitations. A minimum excitation current is required in the primary before there can be a proportional output current. Excitation current is a function of burden, CT construction, and size. Sensitive earth-fault detection requires excitation current to be small.

A large fault current, such as a phase-to-phase fault or an earth fault on a solidly earthed system, can saturate a current transformer. Saturation occurs when a CT cannot maintain a secondary current waveform proportional to a large primary current. Secondary current characteristics in this case are unpredictable and earth-fault protection may not operate.

Surge currents and conductor placement can lead to local saturation in a core-balance CT. Local saturation can cause a core-balance CT secondary output when no zero-sequence current exists, leading to a nuisance trip. Surge currents can be as high as 160% locked-rotor current for motors. Phase conductors should be centered in the CT window, and multi-conductor circuits should be bundled ABC, ABC, etc., not AA, BB, CC, etc., as shown in Fig. 4. The use of a flux conditioner, a ring of magnetically conductive material inserted in the CT window, can reduce local saturation.
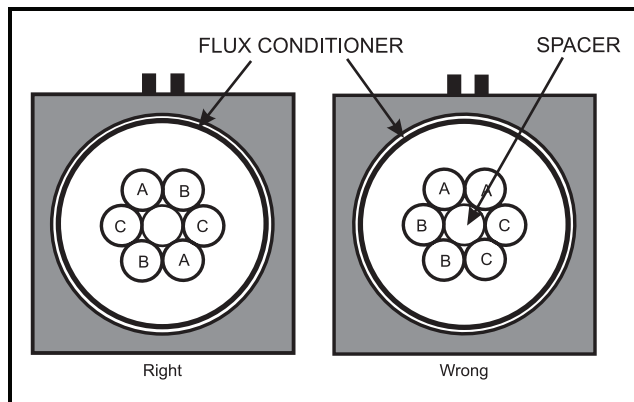

FIGURE 4. Core-Balance Transformer Cable Arrangements.

The presence of harmonic-frequency voltages (integer multiples of the fundamental frequency) in an electrical system cause harmonic-frequency currents that can affect earth-fault detection and minimum trip set points. Harmonics can be the result of the use of adjustable-speed drives (ASD) and solid-state starters. Static switching of line currents cause harmonic voltages that drive harmonic-capacitive current from the phases to earth. Capacitive impedance is inversely proportional to frequency ($Xc = 1/(2\pi fC)$ where f = frequency in Hertz). The higher the frequency, the lower the capacitive impedance, and the greater the current per volt. Except for the triplens, harmonic currents to earth add in the same manner as the fundamental components of capacitive current to earth. That is, only the unbalance in each harmonic contributes to neutral current.

Triplen harmonic-frequency currents present a special case. In a three-phase system, triplen harmonics are in-phase and their sum is three times the individual magnitude. See Fig. 5. In a 50-Hz system, 150-Hz, 300-Hz, 450-Hz, etc. components add to the 50 Hz fundamental component and can cause nuisance earth-fault trips.

Harmonic-frequency current components can necessitate undesirably high earth-fault current-protection pickup levels to avoid nuisance tripping. To mitigate the undesired affects, use an earth-fault protection device that
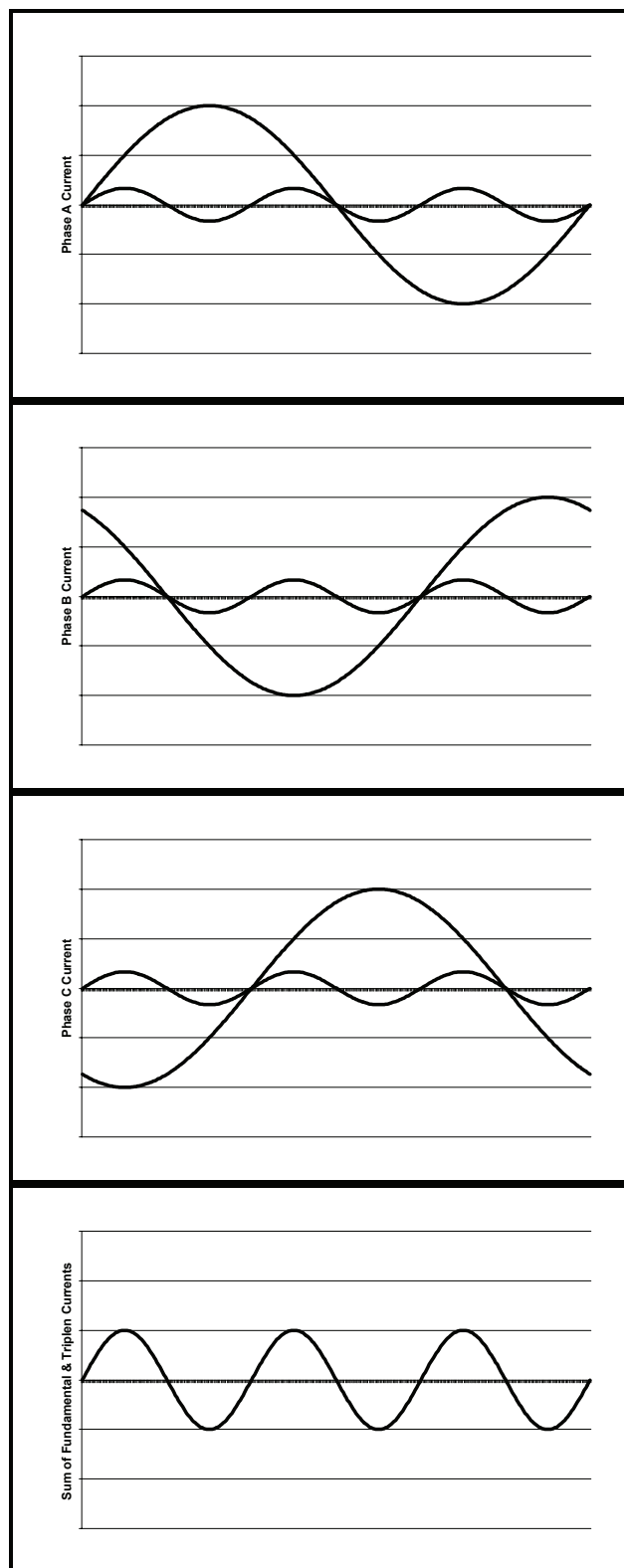

FIGURE 5. Phase Currents with Third Harmonics.

ignores dc-offset and harmonic-frequency current, and responds only to the fundamental-frequency component of current. The filtering characteristic must be fast to allow a short earth-fault trip time.

Digital filtering of the zero-sequence-current waveform provides a fast and accurate solution to many low-level earth-fault detection problems. Digital sampling and digital signal processing techniques can be used to construct a band-pass filter that responds to only the fundamental-frequency component—dc-offset and harmonic components are ignored. The discrete Fourier transform (DFT) algorithm is a mathematical tool that can quickly extract a specific-frequency signal from a multiple-frequency signal. The example shown in Fig. 6 is a 50-Hz signal with a 150-Hz third-harmonic component. The simplified DFT algorithm is:

$$Ip = \frac{2}{m} \sum_{n=0}^{m-1} I(n) \times \sin(\frac{2\pi n}{m})$$

Where: Ip = peak current
m = number of samples per cycle
n = sample number
$I(n)$ = measured sample

The sampler is set to take a known number of samples per cycle of the desired frequency. In the example the filter is tuned to 50-Hz by selecting a sample frequency of 1 kHz (20 samples per cycle). The example summation is:

$$Ip = \frac{2}{20} \sum_{n=0}^{19} I(n) \times \sin(\frac{2\pi n}{20})$$
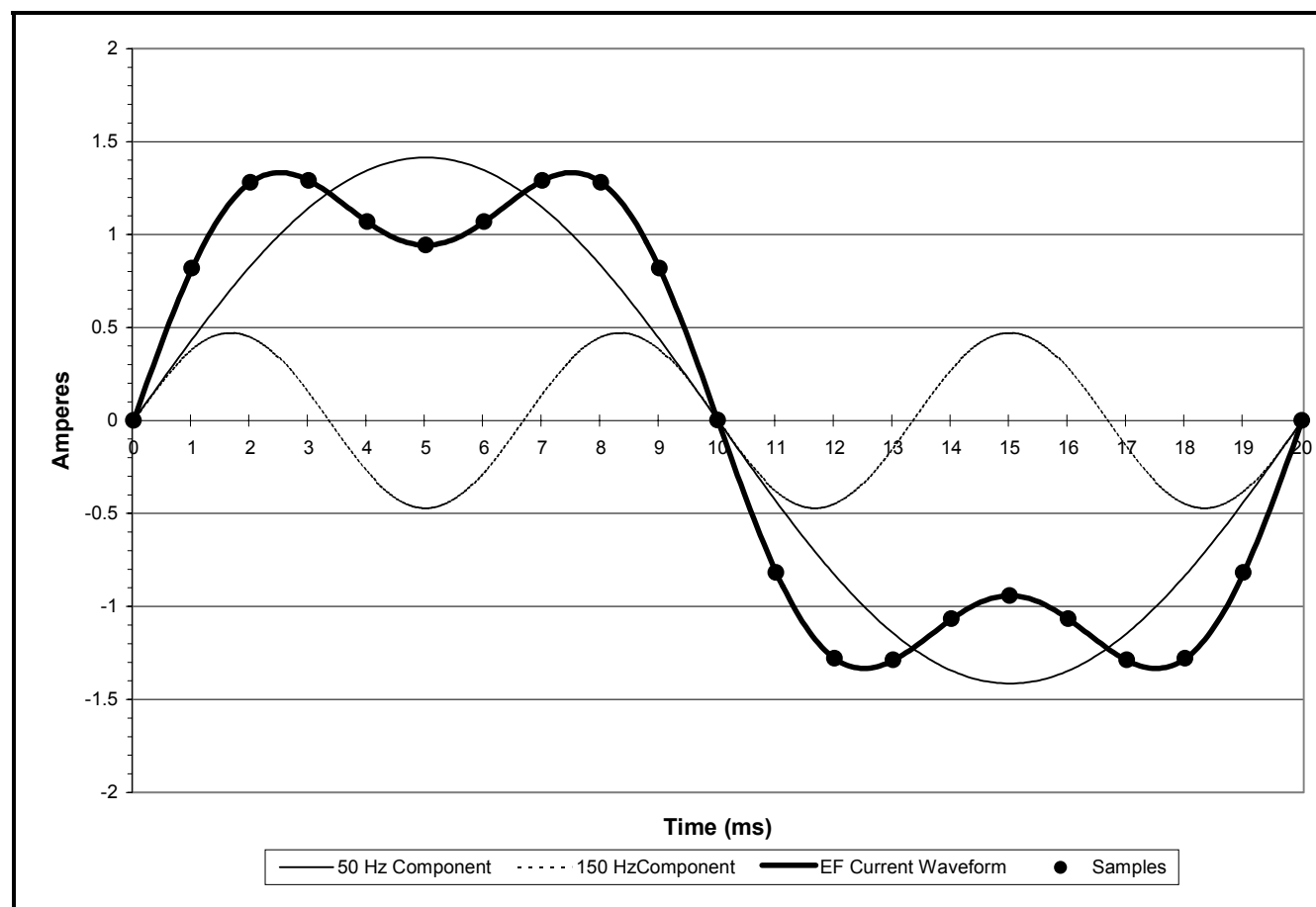
$$Ip = 1.414$$

FIGURE 6. Earth-Fault Current with Fundamental and Harmonic Components.

Table 1 shows the values, from the example in Fig. 6, of the 50 Hz component, the 150 Hz component, and the earth-fault current that is the sum of the two, at each of the sample times, *n*. It also shows the sample-time DFT-component value of both the 50 Hz component and of the sample, and the sum of each over the sample period of *n*=0 to *n*=19. Note that the sum for the fundamental component is the same as the sum for the sampled waveform, showing that this sampling technique has provided an accurate measurement of the fundamental component in spite of the presence of the 150 Hz third harmonic.

Note that only a single cycle of the fundamental component is required for the calculation, here $1/50^{th}$ second, or 20 ms. Thereafter, the value is updated every millisecond and the value is accurate, based on the previous 20 samples.

Earth-fault protection relays that use digital filtering-techniques can reduce nuisance tripping associated with low-level protection. Such devices ignore the dc component when a motor starts, and allow lower trip current and trip time set points. Protection that uses DFT filtering ignores harmonic components of zero-sequence current that results from capacitive unbalance, again allowing a lower trip set point. Triplen harmonic components, whose phase values are additive, are filtered by the DFT algorithm both in terms of capacitance-unbalance current and earth-fault current, again permitting the selection of a lower current trip level, and the one-cycle DFT calculation time allows a rapid trip time.

TABLE 1. COMPONENT AND DFT VALUES.

SAMPLE NUMBER (n)	50 Hz COMP. $I_f(n)$	150 Hz COMP.	SAMPLED VALUE I(n)	$I_f(n)\sin(2*pi*n/20)$	$I(n)\sin(2*pi*n/20)$
0	0.000	0.000	0.000	0.000	0.000
1	0.437	0.381	0.818	0.135	0.253
2	0.831	0.448	1.280	0.489	0.752
3	1.144	0.146	1.290	0.926	1.043
4	1.345	-0.277	1.068	1.279	1.016
5	1.414	-0.471	0.943	1.414	0.943
6	1.345	-0.277	1.068	1.279	1.016
7	1.144	0.146	1.290	0.926	1.043
8	0.831	0.448	1.280	0.489	0.752
9	0.437	0.381	0.818	0.135	0.253
10	0.000	0.000	0.000	0.000	0.000
11	-0.437	-0.381	-0.818	0.135	0.253
12	-0.831	-0.448	-1.280	0.489	0.752
13	-1.144	-0.146	-1.290	0.926	1.043
14	-1.345	0.277	-1.068	1.279	1.016
15	-1.414	0.471	-0.943	1.414	0.943
16	-1.345	0.277	-1.068	1.279	1.016
17	-1.144	-0.146	-1.290	0.926	1.043
18	-0.831	-0.448	-1.280	0.489	0.752
19	-0.437	-0.381	-0.818	0.135	0.253
				14.142	14.142