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GE Low Voltage Circuit Breakers

RMS Digital trips offer increased accuracy and reliability advances in low voltage circuit breaker trip technology

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Current sensitive trip devices for low voltage circuit breakers have, over the years, undergone a succession of design refinements prompted largely by the demand for greater reliability of power distribution systems. With the growing application of static power converters and the subsequent increase in the harmonic content of the power system current, low voltage solid state trip sensing techniques need to be reevaluated. This article will review the function of low voltage circuit breaker trip units, and the need for direct rms (root mean square) overcurrent sensing of the sinusoidal and non-sinusoidal current wave including the percent error analysis.

FUNCTION

The function of the trip device is to initiate the tripping of a circuit breaker whenever it detects abnormal current flow, either between phase conductors, or from phase conductors to ground on grounded systems. To perform this function reliably, the trip is an integral part of a circuit breaker, and does not require a separate source of power. Abnormal current flow initiates tripping either by releasing a trip latch to mechanically engage a trip bar (electromechanical trip) or energize a tripping solenoid (solid state trip).

SOLID STATE TRIP UNITS

Solid state trip units effectively provide the long-time, short-time and instantaneous protection characteristics, with the additional advantage of improved time/current accuracy, and expanded user adjustment for improved system coordination and selectivity.

A solid state trip system consists of current sensors, a protection programmer, and a solenoid or flux shifter. The current sensors provide current signals as well as control power to the protection programmer for the solid state logic, fault indicators, and tripping energy.

CHANGING POWER SYSTEM REQUIREMENTS

It has been well documented that harmonic currents and voltages are generated by discontinuous and nonlinear loads such as rectifiers, resistance welders, arc furnaces, and discharge lighting. Historically, the harmonic current magnitudes have been insignificant in most power systems, and have caused little distortion to the steady state current wave shape. However, due to the increasing use of static power converters such as silicon controlled rectifiers (SCR), power system harmonic current magnitudes are increasing.

The magnitude of the SCR generated harmonic current is governed by the delay angle and the commutating reactance. In terms of multiples of the fundamental 60 hertz current, the predominant harmonics that cause measurable distortion of the power system steady state current wave shape range from the thirds due to discharge lighting, to fifth, seventh, eleventh and thirteenth generated by a typical phase controlled rectifier.

PEAK CURRENT SENSING

Historically, peak-detecting electronic trip units of analog or digital design have been calibrated in rms assuming a steady state sinusoidal current, where the relationship between peak and rms is a fixed ratio of 1.414. For power systems whose current wave is sinusoidal (zero percent harmonic content), peak detecting electronic trip designs provide accurate overload and overcurrent protection. However, as static power equipment is added to a power system, the steady state current becomes increasingly nonsinusoidal due to the increased harmonic content. This may cause the peak detecting electronic trips, for the phase overcurrent function, to overprotect or underprotect.

Over protection occurs when the peak value of the current (harmonic plus fundamental) results in the calculated rms to be greater that the actual rms steady state current. As an example, Figure 1 represents a waveform with 10 percent fifth harmonic current content. The true rms value is 71.1 amperes. Based on the peak value of 110 amperes, however, an rms pure sinusoidal calculation would yield 110/1414 or 77.8 amperes. A peak sensing unit set at 72 amperes would "nuisance trip" and thus overprotect.

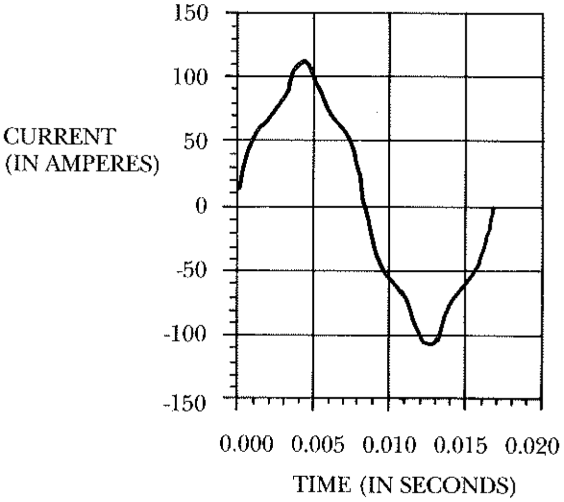

Figure 1.

Conversely, under protection occurs where the calculated rms is less than the actual rms steady state current. Figure 2 depicts a waveform with 20 percent third harmonic. Its true rms value is 71.1 amperes, while a peak detecting trip unit sensing an 85 ampere peak magnitude would calculate an rms value of 85/1.414 or 60.1 amperes, thereby underprotecting.

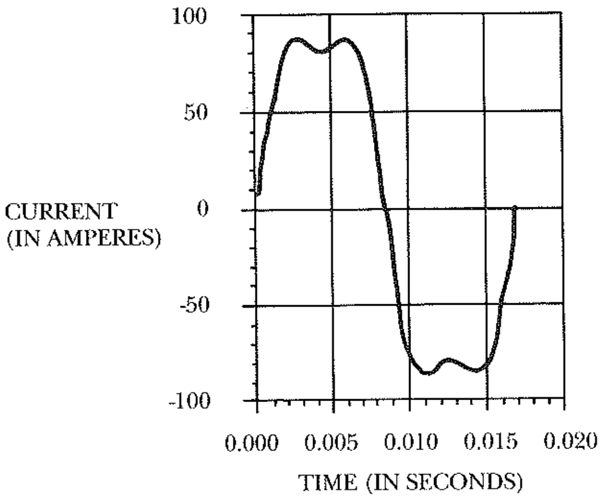

Figure 2.

The opportunity for overprotection or underprotection is governed by the phase angle(s) of the harmonic current(s) in relationship with the fundamental, and the phase angle(s) are variable depending on the changing power system requirements. Therefore, for a power system having a significant harmonic content, application of peak detecting trip units will result in overload protection which is neither accurate nor predictable.

Only the direct measurement of the true rms content of the current wave provides predictable overload protection for both sinusoidal or nonsinusoidal currents. Fortunately, this can be accomplished today at a reasonable cost, using microprocessor digital sampling techniques. In addition, solid state microprocessors are not affected by component tolerance, and do not require compensation for signal distortion. Designs based on complementary metal oxide (CMOS) technology are also less sensitive to extraneous noise produced by lighting, instrumentation, radio, etc.

DIGITAL SAMPLING

The rms value of a current wave is equal to the square root of the mean square, of the variable values sampled throughout one cycle. This relationship is mathematically expressed as:

$$I_{rms} = \sqrt{1/T\ T\ i^2\,dt}$$

Where I_{rms} = Current in amperes
T = Time period in seconds
i = Instantaneous current in amperes
dt = Derivative of time

This definition applies to any current wave form, sinusoidal or nonsinusoidal.

With solid state microprocessor technology, and fast analog to digital converters, it is possible to measure the magnitude of the phase current over several time periods within the cycle. Each measurement is defined as a sample, and the time period between sample measurements is defined as a sample interval. The reciprocal of the sample interval defines the sampling frequency. Figure 3 illustrates the sampling of a nonsinusoidal current wave.

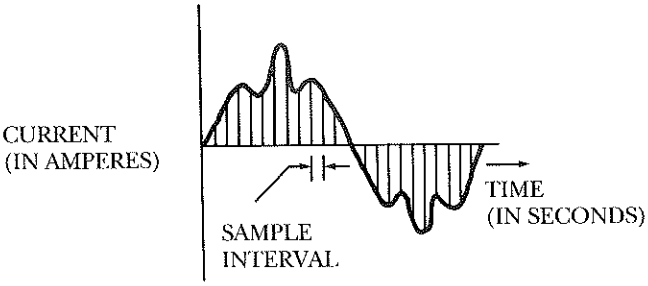

Figure 3.

According to sampling theory (Nyquist criterion), the sampling frequency must be greater than twice the highest frequency of the measured current wave to obtain accurate measurements. Thus, for a power system whose current wave contains the fifth harmonic, the sample rate should be higher than 2*(5) (60 cycles per second) or 600 samples per second.

Since the magnitude of a harmonic is inversely related to its harmonic order, harmonics above the thirteenth are not likely to cause measurable long-time distortion to the steady state current wave in today's power systems. This implies that a sampling rate of [2 (13)0+1] [60 cycles per second] or 1620 samples per second (27 samples per cycle) for each phase current is required to obtain accurate measurements.

Based on the total samples taken over an entire cycle, the rms current value as calculated is expressed mathematically as follows:

$$I = \sqrt{1/N\ (i^2 + i^2 + \text{----} + i^2)}$$

Where I = Calculated rms current in amperes
i_1, i_2, i_N = Instantaneous current magnitudes at each sample for each cycle
N = Number of samples per cycle

With a sample rate of 27 samples per cycle on wave forms having zero to thirteenth harmonic contribution, computer simulations have shown that errors of less than one percent can be expected between the sampled and true rms wave form. The source of errors are A to D converter conversion, microprocessor mathematical round off and variations in the fundamental frequency. It should be noted that variation in the fundamental frequency is generally dependent on the electric utility.

The high sampling rate, resulting in low error, permits accurate microprocessor time delay calculations and monitoring of changing load conditions, particularly where the harmonic content is changing very rapidly due to phase controlled SCR equipment. This digital sampling technique can therefore provide accurate protection with the long-and short-time delay functions of a solid state trip unit.

ANSI/IEEE Standard 519-1981, Table 1, documents the typical harmonic currents present in the input current to typical static power converters which is repeated for convenience.

Table 1. Harmonic Currents Present in Input Current to a Typical Static Power Converter in Per-Unit of the Fundamental Current

Converter	Harmonic Order							
Pulses	5	7	11	13	17	19	23	25
6	0.175	0.11	0.045	0.029	0.015	0.010	0.009	0.008
12	0.026	0.016	0.045	0.029	0.002	0.001	0.009	0.008
18	0.026	0.016	0.007	0.004	0.015	0.010	0.001	0.001
24	0.026	0.016	0.007	0.004	0.002	0.001	0.009	0.008

The percent error introduced by digital sampling for the above 6, 12, 18, and 24 pulse converters are shown in Tables two through five. This assumes an 8 bit A/D converter and sampling the current 27 times a cycle. The errors were determined assuming a current wave form of "B" expressed as follows:

$B = A_1 \sin (wt + \theta,) + A_2 \sin (2wt + \theta_2) + \ldots +$

or

$B_n = A_n \sin (nwt + \theta n)$

where B_n = amplitude of the wave of the harmonic order at time t

A_n = maximum amplitude of the harmonic order

n = harmonic order

w = $2\pi f$

Because the A/D samples the current 27 times a cycle, a low pass filter suppresses the higher order harmonics. B_t is the summation of $B_1, B_5, \ldots, B_{13}$ and represents what the microprocessor would sense.

The phase angle is assumed to be zero degrees for this analysis. Time between samples (t) is 617 microseconds.

"8 Bit Value" is the A/D converter output. This is based on maximum of 2.5 per unit rms. For an 8 bit unit with 255 counts, each 8 bit value is calculated by multiplying B_t with 255/ (2.5* 1.414).

"Actual rms" is the square root of the sum of the square of the A per unit values from the fundamental to the 25th harmonic. The calculated rms accounts for the errors due to harmonic sampling limitation to the 13th harmonic as well as A/D converter resolution round off in the microprocessor and limitation of finite word length.

"Percent Error" is the result of 100*[(actual rms - calculated rms)/actual rms].

This results in a percent error of less than 1% for typical static power converters utilizing digital sampling techniques. It should be noted that harmonic orders above the 13th contribute very little to the rms magnitude of the wave form, justifying sampling the wave form 27 times a cycle.

ALTERNATE SAMPLING APPROACHES

Alternative sampling approaches do not provide accurate rms protection. One approach computes the average of the wave form and determines the rms value by a multiplying factor. This method has predictable error similar to peak detection. Another only samples the current wave over several cycles. Both of these approaches are accurate only if the harmonic content is constant over several cycles, which generally is not the case due to the varying phase control of the SCR. In addition, neither approach has a sufficient sampling rate to permit rms sensing for the short time region.

CONCLUSION

The application of digital microprocessor technology to achieve direct rms sensing adds a new dimension of accuracy and reliability to current sensitive trip mechanisms. It allows the true rms (heating) protection of thermal-electromechanical trip units, along with the precise protection and short time overcurrent protection in power distribution systems with the increasing occurrence of nonsinusoidal currents.

Table 2

Sampling Interval 0.000617 Seconds
Harmonic Error Analysis for Six Pulse Converter

	MAGNITUDE Rms	MAGNITUDE Peak An	PHASE (degrees)
Fundamental	1.000	1.414	0
Fifth	0.175	0.247	0
Seventh	0.110	0.157	0
Eleventh	0.045	0.064	0
Thirteenth	0.029	0.041	0
Seventeenth	0.015	0.021	0
Nineteenth	0.010	0.014	0
Twentythird	0.009	0.013	0
Twentyfifth	0.008	0.011	0

Sample #	B_1	B_5	B_7	B_{11}	B_{13}	B_t^2	Bt	Value	8-BIT Value^2
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0
2	0.326	0.227	0.157	0.035	0.005	0.750	0.562	54	2916
3	0.634	0.180	-0.018	-0.058	-0.010	0.729	0.531	53	2809
4	0.909	-0.084	-0.155	0.063	0.014	0.747	0.557	54	2916
5	1.134	-0.247	0.036	-0.046	-0.019	0.858	0.736	62	3844
6	1.128	-0.112	0.151	0.014	0.023	1.374	1.888	99	9801
7	1.393	0.158	-0.053	0.022	-0.027	1.494	2.231	108	11664
8	1.412	0.237	-0.144	-0.051	0.030	1.484	2.201	107	11449
9	1.355	0.030	0.070	0.064	-0.033	1.485	2.205	107	11449
10	1.225	-0.214	0.136	-0.055	0.036	1.129	1.275	81	6561
11	1.030	-0.199	-0.085	0.028	-0.038	0.735	0.540	53	2916
12	0.779	0.056	-0.127	0.008	0.039	0.755	0.570	54	6561
13	0.485	0.243	0.100	-0.042	-0.041	0.747	0.557	54	2916
14	0.166	0.137	0.115	0.061	0.041	0.521	0.271	38	1444
15	-0.162	-0.134	-0.113	-0.061	-0.041	-0.511	0.261	36	1296
16	-0.482	-0.244	-0.102	0.040	0.040	-0.748	0.559	53	2809
17	-0.775	-0.059	0.125	-0.006	-0.039	-0.755	0.570	53	2809
18	-1.027	0.197	0.088	-0.030	0.037	-0.734	0.539	52	2704
19	-1.223	0.216	-0.135	0.056	-0.035	-1.122	1.259	80	6400
20	-1.354	-0.026	-0.072	-0.063	0.032	-1.484	2.202	106	11236
21	-1.412	-0.236	0.143	0.050	-0.029	-1.484	2.202	106	11236
22	-1.393	-0.161	0.056	-0.020	0.025	-1.493	2.230	107	11449
23	-1.300	0.108	-0.150	-0.016	-0.021	-1.379	1.901	98	9604
24	-1.136	0.247	-0.039	0.047	0.017	-0.863	0.745	61	3721
25	-0.912	0.088	0.154	-0.063	-0.013	-0.746	0.556	53	2809
26	-0.638	-0.178	0.021	0.058	0.008	-0.729	0.531	52	2704
27	-0.330	-0.229	-0.157	-0.033	-0.003	-0.752	0.565	53	2809

Actual Rms = SQRT $(\mathrm{RMS}_1^2 + \mathrm{RMS}_5^2 + \ldots + \mathrm{RMS}_n^2)$
= 1.023
Calculated RMS = [SQRT (Sum of Squares/27)] (2.5*1.414/255)
= 1.016
Percent Error = 0.68%

Table 3

Sampling Interval 0.000617 Seconds
Harmonic Error Analysis for Twelve Pulse Converter

	MAGNITUDE Rms	MAGNITUDE Peak An	PHASE (degrees)
Fundamental	1.000	1.414	0
Fifth	0.026	0.037	0
Seventh	0.016	0.023	0
Eleventh	0.045	0.064	0
Thirteenth	0.029	0.041	0
Seventeenth	0.002	0.003	0
Nineteenth	0.001	0.001	0
Twentythird	0.009	0.013	0
Twentyfifth	0.008	0.011	0

Sample #	B_1	B_5	B_7	B_{11}	B_{13}	B_t^2	Bt	Value	8-BIT Value^2
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0
2	0.326	0.034	0.023	0.035	0.005	0.422	0.178	30	900
3	0.634	0.027	-0.003	-0.058	-0.010	0.591	0.349	43	1849
4	0.909	-0.013	-0.022	0.063	0.014	0.951	0.904	69	4761
5	1.134	-0.037	0.005	-0.046	-0.019	1.038	1.077	75	5625
6	1.128	-0.117	0.022	0.014	0.023	1.340	1.797	97	9409
7	1.393	0.024	-0.008	0.022	-0.027	1.404	1.971	101	10201
8	1.412	0.035	-0.021	-0.051	0.030	1.405	1.974	101	10201
9	1.355	0.004	0.010	0.064	-0.033	1.400	1.960	101	10201
10	1.225	-0.032	0.020	-0.055	0.036	1.194	1.426	86	7396
11	1.030	-0.030	-0.012	0.028	-0.038	0.978	0.956	71	5041
12	0.779	0.008	-0.018	0.008	0.039	0.816	0.666	59	3481
13	0.485	0.036	0.014	-0.042	-0.041	0.454	0.206	33	1089
14	0.166	0.020	0.017	0.061	0.041	0.305	0.093	22	484
15	-0.162	-0.020	-0.016	-0.061	-0.041	-0.300	0.090	21	441
16	-0.482	-0.036	-0.015	0.040	0.040	-0.452	0.205	32	1024
17	-0.775	-0.009	0.018	-0.006	-0.039	-0.811	0.658	58	3364
18	-1.027	0.029	0.013	-0.030	0.037	-0.977	0.955	69	4761
19	-1.223	0.032	-0.019	0.056	-0.035	-1.190	1.416	85	7225
20	-1.354	-0.004	-0.010	-0.063	0.032	-1.400	1.959	100	10000
21	-1.412	-0.035	0.021	0.050	-0.029	-1.405	1.974	100	10000
22	-1.393	-0.024	0.008	-0.020	0.025	-1.404	1.971	100	10000
23	-1.300	0.016	-0.022	-0.016	-0.021	-1.343	1.804	96	9216
24	-1.136	0.037	-0.006	0.047	0.017	-0.041	1.083	74	5476
25	-0.912	0.013	0.022	-0.063	-0.013	-0.952	0.907	68	4624
26	-0.638	-0.026	0.003	0.058	0.008	-0.596	0.355	42	1764
27	-0.330	-0.034	-0.023	-0.033	-0.003	-0.423	0.179	30	900

Actual Rms = SQRT $(\mathrm{RMS}_1^2 + \mathrm{RMS}_5^2 + \ldots + \mathrm{RMS}_n^{2)}$
= 1.002
Calculated RMS = [SQRT (Sum of Squares/27)] (2.5*1.414/255)
= 0.996
Percent Error = 0.60%

Table 4

Sampling Interval 0.000617 Seconds
Harmonic Error Analysis for Eighteen Pulse Converter

	MAGNITUDE Rms	Peak An	PHASE (degrees)
Fundamental	1.000	1.414	0
Fifth	0.026	0.037	0
Seventh	0.016	0.023	0
Eleventh	0.007	0.01	0
Thirteenth	0.004	0.006	0
Seventeenth	0.015	0.021	0
Nineteenth	0.010	0.014	0
Twentythird	0.001	0.001	0
Twentyfifth	0.001	0.001	0

Sample #	B_1	B_5	B_7	B_{11}	B_{13}	B_1^2	Bt	Value	8-BIT Value^2
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0
2	0.326	0.034	0.023	0.001	0.005	0.388	0.151	28	784
3	0.634	0.027	-0.003	-0.001	-0.010	0.648	0.420	47	2209
4	0.909	-0.013	-0.022	0.002	0.014	0.886	0.784	64	4096
5	1.134	-0.037	0.005	-0.003	-0.019	1.093	1.194	79	6241
6	1.128	-0.017	0.022	0.003	0.023	1.309	1.713	94	8836
7	1.393	0.024	-0.008	0.004	-0.027	1.408	1.983	102	10404
8	1.412	0.035	-0.021	-0.004	0.030	1.422	2.023	103	10609
9	1.355	0.004	0.010	0.005	-0.033	1.375	1.890	99	9801
10	1.225	-0.032	0.020	-0.005	0.036	1.210	1.464	87	7569
11	1.030	-0.030	-0.012	0.005	-0.038	0.987	0.974	71	5041
12	0.779	0.008	-0.018	0.005	0.039	0.775	0.601	56	3136
13	0.485	0.036	0.014	-0.006	-0.041	0.524	0.274	38	1444
14	0.166	0.020	0.017	0.006	0.041	0.218	0.048	16	256
15	-0.162	-0.020	-0.016	-0.006	-0.041	-0.213	0.046	14	196
16	-0.482	-0.036	-0.015	0.006	0.040	-0.521	0.271	37	1369
17	-0.775	-0.009	0.018	-0.005	-0.039	-0.772	0.596	55	3025
18	-1.027	0.029	0.013	-0.005	0.037	-0.984	0.969	70	4900
19	-1.223	0.032	-0.019	0.005	-0.035	-1.207	1.457	86	7396
20	-1.354	-0.004	-0.010	-0.004	0.032	-1.374	1.887	98	9604
21	-1.412	-0.035	0.021	0.004	-0.029	-1.422	2.023	102	10404
22	-1.393	-0.024	0.008	-0.004	0.025	-1.409	1.985	101	10201
23	-1.300	0.016	-0.022	-0.003	-0.021	-1.311	1.718	94	8836
24	-1.136	0.037	-0.006	0.002	0.017	-0.096	1.200	78	6084
25	-0.912	0.013	0.022	-0.002	-0.013	-0.888	0.789	63	3969
26	-0.638	-0.026	0.003	0.001	0.008	-0.651	0.424	46	2116
27	-0.330	-0.034	-0.023	-0.000	-0.003	-0.392	0.154	27	729

Actual Rms = SQRT $(\mathrm{RMS}_1^2 + \mathrm{RMS}_5^2 + \ldots + \mathrm{RMS}_n^2)$
= 1.001
Calculated RMS = [SQRT (Sum of Squares/27)] (2.5*1.414/255)
= 0.996
Percent Error = 0.50%

Table 5

Sampling Interval 0.000617 Seconds
Harmonic Error Analysis for Twentyfour Pulse Converter

	MAGNITUDE Rms	Peak An	PHASE (degrees)
Fundamental	1.000	1.414	0
Fifth	0.026	0.037	0
Seventh	0.016	0.023	0
Eleventh	0.007	0.01	0
Thirteenth	0.004	0.006	0
Seventeenth	0.002	0.003	0
Nineteenth	0.001	0.001	0
Twentythird	0.009	0.013	0
Twentyfifth	0.008	0.011	0

Sample #	B_1	B_5	B_7	B_{11}	B_{13}	B_1^2	Bt	Value	8-BIT Value^2
1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0	0
2	0.326	0.034	0.023	0.001	0.005	0.388	0.151	28	784
3	0.634	0.027	-0.003	-0.001	-0.010	0.648	0.420	47	2209
4	0.909	-0.013	-0.022	0.002	0.014	0.886	0.784	64	4096
5	1.134	-0.037	0.005	-0.003	-0.019	1.093	1.194	79	6241
6	1.128	-0.017	0.022	0.003	0.023	1.309	1.713	94	8836
7	1.393	0.024	-0.008	0.004	-0.027	1.408	1.983	102	10404
8	1.412	0.035	-0.021	-0.004	0.030	1.422	2.023	103	10609
9	1.355	0.004	0.010	0.005	-0.033	1.375	1.890	99	9801
10	1.225	-0.032	0.020	-0.005	0.036	1.210	1.464	87	7569
11	1.030	-0.030	-0.012	0.005	-0.038	0.987	0.974	71	5041
12	0.779	0.008	-0.018	0.005	0.039	0.775	0.601	56	3136
13	0.485	0.036	0.014	-0.006	-0.041	0.524	0.274	38	1444
14	0.166	0.020	0.017	0.006	0.041	0.218	0.048	16	256
15	-0.162	-0.020	-0.016	-0.006	-0.041	-0.213	0.046	14	196
16	-0.482	-0.036	-0.015	0.006	0.040	-0.521	0.271	37	1369
17	-0.775	-0.009	0.018	-0.005	-0.039	-0.772	0.596	55	3025
18	-1.027	0.029	0.013	-0.005	0.037	-0.984	0.969	70	4900
19	-1.223	0.032	-0.019	0.005	-0.035	-1.207	1.457	86	7396
20	-1.354	-0.004	-0.010	-0.004	0.032	-1.374	1.887	98	9604
21	-1.412	-0.035	0.021	0.004	-0.029	-1.422	2.023	102	10404
22	-1.393	-0.024	0.008	-0.004	0.025	-1.409	1.985	101	10201
23	-1.300	0.016	-0.022	-0.003	-0.021	-1.311	1.718	94	8836
24	-1.136	0.037	-0.006	0.002	0.017	-0.096	1.200	78	6084
25	-0.912	0.013	0.022	-0.002	-0.013	-0.888	0.789	63	3969
26	-0.638	-0.026	0.003	0.001	0.008	-0.651	0.424	46	2116
27	-0.330	-0.034	-0.023	-0.000	-0.003	-0.392	0.154	27	729

Actual Rms = SQRT $(\mathrm{RMS}_1^2 + \mathrm{RMS}_5^2 + \ldots + \mathrm{RMS}_n^{2)}$
= 1.001
Calculated RMS = [SQRT (Sum of Squares/27)] (2.5* 1.414/255)
= 0.996
Percent Error = 0.50%

GE Electrical Distribution & Control

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