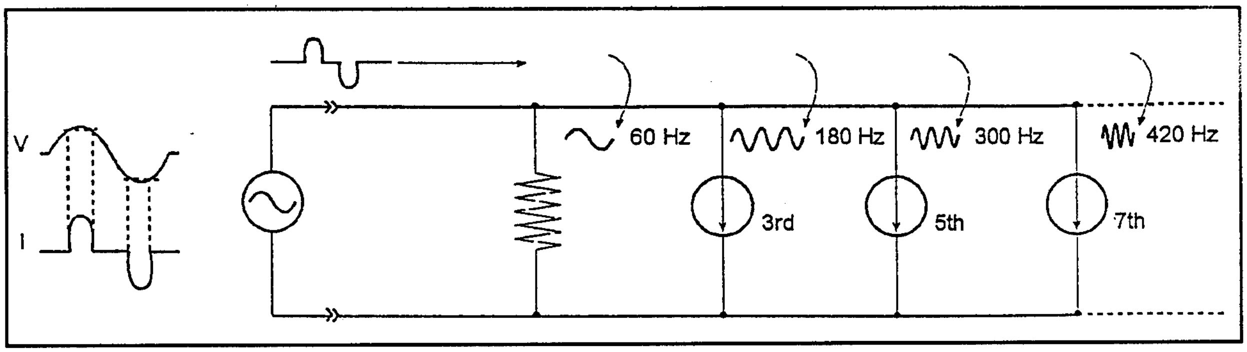
US Army Corps of Engineers
Construction Engineering
Research Laboratories

USACERL Technical Report 96/13
November 1995

A Test of Circuit Breakers Under Harmonic Loading Conditions

by
Tony Estrada, Steve J. Briggs, and Naresh Khosla



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This experiment detected no nuisance tripping with any of the breakers tested. Additionally it was found that varying harmonic loading conditions did not affect manufacturer-specified trip times for thermal-magnetic or solid state circuit breakers. However, under moderate overload conditions, the same experimental harmonic conditions caused hazardous overheating and trip failure in the magnetic-only circuit breakers.

Based on a review of related nonexperimental industry literature on circuit breaker design and performance, the authors postulate that inherent design characteristics leave thermal-magnetic and solid state circuit breakers unaffected by harmonics. The literature also suggests that the construction of the instantaneous tripping element in the magnetic-only breakers may account for their overheating and trip failure in the experiment.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE November 1995	3. REPORT TYPE AND DATES COVERED Final

4. TITLE AND SUBTITLE

A Test of Circuit Breakers Under Harmonic Loading Conditions

5. FUNDING NUMBERS

4A162784
AT45
EX-XF4

6. AUTHOR(S)

Tony Estrada, Steve J. Briggs, and Naresh Khosla

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Construction Engineering Research Laboratories (USACERL)
P.O. Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER

TR 96/13

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Center for Public Works
ATTN: CECPW-EE
Bldg. 1929
Fort Belvoir, VA 22060-5516

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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14. SUBJECT TERMS

harmonic currents
power systems harmonics
military installations

15. NUMBER OF PAGES

38

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

Foreword

This research was conducted for U.S. Army Center for Public Works under Project 4A162784AT45, "Energy and Energy Conservation"; Work Unit EX-XF4, "Clean Electric Power Technology." The technical monitor was Ronald K. Mundt, CECPW-EE.

The study was performed by the Engineering Division (FL-E) of the Facilities Technology Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). The USACERL Principal Investigator was Dr. Steve J. Briggs, CECER-FL-E. Part of the work was performed under contract by Tony Estrada and Naresh Khosla of Enviro-Management & Research, Inc., of Washington, DC. Larry M. Windingland is Acting Chief, CECER-FL-E, Donald F. Fournier is Acting Operations Chief, and Alvin Smith is Acting Chief, CECER-FL. The USACERL technical editor was Gordon L. Cohen, Technical Resources Center.

COL James T. Scott is Commander and Acting Director of USACERL, and Dr. Michael J. O'Connor is Technical Director.

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1 Introduction

Background

Circuit breakers are used universally to provide overcurrent and overload protection for Army installation electrical systems. They protect the electrical conductors and equipment. Typically, on low-voltage general applications (i.e., below 600 volts), molded-case circuit breakers are used to detect an overload or short circuit in the power system. The loads are sometimes nonlinear, which can expose circuit breakers to harmonic currents.

Power system harmonics are a growing problem on Army installations and elsewhere. Harmonics can damage both user loads and the power network. Harmonic problems can be accounted for by two industry trends:

- a dramatic increase in the use of nonlinear loads, such as static power converters (rectifiers), switching power supplies, and other electronic loads
- power devices and load equipment manufactured with minimal design margins as compared to the margins used only a few years ago.

Adjustable speed drives (ASDs) which are increasingly used on Army installations to reduce electricity consumption for certain types of loads, are one example of necessary equipment that create power system harmonics. Harmonics, regardless of their source, can in turn interfere with critical loads such as computers and communications equipment, which have a low design tolerance for harmonics. Service interruptions and data loss can result.

Power system harmonics range from the 2nd harmonic and up. In most power systems the magnitude of higher-order harmonics—especially those over 25th—is often too small to be of concern. Considerable attention nevertheless has been focused on the higher harmonic frequencies, which cause interference with communications and telephone circuits. However, there is very little discussion in the literature about lower-frequency harmonic bands, which can cause heating in electrical devices. No studies have been conducted on the effect of power system harmonics on circuit breakers, and there currently are no industry standards for the level of harmonic currents that circuit breakers are required to interrupt or carry.

The U.S. Army Center for Public Works (USACPW) periodically receives reports from installation maintenance personnel about the nuisance tripping of circuit breakers. In theory, harmonics are one possible cause of nuisance tripping. To compile baseline data for installation electricians and power system designers at Army Engineer Districts, USACPW tasked the U.S. Army Construction Engineering Research Laboratories (USACERL) to study the effects of harmonics on circuit breakers.

Objective

The objective of this research was to conduct a laboratory test of circuit breakers operating under nonlinear loading conditions and to document any findings that may affect the installation or retrofit of circuit breakers operating under such conditions.

Approach

Technical information, test results, operating parameters, technical reports, and publications on circuit breakers by various manufacturers were obtained and examined. A complete panelboard assembly was acquired. The assembly included a harmonics source, plus main and branch circuit breakers working on three different operating principles:

1. thermal-magnetic
2. magnetic
3. solid state.

The panelboard and all breakers used in the experiment were made by a single manufacturer, the GE Co. (General Electric), as discussed below under "Scope." Within each breaker design type, a variety of sizes were tested. Types and sizes were selected to be representative of circuit breakers used for indoor facility applications on Army installations (i.e., molded-case circuit breakers for low-voltage applications).

An experiment was designed to measure continuous current, current overload, voltages, total current harmonic distortion, and temperature rise in the circuit breakers. Measurements were taken on the circuit breakers and compared with pertinent manufacturer and industry specifications. The findings were then interpreted to offer guidance to Army personnel responsible for maintaining, retrofitting, or designing electrical systems.

Scope

This research focused on differences in the types of circuit breakers tested without respect to any specific manufacturer. All components were purchased from a single manufacturer to eliminate any question of manufacturer-specific differences between one type of breaker and another. GE Co. equipment was selected as the outcome of an open bidding process, not for any design-specific attributes. Because design specifications for common circuit breakers are very similar among major manufacturers, the reader cannot draw any valid conclusions pertaining to the brand of equipment used in this research.

It is useful to repeat here for emphasis that all device designs, frame (physical) sizes, and capacity ratings fall into the category of molded-case, low-voltage circuit breakers.

Mode of Technology Transfer

The results of this research were presented at the U.S. Army Corps of Engineers Electrical and Mechanical Engineer Training Conference, St. Louis, MO, 5–9 June 1995. It is recommended that this information also be communicated to the field through USACPW's *Public Works Digest* and a Public Works Technical Bulletin.

2 Harmonics Overview and Management Issues

Description of the Phenomenon

Harmonics may be defined as a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency. For a 60 hertz (Hz) power system, the 2nd harmonic is 120 Hz, the 3rd harmonic is 180 Hz, the 5th harmonic is 300 Hz, and so on. To understand harmonics it is important to understand the nature of "clean" power. A power source is considered clean when its current and voltage waveforms are pure sine wave, as shown in Figure 1.

A sine wave is the plot over time of the sine of the angle (θ) that a vector (M) rotating at a uniform speed through a full revolution of 360° makes from a start or zero-degree position. This waveform contains only one frequency component, whose period is the time of one rotation (revolution) and whose maximum amplitude is M. The positive

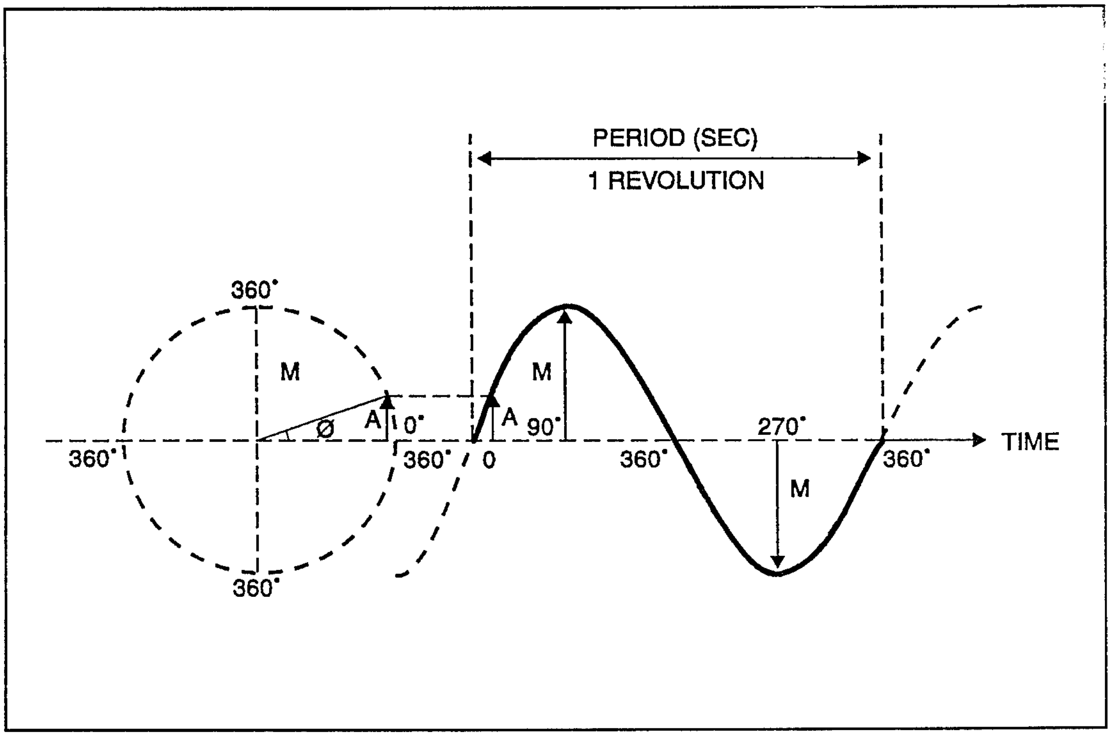
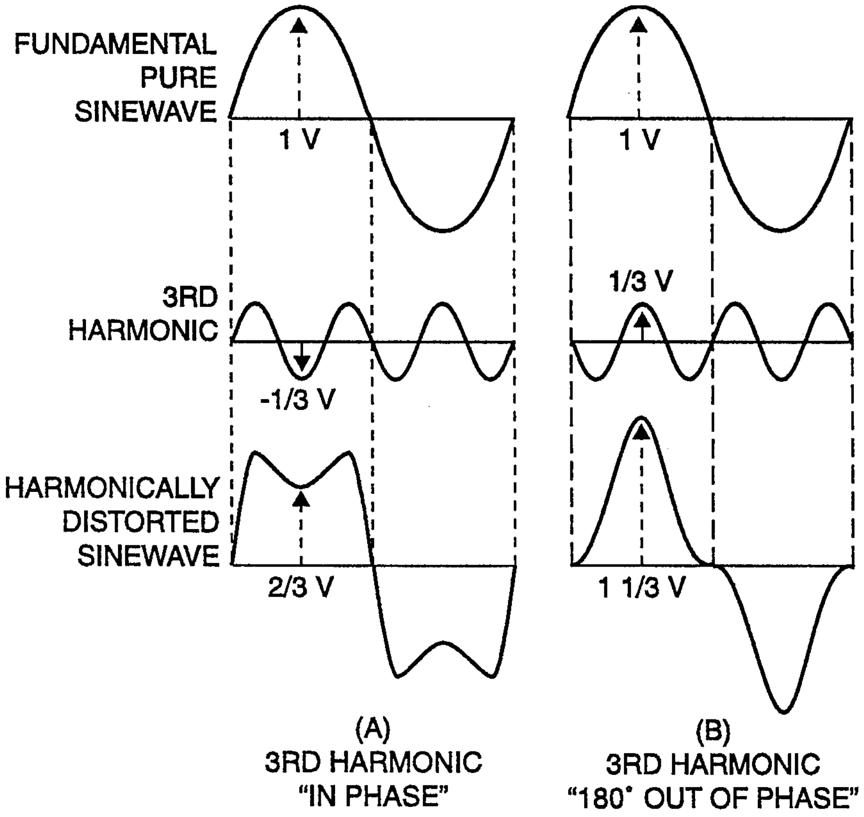


Figure 1. Sine wave.

maximum occurs when θ is 90° (sin 90°=1) and the negative maximum occurs when θ is 270° (sin 270°=-1). Similarly, the amplitude is zero when θ is 0° at the start, at 180° (at half-cycle) and at 360° (at the end of one cycle). Its period is the time it takes for the vector M to complete one revolution. The frequency of this sinusoidal waveform is 1 cycle per period. The frequency of electrical power in the United States is maintained at 60 cycles per second (60 Hz). However, in real power systems, there is always some distortion of voltage and current waveforms. As such, the waveforms are not purely a sine wave. This deviation is equivalent to adding one or more other sine waves of different frequency to the pure 60 Hz sine wave. The sine waves that distort a power system are integral (whole-number) multiples of the fundamental power frequency. These whole-number multiples are called "harmonics" of the fundamental. The distortion caused by adding harmonics to the fundamental sine wave is determined not only by the harmonics frequency, but also by their amplitude and timing (phase relationship) to the fundamental. An example of 3rd harmonic distortion is shown in Figure 2; in Figure 2a the 3rd harmonic is one-third the amplitude and in phase with the fundamental, and in Figure 2b the 3rd harmonic is one-third the amplitude and 180° out of phase with the fundamental.



(A)
3RD HARMONIC
"IN PHASE"

(B)
3RD HARMONIC
"180° OUT OF PHASE"

Figure 2. Harmonic distortion and phase.

The composite waveform in Figure 2a is relatively flat (square) compared to the peaked waveform in Figure 2b. The difference between the two waveforms is due solely to the phase of the 3rd harmonic. Both of the waveforms, however, contain the same frequencies in the same amplitudes, and have the same root mean square (rms) values. The composite waveform shown in Figure 2a is a sine wave whose peaks are clipped by the 3rd (odd) harmonic. Clipping can occur at load saturation—when an increase in voltage does not produce a proportional increase in current, for example. Such nonlinear behavior distorts the current waveform by introduction of odd harmonics, and explains why the many nonlinear loads present in today's power systems are sources of harmonics.

The total harmonic distortion (THD) is defined as the square root of the sum of the squares of rms magnitude of all harmonic voltages or current divided by the square of the amplitude of the fundamental voltage or current, expressed as a percentage. It can be expressed as:

$$THD = \frac{\sqrt{\sum_{n=2}^{N} (V_n)^2}}{V_1} x100 \qquad \text{[Eq 1]}$$

where V_n is the magnitude of harmonics present at harmonic n. THD is the geometric sum of odd and even harmonics, and it is used to quantify the effect of the harmonics on power system voltage or current. THD is a rough measure of how distorted the waveform is (i.e., how much distortion there is in the measured waveform compared to pure sine waveform).

Sources of Harmonics

An electrical load that does not draw current proportional to its applied voltage will generate harmonic currents. There are many such loads within typical military, commercial, and industrial installations. Some generate greater amounts and levels of harmonics than others. Power systems containing nonlinear circuit elements carry currents that are non-sinusoidal (not a pure sine wave) even when the applied voltage is a pure sine wave. In other words, harmonics are generated by any load that draws current which is not proportional to the applied voltage. Most loads are somewhat nonlinear—especially electronic loads, which do not draw continuous current. These loads can be switched on for only part of the cycle, creating considerable harmonic distortion on the power system. Examples of nonlinear loads include:

- static power converters used to control the speed and torque of variable speed motors

- solid state frequency converters that step up 60 Hz to a higher frequency, such as 8500 Hz required for induction heating
- uninterruptible power supplies (UPSs)
- controls for arc welders, furnaces, and ovens
- electronic ballasts and desktop computers.

An important source of harmonics on installations, as noted in Chapter 1, is the static power converter, predominantly used in ASDs. The static power converter changes electrical energy from one form to another by chopping the waveform and reassembling it in a form unique for the required application. This change is made by using solid state devices such as silicon-controlled rectifiers (SCRs) or diodes to periodically energize the conducting circuits of the converter.

ASDs are characterized as a nonlinear load, one in which the load current is not proportional to the instantaneous voltage. The load current is not continuous. It can be switched on for only part of the cycle, as in the inverter, or pulsed, as in the controlled rectifier circuit of the ASD (Figures 3 and 4). ASDs generate harmonic currents.

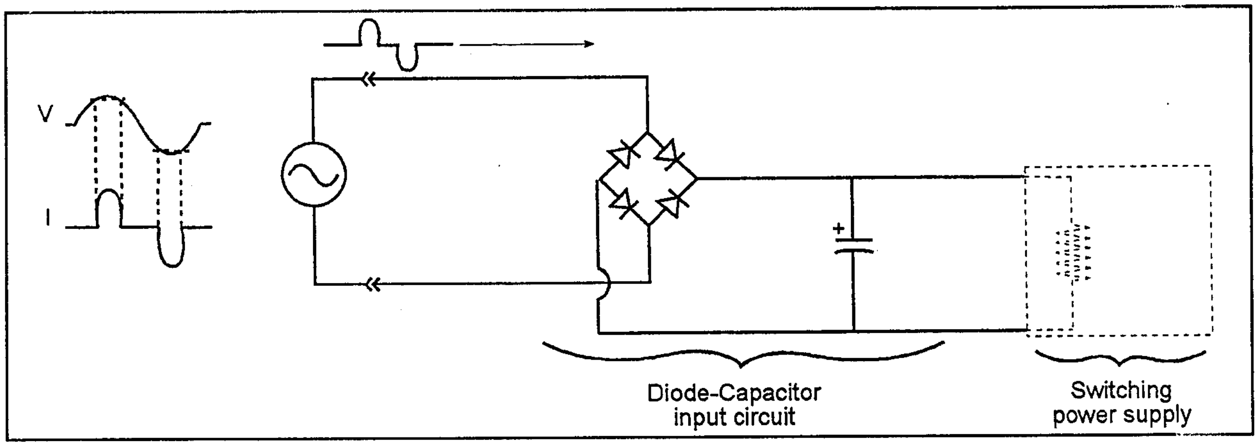


Figure 3. Typical nonlinear load.

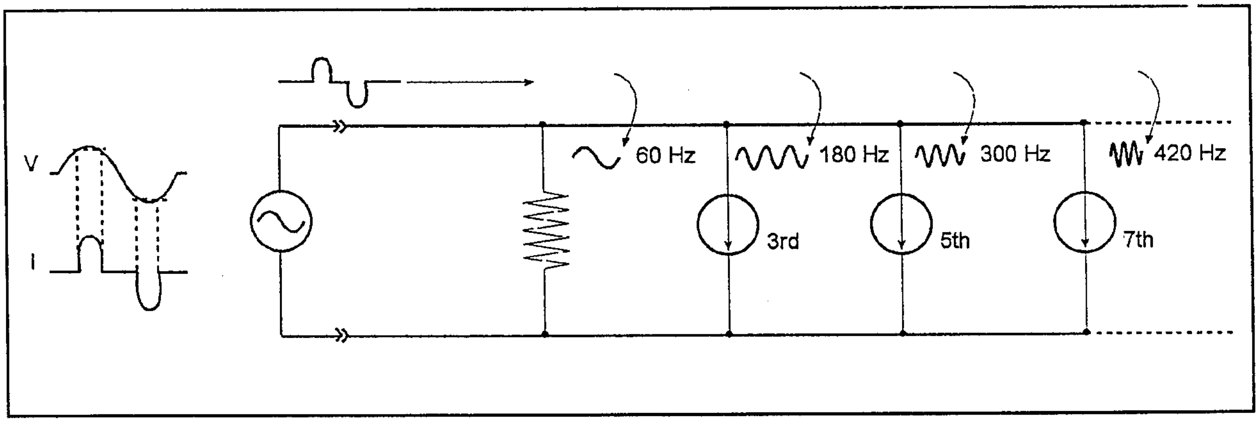


Figure 4. Electrical equivalent of the nonlinear load in Figure 3.

Measurement and Instrumentation

Proper tools are needed to diagnose harmonics problems. Measurements of current and voltage harmonics are essential for the reliable distribution of electric energy. The techniques used for harmonics measurement differ from those used for ordinary power system measurement. The frequency bandwidth of the ordinary measurements of voltage, current, and power can be accomplished with attention to a narrow band of frequencies near the distribution frequency. Substantially wider bandwidths—up to 3 kHz—are required to study power system harmonics. The type of equipment used varies with the complexity of measurements needed. To determine whether a harmonics problem exists, measurement of the true-rms value and the instantaneous peak value of the wave shape is required. For this, a true-rms clamp meter is needed. A handheld digital multimeter that makes true-rms measurements and has a high-speed (1 ms) peak hold circuit also may be used.

"True-rms" refers to the root mean square, or equivalent heating value of a current or voltage shape. The root mean square (rms) is obtained by squaring the waveform, averaging over one period, and taking the square root of the result. "True" distinguishes the measurement from that taken by average-responding meters. Average value is the average of the absolute value of the current or voltage over one period. The vast majority of low-cost portable amperage (amp) clamp meters are average-responding. These instruments give correct readings for pure sine waves only, and will typically read low when confronted with a distorted current waveform. The result is a reading that can be up to 50 percent lower than the actual value. True-rms meters give correct readings for any wave shape within the instrument's crest factor and bandwidth specifications. The crest factor of a waveform is the ratio of the peak value to the rms value. Peak value is the value (i.e., voltage, current) at the peak of a waveform. For a pure sine wave, the crest factor is equal to the square root of 2, or 1.414. A crest factor other than 1.414 indicates the presence of harmonics. The relationship between peak, average, and rms values is important for measurement. Meters that do not give true-rms readings will give incorrect readings when harmonics are present. Therefore, true-rms meters are essential for measuring harmonics. In typical single-phase cases, the greater the difference from 1.414, the higher the harmonic content. For single-phase current harmonics, the typical crest factor is much above 1.414. A single-phase current waveform is shown in Figure 5. Three-phase current waveforms often exhibit the "double hump" waveform shown in Figure 6. For voltage harmonics, the typical crest factor is below 1.414, i.e., a "flat top" waveform. A true-rms meter will have a crest factor specification. This specification relates to the level of peaking that can be measured without errors.

A spectrum (harmonic) analyzer equipped with appropriate measurement capabilities can also be used to measure harmonics. The spectrum analyzer breaks down the voltage or current waveform into all its constituent frequency components and displays them as amplitude versus frequency. The spectrum analyzer is the most convenient instrument to use if a full harmonics analysis is required. It automatically measures the amplitude and percentage of each harmonic and calculates THD.

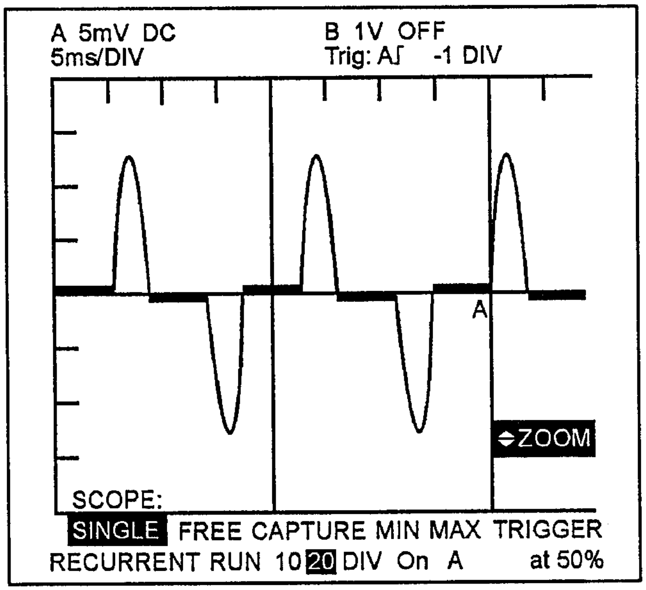

A 5mV DC
5ms/DIV
B 1V OFF
Trig: A∫ -1 DIV
SCOPE:
SINGLE FREE CAPTURE MIN MAX TRIGGER
RECURRENT RUN 10 20 DIV On A at 50%

Figure 5. Single-phase nonlinear load current waveform.

Effects on System and Loads

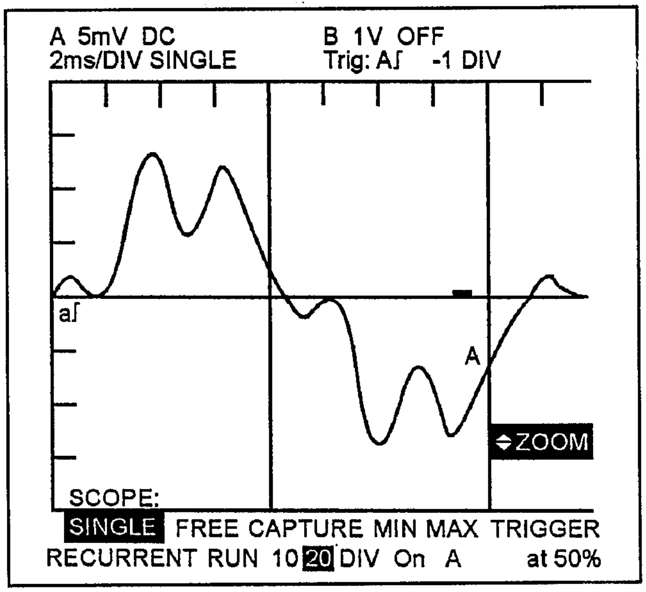

A 5mV DC
2ms/DIV SINGLE
B 1V OFF
Trig: A∫ -1 DIV
SCOPE:
SINGLE FREE CAPTURE MIN MAX TRIGGER
RECURRENT RUN 10 20 DIV On A at 50%

Figure 6. Three-phase nonlinear load current waveform.

The degree to which harmonics can be tolerated is determined by the susceptibility of the load (or power source). The least susceptible type of equipment is heating devices. The most susceptible type is equipment whose design assumes a nearly perfect sinusoidal fundamental input. As noted in Chapter 1, communications and computer equipment are two common types in this category. Falling between these two extremes of susceptibility is the motor load. Most motor loads are relatively tolerant of harmonics.

The negative effects of nonlinear loads and their resultant harmonic currents can show up in several areas of the power system, most commonly in transformers and neutral conductors. Transformers, motors, and standby generators exposed to significant levels of harmonic currents can suffer from serious increases in operating temperature. Excessive current in the neutral conductors not only overheats the conductor—potentially causing insulation damage—but can be reflected back into the three-phase transformer winding as a circulating current, causing additional heat. Since phasecorrection capacitors offer a lower-impedance path to a high-frequency current, they will shunt additional current and generate additional heat. Capacitor failure can result.

Harmonic effects generally can be divided into three categories: *thermal stress* due to current flow; *insulation stress* due to voltage effects, and *load disruption*.

Thermal Stress

The presence of harmonic current increases copper losses, iron losses, and dielectric losses. In general, the resistance of power apparatus increases with frequency. Therefore, the resistance of the apparatus at higher harmonic frequencies is greater than at the fundamental frequency. This variation is due to the "skin effect" inside the conductor of the power apparatus. Harmonic currents cause greater copper losses in the power equipment and loads. Iron losses occur through hysteresis and eddy current loss. The total iron loss is a nonlinear function of frequency and magnetic flux density. In particular, the eddy current losses are proportional to the square of the frequency. In addition, some harmonics—notably the 5th—are negative sequence (i.e., backward rotating) and can give rise to additional losses by inducing higher frequency currents in machine rotors. Also, the high-order harmonics cause heating of power equipment insulation due to voltage stress and corona, and thus increase losses of the insulation system.

Insulation Stress

Insulation stress depends on instantaneous voltage and rate of voltage rise. The presence of voltage harmonics can cause an increase of the voltage crest value, increasing insulation stress. This increase is not of concern in most power system equipment, but capacitor banks are very sensitive to overvoltages and should be protected from overvoltages resulting from harmonics.

Load Disruption

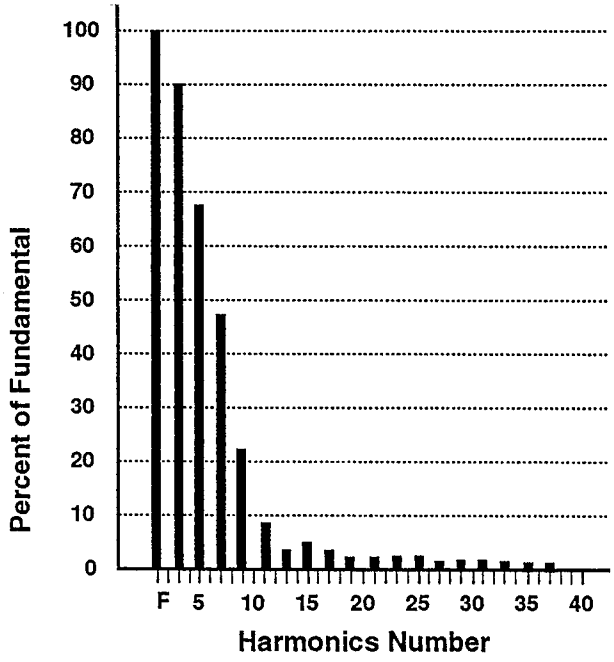
Load disruption is defined as objectionable, abnormal operation or failure caused by voltage distortion. Computers, communications systems, and many other electronic loads are susceptible to load disruption because their normal operation depends on having a pure sinusoidal voltage source.

3 Experiment, Findings, and Discussion

The experiment was performed at the manufacturer's rated supply frequency using a GE (General Electric) model CCB panelboard. Main and branch circuit breakers were individually loaded with a combination of controllable resistive and capacitive loads. The assembled load was rich in harmonics (Figure 7). The circuit breakers were monitored to determine the effects of the harmonics.

Circuit Breaker Selection

Technical characteristics of major circuit breakers under 600 volts (V) currently available in the market are presented in Table 1. This technical information was compiled from the major manufacturers (Westinghouse, GE, Square D Company). The low-voltage circuit breakers, typically of molded case construction, are designed to



Total Harmonic Distortion = 123.3%
Odd Contribution = 123.3%
Even Contribution = 0.7%

3rd:	88.7%	Phase:	192 degrees
5th:	68.5%	Phase:	81 degrees
7th:	44.7%	Phase:	331 degrees
9th:	23.2%	Phase:	225 degrees

Figure 7. Current harmonics for the test set.

Table 1. Manufacturer's circuit breaker specifications.

Circuit Breaker Type	Ampere Rating (RMS)	Max Voltage Rating		Interrupting Ratings (RMS SYM AMPS)			No. Poles	Remarks
			DC	AC	AC	DC		
Molded Case Fixed Thermal Magnetic Trip	15 - 125 100 - 400 15 - 600	120/240 240 480,600	250 - 125 - 500	10kA - 65kA 10kA - 22kA 10kA - 65kA		- 10kA 10 - 20kA	1 - 3 2 - 3 1 - 3	
Molded Case Interchangeable Trip	70 - 225 70 - 1,200	480 600	250 250	22kA - 25kA 18kA - 25kA		10 - 20kA 10 - 20kA	2 - 3 2 - 3	
Molded Case Integrally Fused Thermal Magnetic Trip	15 - 800	600	-	200kA		-	3	
Molded Case Magnetic Trip	3 - 225 3 - 1,200	480 600	250 250	10kA - 100kA 10kA - 100kA		10kA 10kA	2 3	
Solid State Trip	150 - 1,200	600	-	22kA - 42kA		-	3	Digital sensing of true RMS current
Molded Case Ground Fault Circuit Interrupters	15 - 30	240	-	10kA		-	1 - 3	
Molded Case with Shunt Trip	20 - 225	240	-	10-kA		-	1 - 3	
Molded Case Current Limiting	15 - 400	240 480	- -	200kA 150kA		- -	3 3	

sense and trip on rms current. Solid state circuit breakers are designed for true-rms sensing. Their ampere rating ranges from 15 A to 1200 A. The low-amperage breakers are available in single-pole configuration; the high-amperage breakers are available in 3-pole configuration. The UL (Underwriters Laboratories) listed short circuit interrupting ratings (in rms symmetrical amps [A]) range from 10 kA to 200 kA for alternating current (ac) and 10 kA to 20 kA for direct current (dc). The rms symmetrical amps are defined as the envelope of wave peaks that are equal in magnitude (symmetrical) around the zero axis (i.e., the positive half and negative half of the waves are equal in magnitude).

To adequately test and gather enough data on circuit breaker behavior under harmonic conditions, three common types of circuit breakers in various current ratings were tested:

- Thermal-magnetic trip mechanisms. These were rated from 15 A to 50 A, and are used for typical lighting and power loads in the commercial and residential sectors.
- Magnetic-only trip mechanisms. These were rated at 15 A-2P to 50 A-3P[*], and generally are used for motor circuit protection in industrial and commercial power loads.
- Solid state trip mechanisms. These were rated at 150 A-3P and can sense true-rms current under nonlinear loading conditions.

Experimental Apparatus and Loads

Experiments were performed on a General Electric type CCB panelboard, with 12 branch circuit breakers (see Figures 8 and 9). The circuit breakers were tested one at a time and subjected to controllable loads with varying harmonic distortions introduced. Loads equal to 100 percent, 200 percent, 300 percent, and 400 percent of the circuit breaker continuous rms current rating were applied.

Due to the unavailability of a facility capable of handling all the current indicated at full voltage, the applied voltage was stepped down from 208 V ac primary to 20 V ac secondary. At the full voltage level of 208 V, the maximum available current that can be tested at most testing laboratories is 30 A.

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[*] 2P means 2-pole; 3P means 3-pole.

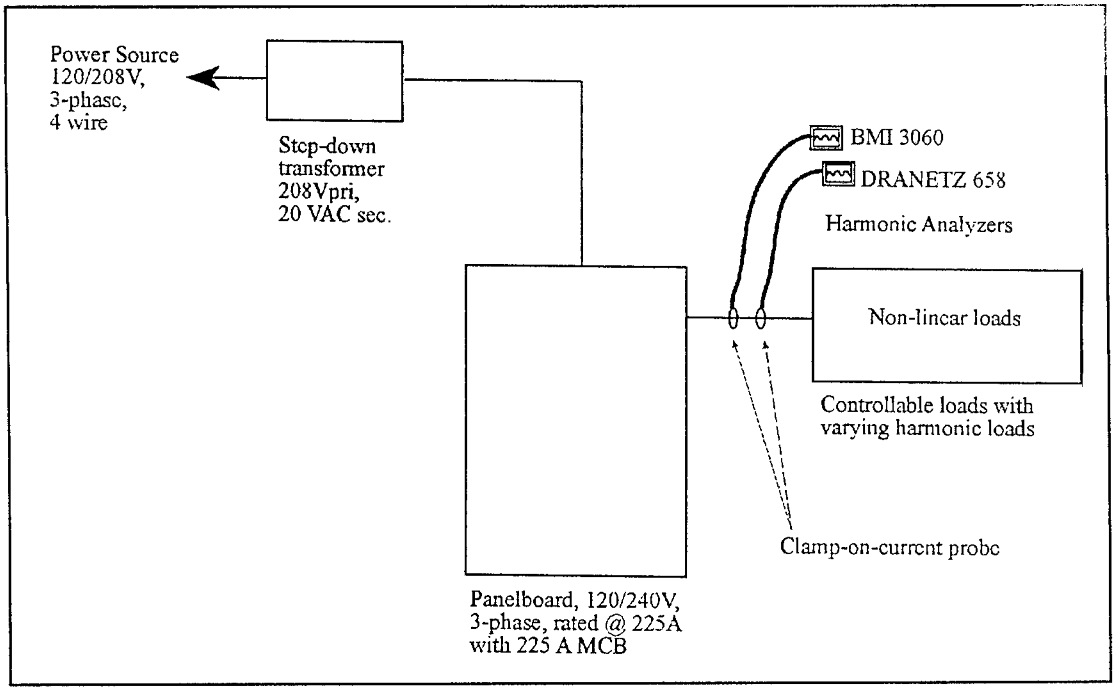

Figure 8. Experimental apparatus.

Since breaker trip time depends on current magnitude, the desired effect of load and harmonic current introduced on the circuit breaker was achieved. Multiple-pole circuit breakers were tested with all of their poles connected in series.

The following categories of data were collected for each circuit breaker tested:

1. rms voltage
2. rms current
3. frequency
4. harmonic current levels
5. waveforms of both current and voltage
6. THD for voltage and current
7. temperatures of the molded case under test conditions
8. breaker trip time.

A low-voltage single phase-rectifier type load with a capacitive input filter was used as the nonlinear load, drawing narrow, discontinuous current pulses with a crest factor of approximately 3 to 1. The test also included variable levels of harmonics. A Dranetz 658 Power Quality Analyzer and a BMI 3060 Power Profiler were used to measure harmonic currents through the attached current probes. Two Fluke 87 handheld multimeters were also used during the bypass through the relay while the desired THD levels and current load were being adjusted.

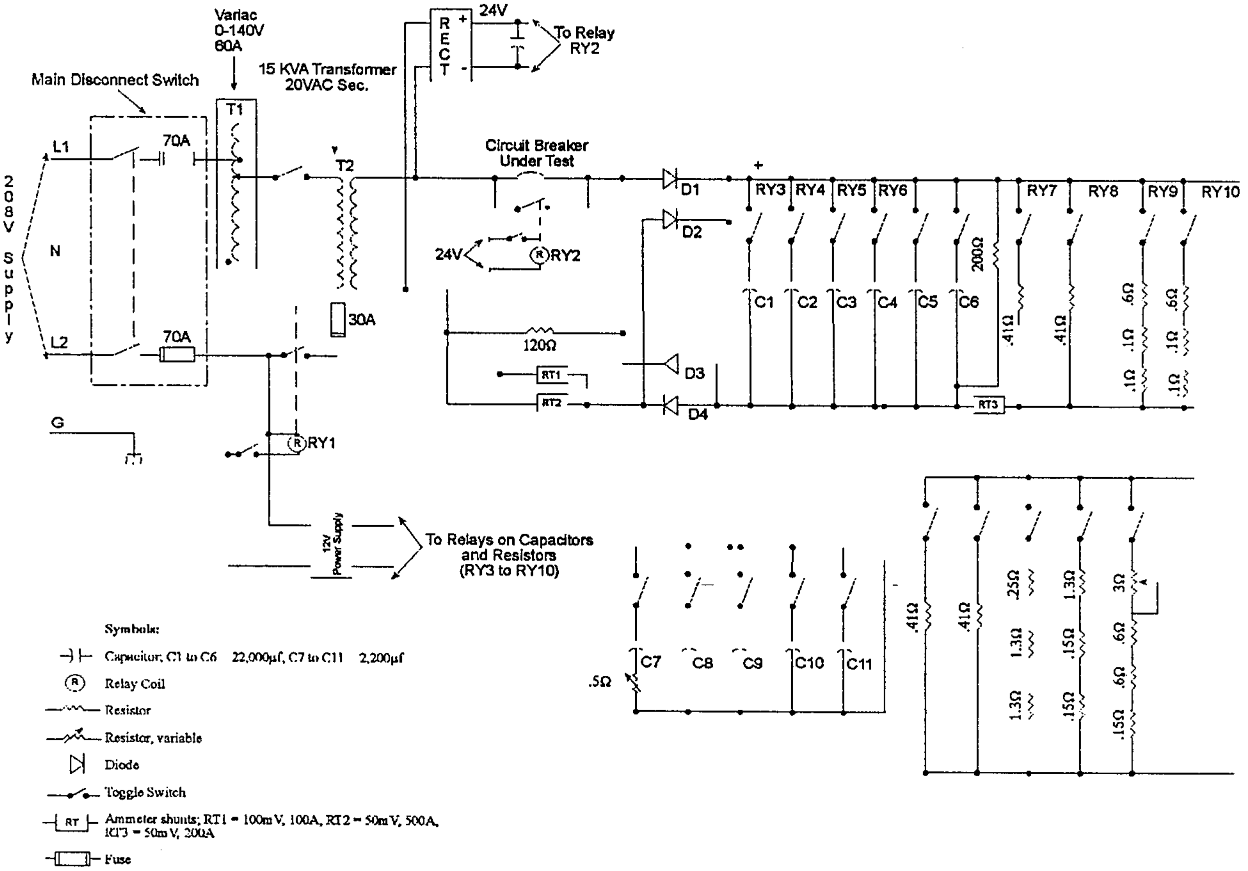

Figure 9. Schematic diagram of the nonlinear load and circuit breaker test setup.

Temperature Observations

The first circuit breaker tested was the 15 A-1P thermal-magnetic type. The temperature rise was found to vary from 1 °F* through 12 °F before the opening or tripping of the circuit breaker. At higher current overloads and variable current THD, the temperature rise ranged from 1 °F to 4 °F. The same observation was recorded for the 20 A-2P and the other thermal-magnetic and solid-state trip type circuit breakers. The entire assembly was not mounted in a temperature-controlled environment; instead,

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* °F = (°C + 17.78) x 1.8

the circuit breakers and the bus bars were installed free-standing outside the panelboard casing. Testing under simultaneous loads on all the circuit breakers could not be performed, so the effect of ambient temperature inside an enclosure was not noted. The temperature rise recorded for the thermal-magnetic and solid state breakers had no significant effect on the tripping time, but did affect the operation of the magnetic-only circuit breakers.

The temperature results for the various circuit breakers are shown in Tables 2 through 7. The temperature rise before tripping was not large for the thermal-magnetic and solid-state types. However, the magnetic-only circuit breakers showed significant temperature increases under harmonic loads.

The magnetic circuit breaker temperature rise was measured starting from the initial temperature, identified as T_1, and continuously recorded for each circuit breaker as the current overload was increased together with the variable current THD (T_2). Under prolonged exposure to harmonic currents, and the consequent rising temperature, the 30 A-3P magnetic-only circuit breaker failed to trip even at high current overload and started to smoke at a recorded temperature of 236 °F. The other magnetic type circuit breakers failed to trip with the introduction of variable current THD and the resulting continuous high temperature. A Raytek Raynger PM 2EM temperature scanner was used to measure temperature rise in the molded case circuit breakers.

Results

Thermal-magnetic and Solid-state Circuit Breakers

The measured trip time for both types of circuit breakers under harmonic conditions and overload (see Tables 2 through 7) did not significantly differ from the manufacturer's test data for linear loads or the applicable National Electrical Manufacturers Association (NEMA) standard for linear loads (see Table 8 for the latter). Under overload conditions, regardless of the harmonics, all of the tested solid-state breakers—and all but one of the thermal-magnetic breakers—tripped within the tolerances shown on the manufacturer's time-current curve. The exception was the thermal-magnetic 50 A-2P breaker which, when subjected to an overload of 150 percent above its continuous current rating and THDs of 50 percent and 125 percent, took longer to trip than specified by the manufacturer's data. For each THD test level, the 50 A-2P breaker took 484.48 and 525.71 seconds, respectively. These results for this one circuit breaker fall outside the manufacturer's trip-time specifications by about 20 percent and 30 percent, respectively.

Table 2. Thermal-magnetic circuit breaker test parameters at 50 percent THD levels.

Circuit Breaker Rating	Continuous Current Rating (amps-rms)	Current Load (%)	Current Load (amps-rms)	Measured Temperature (^{0}F)		Measured Trip Time (seconds)	Time-Current Curve Trip Time (seconds)
				T_1	T_2		
15A - 1 Pole	15	100	15.0	73	85	None	> 1000
		150	22.5	74	82	227.0	60 - 400
		200	30.0	75	81	60.5	25 - 140
		300	45.0	74	78.6	19.69	8 - 35
		400	60.0	75	79.2	10.10	4 - 20
20A - 2 Pole	20	150	30.0	76	84.5	216.31	60 - 400
		200	40.0	81.2	81.5	53.33	25 - 140
		300	60.0	80.9	81.1	18.40	8 - 35
		400	80.0	80.8	81.1	9.41	4 - 20
30A - 2 Pole	30	150	45.0	72.1	95.0	259.69	60 - 400
		200	60.0	74.4	81.0	61.52	25 - 140
		300	90.0	75.0	75.4	20.20	8 - 35
		400	120.0	76.0	81.2	10.30	4 - 20
50A - 2 Pole	50	150	75.0	75.4	116.0	484.48	60 - 400
		200	100.0	86.0	89.1	66.83	25 - 140
		300	150.0	78.7	81.5	20.90	8 - 35

Table 3. Thermal-magnetic circuit breaker test parameters at 125 percent THD levels.

Circuit Breaker Rating	Continuous Current Rating (amps-rms)	Current Load (%)	Current Load (amps-rms)	Measured Temperature (⁰F) T₁	Measured Temperature (⁰F) T₂	Measured Trip Time (seconds)	Time-Current Curve Trip Time (seconds)
15A - 1 Pole	15	150	22.5	73	83.6	197.0	60 - 400
		200	30.0	74	80.5	58.09	25 - 140
		300	45.0	76.5	77.0	20.09	8 - 35
		400	60.0	76.0	78.3	10.68	4 - 20
20A - 2 Pole	20	150	30.0	70.5	84.7	297.54	60 - 400
		200	40.0	78.2	79.8	57.19	25 - 140
		300	60.0	77.6	78.2	19.87	8 - 35
		400	80.0	77.0	77.7	10.98	4 - 20
30A - 2 Pole	30	150	45.0	78.5	89.5	201.03	60 - 400
		200	60.0	74.7	78.5	63.98	25 - 140
		300	90.0	77.2	78.8	21.30	8 - 35
		400	120.0	77.6	78.9	11.83	4 - 20
50A - 2 Pole	50	150	75.0	83.6	113.3	525.71	60 - 400
		200	100.0	83.3	89.4	72.68	25 - 140
		300	150.0	81.0	82.5	23.04	8 - 35

Table 4. Thermal-magnetic circuit breaker test parameters at various current THD levels.

Circuit Breaker Rating	Continuous Current Rating (amps-rms)	Current Load (%)	Current THD Level (%)	Current Load (amps-rms)	Measured Temperature (^{0}F)		Measured Trip Time (seconds)	Time-Current Curve Trip Time (seconds)
					T_1	T_2		
20A - 1 Pole	20	80	175.1	16	71	81	None	Infinite
		100	170.4	20	76	83	None	> 1000
		112.8	176.1	22.56	81	86	335	300 - 400
		143.5	171.0	28.70	76	80	220	100 - 400
		157.0	155.0	31.40	82	86	132	50 - 300

Table 5. Magnetic-only circuit breaker test parameters at various current THD levels.

Circuit Breaker Rating	Current Trip-Set Position (amps-rms)	Current Load (%)	Current Load (amps-rms)	Current THD Level (%)	Measured Temperature (^{0}F)		Measured Trip Time (seconds)	Time-Current Curve Trip Time (seconds)
					T_1	T_2		
30A - 3 Pole	90	50	45.0	50.8	76.3	130	None after 2184.21 sec.	None
	90	101.78	91.6	50.5		160	None	Instantaneaous
	90	111.10	100.0	60.4		190	None	Instantaneous
	90	122.22	110.0	68.4		193	None	Instantaneous
	90	134	120.6	62.3		205	None	Instantaneous
	90	158.89	143.0	51.4		236	CB started to smoke after 3290.91 sec.	Instantaneous

NOTE: Magnetic breaker set at 300 percent of the breaker ampere rating for test purposes. In actual application, the setting of the magnetic trip is determined as a function of the load.

Table 6. Magnetic-only circuit breaker test parameters at various current THD levels.

Circuit Breaker Rating	Current Trip-Set Position (amps-rms)	Current Load (%)	Current Load (amps-rms)	Current THD Level (%)	Measured Temperature (^{0}F)		Measured Trip Time (seconds)	Time-Current Curve Trip Time (seconds)
					T_1	T_2		
30A - 2 Pole	90	88.9	80.0	50	70	83	None	None
	90	99.0	89.1	50		88	None	None
	90	100	90.0	100		95	None	None
	90	100	90.0	125		100	Instantaneous	None
	90	101.44	91.3	50		110	None	Instantaneous
	90	104	93.6	100		148	None	Instantaneous
	90	113.33	102.0	93.1		150	None	Instantaneous
50A - 2 Pole	180	100	180	5	72	75	Instantaneous	Instantaneous
	180	101.33	182.4	43.4		92	None	Instantaneous
	180	110.00	198.0	113.5		114	None	Instantaneous
	180	110.56	199.0	96.6		117	None	Instantaneous
	180	125.00	225.0	95.3		119	None	Instantaneous

NOTE: Magnetic breaker set at 300 percent of the breaker ampere rating for test purposes. In actual application, the setting of the magnetic trip is determined as a function of the load.

Table 7. Solid state circuit breaker test parameters at various current THD levels.

Circuit Breaker Rating	Continuous Current Rating (amps-rms)	Current Load (%)	Current THD Level (%)	Current Load (amps-rms)	Measured Temperature (^{0}F)		Measured Trip Time (seconds)	Time-Current Curve Trip Time (seconds)
					T_1	T_2		
150A - 3 Pole	150	150	107	225	72	73	Instantaneous	Instantaneous
	150	150	50	225		74	Instantaneous	Instantaneous
	150	200	97	300		78	Instantaneous	Instantaneous
	150	200	52	300		81	Instantaneous	Instantaneous
	150	300	80	450		84	Instantaneous	Instantaneous

Magnetic-only Circuit Breakers

The magnetic-only circuit breakers failed to trip most of the time in the presence of varying harmonic currents and sustained overload. The comparison between the established manufacturer's trip time and the measured data is shown in Tables 6 and 7. The 30A-3P rating, when tested for more than 30 minutes under varying harmonic current loads and continuous current overloads, failed to trip even after smoke started to come out of the molded case. The test for this particular circuit breaker was aborted to avoid a possible fire.

Table 8. NEMA standard for automatic tripping time at 200 percent of the marked current rating.

Current (in Amperes)	Maximum Time To Trip (in Seconds)
0 - 30	120
31 - 50	240
51 - 100	360
101 - 150	480
151 - 225	600
226 - 400	720
401 - 600	840
601 - 800	1080
801 - 1000	1200
1001 - 1200	1440
1201 - 1600	1560
1601 - 2000	1680
Over 2000	1800

Source: NEMA Standard Pub. No. AB-1-9-1989.

Interpretation of Results

Applicability of Industry Literature

Manufacturer's literature and industry standards are not clear on the effects of harmonic loads on circuit breakers. Specific, controlled test data on circuit breakers operating under harmonic loads are not available from major component manufacturers or testing laboratories. Furthermore, there currently are no industry standards for the level of harmonic currents that circuit breakers are required to interrupt or to carry. Nevertheless, some available industry publications offer insight into the results of this experiment.

Effects of harmonics have been discussed in several standards and technical publications (e.g., IEEE 519-1992; UL 489; General Electric GET-2779J 1092 BL; Square D Class 601 and Class 602). The GE publication notes different effects that occur at frequencies above 60 Hz—one effect in thermal-magnetic breakers and one in magnetic-only breakers. In thermal-magnetic devices, the bimetal element that provides overload protection responds accurately to harmonic currents. However, the instantaneous-trip element in magnetic-only breakers—a solenoid constructed of copper and steel—becomes hot. This raises the temperature of the breaker, which in turn reduces the continuous-current rating of the device. The instantaneous-trip solenoid becomes hot because of the nature of its construction and materials. In addition to adding heat to the breaker, the solenoid does not respond to the current correctly. The higher the harmonic frequencies, the less accurate is the response. At nominal system frequencies less than 50 Hz but greater than direct current, solid-state trip devices become inoperative due to sensor saturation. Thermal-trip devices remain accurate, but instantaneous-trip solenoids lose accuracy. Square D Class 602 publication (Electronic Trip Molded Case Circuit Breakers) states that harmonically distorted waveforms do not adversely affect rms-sensing devices. The enhanced accuracy of rms sensing results in a more accurate representation of the harmonic heating effects on the system.

Under harmonic conditions, the three types of circuit breakers tested in this study responded as described above.

The Role of Circuit Breaker Construction

The fundamental circuit breakers are thermal-magnetic in tripping action. The current path within the breaker is through a bimetallic strip; the electrical resistance of the bimetal produces heat, which causes the bimetal to bend until it moves far enough to unlatch the mechanism and allow the breaker to trip open (Figure 10). For high-fault currents, however, this thermal action is too slow. To respond to high-fault currents a solenoid magnet—also in the current path within the breaker—attracts a magnetic armature to unlatch and trip the breaker. This magnetic tripping mechanism is illustrated in Figure 11. The thermal action provides inverse time response. That is, a small overload takes a long time to heat the bimetal and trip the breaker. As the overload increases, the heating and tripping time is reduced. The larger the current, the shorter the tripping time, until the current reaches the setting of the magnetic trip.

Magnetic trip response is instantaneous; it either trips without delay or does not trip at all. The result is shown in the time-trip curve for a typical instantaneous magnetic-

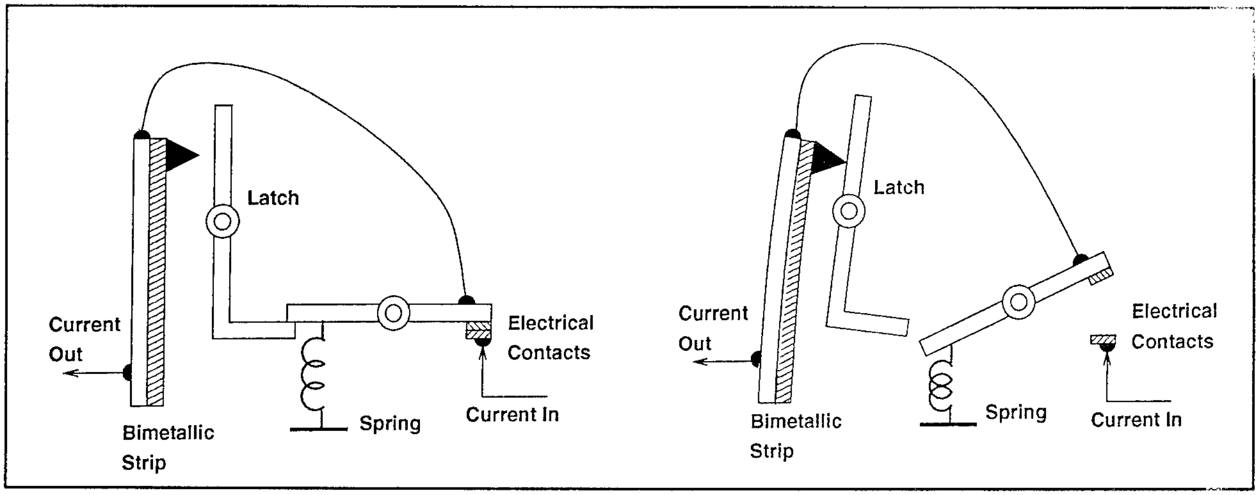

Figure 10. Bimetal thermal-trip mechanism.

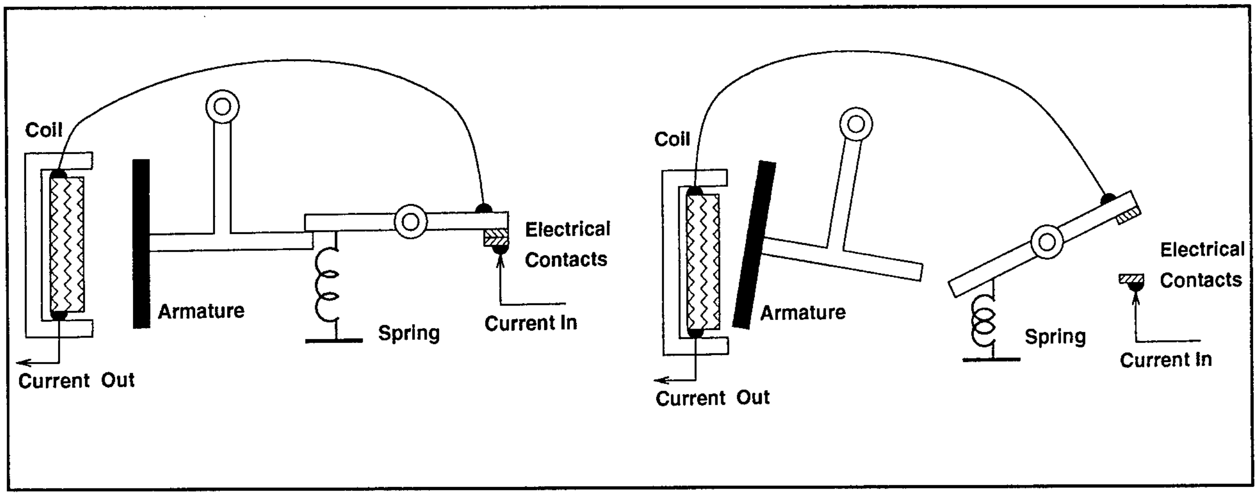

Figure 11. Instantaneous magnetic-trip mechanism.

trip mechanism used in molded-case circuit breakers (see Figure 12). The actual inverse time overcurrent portion of the trip curve can fall anywhere between the maximum and minimum tolerance limits shown, because friction between the bimetal and trip latch may vary, and because of manufacturing tolerances. The instantaneous pickup tolerances are given for high and low limits. When instantaneous tripping occurs, total clearing time can be up to a maximum of about one cycle, with a minimum

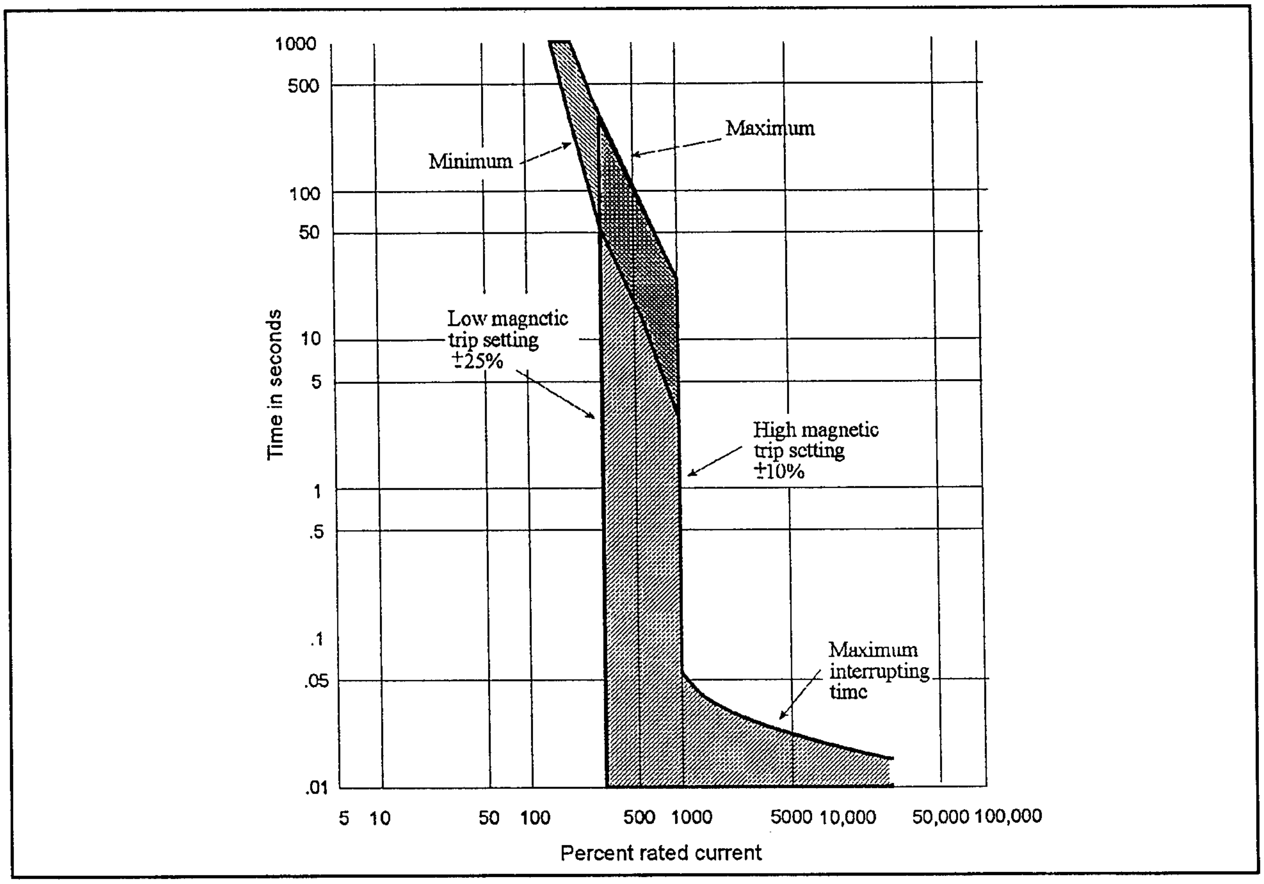

Figure 12. Time-current curve for magnetic-only trip element.

dependent on the breaker physical inertia, and the current and voltage to be interrupted. The tripping characteristic for overcurrent protection is designed toprovide continuity of power as long as feasible without damaging the insulation on conductors.

As the breaker contacts part, an arc is established. The fast-moving contacts stretch the arc, moving it by thermal and magnetic forces into the arc chute, where plates divide the arc into multiple segments and cool the ionized gases. The first time the alternating current wave reaches zero, the arc is extinguished. The entire process takes about a half-cycle. This deionizing principle governs the operations of all molded-case breakers. Thermal-magnetic circuit breakers are available in continuous rating from 15 A-1P up to 2500 A-3P (or larger). However, in frames (standard physical size categories) that accommodate over 1200 A, the solid-state trip unit has almost completely replaced the thermal-magnetic trip. In frames 400 A to 1200 A, solid-state trips and thermal-magnetic trips are both common.

Solid-state circuit breakers typically consist of a current transformer for each phase, printed circuit board, and a shunt trip. The transformers monitor current and reduce it to the required ratio for direct input into the printed circuit board. The circuit board interprets current flow information, makes trip decisions based on predetermined parameters, and signals the shunt trip unit to trip the breaker. The microprocessor-based solid-state circuit breaker works by directly measuring the true rms content of the current flowing through the circuit breaker. This is accomplished by microprocessor digital sampling techniques. Sampling techniques are designed to measure the rms magnitude of the current waveform up to several times (e.g., 27 to 33 times) per cycle on a 60 Hz system as the current flows through the circuit breaker. After sampling the waveform of each cycle, the microprocessor logic calculates the true rms current flowing through the circuit breaker. This technology provides a very accurate computation of the harmonic content in the system, so the microprocessor-based trip unit provides a more realistic view of the conditions in a particular circuit. Also, rms sensing correlates better with the thermal characteristics of conductors and equipment —a key issue in circuit protection. In a typical microprocessor-based breaker, its digital trip unit action, as shown in Figure 13, begins with analog inputs that are transmitted simultaneously to an analog-to-digital converter. The converted data are then sent to a computer chip within a central processing unit. There the data are continuously scanned and updated. Based on real-time *in situ* input, as opposed to a predetermined set of parameters such as time and current, the processor decides whether to initiate the trip signal to the shunt trip. The trip curve for a solid-state circuit breaker (Figure 14) actually is described as a band rather than a curve. Adjustability of the trip unit allows movement of its trip curve in the horizontal and vertical directions. A solid-state trip unit can be adjusted to actually change the shape of the trip curve.

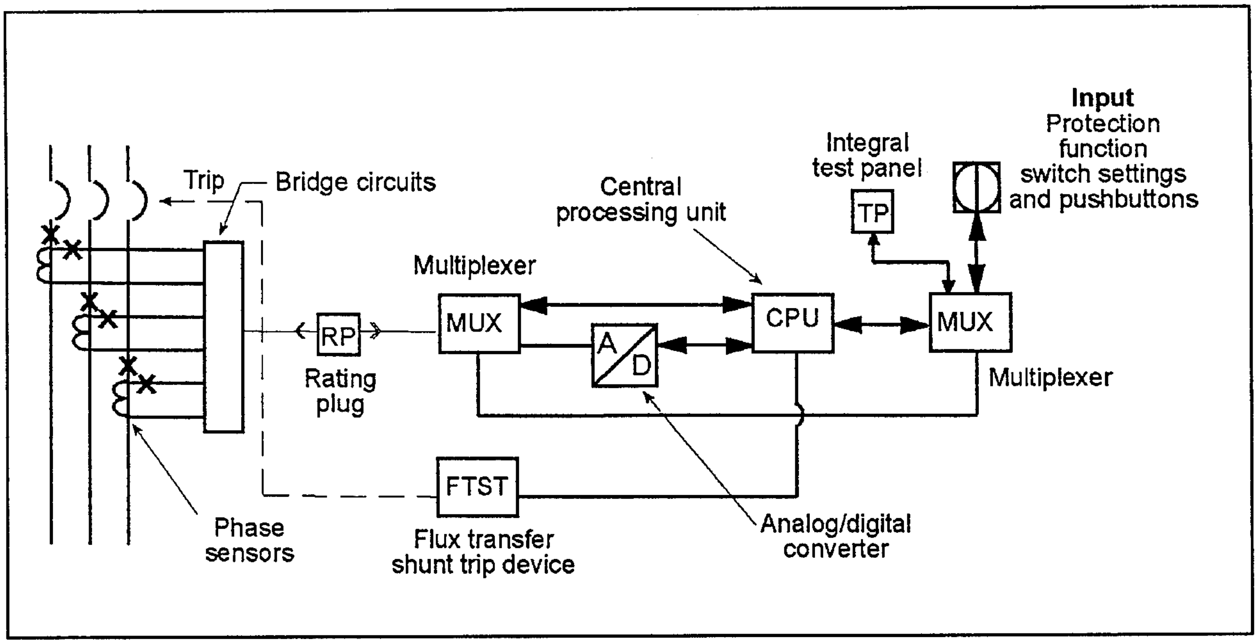

Figure 13. Schematic of a solid state circuit breaker.

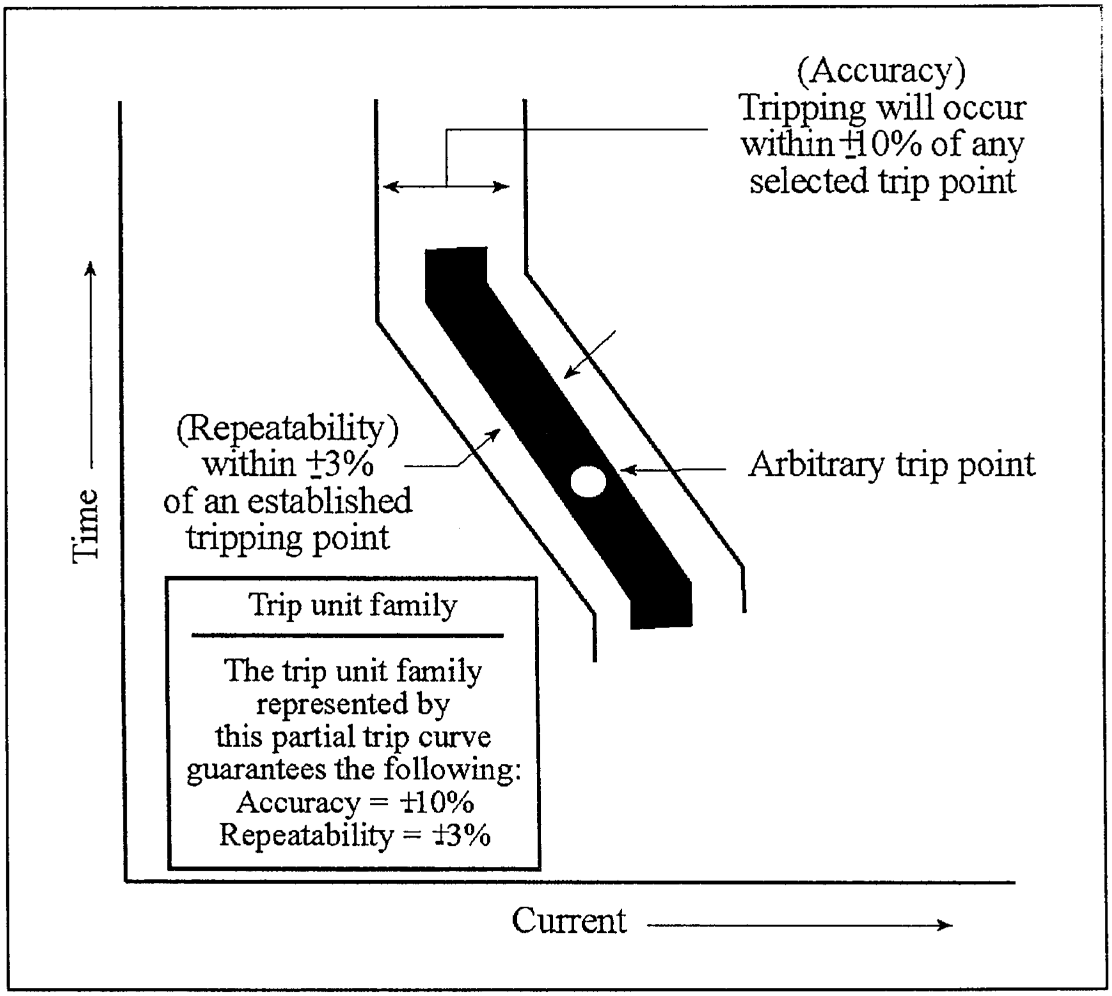

Figure 14. Typical solid-state trip time-current curve.

4 Conclusions and Recommendations

Conclusions

No nuisance tripping was detected for any of the circuit breakers subjected to the experimental overload and harmonic conditions. However, this experiment has shown that the tripping of different types of circuit breakers may vary under harmonic loading conditions:

- All tested solid-state circuit breakers performed within the manufacturer's specifications for linear loads.
- All of the tested thermal-magnetic circuit breakers tripped under the experimental loading conditions, but the 50 A-2P took about 20 to 30 percent longer to trip than specified in the manufacturer's tolerances for linear loads.
- The magnetic-only circuit breakers failed to trip under harmonic loads where the rms current exceeded the breaker's low trip set point, and one specimen presented a fire hazard.

Even in the absence of industry literature directly pertaining to the effects of harmonic loads on circuit breakers, a review of other related literature indicates that each type of circuit breaker has inherent design characteristics that can plausibly explain the observed experimental results:

- Solid-state breakers use a microprocessor-based true-rms sensor, which responds quickly and accurately to the actual conditions within a circuit or equipment.
- Thermal-magnetic breakers use a bimetal heat-sensing element that responds accurately to molded-case temperature increases regardless of whether the magnetic instantaneous-trip element works under the same circuit conditions.
- The magnetic-only breakers use a copper/steel solenoid that tends to overheat under moderate overloading conditions as harmonics increase, raising case temperature and preventing the trip-mechanism from working.

Recommendations

On existing electrical systems, the following practices are recommended:

- A comprehensive inspection of all magnetic-only circuit breakers should be conducted to ensure that they are not loaded with harmonics-generating equipment.
- If harmonic loads are present, ensure that protection on current overload is provided, such as overload relays or heaters in combination starters.
- Monitor any unusual temperature rises found on circuit breakers operating under normal loading conditions.
- Immediately address any measured temperature rise that exceeds the manufacturer's specifications; failure to do so could result in fire, or damage to conductors, insulation, or loads.
- Consider installing harmonics-mitigating devices to reduce the amount of harmonics introduced into circuit breakers.

To reduce harmonics-related temperature rise in molded case circuit breakers, both in existing and new systems, it is recommended that the DPW maintain compliance with the National Electrical Code pertaining to the applicable derating factors.

On new systems, it is recommended that the designer consider the amount of harmonics potentially generated by the planned load and apply a properly specified mitigating device, or specify equipment with a built-in capability to limit harmonics.

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