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Measurement Procedure for Time-Varying Gradient Fields (dB/dt) for Magnetic Resonance Imaging Systems

NEMA

NATIONAL ELECTRICAL MANUFACTURERS ASSOCIATION ■ 2101 L STREET, N.W., WASHINGTON, D.C. 20037

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MEASUREMENT PROCEDURE FOR TIME-VARYING GRADIENT FIELDS (dB/dt) FOR MAGNETIC RESONANCE IMAGING SYSTEMS

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Foreword

Unless otherwise noted, this NEMA Standards Publication has been approved as a NEMA Standard. It describes how the test conditions and parameters which ensure that worst case dB/dt values of the time varying gradient fields used for patient exposure regions in magnetic resonance imaging (MR) are measured. It determines the maximum dB/dt that the gradient system produces when using pulsed waveforms. Magnetic field vectors associated with gradients useful to MR are parallel to the static magnetic field. If the static field lies along z, then the time-varying gradient fields necessary to MR are the dB_z/dt components produced by the x, y, and z gradients. Since the divergence of the time-varying B fields must be zero, components other than z must exist. However, it is assumed that in the region most likely to be occupied by the patient dB_x/dt and dB_y/dt are small compared to dB_z/dt. This standard applies only to the measurement of dB_z/dt. Unless otherwise noted, dB/dt in this document will be taken to mean dB_z/dt. This document does not address time-varying fields produced by radiofrequency coils.

Introduction

In magnetic resonance (MR) imaging, magnetic field gradients are employed for spatial encoding. These time-varying magnetic fields induce currents in the body of the patient. Such currents could stimulate nerve and muscle cells and present a hazard (e.g., ventricular fibrillation) if the current densities and pulse widths exceeded certain thresholds. It is imperative to ensure that the induced currents do not compromise patient safety. The largest currents induced in the body result from gradient waveforms whose rates of change are greatest. The Maximum Gradient Rate (MGR) is defined as the greatest dB/dt that a gradient coil and gradient amplifier set are capable of producing. This is not a likely condition for most clinical imaging sequences but is representative of a worst case. The worst case dB/dt produced under clinical imaging conditions is defined as the Maximum Clinical Rate (MCR). For those systems employing sinusoidal gradients such as echo-planar imaging, a Maximum Sinusoidal Rate (MSR) measurement procedure is defined. The MSR measurement procedure determines the worst-case dB/dt from the sinusoidal gradients. The MGR, MSR, or the MCR shall be measured and reported. The choice of using the MGR, MSR, or the MCR is left to the discretion of the user.

Rationale

Currents induced in the body are proportional to the derivative of the gradient waveform (dB/dt). If the static magnetic field lies along z, then this standard assumes that dBz/dt will be much larger than dB_x/dt and dB_y/dt in the region occupied by the patient. Therefore dB_x/dt and dB_y/dt components are neglected. The terms dB/dt and dB_z/dt will be taken to be equivalent for safety purposes. Nerve and cardiac stimulation depend upon induced electric field amplitudes and on the orientation of the electric field. Electric fields in turn depend upon dB/dt and patient geometry (cross-sectional area). Smaller patients should have higher dB/dt stimulation thresholds. The pulse width, τ, is defined as the full width at half maximum in microseconds of a single dB/dt pulse or the half period of a sinusoidal dB/dt waveform. The parameters required to characterize dB/dt safety include the amplitude of the dB/dt waveform and the pulse width. Both cardiac and peripheral nerve stimulation thresholds follow a strength-duration curve. The dB/dt amplitude, R, required for threshold stimulation may be expressed as:

$$R = \frac{R_O}{1 - \exp^{(-\frac{\tau}{k})}}$$

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Here R_o is the rheobase or infinite pulse width stimulation threshold and K is the time constant. Time constant and rheobase vary as functions of pulse shape and number of pulses in relation to induced membrane charge. Induced current and electric fields also vary as functions of patient orientation with respect to the direction of the dB/dt vector, normally parallel to the static field. If the long axis of the patient is parallel to the static field, then currents induced in the body flow in axial cross sections. If the static field is parallel to the patient's Anterior-Posterior direction, then currents induced by the gradients flow in coronal cross sections. If the static field is lateral, then currents induced by the gradients flow in sagittal cross sections. In each case eddy current loop areas and circumferences differ, resulting in different threshold values for stimulation. The result is that, depending upon the orientation of the static field relative to the body, similar dB/dt levels may not provide an equal margin of safety.

Three methods for measuring dB/dt are specified in this NEMA Standards Publication; namely the Maximum Gradient Rate (MGR), Maximum Sinusoidal Rate (MSR), and the Maximum Clinical Rate (MCR). Values of dB/dt measured by the MGR method are not typical for most clinical imaging sequences but are representative of the worst case that could be produced by the MR system in the region occupied by the patient (patient space). Similarly, the MSR method measures the worst-case dB/dt values for imaging techniques using sinusoidal gradient waveforms such as in echo-planar imaging. For clinical imaging conditions, MCR represents the worst case dB/dt actually experienced by the patient. Typically, MGR or MSR measurements are easier to perform, while MCR measurements are more representative of clinical imaging. A search algorithm, explained in section 2.2.4 or 2.3.5., is used to find the approximate position of maximum dB_z/dt in the patient space of the imager. Such an algorithm simplifies the search procedure and defines the region which may be occupied by the patient.

Scope

This NEMA Standards Publication describes three procedures for measuring maximum dB_z/dt generated by whole-body gradient coils in diagnostic magnetic resonance imaging systems: the Maximum Gradient Rate (MGR), the Maximum Sinusoidal Rate (MSR), and the Maximum Clinical Rate (MCR). This document does not address time-varying fields produced by radiofrequency coils.

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Section 1
REFERENCED STANDARDS AND DEFINITIONS

1.1 REFERENCES

No standards are referenced herein.

1.2 SEARCH COIL

The search coil is a small diameter coil used to measure gradient field rates of change.

1.3 MAGNET ISOCENTER

Magnet isocenter, normally defined by magnet geometry, is the zero crossing for all three gradients in this document.

1.4 PATIENT SPACE RADIUS, ρ

The patient space radius is the distance from magnet isocenter to the patient table (without pads) along the lines (see Figure 1-1).

1.5 dB/dt PULSE WIDTH, τ

The pulse width, τ, is defined as the full width at half maximum in microseconds of a single dB/dt pulse or the half period of a sinusoidal dB/dt waveform (see Figure 1-2).

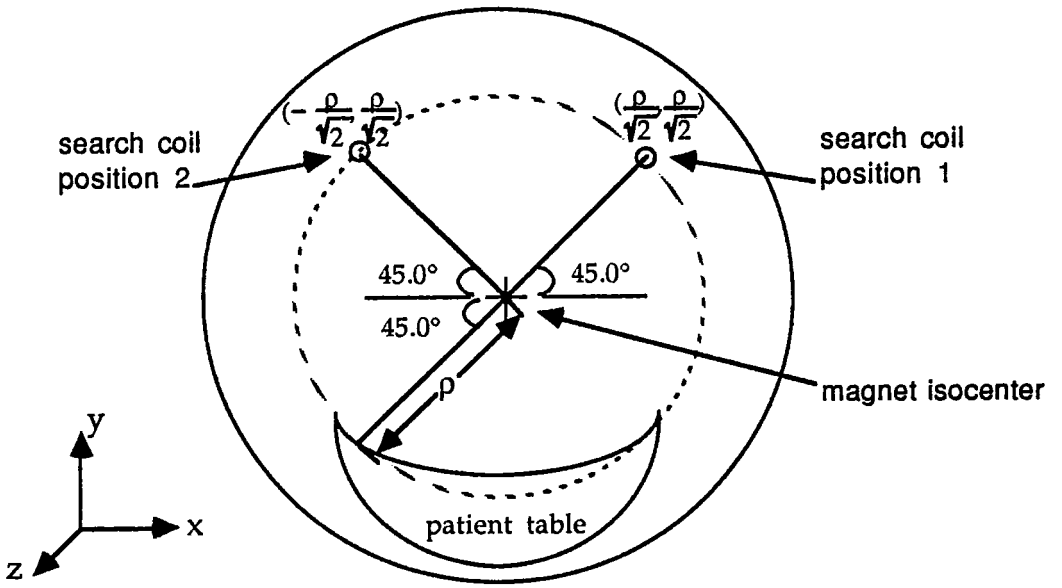
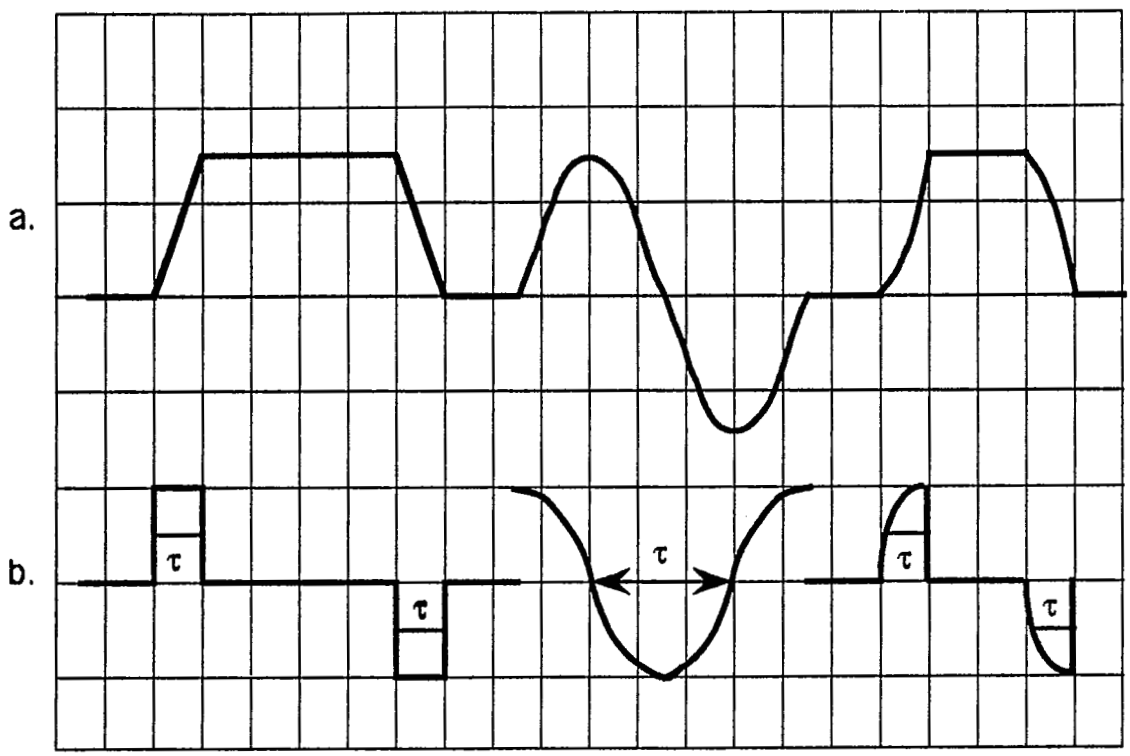


Figure 1-1
SEARCH COIL PLACEMENT

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a. Gradient Waveforms
b. dB/dt Waveforms

Figure 1-2
GRADIENT AND DB/DT WAVEFORMS

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Section 2
METHODS OF MEASUREMENT

2.1 TEST HARDWARE

2.1.1 Search Coil

The search coil shall be circular and shall be small with respect to the gradient coils under test to ensure accuracy. The search coil consists of n turns of wire with a radius of r meters. The axial length of the coil shall be less than 20% of its diameter. The search coil shall be no more than 0.05 meters in diameter. The response of the search coil shall be determined by calculation. The instantaneous magnitude of the component of dB/dt (in tesla/second) coaxial with the search coil shall be determined from the peak voltage, V, induced in the coil by the time-varying magnetic flux:

$$\left|\frac{dB}{dt}\right| = \left|\frac{V}{n\pi r^2}\right|$$

For example, a typical coil would consist of 15 turns of #20 AWG copper wire wound on a form of 0.025 meters radius resulting in a circular coil approximately 0.008 meters long. An induced voltage of 0.200 volts would be indicative of a dB/dt = 6.79 tesla/sec coaxial with the search coil.

2.1.2 Voltage Measurement Device

The device used to measure voltage induced in the search coil shall have a high input impedance and sufficient bandwidth to prevent signal attenuation, e.g., a storage oscilloscope.

The search coil should be connected to the voltage-measurement device by means of a high inductance cable, e.g., a twisted pair to avoid ringing on the waveform that may be experienced with coaxial cables.

2.1.3 Positioning Device

A means shall be provided for positioning and aligning the search coil in the magnet in a stable and reproducible manner. The device shall permit positioning of the search coil throughout the region normally occupied by the patient while maintaining the search coil coaxial with the static magnetic field.

2.2 MGR MEASUREMENT

2.2.1 Turn off or maximally attenuate the radiofrequency (RF) transmitter to prevent interference.

2.2.2 Position the search coil in the MR scanner using the positioning device so the search coil axis is aligned with that of the static magnetic field, regardless of patient orientation.

2.2.3 Begin simultaneous pulsing of all three gradients using the maximum amplitude bipolar gradient waveform (Figure 2-1). The transition times t_1, t_2, t_3, and t_4 shall be the minimum that the system can generate using the standard pulse sequence generation software and hardware used by the manufacturer. The amplitudes, A_{+max} and A_{-max}, are defined as the maximum gradient strength that can be generated by the system under normal operating conditions as stated above.

2.2.4 Move the search coil to locate the position of the maximum induced voltage that can be found within the region of the machine ($y = \pm x$) normally occupied by a patient. Once this position is established, the coil shall be immobilized to prevent movement-induced voltage from interfering with the measurement. For example, the following procedure locates the approximate position of maximum dB_z/dt in the patient space of the imager with an axial field magnet and whole-body gradient coils. Consider a cartesian coordinate system with the *Z* axis pointing in the direction of the static field and the *Y* axis pointing vertically (e.g., as in Figure 1-1). For the MGR procedure, the points of maximum dB/dt will occur where each of the gradients is near maximum and all the gradient fields add. Typically, this is near the maximum winding density for the coil and near the wall of the bore forandgradients. Assume that the distance, ρ, from the magnet isocenter to the patient table along the lines $y=\pm x$ is the same as the maximum distance the patient may extend above magnet isocenter along the lines Then the maximum dB/dt value is located at the points

$$\left(\pm\frac{\rho}{\sqrt{2}}, \frac{\rho}{\sqrt{2}}, Z_m\right)$$

Where:

Z_m= coordinate of maximum dB_z/dt

Assuming all three gradients are applied simultaneously and with equal amplitudes, the highest induced voltages will be found near the walls of the magnet shroud near the ends of the gradient coils along the lines $y=\pm x$ (see Figure 1-1). Search coil position 1 in Figure 1-1 is located at

$$Y = X = \frac{\rho}{\sqrt{2}}$$

Similarly, search coil position 2 is located at:

$$Y = -X = \frac{\rho}{\sqrt{2}}$$

Place the search coil coaxial with the static magnetic field at position 1 and constrain the search coil so it may move only in the ±Z directions. Move the coil in the ±Z directions to the position where the maximum

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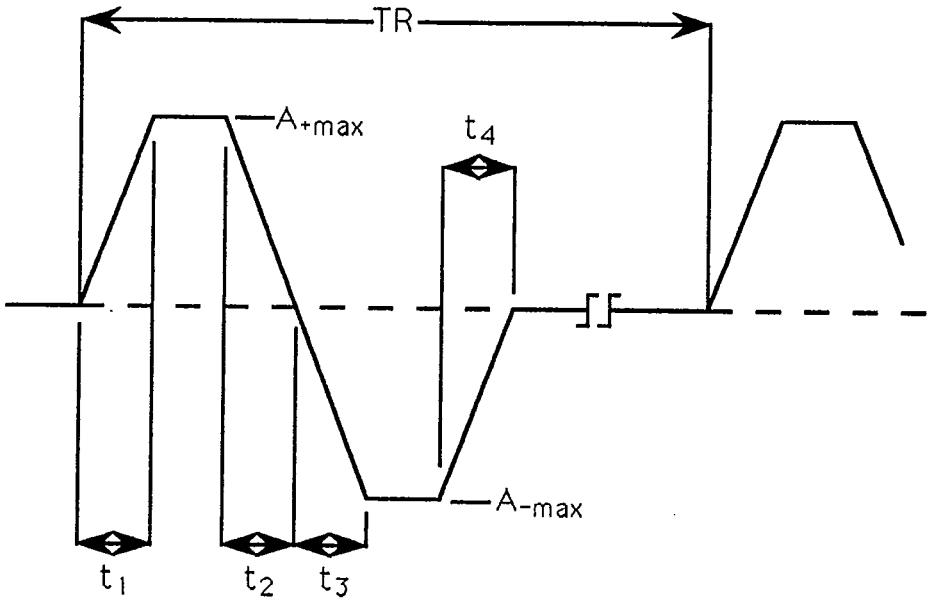


Figure 2-1
Maximum Gradient Rate (MGR) Waveform

voltage is induced in the search coil. Repeat this procedure for position 2. The results from the position which yields the greatest search coil voltage shall be reported as described in Section 3.

2.2.5 Measure the peak voltages which correspond to the maximum dB/dt for transitions t_1, t_2, t_3, and t_4 (see Figure 2-1).

2.2.6 Record the pulse width,), of the dB/dt waveform corresponding to the t_1, t_2, t_3, and t_4 transitions (see Figure 2-1).

2.3 MAXIMUM SINUSOIDAL RATE (MSR) MEASUREMENT

2.3.1 Turn off or maximally attenuate the radiofrequency (RF) transmitter to prevent interference.

2.3.2 Position the search coil in the MR scanner using the positioning device so the search coil axis is aligned with that of the static magnetic field.

2.3.3 Turn off all gradients other than the sinusoidal gradient of interest. Apply the maximum amplitude and frequency waveform that the system can generate using the standard pulse sequence generation software and hardware used by the manufacturer.

2.3.4 Move the search coil to locate the position of the maximum induced voltage that can be found within the region of the machine normally occupied by the patient. Once the position is established, the coil shall be immobilized to prevent movement-induced voltage from interfering with the measurement.

For most coils a suitable search procedure is as follows. For x gradients, fix the coil along X=ρ; Y=0. For y gradients fix the coil along X=0, Y=ρ. For z gradients, fix the coil along X=0, Y=ρ. Then search along z to locate the position of the maximum induced voltage that can be found within the region of the machine normally occupied by the patient.

2.3.5 Measure the peak voltage which corresponds to the maximum dB/dt.

2.3.6 Record the pulse width, τ, of the dB/dt waveform.

2.3.7 Repeat the above procedure for any other sinusoidally driven gradient.

2.4 MCR MEASUREMENT

2.4.1 Turn off or maximally attenuate the radiofrequency (RF) transmitter to prevent interference.

2.4.2 Position the search coil in the MR scanner using the positioning device so the search coil axis is aligned with that of the static magnetic field.

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2.4.3 Select a protocol from each major sequence type and maximize dB/dt by adjusting the following parameters.

a. Maximize gradient amplitude (e.g., minimum field of view, minimum slice thickness, maximum bandwidth, use of spoiler pulses)

b. Minimize gradient transition times (e.g., minimum rise and fall times for trapezoidal pulses, minimum echo time, the highest frequencies and greatest amplitudes for sinusoids)

c. Maximize the number of gradients on simultaneously (double oblique scans)

In general, the rise times and fall times of the gradient waveform should be minimal while the gradient amplitudes shall be maximal. With sinusoidal gradient waveforms, the highest frequencies and greatest amplitudes usually lead to the highest values of dB/dt. Pulse sequences employing 45°, 45° double obliques with spoiler pulses produce higher dB/dt values than pulse sequences which only permit cartesian slices. In addition, the use of double oblique protocols simplifies the search procedure for the spatial peak dB/dt position. Therefore, double oblique sequences are recommended.

2.4.4 Run the selected clinical pulse sequence, modified to repeat at the maximum phase encoding value.

2.4.5 Move the search coil to locate the position of the maximum induced voltage that can be found within the region of the machine normally occupied by the patient. Once this position is established, the coil shall be immobilized to prevent movement-induced voltage from interfering with the measurement.

For 45°, 45° double oblique sequences the search procedure described in section 2.2.4 may be used.

2.4.6 Measure the peak voltage which corresponds to the maximum dB/dt.

2.4.7 Record the pulse widths, τ, of the dB/dt waveform (see Figure 1-2).

2.5 ADDITIONAL MEASUREMENTS

When a measurement of dB/dt is to be used to assess performance relative to a dB/dt safety level which depends on pulse width (or frequency), then measurements shall be made and reported for all applicable values of τ. If the τ which produces the largest dB/dt falls in the region where safety limits are relaxed from the strictest values, then that could result in the largest dB/dt meeting the safety level, while a lesser dB/dt value associated with a larger τ may not. In this case, the dB/dt values measured under the test protocol having larger τ values shall be measured and reported.

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Section 3
RESULTS

3.1 REPORTING dB/dt RESULTS

3.1.1 State the method used (MGR, MSR, or MCR).

3.1.2 State the calculated values of peak dB/dt for the gradient coils.

3.1.3 Report the radius and number of turns of the search coil.

3.1.4 State the position of the search coil with respect to the magnet isocenter.

3.1.5 List the data acquisition parameters as indicated in the following subsection (3.1.5.1). Report the pulse sequence used to produce each of the dB/dt waveforms.

3.1.5.1 DATA ACQUISITION PARAMETERS

3.1.5.1.1 Maximum Gradient Rate (MGR) Method

The following parameters shall be reported for the MGR.

Parameter	Dimension
Maximum gradient pulse amplitude	millitesla/meter
Patient space radius, ρ	meters
t_1	microseconds
t_2	microseconds
t_3	microseconds
t_4	microseconds

3.1.5.1.2 Maximum Sinusoidal Rate (MSR)

The following parameters shall be reported for the MSR method.

Parameter	Dimension
Pulse width, τ	microseconds
Measured dB/dt	tesla/second
Maximum gradient pulse amplitude	millitesla/meter
Patient space radius, ρ	meters

3.1.5.1.3 Maximum Clinical Rate (MCR)

The following parameters shall be reported for the MCR method.

Parameter	Dimension
Sequence type/name	—
Scan plane	—
Pulse width, τ	microseconds
Measured dB/dt	tesla/second
Echo time, TE	milliseconds
Field of view, FOV	centimeters
Slice thickness	millimeter
Angles for oblique scans	degrees
Slice orientation	—
Patient space radius, ρ	meters

3.1.6 List any other parameters required to ensure repeatability.

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NEMA STANDARDIZATION BACKGROUND

The purpose of NEMA standards, their classification, and status are set forth in certain clauses of the NEMA *Standardization Policies and Procedures* manual and are referenced below:

Purpose of Standards

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A standard of the National Electrical Manufacturers Association defines a product, process, or procedure with reference to one or more of the following: nomenclature, composition, dimensions, tolerances, safety, operating characteristics, performance, rating, testing, and the service for which they are designed.

(Standardization Policies and Procedures, p. 1)

Dimensions

Where dimensions are given for interchangeability purposes, alternate dimensions satisfying the other provisions of the Standards Publication may be capable of otherwise equivalent performance.

(Standardization Policies and Procedures, p. 6)

Categories of Standards

National Electrical Manufacturers Association Standards are of three classes, which have received the affirmative vote of at least two-thirds of the Subdivision votes cast in the affirmative or negative:

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2. Suggested Standard for Future Design, which may not have been regularly applied to a commercial product, but which suggests a sound engineering approach to future development.
3. Adoptive Standard, which is adopted in whole or in part from the standards of another organization, either domestic, regional, or international.

(Standardization Policies and Procedures, pp. 5)

Authorized Engineering Information

Authorized Engineering Information consists of explanatory data and other engineering information of an informative character not falling within the classification of NEMA Standard or Suggested Standard for Future Design, which standard has received the affirmative vote of at least two-thirds of the Subdivision votes cast in the affirmative or negative.

(Standardization Policies and Procedures, pp. 5)

Identification of Status

Standards in NEMA Standards Publications are identified as "NEMA Standard," "Suggested Standard for Future Design," or "Adoptive Standard." These indicate the status of the standard. A statement incorporating the auxiliary verb "shall" indicates that compliance with a requirement is mandatory for compliance with the standard. These classes of standards are identified in the foreword or throughout the text.

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