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# **Motors/Generators**

and the

# **NEC**

Course I—Rotating DC Machinery  
Course II—Rotating AC Machinery  
**Course III—NEC: Motors & Generators**

**National Electrical Code as it relates directly or indirectly to DC/AC Motors/Generators**  
**Art. 430: Motors / Art. 445 Generators**

by

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**Nomenclature<sup>1</sup>**

$a$	number of parallel armature paths	-
$a$	ratio of transformation	-
$A$	area	$m^2$
$B$	magnetic flux density	T
$B$	susceptance	S
$B, \mathbf{B}$	magnetic field	$Wb/m (T \cdot m)$
$E$	generated emf	V
$E$	energy	J
$E$	generated voltage	$V^2$
$f$	electrical frequency	Hz
$F, \mathbf{F}$	force	N
$G$	conductance	S
$GFCI$	ground-fault circuit interrupter	-
$I, \mathbf{I}$	constant or rms current	A
$I_B$	magnetization (quadrature current)	A
$I_G$	in-phase component of exciting current	A
$k$	constant	various <sup>3</sup>
$l, \mathbf{L}$	length	m
$L$	loss(es)	-
$n$	rotational speed	rev/min
$N$	number of turns/items	-
$N$	number of series armature paths	-
$p$	number of poles or poles/phase	-
$P$	power or power loss	W
pf	power factor	-
$q$	number of loops	-
$R$	resistance	$\Omega$
$r$	radius	m
$r, R$	resistance	$\Omega$
$s$	slip	-

<sup>1</sup> Not all the nomenclature, symbols, or subscripts may be used in this course—but they are related and may be found when reviewing the references listed for further information. Further, all the nomenclature, symbols, or subscripts will be found in of many electrical courses (on SunCam, PDH Academy, and also in many texts). For guidance on nomenclature, symbols, and electrical graphics: IEEE 280-2021, IEEE Standard Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering, New York: IEEE; and IEEE 315-1975, Graphic Symbols for Electrical and Electronics Diagrams, New York: IEEE, approved 1975, reaffirmed 1993.

<sup>2</sup> Generated voltages are traditionally represented as “E” as the symbol but often “V” is used in everyday contexts. The international standard symbol is “U”. The usage varies with the text.

<sup>3</sup> Rotating machines have numerous constants with differing names and subscripts. Anytime a subscript or superscript changes on the symbology for the constant, some different term (or possibly units) has come into play. Constants include torque (or motor), back-emf (or electrical or voltage), electrical time, mechanical time, power. See Table 1.



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$S$	apparent power	VA
SCR	short-circuit ratio	-
$SR$	speed regulation	-
$S_R$	slew rate	V/s
SR	speed regulation	%
$t$	time	s
$T$	torque	N·m (ft-lbf)
$T$	period	s
$v$	variable voltage	V
$V$	constant or rms voltage	V
$V$	line voltage	V
$v, \mathbf{v}$	velocity	m/s
$V_0$	generated voltage	V
VR	voltage regulation	%
$X$	inductance or reactance	$\Omega$
$Y$	admittance	S
$z$	number of conductors	-
$Z$	impedance	$\Omega$

**Greek Symbols**

$\delta$	torque angle	rad
$\eta$	efficiency	-
$\theta$	angle or phase angle difference	rad
$\kappa$	torque conversion factor	-
$\phi$	angle	rad
$\phi$	flux	Wb
$\phi$	phase	-
$\Phi$	magnetic flux	Wb
$\omega$	angular frequency	rad/s
$\omega_{\text{mech}}$	rotational speed	rad/s

**Subscripts**

0	initial	-
0	stator	-
1	equivalent stator	-
2	equivalent rotor	-
$a$	armature	-
adj	adjusted	-
aux	auxiliary	-
ave	average	-



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<i>b</i>	blocked rotor	-
<i>c</i>	capacitor	-
CEMF	counter-electromotive force	-
<i>cp</i>	commutating pole	-
Cu	copper	-
<i>d</i>	direct	-
ds	direct axis	-
<i>E</i>	emf	-
<i>e</i>	electrical, emf	-
<i>eff</i>	effective	-
<i>f</i>	field	-
<i>f</i>	final	-
<i>fl, fl</i>	full load	-
<i>g</i>	generator	-
<i>h</i>	hysteresis	-
<i>L</i>	line, line-to-neutral, or load	-
<i>m</i>	mechanical or motor	-
max	maximum	-
<i>mech</i>	mechanical	-
net	net field	-
<i>nl, fl</i>	no load	-
<i>n</i>	rotational speed/torque <sup>4</sup>	-
oc	open circuit	-
<i>p</i>	phase	-
pf	power factor	-
pu	per unit	-
<i>q</i>	quadrature	-
<i>r</i>	rotor	-
rev/min	revolutions/minute	-
<i>s</i>	synchronous	-
sc	short circuit	-
<i>st</i>	stator	-
sync	synchronizing	-
<i>t</i>	terminal, total, torque	-
<i>T</i>	torque	-
<i>x</i>	armature	-

<sup>4</sup> Related to the inertia of the rotor. Sometimes shown as “*in*” for inertia. The constant converts torque to speed and is related to a motor’s resistance and voltage.



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### COURSE REFERENCES

The theoretical information is primarily from one of the author's books, Ref. [A]. The NEC Ref. [B] is always a useful source for electrical engineers. Information useful in many aspects of electric engineering may be found in [C] and [D]. Reference [E] has detailed descriptions of analysis techniques. Reference [F] covers many terms in EE with excellent definitions and explanations. Reference [G] is one of the most comprehensive and best explained texts on motor and generator theory. The appendices (A-F) cover information useful in many engineering tasks with App. (G) providing a side by side comparison of electric and magnetic equations. Use these texts or their counterparts for indepth information. References in bold are highly recommended.

This course will focus on basics, that rarely change, that provide the basis for all other knowledge.

### INTRODUCTION

#### **Regulation—Generation—Grid—Transmission [NESC]—Utilization [NEC]**

The following is a top down view leading to the generators and motors requirements encountered by electrical engineers and that eventually becomes focused on the National Electrical Code (NEC) (NFPA 70).<sup>5</sup>

#### **Energy Regulation**

The main law governing the national electrical grid is the *Federal Power Act of 1935*, which assigns authority to the *Federal Energy Regulatory Commission* (FERC) for the interstate transmission and wholesale sale of electricity. Other significant legislation includes the *Public Utility Holding Company Act* of 1934 which first established regulations.<sup>6</sup>

#### **Transmission Regulation**

The *Federal Energy Regulatory Commission*, or FERC, is an independent agency that regulates the interstate transmission of electricity, natural gas, and oil. FERC also reviews proposals to build liquefied natural gas (LNG) terminals and interstate natural gas pipelines as well as licensing hydropower projects. The *Energy Policy Act* of 2005 gave FERC additional responsibilities shown on their website.

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<sup>5</sup> Though not ever Article or Section of the code is covered, the focus will be on a) those most important, b) those most often encountered when designing, repairing, or upgrading an electrical system, and c) those perhaps difficult to understand or apply,

<sup>6</sup> Current proposed laws are focused on grid capacity and reliability.

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**Electrical Generation**

Therefore, if building a generator [or most other projects] one follows the above laws and regulations, and importantly the contract requirements. In general, the flow of requirements follows this pattern:

- Laws & Regulations
- Military Standards
- Industry Standards
- Contract Requirements

Not mentioned is the understanding of theory and the application thereof.

**Electrical Grid**

The next concern is connecting to the grid. For a summary of such requirements see IEEE 1547 (*Standard for Interconnecting Distributed Resources with Electric Power Systems*) is a standard of the Institute of Electrical and Electronics Engineers meant to provide a set of criteria and requirements for the interconnection of distributed generation resources into the power grid.

The U.S. grid is divided into three major regions<sup>7</sup> (see the figure below):

- The Eastern Interconnection, which operates in states east of the Rocky Mountains.
- The Western Interconnection, which covers the Pacific Ocean to the Rocky Mountain states.
- The Texas Interconnected system.

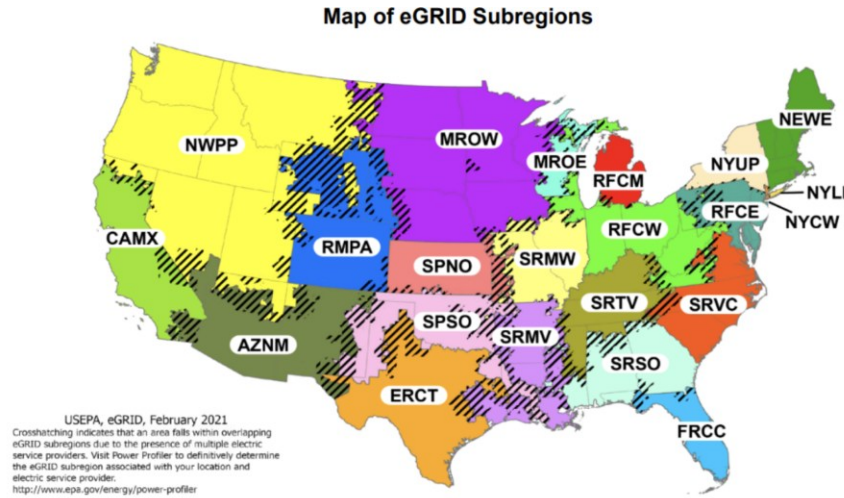


**Figure 1: EPA Map of US Grids**

<sup>7</sup> Alaska is a separate grid. Hawaii has multiple island grids.

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Within each of these regions are interconnected local electricity grids [egrids]. With multiple ways for the power to flow from generation to load centers, this redundancy seeks to ensure minimal loss of service in case of local failures.



**Figure 2: Detailed US Grid Map**

[See <https://www.epa.gov/egrid/code-lookup> for abbreviations.]

The *North American Electric Reliability Corporation* (NERC) is a not-for-profit international regulatory authority whose mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid. NERC oversees six regional reliability entities and encompasses all the interconnected power systems of Canada and the contiguous United States, as well as a portion of Mexico.<sup>8</sup>

Another major player multiple related fields is the *Electric Power Research Institute* (EPRI) which is an American independent, nonprofit organization that conducts research and development related to the generation, delivery, and use of electricity to help address challenges in the energy industry, including reliability, efficiency, affordability, health, safety, and the environment.

**Electrical Transmission**

From the major generators, into the grids, the power travels over transmission lines governed by the *National Electrical Safety Code*.

<sup>8</sup> Grid connections are compliant with North American Reliability Corporation (NERC) Standard FAC-001-4 *Facility Interconnection Requirements*.

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**Electrical Utilization**

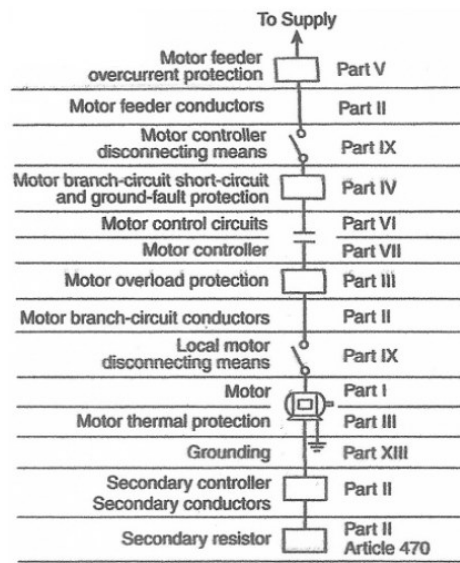
The power then flows then into buildings where it’s governed by the *National Electrical Code*.<sup>9</sup> The NEC provides safety standards for electrical installations. Although it is not a federal law itself, it is a model code widely adopted by states and municipalities.<sup>10</sup> Further, this is usually where the engineer first (and most often) interacts with requirements.

**MOTORS**

Motor requirements are covered in the NEC, Chap. 4, *Equipment for General Use, Art. 430, Motors, Motor Circuits, and Controllers*.

**Part I: General**

The table of contents as it relates to a standard motor circuit is shown in Fig. 3.



**Figure 3: Article 430 by Motor Circuit**

[Source: Article 430.1 Scope, Informational Note 1, Ref. [B]]

Motors are rated, as most utilization equipment, in Volt-Ampere (VA), and sometimes Watts (W), and typically in horsepower output. Since losses and power factor are not often on the nameplate,

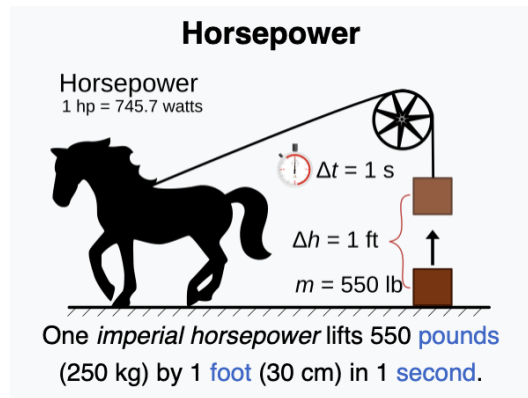
<sup>9</sup> Local Authorities having Jurisdiction (AHJ) may add to or subtract from requirements. The military has building standards in *Unified Facilities Criteria* (UFC) that normally comply with the NEC but may have needs beyond. These can be found in the *Whole Building Design Guide* (WBDG).

<sup>10</sup> Adopted, and possibly adjusted, by the Authority having Jurisdiction (AHJ) in each area.

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engineers must use the accurate input current ratings in Part XIV to ensure properly sized conductors.<sup>11</sup>

As a side note, historically, it was James Watt who standardized the conversion by observing draft horses, and rounding the results found the conversion of 1 hp  $\cong$  746 W. The calculation is illustrated in the figure below. He used it to show how powerful his steam engines were—in terms of work output without considering losses.



**Figure 4: Horsepower**

[Source: <https://en.wikipedia.org/wiki/Horsepower>]

Reconditioned motors are allowed [430.4]. How to repair them can be found in ANSI/EASA AR 100-2020, *Recommended Practice for Repair of Rotating Electrical Apparatus*.<sup>12</sup> Part-winding motor protection is covered in 430.4.<sup>13</sup> Motors must comply with other portions of the NEC [430.5](see Table 1 for an excerpt).

**Table 1: Articles Applicable to Motors Outside of 430**

Equipment/Occupancy	Article	Section
Capacitors		460.8, 460.9
Cranes	610	
Hazardous Locations	500-503, 505, 506	
Transformers	450	

<sup>11</sup> See Art. 440 for air-conditioning and refrigeration equipment. See Table 430.5 for motor requirements outside Art. 430.

<sup>12</sup> EASA is the “Electrical Apparatus Service Association” in the U.S. and is trade marked as “The Electro-Mechanical Authority”. The AR stands for “Authority Requirements”. It is international in scope but is adopted by ANSI for the U.S. NEMA uses/adopts some EASA standards. In Europe EASA is the European Union Aviation Safety Agency—the equivalent of our FAA.

<sup>13</sup> Part-winding motors are those using less than all their windings for startup to lower inrush.



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Conductor ampacity for motor equipment selected from 310.15 or calculated [310.14(B)]. If using flexible cord, see 400.5. The *required ampacity and motor ratings* come from 430.6.

For *general motor applications the current ratings* for the motors built for high speeds ( $\geq 1200$  rpm), high torques, or multiple speeds are determined by Tables 430.247, 430.248, 430.249, and Table 430.250 ***instead of the actual current rating marked on the nameplate*** for the following [430.6(A)(1)].

- ampacity of the conductors
- current ratings of switches
- current ratings of short-circuit and ground-fault protection

Of note, the tables listed are in horsepower as the input data. If a *motor is marked in amperes you use the amperes as the input to obtain the **correct horsepower*** rating from the, which is then used as your input for further calculations/research, table [430.6(A)(1) Table Values].

There are three exceptions to this that should be read carefully. *Exception 3* states if a *motor-operated* appliance is marked with both horsepower and full-load current, the full-load current is used for the following current ratings.

- branch circuit conductor
- disconnecting means
- motor controllers
- short-circuit and ground-fault
- separate overload devices

One should *use the nameplate current rating* also on the following [430.6(A)(2) Nameplate Values].

- separate overload protection
- low-speed ( $< 1200$  rpm) motor conductor, switches, protection
- large motors [if exceeding the Table Values in Part XIV—Tables 430.247-250]
- Torque Motors [430.6(B)]
- Alternating-Current Adjustable Voltage Motors [430.6(C)]
- Valve Actuator Motor Assemblies [430.6(D)]



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In Section 430.7 are motor marking requirements. Of note, and sometimes useful to the engineer, are the locked-rotor code letters that provide the kVA/hp on a locked rotor. Examples are in the following table.

**Table 2: Locked Rotor Codes**

<b>Code Letter</b>	<b>Kilovolt-Amperes per Horsepower with Locked Rotor</b>
A	0-3.14
E	4.5-4.99
J	7.1-7.99
N	11.2-12.49
T	18.0-19.99
V	22.4 and up

In Sec. 430.9 the color and torque requirements are given. Of interest, for terminals with 14 AWG wire or smaller the minimum torque is 0.8 N·m (7 lb-in).

The minimum wire bending space in motor enclosures is given in NEC Table 430.10(B) and depends on the number of wires per terminal and their size. Motor-terminal housings have usable dimension, wire spacing, volume, and terminal distance requirements of primary interest to the motor designer [430.12]. Bushings are required for wires passing through openings [430.13].

### Part II: Motor Circuit Conductors

This part specifies the ampacities of the conductors required (except for those motors rated over 1000 V nominal) [430.21].

Single motors used in continuous duty applications use conductors with an ampacity of 125% of motor full-load current [430.22].<sup>14</sup> For those motors not running under continuous duty, Table 430.22(E) provides adjusted percentages.<sup>15</sup> The conditions for using 14 AWG, 16 AWG, and 18 AWG wire are specified in Subsections 430.22(F) and (G).

Conductors supplying several motor and/or other loads must have the ampacity not less than the sum of all of the following [430.24].

- 125% of full-load current of highest rated motor
- Sum of full-load current of all other motors

<sup>14</sup> Continuous duty defined as operation at a substantially constant load for an indefinitely long time.

<sup>15</sup> Be sure to look up the definitions for each type of duty: short-time, intermittent, periodic, and varying in Art. 100.



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- 100% of noncontinuous non-motor loads
- 125% of continuous non-motor load

Feeder tap requirements are in 430.28 and contain varying length requirements and should be read carefully.

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### Example 1

A passenger elevator motor rated for continuous duty has nameplate FLA (full-load amperes) of 75 A.

What is the required ampacity of the conductors supplying the motor, if no other loads are on the circuit?

#### *Solution*

Per Table 430.22(E) [not shown] a passenger elevator is in the intermittent duty column for “classification of service”. In the continuous rated motor column, the percentage of FLA the conductors are required to carry is 140%. Therefore,

$$I_{\text{conductors}} = (140\%)(\text{FLA}) = (1.4)(75 \text{ A}) = 105 \text{ A}$$

---

### Part III: Motor and Branch-Circuit Overload Protection

This part specifies overload devices to motors and associated equipment from excessive heating due to overloads and failure to start [430.31].<sup>16</sup> Part III does NOT apply where a power loss would result in a hazard, e.g., losing fire pumps; nor does it apply to motor circuits over 1000 V (see Part XI).

The sections and subsections cover motors based on power (hp), whether the overload is integral or separate from the motor, whether thermal or electronic, intermittent environment, starting period

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<sup>16</sup> An **overcurrent** is a *general term for any excessive current*, including sudden, massive surges from short circuits or faults, while an **overload** is a specific, sustained overcurrent (above rated, but below fault levels). In lay terms, overcurrents are protected from by quick trip devices, while overloads are protected from with slower heat type elements.



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(delay), fused, and a few other requirements—including whether the motor is on a branch circuit. Hence, this deserves careful reading. Nonetheless, some takeaways should be noted.

A separate overload (OL) on a motor of >1 hp should be rated based on full-load current (FLA) as follows [430.32(A)(1)].

- Service Factor  $\geq 1.15$ : 125% of FLA
- $\leq 40^{\circ}\text{C}$  Temperature Rise: 125% of FLA
- All other Motors: 115% of FLA

Additionally, when the sensing element or sizing is not sufficient to start the motor or carry the load, one is allowed the following setting [430.32(C)].

- Service Factor  $\geq 1.15$ : 140% of FLA
- $\leq 40^{\circ}\text{C}$  Temperature Rise: 140% of FLA
- All other Motors: 130% of FLA

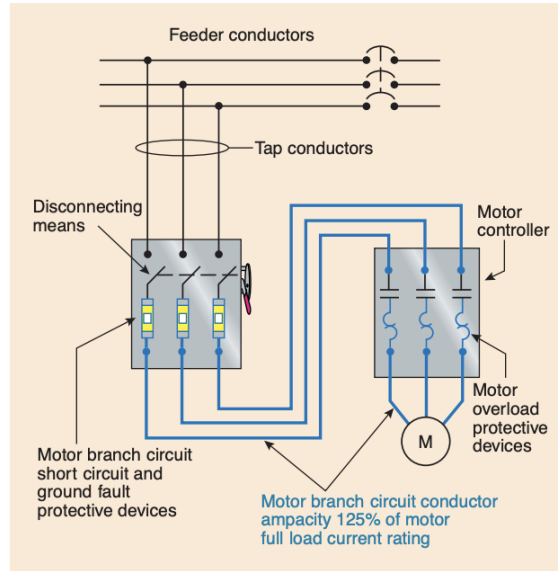
### Part IV: Motor Branch-Circuit Short-Circuit and Ground-Fault Protection

This section covers short-circuit and ground-fault protection directly related to motors. A short-circuit is a fault between two or more conductors. A ground-fault is between an ungrounded conductor and ground. For small motors one may be able to use a fuse or circuit breaker to protect against short-circuit, ground-fault, and overload protection provided the device meets all the requirements of Parts III and IV. [430.51]

Ratings and settings *for individual motor circuits* are in 430.52. Of importance, in 430.6 the actual nameplate current rating was NOT used. Instead, *the current rating in Tables 430.247-430.250 were used using the horsepower on the nameplate*. This provided the ratings of the switches (disconnecting means), branch-circuit overcurrent devices, and the ampacity of the conductors. But recall, *separate motor overload protection MUST be based on the motor nameplate rating*. Having noted all this, setting *the short-circuit and ground-fault protection in accordance with 430.52 may result in ratings higher than the ampacity of the conductor*. Nevertheless, all settings are in compliance with the code. See the figure below for the various portions of the motor circuits covered by the sections mentioned. The NEC Table 430.52(C)(1) shown in Table 2 indicates how

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the requirements of for short-circuit and ground-fault may exceed the ampacity of the conductors.<sup>17,18</sup>



**Figure 5: Motor Circuit Installation Components**

Each of the items shown in Fig. 5 has a section or subsection listing the requirements.

**Table 3: Maximum Rating/Setting for Motor Short-Circuit & Ground-Fault Protection**

Type of Motor	Percentage of Full-Load Current			
	Nontime Delay Fuse <sup>1</sup>	Dual Element (Time-Delay) Fuse <sup>1</sup>	Instantaneous Trip Breaker	Inverse Time Breaker <sup>2</sup>
Single-phase motors	300	175	800	250
AC polyphase motors other than wound-rotor	300	175	800	250
Squirrel cage — other than Design B energy-efficient	300	175	800	250
Design B energy-efficient	300	175	1100	250
Synchronous <sup>3</sup>	300	175	800	250
Wound-rotor	150	150	800	150
DC (constant voltage)	150	150	250	150

Table Notes not Shown

<sup>17</sup> It is the heating effect, which is based on the current flowing and the time duration, that determines if a current will damage the component.

<sup>18</sup> The table is from the 2017 Code, though changes are minimal. The *Handbook* of the 2023 Code must be purchased.



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### Part V: Motor Feeder Short-Circuit and Ground Fault Protection

This part specifies the devices and ratings of same to protect feeder conductors for short-circuit and ground-faults. Informative Annex D, Example D8 in the Code provides a hands-on example.

*A feeder supplying multiple load(s) shall have a protective device set at NOT greater than the largest branch-circuit short-circuit and ground-fault device for any motor so supplied (based on the maximum permitted value of the specific type of device per 430.52 or 440.22(A) used in both). Meaning thus, the trip protective devices on the feeder and branch circuit supplying the motor must be of the same type, e.g., fuse, time-delay fuse, instantaneous trip circuit breaker, inverse time circuit breaker. [430.62]*

On *other installations* [430.62(B)], those involving motors and different types of loads, feeder conductors that have an ampacity greater than that required by 430.24 shall be permitted to have overcurrent protective devices set at the ampacity of the feed conductors themselves.<sup>19</sup>

---

#### Example 2

Determine the minimum required a) conductor ampacity, b) motor overload and c) the feeder short-circuit protection (for a non-delay type fuse) for the following squirrel cage induction motor.

20 hp

460 V

3 $\phi$

Nameplate: 25 A / Design B / SF 1.15

#### *Solution*

a) The full-load current for conductor ampacity using the horsepower rating from Table 430.250 (see 430.6(A)—27 A. To obtain the minimum conductor, multiply by 1.25 (see 430.22).

$$I \square 1.25 = 27 \text{ A} \square 1.25 = 33.75 \text{ A} \quad (34 \text{ A})$$

---

<sup>19</sup> How does one keep track of all the back and forth? Here is one method the author has used. Start at the main section, in this case 430.62(B); then, go to the next section referenced. If it's applicable, write down the requirement limits; then proceed to the next section referenced and repeat. Continue this until all "rabbit holes" have been searched and one finds oneself back at the original section (requirement), at which time one can be relative certain nothing (no requirement) has been left off.



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b) Separate motor overload protection should not be more than *125% of the motor nameplate rating* (see 430.6(A)).

$$I_{\text{nameplate}} \times 1.25 = 25 \text{ A} \times 1.25 = 31.25 \text{ A} \quad (32 \text{ A})$$

c) The feeder short-circuit protection (for a non-delay type fuse) for the following squirrel cage induction motor should not exceed 300% (per 430.52 and Table 430.52(C)(1)).

$$I_{\text{fuse}} = 300\% \times 34 \text{ A} = 102 \text{ A}$$

But, 102 A is not a standard size. But per 430.52(C)(1)(a) and 430.52(C)(1)(b)(1), this size may be increased to the next standard size [110 A per 240.6]. Also, if this won't start the motor the fuse may increase as long as it doesn't exceed 400% the full-load current [32 A x 4 = 128 A].

Thus, the answer is 110 A.

—

—

## Part VI: Motor Control Circuits

This part modifies general requirements as they apply to motor control circuits. Of note, the requirements depend on where the control circuit is tapped, e.g., from the load side of the motor branch circuit [430.72(A), (B), and (C)] and the Class of the Circuit [see Art. 100, Definitions for Class 1-4].<sup>20</sup> It contains the requirement to protect conductors in the control circuit when they are physically located outside the control device itself [430.73].

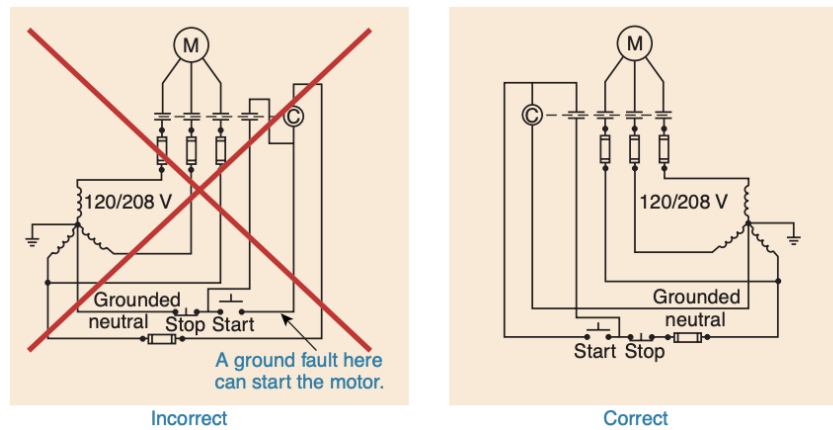
Finally, coverage of the requirement depending on the arrangement of the control circuitry [430.74]. This is especially important when a transformer is used to supply the motor and control circuitry since a ground fault could conceivably start the motor (see Fig. 6).

The disconnecting means may consist of two separate devices, but they must be located immediately adjacent to one another [430.75]. The requirement for adjacency or “within sight” of components exists in numerous locations in the NEC and should be noted by the electrical engineer and expressed in construction and one-line drawings.

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<sup>20</sup> This also brings into play 740.30 through 740.52 for the various classes impact on transformer requirements [430.72(C)(1)].

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**Figure 6: Control Wiring Importance**

### Part VII: Motor Controllers

This part is meant to ensure motor controllers are suitable for all motors.

For stationary motors of 1/8 hp or less the branch circuit supplying the motor is considered the controller [430.81(A)]. For portable motors of 1/3 hp or less the “controller” is the attachment plug and receptable or cord connector [430.81(B)].

Motor Controller Design includes the ability to start and stop the motor, and to disconnect the motor when drawing locked rotor current [430.82(A)]. Special design conditions exist for autotransformers and rheostats [430.82(B) and (C)]. Ratings for motor controllers vary with type of breaker, size of the motor, and type of motor (torque, adjustable speed) [430.83 and 430.88]. And, interestingly, a fuse and switch is considered a controller [430.90].

### Part VIII: Motor Control Centers [MCC]

This part covers MCC installations for the control of motors, lighting, and power circuits. [Much like a switchboard composed of multiple motor controllers.] These installations also must meet clearances and access listed in 100.26 and specifically 110.26(E) for MCCs.

Overcurrent protection is governed by Art. 240, Part I, II, and III [430.94]. Additionally other Motor Control Center requirements relate back to earlier sections and subsections including 250.28(D)—disconnecting; 250.122—grounding; and markings—110.21. Busbar spacing is also included; see an example in the table below. Of note, spacing is smaller/less in free air.



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**Table 4: Minimum Spacing Between Bare Metal Parts**

Nominal Voltage	Opposite Polarity Where Mounted on the Same Surface		Opposite Polarity Where Held Free in Air		Live Parts to Ground	
	mm	in.	mm	in.	mm	in.
Not over 125 volts, nominal	19.1	¾	12.7	½	12.7	½
Not over 250 volts, nominal	31.8	1¼	19.1	¾	12.7	½
Not over 600 volts, nominal	50.8	2	25.4	1	25.4	1

**Part IX: Disconnecting Means**

This part covers disconnecting means capable of disconnecting motors and motor controllers.

The disconnecting means is required for each motor controller and *must be located within sight of the motor controller* [430.102(A) with exceptions]. One of the exceptions allows out of sight disconnecting means if such disconnecting means is “lockable” [430.102(B) Exceptions (1) and (2)].

The disconnecting means shall open all ungrounded conductors and designed so that no pole shall be operated independently [430.103]

Several additional requirements exist and the use the word “listed”. From definitions, listed means equipment, materials, or services included in a list published by an organization acceptable to the authority having jurisdiction. Underwriters Laboratories (now, UL Solutions) is often used. Example markings can be found in <https://www.ul.com> and the figure below.



**Figure 7: UL Solutions Symbol**

Disconnecting means vary by type of motor and horsepower. But, for all rated at 1000 V or less, the current rating of the *disconnecting means shall be not less than 115% of the full-load current rating of the motor* [430.110].

When multiple motors are connected along with other loads one calculates two values. The first is the full-load current equivalent to the horsepower rating from Tables 430.247-250. The second calculates the locked rotor current equivalent from Table 430.251(A) or (B). Then add all the other



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loads to the first and second methods. The largest value obtained is used. Where two or more motors cannot be started simultaneously, the largest sum of locked rotor currents that can be started simultaneously shall be used. [430.110(C)]

Locked rotor currents for polyphase Design A motors are not listed in Table 430.251(B) because Design A motors are not limited to a maximum starting or locked rotor current. Hence, exceptions for such motors are explained in 430.11(C), Exception (1).

Exception (1) says, if available use the motor's marked value of locked-rotor amperes. If not, use the locked-rotor codes of Table 2 [NEC Table 430.7(B)] *maximum value* and the following formula.

**Equation 1: Locked Rotor Amps for Design A Motor**

$$I_{\text{Locked-Rotor Amperes}} = \left( \frac{\text{kVA}}{\text{hp}} \right) \left[ \frac{\left( \frac{1000 \text{ VA}}{1 \text{ kVA}} \right) (\text{HP}_{\text{marked}})}{\sqrt{3} (V_{\text{rated}})} \right]$$

**Example 3**

A Design A motor has a locked-rotor code of T from Table 2 of the course, Table 430.7(B) of the NEC—Maximum Value: 19.99 kVA/hp. The motor is rated for 10 hp at 208 V.

What is the value of the locked-rotor amperes,  $I_{LRA}$ ?

*Solution*

Using Eq. 1 and the given information results in the following.

$$I_{LRA} = \left( \frac{\text{kVA}}{\text{hp}} \right) \left[ \frac{\left( \frac{1000 \text{ VA}}{1 \text{ kVA}} \right) (\text{HP}_{\text{marked}})}{\sqrt{3} (V_{\text{rated}})} \right] = \left( 19.99 \frac{\text{kVA}}{\text{hp}} \right) \left[ \frac{\left( \frac{1000 \text{ VA}}{1 \text{ kVA}} \right) (10 \text{ hp})}{\sqrt{3} (208 \text{ V})} \right] = 554.87 \text{ A}$$



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Note this is much higher than the value in NEC Table 430.251(B) for a polyphase motor at 208 V and 10 hp—179 A.

Design A is similar to Design B but with higher starting currents used for fans and pumps. A and B are general application motors. In general,

- **A & B:** Focus on efficiency and *general use*
- **B** is the standard—that is, the “energy efficient” design
- **C:** Prioritizes high starting torque for tough starts.
- **D:** Offers the highest starting torque for extreme, high-inertia loads, sacrificing some efficiency.

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Of some importance, when a motor or motor-operated equipment receive power from more than one source, they shall have a disconnecting means for both and have a posted warning sign indicating that multiple sources must be shut off to remove all power.

### Part X: Adjustable-Speed Drive Systems

This part covers those requirements specific to adjustable-speed drive [ASD] systems beyond those in Parts I-Parts IX. ASD systems are also known as variable-frequency drives [VFD].

Conductors must have an ampacity of 125% of the rated input current. This includes the input conductors and output conductors to the motor, though some exceptions exist. [430.122(A) and (B), Exceptions (1) and (2)]

Over temperature protection must protect for the full speed range at which the motor is expected to operate [430.126]

Branch-circuit short-circuit and ground-fault protection for motors with ASD or VFD systems generally follows 430.52 except when the power conversion equipment is listed and marked “Suitable for Output Motor Conductor Protection”. See the informational notes under 430.130(A)(1) Exception (1).



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### **Part XI: Over 1000 Volts, Nominal**

This part covers motors operating over 1000 V nominal and should be review for additional requirements if utilizing such equipment. [430.201]

### **Part XII: Protection of Live Parts**

A “live part” is one operating at 50 V or more and exposed. It provide for the protection of personnel against such hazards. [430.21]

### **Part XIII: Grounding—All Voltages**

This part covers the grounding of exposed non-current carrying metal parts, motors, frames likely to become energized to limit the voltage to ground in the event of accidental contact. [430.241]

Motors operating at over 150 V to ground shall be guarded or grounded. [430.243] The actual connection to ground is accomplished per Art. 250.

### **Part XIV: Tables**

This part contains the tables applicable to motors.

## **GENERATORS**

Generator requirements are covered in the NEC, Chap. 4, *Equipment for General Use*, **Art. 445, Generators**.

This article covers installation and other requirements for generators [445.1] One should also see Art. 695 for fire pumps; Art. 700 for emergency systems; Art. 701 for legally required standby systems; Art. 702 for optional standby systems; Art. 705 for interconnected power sources; and Art. 708 for critical operations systems.

Stationary generators must be “listed” [445.6]. UL 2200, *Standard for Stationary Engine Generator Assemblies* provides additional information. NFPA 37-2021, *Standard for Installation and use of Stationary Combustion Engines and Gas Turbines* should also be consulted during the design phase.

Marking is required for those generators over 15 kW [445.11]. Overcurrent protection varies by the type of generator [445.12]. Conductors from the generator output terminals shall be protected



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at not less than 115% of the nameplate current rating [445.13]. Other component requirements are similar to that for motors. One requirement that differs is the need for an emergency shutdown of the prime mover.

Small portable generators are now required to have GFCI devices on supplied receptacles [445.20].

Construction and connection of generators have additional requirements beyond the NEC. Some of those associated with IEEE follow.

- **IEEE C50.13 (Synchronous Generators):** Focuses on large (10 MVA+) cylindrical-rotor generators driven by steam/gas turbines, covering operational and construction requirements.
- **IEEE 1547 Series (Distributed Energy Resources):** Essential for generators connecting to the grid, mandating features like fault ride-through for grid support.
- **IEEE 2420 (Nuclear Standby Power):** Criteria for combustion turbine-generator units in nuclear facilities.
- **IEEE P3005.2 (Emergency/Standby Power):** Recommended practice for engine/turbine-driven generators in commercial/industrial systems.
- **IEEE 2030 Series (Grid Integration):** Guides for integrating distributed energy resources (DERs) and microgrids, promoting sustainability and interoperability.
- **IEEE C37 Standards (Switchgear/Protection):** While covering circuit breakers (C37.04), these relate to generator protection, often referencing **IEC/IEEE Std 62271-37-013** for generator circuit breakers.



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**REFERENCES**

Items (latest editions) in **bold** are highly recommended for in-depth study.

- A. Camara, John A. *PE Power Reference Manual*. Belmont, CA: PPI (Kaplan), 2021.**
- B. Earley, Mark, ed. *NFPA 70, National Electrical Code Handbook*. Quincy, Massachusetts: NFPA, 2020.**

NOTE

Electrical refers to something related to electricity while “electric” refers to a device or machine that runs on electricity. Nevertheless, the NEC is sometimes referred to as the National Electric Code. This Handbook with its illustrations, commentaries, and guidance is the best source found for those dealing with the NEC frequently in their projects.

- C. IEEE 315-1975. *Graphic Symbols for Electrical and Electronics Diagrams*. New York: IEEE, approved 1975, reaffirmed 1993.
- D. IEEE 280-2021. *IEEE Standard Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering*. New York: IEEE.
- E. Grainger, John J., and William Stevenson, Jr. *Power System Analysis*. New York, McGraw Hill, 1994.
- F. Parker, Sybil P., editor in chief. *McGraw-Hill Dictionary of Scientific and Technical Terms*, 5<sup>th</sup> ed. New York, McGraw-Hill, 1994.
- G. Wildi, Theodore. *Electrical Power Technology*. New York: John Wiley & Sons, 1981.**



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**Appendix A: Equivalent Units Of Derived And Common SI Units**

Symbol	Equivalent Units			
A	C/s	W/V	V/Ω	J/(s⋅V)
C	A⋅s	J/V	(N⋅m)/V	V⋅F
F	C/V	C <sup>2</sup> /J	s/Ω	(A⋅s)/V
F/m	C/(V⋅m)	C <sup>2</sup> /(J⋅m)	C <sup>2</sup> /(N⋅m <sup>2</sup> )	s/(Ω⋅m)
H	W/A	(V⋅s)/A	Ω⋅s	(T⋅m <sup>2</sup> )/A
Hz	1/s	s <sup>-1</sup>	cycles/s	radians/(2π⋅s)
J	N⋅m	V⋅C	W⋅s	(kg⋅m <sup>2</sup> )/s <sup>2</sup>
m <sup>2</sup> /s <sup>2</sup>	J/kg	(N⋅m)/kg	(V⋅C)/kg	(C⋅m <sup>2</sup> )/(A⋅s <sup>3</sup> )
N	J/m	(V⋅C)/m	(W⋅C)/(A⋅m)	(kg⋅m)/s <sup>2</sup>
N/A <sup>2</sup>	Wb/(N⋅m <sup>2</sup> )	(V⋅s)/(N⋅m <sup>2</sup> )	T/N	1/(A⋅m)
Pa	N/m <sup>2</sup>	J/m <sup>3</sup>	(W⋅s)/m <sup>3</sup>	kg/(m⋅s <sup>2</sup> )
Ω	V/A	W/A <sup>2</sup>	V <sup>2</sup> /W	(kg⋅m <sup>2</sup> )/(A <sup>2</sup> ⋅s <sup>3</sup> )
S	A/V	1/Ω	A <sup>2</sup> /W	(A <sup>2</sup> ⋅s <sup>3</sup> )/(kg⋅m <sup>2</sup> )
T	Wb/m <sup>2</sup>	N/(A⋅m)	(N⋅s)/(C⋅m)	kg/(A⋅s <sup>2</sup> )
V	J/C	W/A	C/F	(kg⋅m <sup>2</sup> )/(A⋅s <sup>3</sup> )
V/m	N/C	W/(A⋅m)	J/(A⋅m⋅s)	(kg⋅m)/(A⋅s <sup>3</sup> )
W	J/s	V⋅A	V <sup>2</sup> /Ω	(kg⋅m <sup>2</sup> )/s <sup>3</sup>
Wb	V⋅s	H⋅A	T/m <sup>2</sup>	(kg⋅m <sup>2</sup> )/(A⋅s <sup>2</sup> )



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**Appendix B: Physical Constants**

Table Note 1

Quantity	Symbol	US Customary	SI Units
<b>Charge</b>			
electron	$e$		$-1.6022 \times 10^{-19} \text{ C}$
proton	$p$		$+1.6022 \times 10^{-19} \text{ C}$
<b>Density</b>			
air [STP][32°F, (0°C)]		0.0805 lbm/ft <sup>3</sup>	1.29 kg/m <sup>3</sup>
air [70°F, (20°C), 1 atm]		0.0749 lbm/ft <sup>3</sup>	1.20 kg/m <sup>3</sup>
sea water		64 lbm/ft <sup>3</sup>	1025 kg/m <sup>3</sup>
water [mean]		62.4 lbm/ft <sup>3</sup>	1000 kg/m <sup>3</sup>
<b>Distance</b>			
Earth radius <sup>2</sup>	⊕	$2.09 \times 10^7 \text{ ft}$	$6.370 \times 10^6 \text{ m}$
Earth-Moon separation <sup>2</sup>	⊕☾	$1.26 \times 10^9 \text{ ft}$	$3.84 \times 10^8 \text{ m}$
Earth-Sun separation <sup>2</sup>	⊕☉	$4.89 \times 10^{11} \text{ ft}$	$1.49 \times 10^{11} \text{ m}$
Moon radius <sup>2</sup>	☾	$5.71 \times 10^6 \text{ ft}$	$1.74 \times 10^6 \text{ m}$
Sun radius <sup>2</sup>	☉	$2.28 \times 10^9 \text{ ft}$	$6.96 \times 10^8 \text{ m}$
first Bohr radius	$a_0$	$1.736 \times 10^{-10} \text{ ft}$	$5.292 \times 10^{-11} \text{ m}$
<b>Gravitational Acceleration</b>			
Earth [mean]	$g$	32.174 (32.2) ft/sec <sup>2</sup>	9.8067 (9.81) m/s <sup>2</sup>
<b>Mass</b>			
atomic mass unit	$\mu$ or $m_\mu$ $\frac{1}{12} m(^{12}\text{C})$	$3.66 \times 10^{-27} \text{ lbm}$	$1.6606 \times 10^{-27} \text{ kg}$ or $10^{-3} \text{ kg mol}^{-1} / N_A$
Earth <sup>2</sup>	⊕	$4.11 \times 10^{23} \text{ slugs}$	$6.00 \times 10^{24} \text{ kg}$
Earth [customary U.S.] <sup>2</sup>	⊕	$1.32 \times 10^{25} \text{ lbm}$	-
Moon <sup>2</sup>	☾	$1.623 \times 10^{23} \text{ lbm}$	$7.36 \times 10^{22} \text{ kg}$
Sun <sup>2</sup>	☉	$4.387 \times 10^{30} \text{ lbm}$	$1.99 \times 10^{30} \text{ kg}$
electron rest mass	$m_e$	$2.008 \times 10^{-30} \text{ lbm}$	$9.1095 \times 10^{-31} \text{ kg}$
neutron rest mass	$m_n$	$3.693 \times 10^{-27} \text{ lbm}$	$1.6750 \times 10^{-27} \text{ kg}$
proton rest mass	$m_p$	$3.688 \times 10^{-27} \text{ lbm}$	$1.6727 \times 10^{-27} \text{ kg}$



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<b>Pressure</b>			
atmospheric		14.696 (14.7) lbf/in <sup>2</sup>	1.0133 $\times 10^5$ Pa
<b>Temperature</b>			
standard		32° F (492° R)	0° C (273 K)
absolute zero		-459.67° F (0° R)	-273.16° C (0 K)
<b>Velocity<sup>3</sup></b>			
Earth escape		3.67 $\times 10^4$ ft/sec	1.12 $\times 10^4$ m/s
light (vacuum)	<i>c, c<sub>0</sub></i>	9.84 $\times 10^8$ ft/sec	2.9979 (3.00) $\times 10^8$ m/s
sound [air, STP]	<i>a</i>	1090 ft/sec	331 m/s
sound [air, 70°F, (20°C), 1 atm]		1130 ft/sec	344 ft/s
<b>Volume</b>			
Volume: molal ideal gas (STP) <sup>4</sup>		359 ft <sup>3</sup> / lbmol	22.41 m <sup>3</sup> /kmol

Table 1 Notes

1. Units come from a variety of sources, but primarily from the Handbook of Chemistry and Physics, The Standard Handbook for Aeronautical and Astronautical Engineers, and the Electrical Engineering Reference Manual for the PE Exam. See also the NIST website at <https://pml.nist.gov/cuu/Constants/>.
2. Symbols shown for the solar system are those used by NASA. See <https://science.nasa.gov/resource/solar-system-symbols/>.
3. Velocity technically is a vector. It has direction.
4. The unit "lbmol" is an actual unit, not a misspelling.



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**Appendix C: Fundamental Constants**

Quantity	Symbols	US Customary	SI Units
Avogadro's number	$N_A, L$		$6.022 \times 10^{23} \text{ mol}^{-1}$
Bohr magneton	$\mu_B$		$9.2732 \times 10^{-24} \text{ J/T}$
Boltzmann constant	$\kappa$	$5.65 \times 10^{-24} \text{ ft-lbf/R}$	$1.3805 \times 10^{-23} \text{ J/T}$
electron volt: $\left(\frac{e}{C}\right) \text{ J}$	eV		$1.602 \times 10^{-19} \text{ J}$
Faraday constant, $N_A e$	F		96485 C/mol
fine structure constant, inverse $\alpha^{-1}$	$\alpha$ $\alpha^{-1}$		$7.297 \times 10^{-3}$ ( $\approx 1/137$ ) 137.035
gravitational constant	$g_c$	$32.174 \text{ lbf-ft/lbf-sec}^2$	
Newtonian gravitational constant	G	$3.44 \times 10^{-8} \text{ ft}^4 / \text{lbf-sec}^4$	$6.672 \times 10^{-11} \text{ N}\cdot\text{m}^2 / \text{kg}^2$
nuclear magneton	$\mu_N$		$5.050 \times 10^{-27} \text{ J/T}$
permeability of a vacuum	$\mu_0$		$1.2566 \times 10^{-6} \text{ N/A}^2 \text{ (H/m)}$
permittivity of a vacuum, electric constant $1 / \mu_0 c^2$	$\epsilon_0$		$8.854 \times 10^{-12} \text{ C}^2 / \text{N}\cdot\text{m}^2 \text{ (F/m)}$
Planck's constant	h		$6.6256 \times 10^{-34} \text{ J}\cdot\text{s}$
Planck's constant: $h/2\pi$			$1.0546 \times 10^{-34} \text{ J}\cdot\text{s}$
Rydberg constant	$R_\infty$		$1.097 \times 10^7 \text{ m}^{-1}$
specific gas constant, air	R	$53.3 \text{ ft-lbf/lbm-R}$	$287 \text{ J/kg}\cdot\text{K}$
Stefan-Boltzmann constant		$1.71 \times 10^{-9} \text{ BTU/ft}^2\text{-hr}\cdot\text{R}^4$	$5.670 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4$
triple point, water		32.02 F, 0.0888 psia	0.01109 C, 0.6123 kPa
universal gas constant	$R^*$	$1545 \text{ ft-lbf/lbmol-R}$ $1.986 \text{ BTU/lbmol-R}$	$8314 \text{ J/kmol}\cdot\text{K}$

Table Notes

1. Units come from a variety of sources, but primarily from the Handbook of Chemistry and Physics, The Standard Handbook for Aeronautical and Astronautical Engineers, and the Electrical Engineering Reference Manual for the PE Exam. See also the NIST website at <https://pml.nist.gov/cuu/Constants/>. The unit in Volume of "lbmol" is an actual unit, not a misspelling.



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**Appendix D: Mathematical Constants, Signs/Symbols, Maxwell’s Equations**

Quantity	Symbol	Value
Archimedes’ constant (pi)	$\pi$	3.1415926536
base of natural logs	$e$	2.7182818285
Euler’s constant	$C$ or $\tau$	0.5772156649

Signs/Symbols	Meaning
$\cdot$	multiplied by
$/$	divided by
$:$	ratio
$\gg$	much greater than
$\ll$	much less than
$=$	equals
$\equiv$	identical with
$\sim$	similar to
$\approx$	approximately equals
$\cong$	approximately equals, congruent
$\rightarrow, \dot{\rightarrow}$	approaches
$\propto$	proportional, varies as
$\therefore$	therefore

**Maxwell’s Equations**

integral form	point form	remarks
$\oint_s \mathbf{D} \cdot d\mathbf{s} = \int_V \rho \, dv$	$\nabla \cdot \mathbf{D} = \rho$	Gauss’ law
$\oint_s \mathbf{B} \cdot d\mathbf{s} = 0$	$\nabla \cdot \mathbf{B} = 0$	nonexistence of magnetic monopoles
$\oint \mathbf{E} \cdot d\mathbf{l} = \int_s \left( \frac{-\partial \mathbf{B}}{\partial t} \right) \cdot d\mathbf{s}$	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	Faraday’s law
$\oint \mathbf{H} \cdot d\mathbf{l} = \int_s \left( \mathbf{J}_c + \frac{\partial \mathbf{D}}{\partial t} \right) \cdot d\mathbf{s}$	$\nabla \times \mathbf{H} = \mathbf{J}_c + \frac{\partial \mathbf{D}}{\partial t}$	Ampère’s law

**Free-Space Form**

integral form	point form
$\oint_s \mathbf{D} \cdot d\mathbf{s} = 0$	$\nabla \cdot \mathbf{D} = 0$
$\oint_s \mathbf{B} \cdot d\mathbf{s} = 0$	$\nabla \cdot \mathbf{B} = 0$
$\oint \mathbf{E} \cdot d\mathbf{l} = \int_s \left( \frac{-\partial \mathbf{B}}{\partial t} \right) \cdot d\mathbf{s}$	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
$\oint \mathbf{H} \cdot d\mathbf{l} = \int_s \left( \frac{\partial \mathbf{D}}{\partial t} \right) \cdot d\mathbf{s}$	$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t}$

**Electromagnetic Field Vector Equations**

$$\mathbf{D} = \epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \mathbf{P} = \epsilon_0(1 + \chi_e) \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H} = \mu_0 \mathbf{H} + \mu_0 \mathbf{M} = \mu_0(1 + \chi_m) \mathbf{H}$$

$$\mathbf{J} = \sigma \mathbf{E} = \rho \mathbf{v}$$



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**Appendix E: The Greek Alphabet**

A	$\alpha$	alpha	N	$\nu$	nu
B	$\beta$	beta	$\Xi$	$\xi$	xi
$\Gamma$	$\gamma$	gamma	O	$o$	omicron
$\Delta$	$\delta$	delta	$\Pi$	$\pi$	pi
E	$\epsilon$	epsilon	P	$\rho$	rho
Z	$\zeta$	zeta	$\Sigma$	$\sigma$	sigma
H	$\eta$	eta	T	$\tau$	tau
$\Theta$	$\theta$	theta	$\Upsilon$	$\upsilon$	upsilon
I	$\iota$	iota	$\Phi$	$\phi$	phi
K	$\kappa$	kappa	X	$\chi$	chi
$\Lambda$	$\lambda$	lambda	$\Psi$	$\psi$	psi
M	$\mu$	mu	$\Omega$	$\omega$	omega

**Appendix F: SI Prefixes**

<u>symbol</u>	<u>prefix</u>	<u>value</u>
a	atto	$10^{-18}$
f	femto	$10^{-15}$
p	pico	$10^{-12}$
n	nano	$10^{-9}$
$\mu$	micro	$10^{-6}$
m	milli	$10^{-3}$
c	centi	$10^{-2}$
d	deci	$10^{-1}$
da	deka	10
h	hecto	$10^2$
k	kilo	$10^3$
M	mega	$10^6$
G	giga	$10^9$
T	tera	$10^{12}$
P	peta	$10^{15}$
E	exa	$10^{18}$

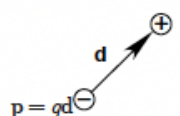
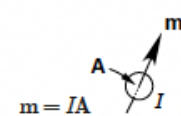


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**Appendix G: Comparison of Electric & Magnetic Equations**

equation description	electric version	magnetic version	remarks
experimental force law	<p>Coulomb's law</p> $\mathbf{F} = \frac{Q_1 Q_2}{4\pi\epsilon r^2} \mathbf{r}$	<p>force between two current elements</p> $d\mathbf{F} = \left( \frac{\mu_0}{4\pi} \right) \frac{I_2 d\mathbf{l}_2 \times (I_1 d\mathbf{l}_1 \times \mathbf{r})}{r^2}$	<p>The term <math>I dl</math> in the magnetic column is the equivalent of a "magnetic charge" <math>q_m</math>. The <math>I</math> or the <math>dl</math> can be the vector. The <math>r</math> is a unit vector pointing from 1 to 2.</p>
field definitions from force law	$\mathbf{F} = Q\mathbf{E}$	$d\mathbf{F} = \mathbf{I} \times \mathbf{B} dl$ current element $d\mathbf{F} = \mathbf{J} \times \mathbf{B} dV$ distributed current element $d\mathbf{F} = q\mathbf{v} \times \mathbf{B}$ moving charge	<p>The <math>V</math> used in this row represents volume, not voltage. The <math>v</math> is the velocity.</p>
general force law	$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$ $d\mathbf{F} = (\rho\mathbf{E} + \mathbf{J} \times \mathbf{B}) dV \text{ where } dQ = \rho dV$		<p>The <math>V</math> in this row represents the volume, not voltage. The <math>v</math> is the velocity.</p>
definition of scalar and vector potential	$\mathbf{E} = -\nabla V$	$\mathbf{B} = \nabla \times \mathbf{A}$	<p><math>\mathbf{A}</math> is the magnetic vector potential.</p>
Poisson's equation for the potential function	$\nabla^2 V = -\frac{\rho}{\epsilon}$	$\nabla^2 \mathbf{A} = -\mu_0 \mathbf{J}$	<p>From a knowledge of the charge distribution, the potential can be found and then the <math>\mathbf{E}</math> and <math>\mathbf{B}</math> fields determined.</p>
Gauss's law enclosing charge and Ampère's law enclosing current	$\oiint \mathbf{D} \cdot d\mathbf{A} = \iiint \rho dV = Q$ $\nabla \cdot \mathbf{D} = \rho$	$\oint \mathbf{H} \cdot d\mathbf{l} = I$ $\nabla \times \mathbf{H} = \mathbf{J}$	<p>The <math>V</math> in this row represents volume.</p>
constitutive relations	$\mathbf{D} = \epsilon \mathbf{E}$ $\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$	$\mathbf{B} = \mu \mathbf{H}$ $\mathbf{B} = \mu_0 \mathbf{H} + \mu_0 \mathbf{M}$	<p>The second set of equations is always valid. The first set assumes the medium is linear and isotropic.</p>
definitions of relative permittivity and permeability	$\epsilon_r = \frac{\epsilon}{\epsilon_0}$ $\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$	$\mu_r = \frac{\mu}{\mu_0}$ $\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$	

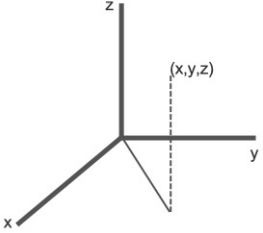
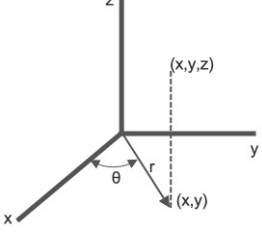
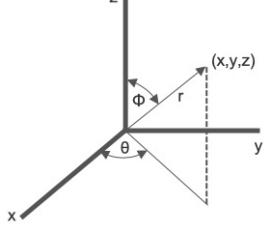
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equation description	electric version	magnetic version	remarks
capacitance and inductance of a field cell	$\epsilon_0 = \frac{C}{l}$	$\mu_0 = \frac{L}{l}$	Field cells are a construct designed to represent free space in terms of a parallel plate capacitor and an inductor. This capacitance and inductance exist regardless of the presence of an electric or magnetic field.
capacitance and inductance	$C = \frac{Q}{V}$	$L = \frac{\Lambda}{I}$	$\Lambda$ is the flux linkage.
energy density of a field	$U = \frac{1}{2} \epsilon E^2$	$U = \frac{1}{2} \mu H^2$	Both energy and momentum are carried by a field.
energy stored by capacitance and inductance	$W = \frac{1}{2} CV^2$	$W = \frac{1}{2} LI^2$	
electromotive and magnetomotive force with sources present	$\oint \mathcal{E} \cdot dl = \mathcal{E} = V$	$\oint \mathbf{H} \cdot d\mathbf{l} = NI = F_m = V_m$	The $\mathcal{E}$ is the emf, not the permittivity. Without sources present, both line integrals are equal to zero.
dipole moments	 <p><math>\mathbf{p} = q\mathbf{d}</math></p>	 <p><math>\mathbf{m} = I\mathbf{A}</math></p>	
dipole torque	$\mathbf{T} = \mathbf{p} \times \mathbf{E}$	$\mathbf{T} = \mathbf{m} \times \mathbf{B}$	This torque occurs due to the dipole being immersed in an external $\mathbf{E}$ or $\mathbf{B}$ field.
dipole potential energy	$W = -\mathbf{p} \cdot \mathbf{E}$	$W = -\mathbf{m} \cdot \mathbf{B}$	

electric	magnetic
emf $= V = IR$	mmf $= V_m = \phi \mathcal{R}$
current $I$	flux $\phi$
emf $\mathcal{E}$ or $V$	mmf $V_m$
resistance $R = \rho l/A = l/\sigma A$	reluctance $\mathcal{R} = l/\mu A$
resistivity $\rho$	reluctivity $1/\mu$
conductance $G = 1/R$	permeance $P_m = \mu A/l$
conductivity $\sigma = 1/\rho$	permeability $\mu$



**Appendix H: Coordinate Systems and Related Operations**

Mathematical Operations	Rectangular Coordinates	Cylindrical Coordinates	Spherical Coordinates
Conversion to Rectangular Coordinants	 <p> <math>x = x</math>  <math>y = y</math>  <math>z = z</math> </p>	 <p> <math>x = r \cos \theta</math>  <math>y = r \sin \theta</math>  <math>z = z</math> </p>	 <p> <math>x = r \sin \phi \cos \theta</math>  <math>y = r \sin \phi \sin \theta</math>  <math>z = r \cos \phi</math> </p>
Gradient	$\nabla f = \frac{\partial f}{\partial x} \mathbf{i} + \frac{\partial f}{\partial y} \mathbf{j} + \frac{\partial f}{\partial z} \mathbf{k}$	$\nabla f = \frac{\partial f}{\partial r} \mathbf{r} + \frac{1}{r} \frac{\partial f}{\partial \theta} \boldsymbol{\theta} + \frac{\partial f}{\partial z} \mathbf{k}$	$\nabla f = \frac{\partial f}{\partial r} \mathbf{r} + \frac{1}{r} \frac{\partial f}{\partial \phi} \boldsymbol{\phi} + \frac{1}{r \sin \theta} \frac{\partial f}{\partial \theta} \boldsymbol{\theta}$
Divergence	$\nabla \cdot \mathbf{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$	$\nabla \cdot \mathbf{A} = \frac{1}{r} \frac{\partial (r A_r)}{\partial r} + \frac{1}{r} \frac{\partial A_\theta}{\partial \theta} + \frac{\partial A_z}{\partial z}$	$\nabla \cdot \mathbf{A} = \frac{1}{r^2} \frac{\partial (r^2 A_r)}{\partial r} + \frac{1}{r \sin \phi} \frac{\partial (A_\phi \sin \phi)}{\partial \phi} + \frac{1}{r \sin \phi} \frac{\partial A_\theta}{\partial \theta}$
Curl	$\nabla \times \mathbf{A} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ A_x & A_y & A_z \end{vmatrix}$	$\nabla \times \mathbf{A} = \begin{vmatrix} \frac{1}{r} \mathbf{r} & \boldsymbol{\theta} & \frac{1}{r} \mathbf{k} \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \theta} & \frac{\partial}{\partial z} \\ A_r & A_\theta & A_z \end{vmatrix}$	$\nabla \times \mathbf{A} = \begin{vmatrix} \frac{1}{r^2 \sin \theta} \mathbf{r} & \frac{1}{r^2 \sin \theta} \boldsymbol{\phi} & \frac{1}{r} \boldsymbol{\theta} \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \phi} & \frac{\partial}{\partial \theta} \\ A_r & r A_\phi & r A_\theta A_\phi \end{vmatrix}$
Laplacian	$\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2}$	$\nabla^2 f = \frac{1}{r} \frac{\partial r}{\partial r} \left( r \frac{\partial f}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 f}{\partial \theta^2} + \frac{\partial^2 f}{\partial z^2}$	$\nabla^2 f = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial f}{\partial r} \right) + \frac{1}{r^2 \sin \phi} \frac{\partial}{\partial \phi} \left( \sin \phi \frac{\partial f}{\partial \phi} \right) + \frac{1}{r^2 \sin^2 \phi} \left( \frac{\partial^2 f}{\partial \theta^2} \right)$