PDHonline Course E319 (3 PDH)

Electrical Calculation Methods and Examples

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1. SHORT CIRCUIT CURRENT EFFECTS

1.1. Electrical distribution systems must be designed to withstand the maximum expected fault (short circuit) current until the short circuit current is cleared by a protective device. This is a fundamental electrical requirement. NEC Article 110.9 (2008 Edition) requires that all protective devices intended to interrupt current at fault levels must have an interrupting rating sufficient for the nominal circuit voltage and the current that is available at the line terminals of the equipment. For this reason, the maximum available short circuit current must be determined for all locations throughout the electrical system.

1.2. Figure 1-1 shows a simplified short circuit study for a small section of an electrical distribution system. The available fault current is shown at the service bus and at an MCC bus. As can be seen, the bulk of the short circuit current is provided by the distribution system through the transformer, with a lesser amount of current provided by each of the motors.

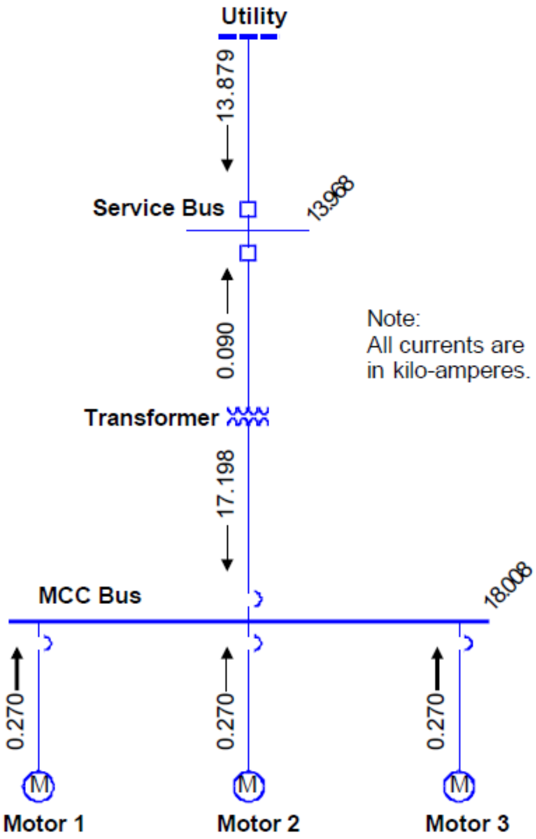


Figure 1-1. Sample Short Circuit Results—1 MVA Transformer

1.3. The transformer size has a significant effect on the available short circuit current. Whenever a transformer is replaced with a larger transformer, a short circuit study for the larger transformer has to be performed to verify that all equipment is properly sized for the increased short circuit current. Figure 1-2 shows an example of the increase that might be observed as a transformer size is increased from 1 MVA to 2 MVA. Comparing Figure 1-1 to Figure 1-2, the MCC bus fault current has increased from 18,000 amperes to over 30,000 amperes. Although the system breakers might have been adequately rated for use with the 1 MVA transformer, the larger 2 MVA transformer could allow a short circuit current in excess of the breakers' ratings. This example illustrates the importance of evaluating the entire electrical system whenever a change is made.

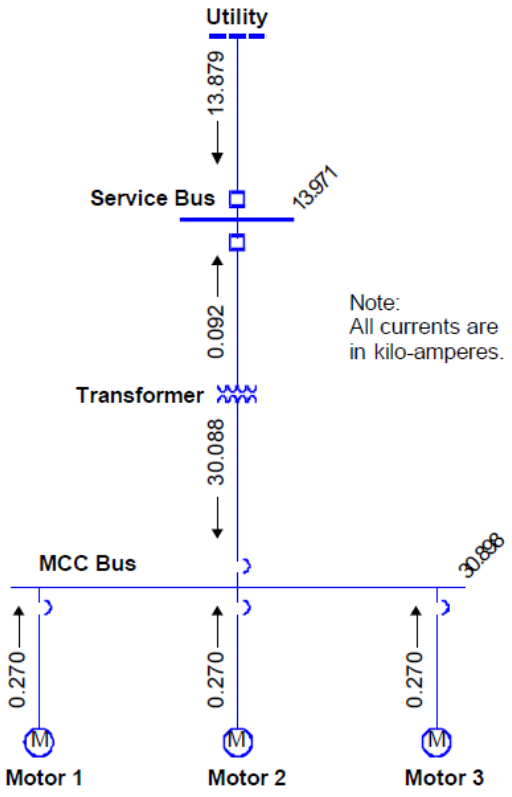


Figure 1-2. Sample Short Circuit Results—2 MVA Transformer

1.4. The computer program used for short circuit analysis should be capable of identifying overduty breakers (breakers in which the short-circuit current, including asymmetric current effects, exceeds the breaker interrupting rating). Figure 1-3 shows an example of overduty breakers. The feeder breaker to the MCC bus is 7 percent below its interrupting rating and the downstream load breakers are 33 percent over their interrupting rating.

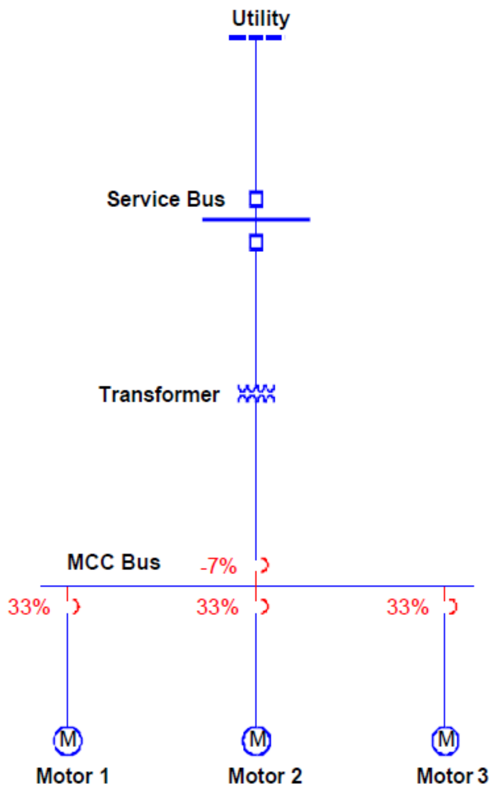


Figure 1-3. Overduty Molded Case Circuit Breakers

2. VOLTAGE DROP

2.1. Voltage drop should be calculated by the following equation:

$$Voltage\ Drop = I_L \times (R\ Cos\theta + X\ \ Sin\theta)$$

Where,

I_L = *Line Current in amperes*
R = *Resistance of line in ohms*
X = *Reactance of line in ohms*
θ = *Phase angle between voltage and current-If phase angle is not known, a phase angle of 36.9 degrees corresponding to a power factor of 0.8 should be assumed*

2.2. The above equation is simplified, but usually provides acceptable results. In the above equation, the conductor resistance and reactance values as a function of gauge size should be obtained from NEC Chapter 9, Tables 8 and 9 (2008 Edition). Note that NEC conductor resistance values are based on 75 °C (167 °F) and will usually require correction to the actual expected temperature (refer to NEC Chapter 9, Table 8, or the first example in section 6.1 for how to convert the resistance to a different temperature). The line current is calculated based on the expected real power requirement and phase angle. The following equations show the calculation of line current:

<u>Single- Phase Circuits</u>

$$I_L = \frac{P}{V \times Cos\theta}$$

Where,

I_L = *Line Current in amperes*
P = *Real power, in kW*
V = *Voltage, RMS-in kV to match power units*
θ = *Phase angle between voltage and current*

<u>Three- Phase Circuits</u>

$$I_L = \frac{P}{\sqrt{3} \times V \times Cos\theta}$$

Where,

I_L = *Line Current in amperes*
P = *Total three-phase real power, in kW*
V = *Line voltage, RMS-in kV to match power units*
θ = *Phase angle between voltage and current*

2.3. If comparing voltage drops across different nominal voltages, voltage drop calculations should be referenced to a 120 volt base to allow ready comparison of the voltage drops throughout the system, regardless of the actual voltage level. The following expression should be used to convert a voltage drop at some nominal voltage to a 120 volt base:

$$\text{Actual Voltage Drop (120 V base)} = \frac{\text{Actual Voltage Drop} \times 120}{\text{System Nominal Voltage}}$$

3. TRANSFORMER RATED CURRENT

3.1. Transformer rated secondary current is calculated by dividing the rated kVA capacity by the rated secondary voltage. The following examples illustrate the rated secondary current calculation.

EXAMPLE: What is the rated secondary current of a 30-kVA single-phase transformer with a rated secondary voltage of 240 volts?

$$I_s = \frac{30\ kVA \times 1000}{240\ V} = 125\ amperes$$

EXAMPLE: What is the rated secondary current of a 100-kVA three-phase transformer with a rated secondary voltage of 480 volts?

$$I_s = \frac{100\ kVA \times 1000}{\sqrt{3} \times 480\ V} = 120\ amperes$$

3.2. The above examples do not include the effect of any losses; however, the calculations provide approximate values that are usually adequate for use.

4. TRANSFORMER IMPEDANCE EFFECTS

4.1. For a given kVA rating, a transformer will provide a higher short circuit current as its impedance is lowered. Transformer impedance is usually expressed as a percent. A transformer rated at 10 percent impedance can supply 100%/10% = 10 times its rated secondary current into a short circuit. A transformer rated at 4 percent impedance can supply 100%/4% = 25 times its rated secondary current into a short circuit. Notice that two transformers of equal kVA capacity can have significantly different short circuit currents. This feature must be evaluated as part of the transformer sizing and selection process.

EXAMPLE: Compare the secondary short circuit current of a 500-kVA, 480 volt secondary, three-phase transformer with a 10 percent impedance to an equal capacity transformer with a 2 percent impedance.

First, calculate the rated secondary current:

$$I_{rated} = \frac{500\ kVA \times 1000}{\sqrt{3} \times 480\ V} = 600\ amperes$$

The 10 percent impedance transformer has the following expected short circuit current:

$$I_{sc-10\%} = \frac{100\%}{10\%} \times 600\ amperes = 10 \times 600\ amperes = 6{,}000\ amperes$$

The 2 percent impedance transformer has the following expected short circuit current:

$$I_{sc-2\%} = \frac{100\%}{2\%} \times 600\ amperes = 50 \times 600\ amperes = 30{,}000\ amperes$$

Notice that the 2 percent impedance transformer has 5 times the short circuit current of the 10 percent impedance transformer. The 2 percent impedance transformer might require a complete redesign of downstream electrical equipment to withstand the higher short circuit currents.

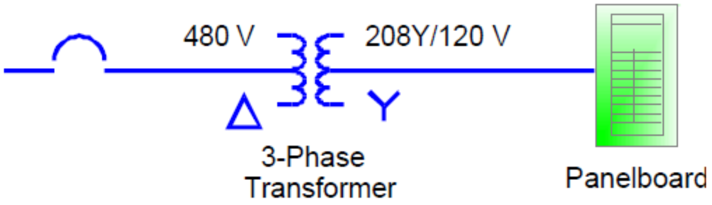
4.2. Impedance affects transformer regulation. As the impedance increases, the voltage regulation tends to increase. Voltage regulation is defined as the voltage change from no load to full load conditions:

$$Regulation\ (percent) = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100\%$$

5. TRANSFORMER SIZING

5.1. The following example illustrates the sizing process for a simple transformer installation. Primary and secondary conductor sizes are also determined.

EXAMPLE: A feeder supplies three-phase power to a 480 volt transformer. The transformer steps down to 208Y/120 volts to a lighting panel with a continuous load of 30 amperes on each phase. What is the required transformer kVA capacity, and required amperage on the primary and secondary?



Transformer Size

The transformer required kVA capacity is given by:

$$Required\ kVA = \sqrt{3} \times 208 \times 30 = 10.8\ kVA$$

Transformers are provided in standard sizes. The next larger standard size above 10.8 kVA is 15 kVA. So, a 15 kVA transformer should be chosen for this load. If additional load growth is anticipated, a larger transformer might have been selected instead.

Primary Ampacity

Assume that the transformer will eventually be fully loaded. The required primary amperage is:

$$I_p = \frac{15\ kVA \times 1000}{\sqrt{3} \times 480\ V} = 18\ amperes$$

Referring to NEC Table 310.16 (2008 Edition), a #12 AWG copper conductor would be selected for the primary. A #14 AWG copper conductor would not be selected even though it appears to have adequate current-carrying capacity because the footnote to NEC Table 310.16 requires that overcurrent protection be limited to 15 amperes for a #14 AWG conductor.

The NEC has an additional requirement relating to the transformer primary conductor. NEC Article 215.2(A) (1) (2008 Edition) requires that feeder conductors be sized for the noncontinuous load plus 125 percent of the continuous load. In this case, the primary conductor would be sized for 125 percent of 18 amperes, or 22.5 amperes. Referring again to NEC Table 310.16, a #12 AWG copper conductor is still acceptable for use because it has an ampacity of 25 amperes. Note that the footnote to NEC Table 310.16 requires that overcurrent protection be limited to 20 amperes for a #12 AWG conductor; however, this load limit still exceeds the 18 ampere actual load requirement and is therefore acceptable.

Secondary Ampacity

The required secondary amperage is:

$$I_p = \frac{15\ kVA \times 1000}{\sqrt{3} \times 208\ V} = 41.6\ amperes$$

NEC Article 215.2(A) (1) requires that feeders be sized for the noncontinuous load plus 125 percent of the continuous load. In this case, the secondary conductor would be sized for 125 percent of 41.6 amperes, or 52 amperes. Referring to NEC Table 310.16, a #6 AWG copper conductor would be selected.

6. ENERGY SAVINGS WITH OVERSIZED CONDUCTORS

6.1. Significant energy savings can be realized by installing conductors one size larger than required by the NEC. The following examples illustrate the evaluation process as well as the potential savings that can be realized.

EXAMPLE: A three-phase circuit feeds a 125 horsepower (93,250 watts), 460 volt motor, operating at 75 percent load, 76.2 meters (250 feet) from the load center. Assume that the motor operates only 50 percent of the time (4,380 hours per year). The motor full load current is 156 amperes and 75 percent of this load is 117 amperes. A #3/0 AWG conductor satisfies the electrical requirements. As shown below, a larger #4/0 AWG conductor pays for itself within 5 years. Thereafter, the installation continues to save energy costs of almost $50 per year compared to the smaller #3/0 AWG conductor.

Input Data	#3/0 AWG	#4/0 AWG
Conduit size	51 mm (2 inch)	51 mm (2 inch)
Conductor resistance (30°C)	0.0164	0.0130
Estimated Power Loss (3 phase)	673 W	534 W
Estimated wire cost	$991	$1,232
Estimated conduit cost	$365	$365
Incremental Cost		$241
Projected energy savings		609 kWh/year
Cost savings at $0.08 per kWh		$48.72/year
Payback period		5 years

In the above example, the copper conductor resistance was obtained from NEC Chapter 9, Table 8 (2008 Edition), and corrected for use at 30 °C (rather than 75 °C as listed in the table) in accordance with the following expression provided by a footnote in the same table:

$$R_2 = R_1 \times [1 + 0.00323 \times (T - 75)]$$

where R_1 is the copper conductor resistance at 75 °C

The estimated power loss was then calculated by:

$$Power\ Loss = 3 \times I^2 \times R$$

EXAMPLE: A single-phase, 15 ampere lighting load operates only 50 hours per week (2,600 hours per year) and is located 30.5 meters (100 feet) from the load center. As shown below, the larger #10 AWG conductor pays for itself in just over 1 year. Thereafter, the installation continues to save energy costs of almost $6 per year compared to the smaller #12 AWG conductor.

Input Data	#12 AWG	#10 AWG
Conduit size	12.7 mm (0.5 inch)	12.7 mm (0.5 inch)
Conductor resistance (30°C)	0.3384	0.2120
Estimated Power Loss (1 phase)	76 W	48 W
Estimated wire cost	$12	$19
Estimated conduit cost	$42	$42
Incremental Cost		$7
Projected energy savings		73 kWh/year
Cost savings at $0.08 per kWh		$5.8/year
Payback period		1.2 years

EXAMPLE: Even if a larger conduit is required, an acceptable payback can be achievable with a larger wire size. For this example, assume that a three-phase, 40 ampere lighting load operates for only 4,000 hours per year (which is about 11 hours per day) and is located 61 meters (200 feet) from the load center. As shown below, the larger #6 AWG conductor pays for itself in 1.5 years. Thereafter, the installation continues to save energy costs of over $75 per year compared to the smaller #8 AWG conductor.

Input Data	#8 AWG	#6 AWG
Conduit size	19.1 mm (0.75 inch)	25.4 mm (1inch)
Conductor resistance (30°C)	0.1330	0.0839
Estimated Power Loss (3 phase)	638 W	403 W
Estimated wire cost	$117	$166
Estimated conduit cost	$128	$192
Incremental Cost		$113
Projected energy savings		940 kWh/year
Cost savings at $0.08 per kWh		$75.2/year
Payback period		1.5 years

6.2. As the above examples illustrate, a significant energy savings can be realized by increasing the conductor size to the next higher gauge size

7. ADJUSTABLE SPEED DRIVE ECONOMIC EVALUATION

7.1. If an ASD installation is considered on the basis of energy efficiency, an economic evaluation should be performed in accordance with the following flow chart:

Adjustable Speed Drive
Economic Evaluation

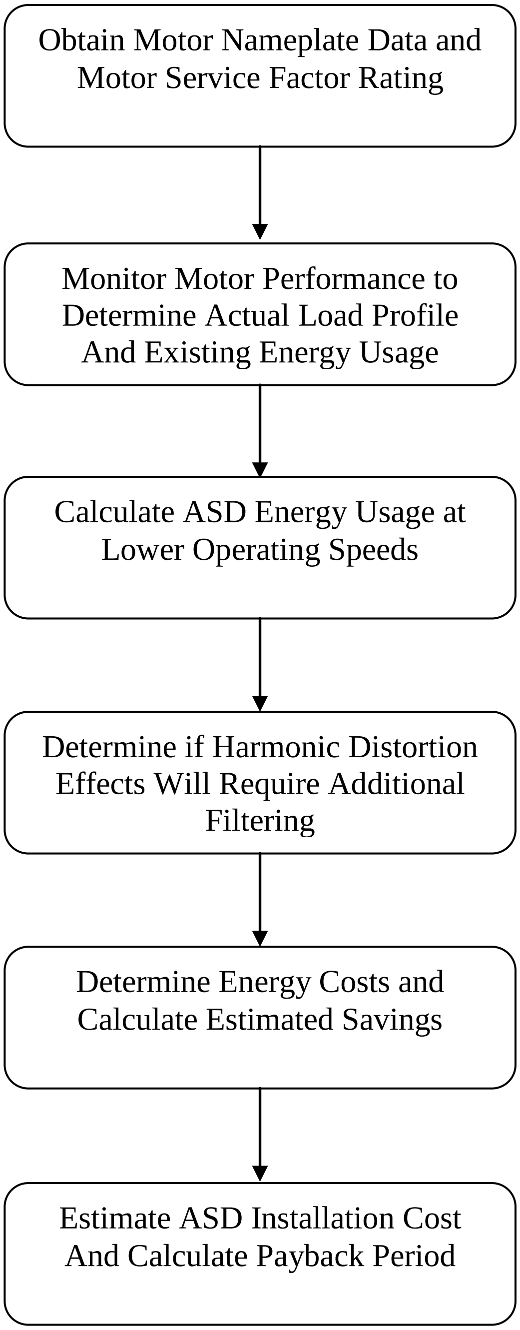


Figure 7-1. Adjustable Speed Drive Economic Evaluation

7.2. The key to an economic evaluation is to determine whether or not the motor will be fully loaded under expected operating conditions. If the motor is always loaded at or near 100 percent of rated load, then little if any savings will be realized. Fortunately, it is common to discover that the actual load current is significantly less than rated. For example, Figure 7-2 shows a typical case in which a 60 horsepower (44,800 watts) motor normally operates at a load of less than 24 kW. In this case, an ASD can provide substantial savings.

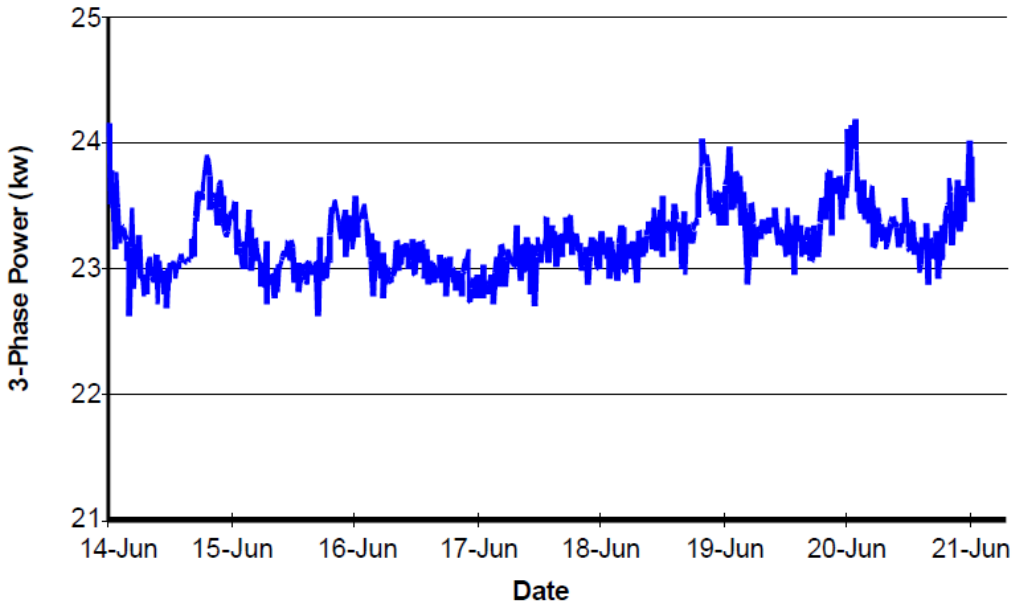


Figure 7-2. Typical Motor Load Profile with Motor Operating at Half of Rated Load

7.3. Table 7-1 provides a sample economic evaluation for an ASD installation for a continuously operating HVAC system motor. This evaluation was for a hospital application in which higher initial ASD costs were expected in order to address harmonic distortion concerns as part of the design. Even so, a payback period of less than 2 years was estimated. As can be seen in Table 7-1, an ASD economic evaluation is most sensitive to the following assumptions:

- Total motor operating time per year—unless it is fully loaded, a continuously energized motor will show a faster payback than an intermittently energized motor.
- Estimated actual motor load/speed—for a typical centrifugal fan motor, energy usage is proportional to the $(\text{speed})^3$. For example, if the motor speed can be reduced to 90 percent of rated speed, the energy usage can be reduced to almost 70 percent of its nominal value.
- Cost per kilowatt hour—the local average energy cost should be used.
- ASD equipment and installation cost—for critical locations, the added cost of ensuring acceptable power quality can double the total initial cost.

Input Data for Existing Application

Motor ID#	HVAC Fan-1	Comments
Motor hP/Watts	60/44,760	Larger motors provide greater payback
Motor Efficiency (from Nameplate)	91.7%	Efficiency should be evaluated at less than full load
Motor Load Factor	50.0%	Existing energy usage is lower if the motor is operating at less than full load. This value is obtained from metering or monitoring.
Number of Operation per Year	8,760	Hours of Operation is Particularly important to energy analysis.
Existing Motor Energy Use (kWh/yr)	213,794	$= \left[\frac{60 \times 1.746}{0.917}\right] \times 8760 \times 0.5$

Calculation for Adjustable Speed Operation

ASD Efficiency 95.0%

Operating Schedule With ASD	Frequency	Percent Speed	Percent Time	Energy (kWh)
32,812 = [213,794 × $(0.9)^3$ × 0.2] /.95	54	90.0%	20.0%	32,812
40,328 = [213,794 × $(0.8)^3$ × 0.35] /.95	48	80.0%	35.0%	40,328
27,017 = [213,794 × $(0.7)^3$ × 0.35] /.95	42	70.0%	35.0%	27,017
4,861 = [213,794 × $(0.6)^3$ × 0.1] /.95	36	60.0%	10.0%	4,861
Estimated Energy Use With ASD			Total	105,018

Economic Analysis and Payback Calculation

Annual Energy Savings (kWh):	108,776	= (213,794 - 105,018)
Cost per Kilowatt Hour:	$0.06	Based on local commercial power rates.
Annual Cost Savings:	$6,527	= (108,776 × $0.06)
Estimated Installation Cost Per Motor Horsepower	$225	Estimate based on ASD operating requirements and features.
Estimated Installation Cost:	$13,500	$= (60\ hp \times \$225)$
Payback Period (Years)	2.07	= (13,500 / 6,527)

Table 7-1. Example Adjustable Speed Drive Energy Savings Worksheet

7.4. Payback periods greater than 5 years should not be approved solely on the basis of economic savings; operating system improvements should also be an identified need for these cases.

8. AUTOMATIC TRANSFER SWITCH SIZING

8.1. The following example illustrates the sizing process for an ATS that is UL listed for *Total System Load capability*.

EXAMPLE: Determine the required size for an ATS rated for *Total System Loads*, for a 208Y/120 volt, three-phase circuit consisting of the following three-phase balanced loads:

1. Resistive heating load: 100 kW or $I = \frac{100\ kW}{\sqrt{3} \times 208\ V} = 278\ amperes$
2. Incandescent lighting load: 50 kW or $I = \frac{50\ kW}{\sqrt{3} \times 208\ V} = 139\ amperes$
3. Motors (4) at 32 amperes each, or 128 amperes continuous load, and each motor has approximately 192 amperes inrush on starting.

The total continuous load requirement is 545 amperes. The incandescent lighting load does not exceed 30 percent of the total load. The selected ATS should be rated for 600 amperes (the next standard ATS size above 545 amperes). The manufacturer should be consulted to verify that the ATS is acceptable for the expected motor inrush currents (although it should be fully capable of this inrush per UL 1008).

9. SIZING CAPACITORS FOR POWER FACTOR CORRECTION

9.1. Determining Capacitor Size

9.1.1. The required capacitor size to improve power factor should be determined in accordance with the following expression:

$$kVAR_{cap} = kW \times (tan\theta_1 - tan\theta_2)$$

Where,

$kVAR_{cap}$ = Required capacitor size in kVARs
kW = Active power in circuit
θ_1 = Phase angle before applying power factor correction
θ_2 = Phase angle after applying power factor correction

9.1.2. Figure 9-2 shows the phasor relationship for power factor correction. The addition of kVARs by a shunt capacitor reduces the supplied kVAR.

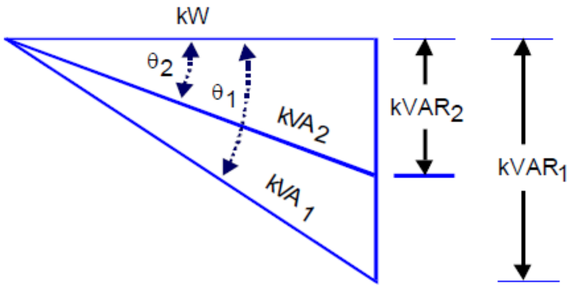


Figure 9-2. Phasor Diagram for Power Factor Correction

EXAMPLE: A three-phase, 460-volt, 50 horsepower (37,300 watts) motor has a power factor of 0.65. What capacitor rating is needed to improve the power factor to 0.95?

First, calculate the power required by the motor at full-load conditions. NEC Table 430.250 (2008 Edition) specifies a typical full-load current of 65 amperes. The load power is then calculated by:

$$P\ (kW) = \frac{\sqrt{3} \times V \times I \times pf}{1000} = \frac{1.73 \times 460 \times 65 \times 0.65}{1000} = 33.7\ kW$$

The required capacitor size is given by:

$$kVAR_{cap} = kW \times \ (\tan\theta_1 - \tan\theta_2) = 33.7\ \times\ (1.17 - 0.33) = 28.3\ kVAR$$

9.1.3. Look-up tables are often used to perform the above calculation. Table 9-1 shows a typical table.

EXAMPLE: The previous example determined the required capacitor size for an active power of 33.7 kW with a power factor of 0.65 to obtain a desired power factor is 0.95. Using Table 9-1, the applicable correction factor is 0.84 and the required capacitor size is:

33.7 kW x 0.84 = 28.3 kVAR

Original Power Factor	Desired Power Factor							
	0.86	0.87	0.88	0.89	0.90	0.91	0.92	0.93
0.50	1.139	1.165	1.192	1.220	1.248	1.276	1.303	1.337
0.51	1.093	1.119	1.146	1.174	1.202	1.230	1.257	1.291
0.52	1.051	1.077	1.104	1.132	1.160	1.188	1.215	1.249
0.53	1.007	1.033	1.060	1.088	1.116	1.144	1.171	1.205
0.54	0.966	0.992	1.019	1.047	1.075	1.103	1.130	1.164
0.55	0.926	0.952	0.979	1.007	1.035	1.063	1.090	1.124
0.56	0.887	0.913	0.940	0.968	0.996	1.024	1.051	1.085
0.57	0.849	0.875	0.902	0.930	0.958	0.986	1.013	1.047
0.58	0.812	0.838	0.865	0.893	0.921	0.949	0.976	1.010
0.59	0.775	0.801	0.828	0.856	0.884	0.912	0.939	0.973
0.60	0.741	0.767	0.794	0.822	0.849	0.878	0.905	0.939
0.61	0.706	0.732	0.759	0.787	0.815	0.843	0.870	0.904
0.62	0.672	0.698	0.725	0.753	0.781	0.809	0.836	0.870
0.63	0.640	0.666	0.693	0.721	0.749	0.777	0.804	0.838
0.64	0.607	0.633	0.660	0.688	0.716	0.744	0.771	0.805
0.65	0.576	0.602	0.629	0.657	0.685	0.713	0.740	0.774
0.66	0.545	0.571	0.598	0.626	0.654	0.682	0.709	0.743
0.67	0.515	0.541	0.568	0.596	0.624	0.652	0.679	0.713
0.68	0.486	0.512	0.539	0.567	0.595	0.623	0.650	0.684
0.69	0.456	0.482	0.509	0.537	0.565	0.593	0.620	0.654
0.70	0.427	0.453	0.480	0.508	0.536	0.564	0.591	0.625
0.71	0.399	0.425	0.452	0.480	0.508	0.536	0.563	0.597
0.72	0.370	0.396	0.423	0.451	0.479	0.507	0.534	0.568
0.73	0.343	0.369	0.396	0.424	0.452	0.480	0.507	0.541
0.74	0.316	0.342	0.369	0.397	0.425	0.453	0.480	0.514
0.75	0.289	0.315	0.342	0.370	0.398	0.426	0.453	0.487
0.76	0.262	0.288	0.315	0.343	0.371	0.399	0.426	0.460
0.77	0.236	0.262	0.289	0.317	0.345	0.373	0.400	0.434
0.78	0.210	0.236	0.263	0.291	0.319	0.347	0.374	0.408
0.79	0.183	0.209	0.236	0.264	0.292	0.320	0.347	0.381
0.80	0.157	0.183	0.210	0.238	0.266	0.294	0.321	0.355
0.81	0.131	0.157	0.184	0.212	0.240	0.268	0.295	0.329
0.82	0.105	0.131	0.158	0.186	0.214	0.242	0.269	0.303
0.83	0.079	0.105	0.132	0.160	0.188	0.216	0.243	0.277
0.84	0.053	0.079	0.106	0.134	0.162	0.190	0.217	0.251
0.85	0.027	0.053	0.080	0.108	0.136	0.164	0.191	0.225

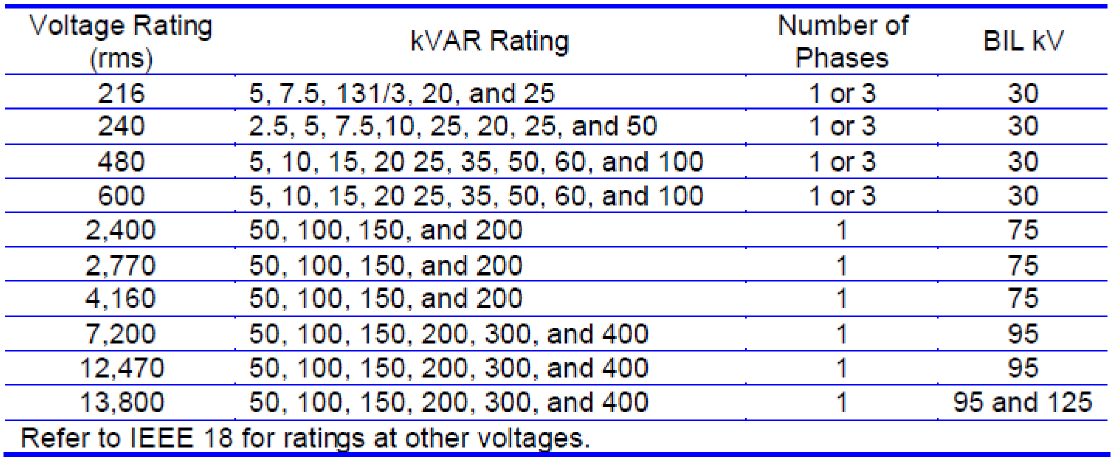
Table 9-1. Correction Factors for Capacitor Sizing

Original Power Factor	Desired Power Factor						
	0.94	0.95	0.96	0.97	0.98	0.99	1.00
0.50	1.369	1.402	1.441	1.481	1.529	1.590	1.732
0.51	1.320	1.357	1.395	1.435	1.483	1.544	1.686
0.52	1.281	1.315	1.353	1.393	1.441	1.502	1.644
0.53	1.237	1.271	1.309	1.349	1.397	1.458	1.600
0.54	1.196	1.230	1.268	1.308	1.356	1.417	1.559
0.55	1.156	1.190	1.228	1.268	1.316	1.377	1.519
0.56	1.117	1.151	1.189	1.229	1.277	1.338	1.480
0.57	1.079	1.113	1.151	1.191	1.239	1.300	1.442
0.58	1.042	1.076	1.114	1.154	1.202	1.263	1.405
0.59	1.005	1.039	1.077	1.117	1.165	1.226	1.368
0.60	0.971	1.005	1.043	1.083	1.131	1.192	1.334
0.61	0.936	0.970	1.008	1.048	1.096	1.157	1.299
0.62	0.902	0.936	0.974	1.014	1.062	1.123	1.265
0.63	0.870	0.904	0.942	0.982	1.030	1.091	1.233
0.64	0.837	0.871	0.909	0.949	0.997	1.058	1.200
0.65	0.806	0.840	0.878	0.918	0.966	1.027	1.169
0.66	0.775	0.809	0.847	0.887	0.935	0.996	1.138
0.67	0.745	0.779	0.817	0.857	0.905	0.966	1.108
0.68	0.716	0.750	0.788	0.828	0.876	0.937	1.079
0.69	0.686	0.720	0.758	0.798	0.840	0.907	1.049
0.70	0.657	0.691	0.729	0.769	0.811	0.878	1.020
0.71	0.629	0.663	0.701	0.741	0.783	0.850	0.992
0.72	0.600	0.634	0.672	0.712	0.754	0.821	0.963
0.73	0.573	0.607	0.645	0.685	0.727	0.794	0.936
0.74	0.546	0.580	0.618	0.658	0.700	0.767	0.909
0.75	0.519	0.553	0.591	0.631	0.673	0.740	0.882
0.76	0.492	0.526	0.564	0.604	0.652	0.713	0.855
0.77	0.466	0.500	0.538	0.578	0.620	0.687	0.829
0.78	0.440	0.474	0.512	0.552	0.594	0.661	0.803
0.79	0.413	0.447	0.485	0.525	0.567	0.634	0.776
0.80	0.387	0.421	0.459	0.499	0.541	0.608	0.750
0.81	0.361	0.395	0.433	0.473	0.515	0.582	0.724
0.82	0.335	0.369	0.407	0.447	0.489	0.556	0.698
0.83	0.309	0.343	0.381	0.421	0.463	0.530	0.672
0.84	0.283	0.317	0.355	0.395	0.437	0.504	0.645
0.85	0.257	0.291	0.329	0.369	0.417	0.478	0.620

Table 9-1. Correction Factors for Capacitor Sizing, (continued)

9.2. Capacitor Ratings

9.2.1. Capacitors are built to standard sizes as specified by IEEE 18, IEEE Standard for Shunt Power Capacitors. Table 9-2 shows the capacitor sizes of potential interest to facility interior electrical design.



Voltage Rating (rms)	kVAR Rating	Number of Phases	BIL kV
216	5, 7.5, 131/3, 20, and 25	1 or 3	30
240	2.5, 5, 7.5,10, 25, 20, 25, and 50	1 or 3	30
480	5, 10, 15, 20 25, 35, 50, 60, and 100	1 or 3	30
600	5, 10, 15, 20 25, 35, 50, 60, and 100	1 or 3	30
2,400	50, 100, 150, and 200	1	75
2,770	50, 100, 150, and 200	1	75
4,160	50, 100, 150, and 200	1	75
7,200	50, 100, 150, 200, 300, and 400	1	95
12,470	50, 100, 150, 200, 300, and 400	1	95
13,800	50, 100, 150, 200, 300, and 400	1	95 and 125

Refer to IEEE 18 for ratings at other voltages.

Table 9-2. Common Capacitor Reactive Power Ratings

9.2.2. The calculated capacitor size will rarely exactly match one of the available sizes. The decision of whether to select the next larger or the next smaller size depends on the circuit configuration and the desired power factor. Section 9.3 provides specific design criteria regarding capacitor size.

9.2.3. IEEE 18 establishes the required design tolerances for capacitors.

9.3. Design Criteria

9.3.1. Requiring power factor correction should be considered as part of the overall facility design. Power factor correction has to be justifiable based upon operational performance improvements or cost-savings, including any potential effects caused by interaction with other devices.

9.3.2. If used, capacitors should be applied to obtain a power factor range of 0.85 to 0.95. A power factor of 0.85 will satisfy most operational requirements, but the actual minimum value should also be based on any revenue metering penalties established by the local commercial utility for low power factors. Little, if any, economic advantage will usually be realized if attempting to correct above a power factor of 0.95. Care has to be taken to make sure that power factor correction will not cause a leading power factor under no-load conditions.

9.3.3. Power factor correction requires particular attention if nonlinear loads are a significant portion of the facility load; this includes electronic equipment, ASDs, UPS systems, and other significant sources of harmonic distortion. Capacitors can resonate with nonlinear loads and cause additional distortion of the electrical system voltage and current. In this case, the capacitor(s) might not improve the power factor at all. Also, resonant conditions can cause capacitor failure. If facilities contain a significant proportion of nonlinear loads, the application of a synchronous condenser should be evaluated instead. Synchronous condensers are often applied at the service entrance, which might not solve all power factor problems throughout the facility.

9.3.4. For facility applications, continuously energized capacitors are preferred over switching capacitors, even though this might necessitate the addition of a smaller amount of capacitance. If a pre-selected quantity of capacitors cannot be connected and left connected to the line in a constantly energized state, the facility electrical system would probably be better off without them. Each capacitor on-off cycle causes transient voltage surges that are potentially damaging to other equipment over time. Additional design considerations such as soft-start or pre-insertion resistors are necessary if capacitors are routinely switched. Also, surge protection should be applied for switched capacitors in accordance with IEEE 141 and PDH course E288 “Surge Protection Systems Performance and Evaluation”.

9.3.5. Capacitors installed strictly for motor applications should be evaluated based on the number of motors requiring power factor correction. If only a single motor or a small number of motors require power factor correction, the capacitor can be installed at each motor such that it is switched on and off with the motor. If several motors connected to a single bus require power factor correction, the capacitor(s) should be installed at the bus. For new installations, the MCC’s should be specified to contain the capacitor(s). For existing installations, studies need to be performed to see if spare cubicles can be refurbished to accept the capacitor(s). NEMA MG 1, IEEE 141 and IEEE 1036, IEEE Guide for Application of Shunt Power Capacitors, provide additional information on capacitors.

9.3.6. Capacitors should not be installed directly onto a motor circuit under the following conditions:

- If solid-state starters are used.
- If open-transition starting is used.
- If the motor is subject to repetitive switching, jogging, inching, or plugging.
- If a multi-speed motor is used.
- If a reversing motor is used.
- If a high-inertia load is connected to the motor.

9.3.7. The ampacity of capacitor circuit conductors should be sized at least 135 percent of the rated capacitor current in accordance with NEC Article 460.8 (2008 Edition). Overcurrent protection and disconnection means should be provided as specified by the NEC. IEEE 1036 provides additional guidance for sizing protective devices for the maximum possible inrush current.

9.3.8. The manufacturer should be consulted before applying a capacitor under any of the specified abnormal service conditions of IEEE 18.

9.3.9. Liquid dielectrics used in capacitors must be non-PCB mineral oil or other less flammable liquid type. Capacitors with tetrachloroethylene (perchloroethylene) and 1,2,4, trichlorobenzen fluids should not be used.

9.3.10. All capacitors used for power factor correction should be provided with an automatic means of draining the stored charge after the capacitor is disconnected from its source of supply.

9.3.11. Power capacitors can fail in such a manner to cause “noise” on communication lines. Care has to be taken to make sure that capacitors are not located near communications equipment.

9.4. Information Sources

9.4.1. The following references provide additional information regarding power factor correction:

- IEEE 18—provides information regarding the ratings and testing of capacitors.
- IEEE 141—provides a detailed technical overview of power factor correction.
- IEEE 519—addresses power factor correction in a nonlinear load environment.
- IEEE 1036—provides application guidelines for shunt power capacitors and is intended for 2,400 volts and higher, although the principles apply to lower voltage applications also.
- NEC Article 460—provides marking, installation, protection, and grounding requirements for capacitors.
- NEMA MG 1—provides recommendations regarding the application of capacitors to motor circuits.

10. BATTERY AND BATTERY CHARGER SIZING

10.1. Battery Sizing for Applications with Duty Cycle

10.1.1. The battery size has to be determined by the designer of a backup power system. The battery can carry more load or perform longer as it is made larger, but a larger battery is also more expensive, requires more floor space, and increases the life cycle cost. For these reasons, a technical basis for the battery size has to be provided.

10.1.2. The classic method of sizing a battery is based on determining the specific load requirements and selecting a battery size capable of supplying that load for the specified time. IEEE 485 is the best industry reference for this type of cell sizing and should be reviewed as part of a battery sizing evaluation. IEEE 1115, IEEE Recommended Practice for Sizing Nickel-Cadmium Batteries for Stationary Applications, provides equivalent sizing information for nickel-cadmium batteries.

10.1.3. The battery duty cycle is the load that the battery is expected to supply for a specified period of time. Generally, the duty cycle is described in terms of the worst-case load that the battery is expected to supply. The battery would have to carry all or part of the connected load under any of the following conditions:

- System load exceeds the battery charger capability.
- Battery charger output is lost (charger failure or loss of ac input).
- All ac power is lost in the facility.

10.1.4. The worst case load usually occurs when all ac power is lost because other emergency loads might be energized in addition to the normally-energized loads. For example, loss of all ac power might require the additional energization of emergency lighting, circuit breaker components such as trip coils or spring charging motors, and emergency diesel engine cranking power. The duty cycle must consider all of these loads.

10.1.5. The following design inputs are needed to determine a battery size:

- Discharge capability of selected battery type.
- Load requirements, including duration.
- Minimum and maximum system voltage limits.
- Temperature, aging, and design margin allowances.

10.1.6. The duty cycle, should be evaluated section by section, to determine which section of the duty cycle is limiting in terms of battery size. The cell size is selected based on the most limiting portion of the duty cycle. A generalized representation of a duty cycle is shown in Figure 10-1.

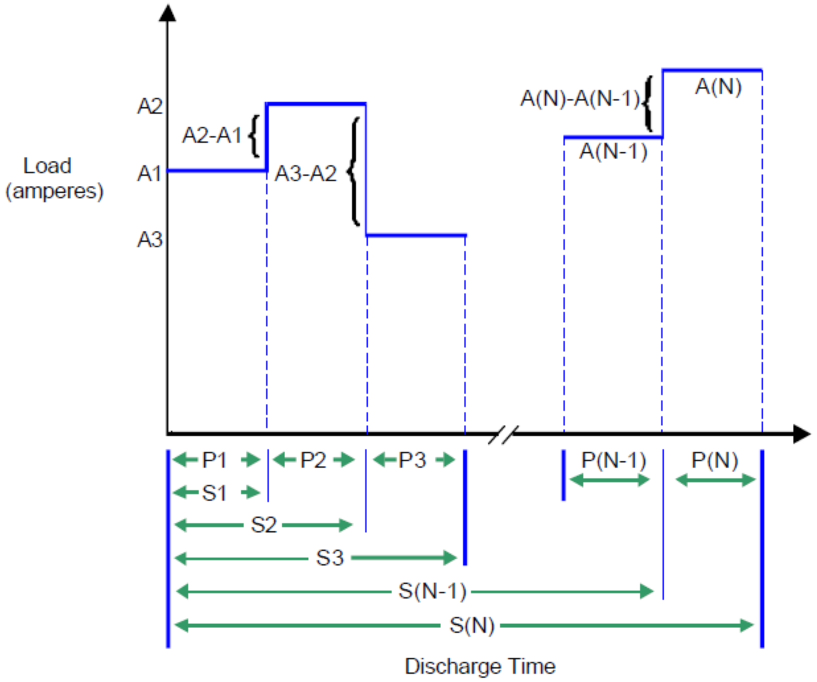


Figure 10-1. Generalized Duty Cycle

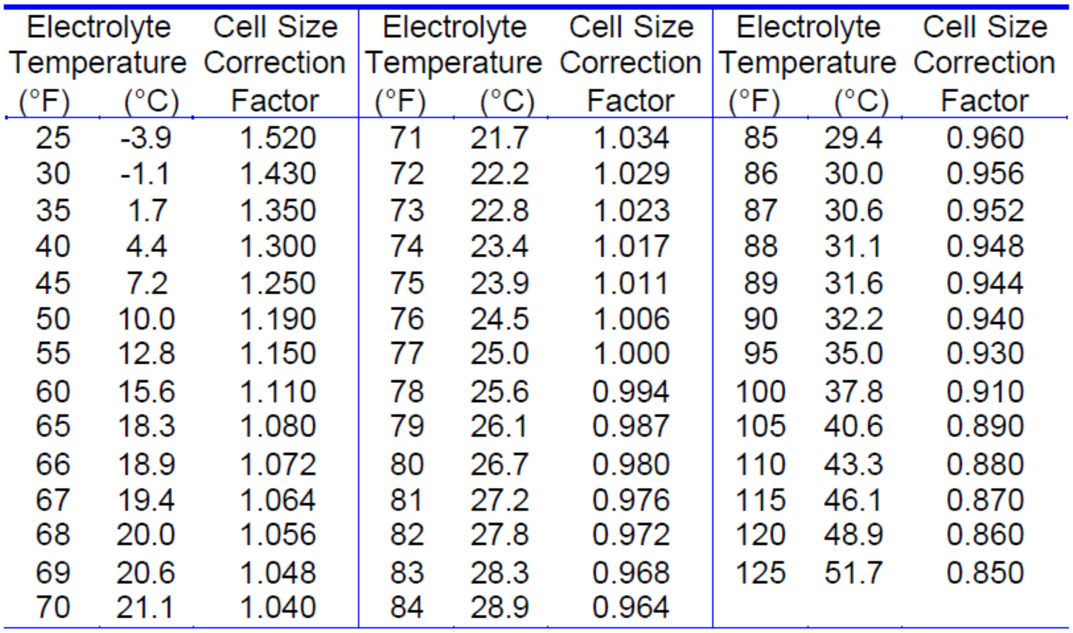
10.1.7. The battery sizing analysis of a duty cycle determines the required cell size for each section. Depending on the load profile, it is not guaranteed that the last section containing all periods will be limiting. For example, the cell size might be established by the first minute of the duty cycle if many loads are energized at once. IEEE 485 provides worksheets to assist with the calculation process. Battery manufacturers provide similar worksheets.

10.1.8. The battery sizing methodology determines the cell size for the defined duty cycle when the battery capacity is 100 percent and at the reference temperature of 25 °C (77 °F). For most batteries, end-of-life occurs when capacity falls to 80 percent of the rated capacity. Also, depending on the installation, the actual battery temperature might be well below 25 °C (77 °F), and battery capacity decreases as temperature decreases. Correction factors should be applied to the calculated cell size to account for these effects. The net result is that the selected cell size must be larger so that it can meet its design requirements at end-of-life at the design low temperature.

10.1.9. Under ideal conditions, a battery can have 90 percent to over 100 percent capacity when new. As the battery ages, its capacity will eventually fall to 80 percent, which is the commonly accepted point at which the battery should be replaced. Below this capacity, the rate of degradation can increase rapidly. As part of the battery sizing process, the battery should be sized so that it can fulfill the duty cycle requirements at its end of life. The following correction factor should be applied to the calculated cell size; the calculated cell size is made 25 percent larger to ensure that it can supply the required load at end of life:

$$\text{Aging Correction Factor} = \frac{1}{0.8} = 1.25$$

10.1.10. The manufacturer specifies battery performance at the reference temperature of 25 °C (77 °F). As the battery temperature falls below 25 °C (77 °F), battery capacity decreases. As the battery temperature rises above 25 °C (77 °F), battery capacity increases. If the expected operating temperature will be less than 25 °C (77 °F), the cell size should be adjusted to account for the reduced capacity at the lower temperature. Table 10-1 shows the correction factors for different battery temperatures. This table is based on vented lead-acid cells with a nominal 1.215 specific gravity. For a different specific gravity, the manufacturer should be consulted to confirm the applicability of these correction factors. VRLA cells can have a completely different temperature response; the manufacturer should be consulted for the appropriate temperature correction factors. Nickel-cadmium cells also require a manufacturer-provided temperature correction factor for low temperature operation, but the correction factor is not as large as for lead-acid batteries.



Electrolyte Temperature (°F)	(°C)	Cell Size Correction Factor	Electrolyte Temperature (°F)	(°C)	Cell Size Correction Factor	Electrolyte Temperature (°F)	(°C)	Cell Size Correction Factor
25	-3.9	1.520	71	21.7	1.034	85	29.4	0.960
30	-1.1	1.430	72	22.2	1.029	86	30.0	0.956
35	1.7	1.350	73	22.8	1.023	87	30.6	0.952
40	4.4	1.300	74	23.4	1.017	88	31.1	0.948
45	7.2	1.250	75	23.9	1.011	89	31.6	0.944
50	10.0	1.190	76	24.5	1.006	90	32.2	0.940
55	12.8	1.150	77	25.0	1.000	95	35.0	0.930
60	15.6	1.110	78	25.6	0.994	100	37.8	0.910
65	18.3	1.080	79	26.1	0.987	105	40.6	0.890
66	18.9	1.072	80	26.7	0.980	110	43.3	0.880
67	19.4	1.064	81	27.2	0.976	115	46.1	0.870
68	20.0	1.056	82	27.8	0.972	120	48.9	0.860
69	20.6	1.048	83	28.3	0.968	125	51.7	0.850
70	21.1	1.040	84	28.9	0.964			

Table 10-1. Temperature Correction Factors for Vented Lead-Acid Cells (1.215 Specific Gravity)

10.1.11. The aging and temperature correction factors account for inevitable aging and temperature effects. The battery is sized for a particular duty cycle and, depending on the facility, load growth can occur over time. A design margin correction factor can be applied to provide additional assurance that the battery will meet its future design requirements. The design margin correction factor also adds a capacity margin to allow for less-than-optimum battery operating conditions due to improper maintenance, recent battery discharge, lower than expected operating temperatures, or other effects. Simply stated, the design margin correction factor is an additional margin to help ensure the battery has adequate capacity to perform its job. A design margin of 10 percent to 15 percent is typical.

EXAMPLE: Suppose the sizing calculation for a vented lead-acid battery determined that 5 positive plates per cell were required for the specified duty cycle. What size cell is needed to account for aging and an expected low operating temperature of 15.6 °C (60 °F)? Also, the designer would like to add a 10 percent design margin. The aging correction factor is 1.25 to ensure adequate capacity when the battery is at end of life. From Table 10-1, the temperature correction factor is 1.11 for an operating temperature of 15.6 °C (60 °F). The design margin correction factor is 1.10. The required cell size is as follows:

$$Corrected\ Cell\ Size = (5\ positive\ plates) \times 1.25 \times 1.11 \times 1.10 \quad = 7.63\ positive\ plates$$

In this case, 8 positive plates will be required. If the application of design margin causes the calculated cell size to slightly exceed the next size cell, for example, 7.05 positive plates, the designer should, in this case, determine if 7 positive plates are adequate. Rounding up to the next cell size results in a larger and more expensive battery. The battery must be big enough to do its job throughout its service life, but a grossly oversized battery is not desirable either.

10.1.12. In summary, the battery should be sized for the limiting portion of the duty cycle, including corrections for performance at end of battery life and for the minimum expected operating temperature. If needed, an additional design margin should be included.

10.2. Battery Sizing for UPS Applications

10.2.1. Compared to duty cycle sizing, UPS applications often involve a different approach to battery sizing. If the UPS is the only load placed on the battery (which is common for many UPS systems), the battery can be sized more easily based on the UPS constant power requirements. Battery manufacturers also provide sizing charts based on a constant power discharge. The method of analysis is particularly straightforward, consisting of the following steps:

10.2.2. The total load (and duration) the UPS will place on the battery should be determined. The duration can be the most difficult design factor to specify. If additional backup power such as a diesel generator is not available, the UPS battery has to be large enough for the staff to place the system in a safe state in response to a power outage. If diesel generator backup is available, a 5-minute backup time might be adequate if the diesel system operates properly. If the designer allows for diesel starting difficulties, a backup time of over 30 minutes might be needed.

10.2.3. Cell sizing correction factors should be applied so that the battery can provide the required load at end of life and the design low temperature.

10.2.4. The minimum and maximum system voltage should be determined. The number of cells should selected based on the minimum and maximum voltage limits.

10.2.5. The load on each cell should be calculated and a cell size should be selected capable of supplying the required load.

10.2.6. As a battery discharges, the battery voltage declines in a predictable manner. For a constant power discharge, the current will increase in direct proportion to the voltage decrease in accordance with the following relationship.

$$Power = Voltage \times Current$$

EXAMPLE: The easiest way to discuss battery sizing for a UPS application is with an example. Assume the UPS specifications applicable to the battery are as follows:

Size: 7.5 kVA @ 0.8 power factor (6.0 kW)
Inverter efficiency: 0.92 at full load
Maximum input dc voltage: 140 volts
Low voltage cutout: 105 volts

The user specifies that the UPS must power critical loads for a minimum of 30 minutes following a loss of normal power. The user believes that the UPS will be almost fully loaded for the entire discharge duration. First, calculate the total battery load. Assume the UPS is fully loaded at 7.5 kVA. The power required from the battery is the real power produced by the UPS including efficiency losses. The real power produced by the inverter is 6.0 kW (7.5 kVA x 0.8 PF). Thus, the required battery load is:

$$Battery\ Load\ (kW) = \frac{Power}{Efficiency} = \frac{6.0\ kW}{0.92} = 6.52\ kW$$

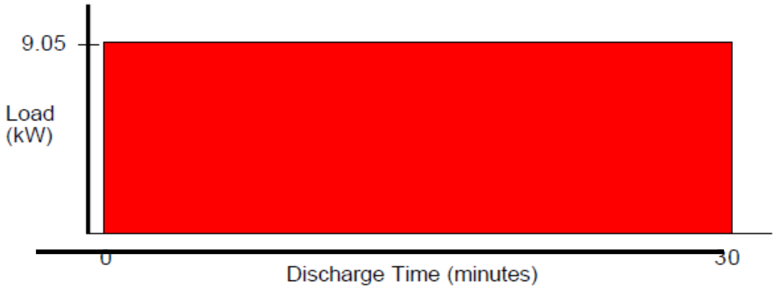
This is the nominal load that the battery must be capable of providing when the battery has 100 percent capacity at 25 °C (77 °F). As discussed previously, the battery will have less than rated capacity if the temperature is less than 25 °C (77 °F). Also, a lead-acid battery is normally sized to be capable of fulfilling its design load requirements at end of battery life (80 percent capacity). Appropriate correction factors need to be applied to ensure that the battery can meet this load requirement at end of battery life at the lowest expected temperature. The correction factors are as follows:

Aging: 1.25 (corresponding to 80 percent capacity)
Temperature: 1.11 (assume lowest expected temperature is 15.6 °C or 60 °F)

The corrected battery load is:

$$Corrected\ Battery\ Load\ (kW) = \frac{6.0\ kW}{0.92} \times 1.25 \times 1.11 = 9.05 kW$$

Notice that the designer chose not to add design margin because the UPS is already assumed to be fully loaded. For this typical example, the duty cycle consists of the above constant load for 30 minutes.



The UPS maximum dc input voltage was specified as 140 volts. This voltage is the maximum allowed voltage on the system. Also, assume that the manufacturer recommends a maximum battery equalize voltage of 2.33 volts per cell. The maximum number of cells is given by:

$$Maximum\ Number\ of\ Cells = \frac{Max.System\ Voltage}{Equalize\ Voltage} = \frac{140}{2.33} = 60.9\ Cells$$

In this case, choose 60 cells. Next, determine the minimum allowed voltage per cell based on the system minimum voltage requirement of 105 volts:

$$\text{Minimum Cell Voltage} = \frac{\text{Minimum System Voltage}}{\text{Number of Cells}} = \frac{105}{60} = 1.75\ \text{volts}$$

The designer needs 60 cells capable of providing 9.05 kW for 30 minutes without allowing voltage to drop below 1.75 volts per cell. Each cell must deliver:

$$\frac{9.05\ kW}{60\ Cells} = 0.151\ kW\ per\ cell$$

This is the information needed to select a cell from the manufacturer's data sheets. Each cell must be capable of providing 0.151 kW for 30 minutes without individual cell voltage falling below 1.75 volts.

10.2.7. Refer to IEEE 1184, IEEE Guide for the Selection and Sizing of Batteries for Uninterruptible Power Supply Systems, for additional information regarding sizing of UPS batteries.

10.3. Battery Sizing for Engine Starting Applications

10.3.1. Depending on the design, a diesel engine might be started by an air system or an electric motor (starting motor). Electric starting is the most convenient to use, is usually the least expensive, and is the most adaptable method for remote control and automation. The ambient temperature and lubricating oil viscosity affect the starting ability of a diesel engine. The diesel relies on the heat generated by compression to ignite the fuel. When first starting, this compression and heat is created by the diesel cranking (starting) process, which is a function of the cranking speed and cranking time. When the engine is cold, longer cranking periods are required to develop ignition temperatures. The battery powers an electric starting motor to accomplish this cranking process. Lubricating oil imposes the greatest load on the cranking motor; oil viscosity varies with oil type and temperature. For example, Society of Automotive Engineers (SAE) 30 oil viscosity approaches that of grease below 0 °C (32 °F).

10.3.2. Either lead-acid or nickel-cadmium batteries can be used for engine starting. The nickel-cadmium type is often used so that the battery can be located very near the engine, which is usually a higher ambient temperature environment. Also, nickel-cadmium batteries are capable of very high-rate discharges for the few seconds needed for an engine cranking application.

10.3.3. In many cases, the associated battery's only purpose is to provide cranking power to start the diesel engine. In these cases, battery sizing is performed differently than described in the previous sections. The primary considerations for sizing a diesel engine battery are:

- The lowest temperature at which the engine might be cranked. Oil viscosity increases with decreasing temperature and affects how long the starter motor must turn before fuel ignition temperature is reached. Note also that lower temperatures affect the battery's capacity. At lower temperatures, the battery's capacity requires adjustment for both oil viscosity and decreased battery capacity. For very cold applications, engine heaters or glow plugs should be considered to minimize the battery size requirements.
- How many start attempts will be allowed? A battery that can provide at least four 30 second cranking periods (total of 2 minutes of cranking) should be selected. Engines are often rated for up to 30 seconds of cranking before the starter motors begin to overheat. The starter motor limitations should be confirmed with the manufacturer.

10.3.4. EGSA 100B provides guidance for sizing a diesel engine starting battery. This performance standard should be used for battery sizing; it recommends providing the following information to the battery manufacturer as part of a battery sizing evaluation:

- Nominal volts needed for the starter motor.
- Starting current of starter motor.
- Engine model and make.
- Cubic inches displacement. Some battery manufacturers have sizing guidelines based on the cubic inches displacement.
- Number of cranks and possible duration of each crank.
- Rest period for battery recovery, if needed.
- Worst case low battery temperature.
- Worst case low engine temperature and oil viscosity.
- Battery type and desired life.
- Seismic or vibration requirements.

10.3.5. As part of the sizing process for a diesel engine battery, voltage drop between the battery and the starter motor should be considered. The starter motor usually draws significant current from the battery. For this reason, batteries are often located very near the diesel engine to minimize the voltage drop caused by the high current. Typical connecting devices between the battery and the starter motor include:

- Cable—resistance varies with cable size and length.
- Contactors (relays, solenoid, switches)—resistance less than 0.002 ohms is typical.
- Connections—each connection resistance less than 0.001 ohms is typical.

10.3.6. The diesel engine manufacturer usually specifies the minimum system requirements, including the maximum connection resistance between the battery and the starter motor. Care has to be taken to make sure that these minimum requirements are met by the installation.

10.4. Charger Sizing

10.4.1. Each battery charger should to be large enough to power the normal system loads while recharging a discharged battery within a reasonable amount of time. Manufacturers recommend a recharge time of 8 to 12 hours. Shorter recharge times require larger battery chargers and might result in excessive current flow into the battery during the recharge process. For this reason, 8 hours is usually the minimum recharge time for a discharged battery. On the high end, 12 hours is often recommended for an upper limit; however, this recharge time is somewhat arbitrary and 14 hours or 16 hours might be acceptable, depending on the application and how the recharge is controlled. The primary consideration is that the charger should be sized to recharge the battery within a reasonable amount of time.

10.4.2. The charger should be sized to supply the normal continuous loads while also recharging the battery within a reasonable time period. The charger sizing formula is as follows:

$$A = \frac{kC}{H} + L_c$$

where

$A =$ Output rating of the charger in amperes.

$k =$ Efficiency factor to return 100 percent of ampere-hours removed. Efficiency factor of 1.1 for Lead- acid batteries and 1.4 for nickel-cadmium batteries should be used.

$C =$ Calculated number of ampere-hours discharged from the battery (calculated based on duty cycle).

$H =$ Recharge time to approximately 95 percent of capacity in hours. A recharge time of 8 to 12 hours is usually recommended.

$L_c =$ Continuous load (amperes).

10.4.3. The above sizing method is recommended, but tends to provide an optimistic recharge time. The actual recharge time is usually longer than indicated above because the charging current tends to decrease as the battery voltage increases during recharge.

EXAMPLE: Determine the charger rating if a) the continuous load is 100 amperes, b) 300 ampere-hours are discharged from a lead-acid battery, and c) the battery is to be recharged within 10 hours.

$$A = \frac{1.1 \times 300}{10} + 100 = 133 \ amperes$$

EXAMPLE: Suppose that the above system has 50 amperes of noncontinuous loads that can be energized at any time. In this case, the total charger load is the sum of the continuous and noncontinuous load before consideration of battery recharge requirements. At any time, the charger load can be as high as:

$$A = L_c + L_n = 100 + 50 = 150\ amperes$$

If the charger in the previous example was selected to have a capacity of 133 amperes, the battery would have to supply the additional load whenever the noncontinuous load is energized. So, the charger should instead be sized to provide the expected system loads, or 150 amperes in this example. Note that this assumes the noncontinuous loads will not be energized for long periods when the battery is being recharged.