

IEEE Guide for Application of Shunt Power Capacitors

IEEE Power & Energy Society

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Transmission and Distribution Committee

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USA

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IEEE Guide for Application of Shunt Power Capacitors

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**Transmission and Distribution Committee
of the
IEEE Power & Energy Society**

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Abstract: This guide applies to the use of 50 Hz and 60 Hz shunt power capacitor units rated 2400 Vac and above, and assemblies of such capacitors. Included are guidelines for the application, protection, and ratings of equipment for the safe and reliable utilization of shunt power capacitors. The guide is general and intended to be basic and supplemental to specific recommendations of the manufacturer. The guide covers applications that range from simple capacitor unit utilization to complex capacitor bank situations.

Keywords: capacitor, capacitor banks, externally fused, fuseless, internally fused, power factor correction, shunt power capacitors

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Introduction

This introduction is not part of IEEE Std 1036-2010, IEEE Guide for Application of Shunt Power Capacitors.
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This standard was revised in response to a need created by changes in capacitor technology, primarily in the areas of internally fused and fuseless capacitors. In addition, capacitor application information previously contained in IEEE Std 18-2002^a was moved to this application guide. It was also the aim of this revision to coordinate the information contained in this standard, whenever possible, with other pertinent national and international standards.

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^a Information on references can be found in Clause 2.

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1. Scope

This guide applies to the use of 50 Hz and 60 Hz shunt power capacitors rated 2400 Vac and above, and assemblies of such capacitors. Included are guidelines for the application, protection, and ratings of equipment for the improved safety and reliability in the utilization of shunt power capacitors. The guide is general and intended to be basic and supplemental to specific recommendations of the manufacturer. The guide covers applications that range from simple capacitor unit utilization to complex capacitor bank situations.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C2-2007, National Electrical Safety Code, American National Standards Institute.¹

ANSI C37.06-2009, American National Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities.²

ANSI C37.66-2005, American National Standard Requirements for Oil-Filled Capacitor Switches for Alternating-Current Systems.

IEEE Std 18™-2002, IEEE Standard for Shunt Power Capacitors.^{3, 4}

IEEE Std C37.04™-1999, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers.

IEEE Std C37.012™-2005, IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.48™-2005, IEEE Guide for Application, Operation, and Maintenance of High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.99-2000, IEEE Guide for Protection of Shunt Capacitor Banks.

IEEE Std C62.2-1987, IEEE Guide for the Application of Gapped Silicon-Carbide Surge Arresters for Alternating-Current Systems.

IEEE Std C62.22™-2009, IEEE Guide for the Application of Metal Oxide Surge Arresters for Alternating-Current Systems.

IEEE Std 141™-1993 (Reaff 1999), IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (IEEE Red Book™).

IEEE Std 262B-1977, IEEE Trial-Use Standard Dielectric Test Requirements for Power Transformers for Operation on Effectively Grounded Systems 345 kV and Above (Trial-Use Supplement to IEEE Std 262-1973, ANSI C57.12.90-1973).⁵

IEEE Std 519-2004, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.

IEEE Std 1247™-2005, IEEE Standard for Interrupter Switches for Alternating Current, Rated Above 1,000 Volts.

IEEE Std 1531™-2003, IEEE Guide for Application and Specification of Harmonic Filters.

NFPA 70-2008, National Electrical Code® (NEC®).⁶

¹The National Electrical Safety Code is available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, Piscataway, NJ 08854, USA; and from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

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3. Definitions

For the purposes of this document, the following terms and definitions apply. *The IEEE Standards Dictionary: Glossary of Terms & Definitions* should be referenced for terms not defined in this clause.⁷

3.1 ambient temperature: The temperature of the medium, such as air, water, or earth, into which the heat of the equipment is dissipated.

NOTE 1—For self-ventilated equipment, the ambient temperature is the average temperature of the air in the immediate vicinity of the equipment.

NOTE 2—For air- or gas-cooled equipment with forced ventilation or secondary water cooling, the ambient temperature is taken as that of the ingoing air or cooling gas.

NOTE 3—For self-ventilated enclosed (including oil-immersed) equipment considered as a complete unit, the ambient temperature is the average temperature of the air outside of the enclosure in the immediate vicinity of the equipment. See 5.7 and Table 1 of IEEE Std 18-2002.

3.2 back-to-back capacitor bank switching (back-to-back switching, back-to-back capacitor switching): Switching a capacitor bank in close enough electrical proximity to one or more other energized capacitor banks and/or cables to significantly influence the inrush current.

3.3 capacitor bank: An assembly at one location of capacitor(s) and all necessary accessories, such as switching equipment, protective equipment, controls, et cetera, required for a complete operating installation. It may be a collection of components assembled at the operating site or may include one or more pieces of factory-assembled equipment.

3.4 capacitor control: The device required to automatically operate the switching device(s) to energize and de-energize shunt power capacitor banks.

3.5 capacitor element: The basic component of a capacitor unit consisting of two electrodes separated by a dielectric.

3.6 capacitor equipment: A complete assembly of capacitors, including accessories such as buses, connectors, dischargers, and fuses suitable for connection to a power system.

3.7 capacitor line fuse (capacitor group fuse): A fuse applied to disconnect a faulted phase of a capacitor bank from the power system.

3.8 externally fused capacitor bank: A capacitor equipment with fuses external to the (power) capacitor units.

3.9 filter capacitor: Capacitor(s) utilized with inductors and/or resistors for controlling harmonic voltages and currents in the power system.

3.10 fixed capacitor bank: A capacitor bank not designed for automatic operation or frequent switching.

3.11 fused capacitor: A capacitor having fuses mounted on its terminals, or inside a terminal enclosure, or inside the capacitor case, for the purpose of interrupting a failed capacitor element, unit or group.

3.12 fuseless capacitor bank: A capacitor bank without any fuses, internal or external, that is constructed of (parallel) strings of capacitor units. Each string consists of capacitor units connected in series.

⁷ *The IEEE Standards Dictionary: Glossary of Terms & Definitions* is available at <http://shop.ieee.org/>.

3.13 indoor (prefix): Not suitable for exposure to the weather.

NOTE—For example, an indoor capacitor unit is designed for indoor service or for use in a weatherproof housing.

3.14 inrush current: The transient charging current that flows in a capacitor when a capacitor bank is initially connected to a voltage source.

3.15 internal fuse: A fuse connected inside a capacitor unit, in series with an element or a group of elements.

3.16 internally fused capacitor (unit): A capacitor unit that includes internal fuses.

3.17 internally fused capacitor bank: A capacitor bank equipment with internally fused capacitor units.

3.18 isolated capacitor bank: A capacitor bank whose inrush current is limited by the inductance of the source and its own capacitance. Other capacitor banks and cables are not sufficiently coupled to the bank to significantly influence the inrush current.

3.19 metal-enclosed (prefix): A capacitor equipment assembly enclosed in a metal enclosure or metal house, usually grounded, to prevent accidental contact with live parts. *Syn:* **metal-housed.**

3.20 metal-housed (prefix): *See:* **metal-enclosed.**

3.21 outrush current: The transient discharge current that flows when an energized capacitor bank is initially connected to a short circuit.

3.22 power capacitor (shunt capacitor, capacitor unit): An assembly of dielectric and electrodes in a container (case), with terminals brought out, that is intended to introduce capacitance into an electric power circuit.

NOTE—The abbreviated term “capacitor” or “capacitor unit” is used interchangeably with “power capacitor” throughout this standard.

3.23 string (string of capacitors) (string of capacitor elements): Capacitors connected in series between two terminals without parallel connection(s).

3.24 switched capacitor (switched capacitor bank): A capacitor bank designed for controlled operation and/or frequent switching.

3.25 weatherproof: An apparatus is designated as weatherproof, when so constructed, protected, or treated that its successful operation is not interfered with when subjected to adverse weather.

4. Power system considerations

4.1 Capacitor benefits

As power systems become heavily loaded (above surge impedance loading), shunt power capacitors become essential to the reliable operation of the power system. The capacitors support the system voltage and reduce the reactive current flow through the power system. Acceptable system voltages generally

cannot be maintained by the generators and transmission system alone. Shunt power capacitors are required.

During system contingencies, when parts of the transmission system are unavailable, increased loading on the remaining system causes additional voltage drop. Shunt capacitors are required to support the system voltage during these contingencies. The lack of available shunt capacitors can (and has) lead to system voltage collapse.

Most power system loads and delivery apparatus (e.g., motors, lines and transformers) are inductive in nature and therefore operate at a lagging power factor. When operating at a lagging power factor, power system loads require reactive current from the system, which results in reduced system capacity, increased system losses, and reduced system voltage.

Figure 1 illustrates how the application of shunt power capacitors increases system capacity and reduces system losses by reducing reactive power needs from Q_{r1} to Q_{r2} through the addition of Q_c . As a result, the system load is reduced from S_1 to S_2 as shown in Figure 1.

Table 1 gives a summary of benefits derived from shunt power capacitors as they apply to transmission and distribution systems. Var support and voltage control are the primary benefits for a transmission system while the distribution system benefits may be more varied depending upon whether the system belongs to a generating utility, a nongenerating utility, or an industrial power user. The following subclauses describe each of these benefits in more detail.

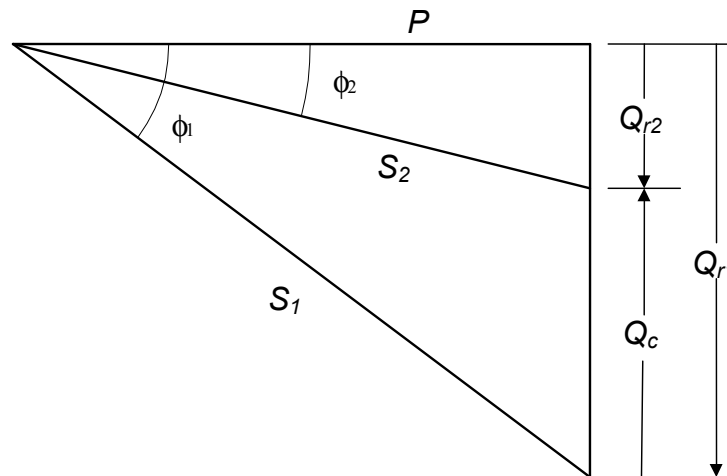


Figure 1— Effect of adding shunt capacitors

Table 1—Summary of benefits of applying shunt power capacitors

Benefits	Transmission system	Distribution system
Voltage support	*	*
Var support	*	†

Benefits	Transmission system	Distribution system
Increase system capacity	†	*
Reduce system power loss	†	*
Reduce billing charges	†	*

*This is generally a primary benefit

† This is generally a secondary benefit

4.1.1 Voltage support

Applying shunt capacitors to a system results in a voltage rise. This voltage rise is caused by the flow of capacitor current (or the reduction of inductive current) through the inductive reactance of the system from the point of installation back to the generation. The voltage rise at the capacitor location is approximately equal to the capacitor current I_C times the inductive reactance of the system to the capacitor location X_L . There is a voltage rise all the way back to the voltage source, the magnitude depending on the inductive reactance between the source and the location. In a radial system, there is also an increase in the voltage beyond the capacitor location resulting from the increase at the capacitor location.

There are a number of formulas that can be used to estimate the voltage rise that capacitors will produce. Based on the capacitor current and the inductive reactance of the system to the capacitor location:

$$\Delta V \approx I_C X_L \quad (1)$$

For systems with a reasonably high X/R ratio, where the short-circuit impedance to the capacitor location is about the same as the inductive reactance, the X_L of Equation (1) is the impedance that determines the system short-circuit current available at the capacitor location. This short-circuit current is useful in estimating the voltage rise. A commonly used estimate is as follows in Equation (2).

$$\Delta V \approx \frac{I_C}{I_{SC}} = \frac{Q_C \text{ kvar}}{S_{SC} \text{ kva}} \quad (2)$$

where

- ΔV is the per unit voltage rise at the point of the capacitor installation
- I_C is the capacitor current in amps
- I_{SC} is the system short-circuit current at the capacitor location
- Q_C is the capacitor three-phase kvar at system voltage
- S_{SC} is the system three phase short-circuit kva at the capacitor location

Capacitor banks are typically installed on the transmission system at major buses to provide voltage support for a large area. They are also installed at distribution buses and directly on customer delivery buses to provide voltage support to smaller areas and to individual customers. Capacitor banks installed on distribution lines support voltage along the entire length of line.

Capacitor banks that are installed for voltage support are generally switched on during the peak loading periods or low-voltage conditions and switched off during light loading periods or high-voltage conditions.

Capacitors have also been used on distribution feeders to keep the feeder voltage constant (acceptable, but low) during substation voltage reduction contingencies. Voltage reduction can decrease feeder power and current during peak load conditions.

4.1.2 Var support

Reactive power (var) support encompasses many of the different benefits of shunt power capacitors, such as improved voltage control and power factor; reduced system losses and reactive power requirements at generators; and increased steady-state stability limits. Capacitors are sized and located at transmission and distribution substations to supply reactive power close to the loads or to provide midway support across heavily loaded transmission circuits.

4.1.3 Increased system capacity

Increased system capacity may justify the addition of shunt power capacitors on a distribution system. This is particularly significant when loads supplied by the system are increasing rapidly. The addition of shunt power capacitors reduces the kilovoltampere loading on the system, thereby releasing capacity that can then be used to supply future load increases. The optimum economical power factor for a system, with regard to released capacity only, can be estimated by use of Equation (3).

$$PF = \sqrt{1 - \left(\frac{C}{S}\right)^2} \quad (3)$$

where

- C is the cost per kilovar of capacitor bank
- S is the cost per kilovoltamperes of system equipment
- PF is optimum power factor

Equation (3) compares the cost of capacitor banks to the cost of transformers, regulators, and/or other system equipment, as an alternative means of providing increased system capacity. The graph of the formula, the optimum power factor as a function of the cost ratio of the capacitor bank versus other system equipment, is illustrated in Figure 2.

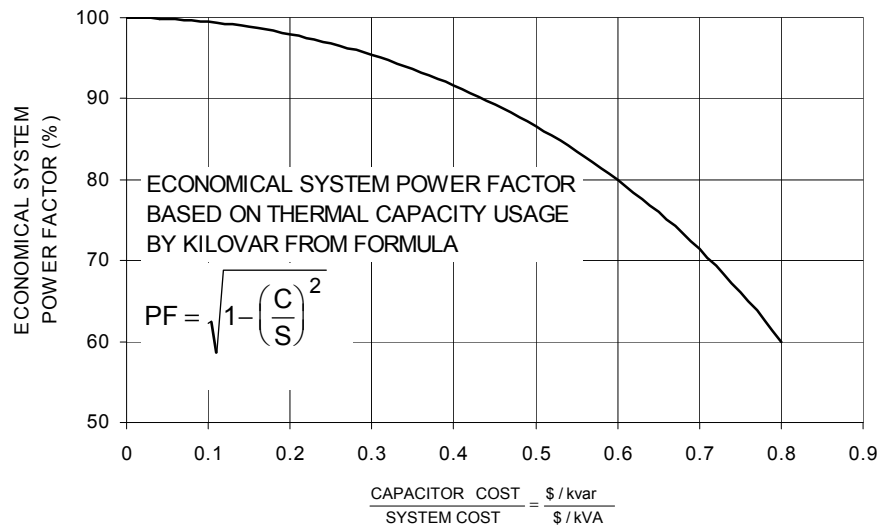


Figure 2— Economical system power factor

The power factor required to release a desired amount of system kilovoltamperes can be determined by Equation (4).

$$PF_{new} = \frac{PF_{old}}{1 - S_{release} \text{ kva}} \quad (4)$$

where

PF_{new} is the corrected power factor
 PF_{old} is the existing power factor
 $S_{release}$ is the amount of kilovoltamperes to be released (in per unit of existing kilovoltamperes)

To calculate the capacitive kilovar necessary to correct to a new, higher power factor, one must subtract the inductive kvar of the new (corrected) power factor from the old (existing) power factor. The difference is the amount of capacitive kilovar to be added to the system. Equation (5) is a convenient way of doing this.

$$Q_C \text{ kvar} = P_S \text{ kW} [\tan(\cos^{-1} PF_{old}) - \tan(\cos^{-1} PF_{new})] \quad (5)$$

where

P_S is the system kilowatt load
 Q_C is the amount of capacitive kilovar to be added

Table 2 is a chart that may be used in place of this formula. Simply find the row corresponding to the existing system power factor and the column corresponding to the corrected new power factor. The number located where these intersect should be multiplied by the system kilowatt load to arrive at the total capacitive kilovar necessary to correct to the new power factor.

Table 2—Power factor correction kilowatt multipliers

	Corrected power factor																				
	0.80	0.81	0.82	0.83	0.84	0.85	0.86	0.87	0.88	0.89	0.90	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.0
0.50	0.982	1.008	1.034	1.060	1.086	1.112	1.139	1.165	1.192	1.220	1.248	1.276	1.306	1.337	1.369	1.403	1.440	1.481	1.529	1.589	1.732
0.51	0.937	0.962	0.989	1.015	1.041	1.067	1.094	1.120	1.147	1.175	1.203	1.231	1.261	1.292	1.324	1.358	1.395	1.436	1.484	1.544	1.687
0.52	0.893	0.919	0.945	0.971	0.997	1.023	1.050	1.076	1.103	1.131	1.159	1.187	1.217	1.248	1.280	1.314	1.351	1.392	1.440	1.500	1.643
0.53	0.850	0.876	0.902	0.928	0.954	0.980	1.007	1.033	1.060	1.088	1.116	1.144	1.174	1.205	1.237	1.271	1.308	1.349	1.397	1.457	1.600
0.54	0.809	0.835	0.861	0.887	0.913	0.939	0.966	0.992	1.019	1.047	1.075	1.103	1.133	1.164	1.196	1.230	1.267	1.308	1.356	1.416	1.559
0.55	0.769	0.795	0.821	0.847	0.873	0.899	0.926	0.952	0.979	1.007	1.035	1.063	1.093	1.124	1.156	1.190	1.227	1.268	1.316	1.376	1.519
0.56	0.730	0.756	0.782	0.808	0.834	0.860	0.887	0.913	0.940	0.968	0.996	1.024	1.054	1.085	1.117	1.151	1.188	1.229	1.277	1.337	1.480
0.57	0.692	0.718	0.744	0.770	0.796	0.822	0.849	0.875	0.902	0.930	0.958	0.986	1.016	1.047	1.079	1.113	1.150	1.191	1.239	1.299	1.442
0.58	0.655	0.681	0.707	0.733	0.759	0.785	0.812	0.838	0.865	0.893	0.921	0.949	0.979	1.010	1.042	1.076	1.113	1.154	1.202	1.262	1.405
0.59	0.619	0.645	0.671	0.697	0.723	0.749	0.776	0.802	0.829	0.857	0.885	0.913	0.943	0.974	1.006	1.040	1.077	1.118	1.166	1.226	1.369
0.60	0.583	0.609	0.635	0.661	0.687	0.713	0.740	0.766	0.793	0.821	0.849	0.877	0.907	0.938	0.970	1.004	1.041	1.082	1.130	1.190	1.333
0.61	0.549	0.575	0.601	0.627	0.653	0.679	0.706	0.732	0.759	0.787	0.815	0.843	0.873	0.904	0.936	0.970	1.007	1.048	1.096	1.156	1.299
0.62	0.516	0.542	0.568	0.594	0.620	0.646	0.673	0.699	0.726	0.754	0.782	0.810	0.840	0.871	0.903	0.937	0.974	1.015	1.063	1.123	1.266
0.63	0.483	0.509	0.535	0.561	0.587	0.613	0.640	0.666	0.693	0.721	0.749	0.777	0.807	0.838	0.870	0.904	0.941	0.982	1.030	1.090	1.233
0.64	0.451	0.477	0.503	0.529	0.555	0.581	0.608	0.634	0.661	0.689	0.717	0.745	0.775	0.806	0.838	0.872	0.909	0.950	0.998	1.068	1.201
0.65	0.419	0.445	0.471	0.497	0.523	0.549	0.576	0.602	0.629	0.657	0.685	0.713	0.743	0.774	0.806	0.840	0.877	0.918	0.966	1.026	1.169
0.66	0.388	0.414	0.440	0.466	0.492	0.518	0.545	0.571	0.598	0.626	0.654	0.682	0.712	0.743	0.775	0.809	0.846	0.887	0.935	0.995	1.138
0.67	0.358	0.384	0.410	0.436	0.462	0.488	0.515	0.541	0.568	0.596	0.624	0.652	0.682	0.713	0.745	0.779	0.816	0.857	0.905	0.965	1.108
0.68	0.328	0.354	0.380	0.406	0.432	0.458	0.485	0.511	0.538	0.566	0.594	0.622	0.652	0.683	0.715	0.749	0.786	0.827	0.875	0.935	1.078
0.69	0.299	0.325	0.351	0.377	0.403	0.429	0.456	0.482	0.509	0.537	0.565	0.593	0.623	0.654	0.686	0.720	0.757	0.798	0.846	0.906	1.049
0.70	0.270	0.296	0.322	0.348	0.374	0.400	0.427	0.453	0.480	0.508	0.536	0.564	0.594	0.625	0.657	0.691	0.728	0.769	0.817	0.877	1.020
0.71	0.242	0.268	0.294	0.320	0.346	0.372	0.399	0.425	0.452	0.480	0.508	0.536	0.566	0.597	0.629	0.663	0.700	0.741	0.789	0.849	0.992
0.72	0.214	0.240	0.266	0.292	0.318	0.344	0.371	0.397	0.424	0.452	0.480	0.508	0.538	0.569	0.601	0.635	0.672	0.713	0.761	0.821	0.964
0.73	0.186	0.212	0.238	0.264	0.290	0.316	0.343	0.369	0.396	0.424	0.452	0.480	0.510	0.541	0.573	0.607	0.644	0.685	0.733	0.793	0.936
0.74	0.159	0.185	0.211	0.237	0.263	0.289	0.316	0.342	0.369	0.397	0.425	0.453	0.483	0.514	0.546	0.580	0.617	0.658	0.706	0.766	0.909
0.75	0.132	0.158	0.184	0.210	0.236	0.262	0.289	0.315	0.342	0.370	0.398	0.426	0.456	0.487	0.519	0.553	0.590	0.631	0.679	0.739	0.882
0.76	0.105	0.131	0.157	0.183	0.209	0.235	0.262	0.288	0.315	0.343	0.371	0.399	0.429	0.460	0.492	0.526	0.563	0.604	0.652	0.712	0.855
0.77	0.079	0.105	0.131	0.157	0.183	0.209	0.236	0.262	0.289	0.317	0.345	0.373	0.403	0.434	0.466	0.500	0.537	0.578	0.626	0.685	0.829
0.78	0.052	0.078	0.104	0.130	0.156	0.182	0.209	0.235	0.262	0.290	0.318	0.346	0.376	0.407	0.439	0.473	0.510	0.551	0.599	0.659	0.802
0.79	0.026	0.052	0.078	0.104	0.130	0.156	0.183	0.209	0.236	0.264	0.292	0.320	0.350	0.381	0.413	0.447	0.484	0.525	0.573	0.633	0.776
0.80	0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.238	0.266	0.294	0.324	0.355	0.387	0.421	0.458	0.499	0.547	0.609	0.750
0.81		0.000	0.026	0.052	0.078	0.104	0.131	0.157	0.184	0.212	0.240	0.268	0.298	0.329	0.361	0.395	0.432	0.473	0.521	0.581	0.724
0.82			0.000	0.026	0.052	0.078	0.105	0.131	0.158	0.186	0.214	0.242	0.272	0.303	0.335	0.369	0.406	0.447	0.495	0.555	0.698
0.83				0.000	0.026	0.052	0.079	0.105	0.132	0.160	0.188	0.216	0.246	0.277	0.309	0.343	0.380	0.421	0.469	0.529	0.672
0.84					0.000	0.026	0.053	0.079	0.106	0.134	0.162	0.190	0.220	0.251	0.283	0.317	0.354	0.395	0.443	0.503	0.646
0.85						0.000	0.027	0.053	0.080	0.108	0.136	0.164	0.194	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
0.86							0.000	0.026	0.053	0.081	0.109	0.137	0.167	0.198	0.230	0.264	0.301	0.342	0.390	0.450	0.593
0.87								0.000	0.027	0.055	0.083	0.111	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
0.88									0.000	0.028	0.056	0.084	0.114	0.145	0.177	0.211	0.248	0.289	0.337	0.397	0.540
0.89										0.000	0.028	0.056	0.086	0.117	0.149	0.183	0.220	0.261	0.309	0.369	0.512
0.90											0.000	0.028	0.058	0.089	0.121	0.155	0.192	0.233	0.281	0.341	0.484
0.91												0.000	0.030	0.061	0.093	0.127	0.164	0.205	0.253	0.313	0.456
0.92													0.000	0.031	0.063	0.097	0.134	0.175	0.223	0.283	0.426
0.93														0.000	0.032	0.066	0.103	0.144	0.192	0.252	0.395
0.94															0.000	0.034	0.071	0.112	0.160	0.220	0.363
0.95																0.000	0.037	0.079	0.126	0.186	0.329
0.96																	0.000	0.041	0.089	0.149	0.292
0.97																		0.000	0.048	0.108	0.251
0.98																			0.000	0.060	0.203
0.99																				0.000	0.143
																					0.000

4.1.4 Reduced system power losses

On some distribution and transmission systems, a significant reduction in losses may be achieved by the installation of shunt power capacitors.

The installation of shunt power capacitors reduces current flow through the system from the point of the capacitor installation back to the generation. Since power losses are directly proportional to the square of the current, a reduction of current flow results in a much greater reduction of power losses. Capacitors are often installed as close to the load as possible for this reason.

The ratio of the system losses associated with the local load, with and without capacitors installed, can be estimated with Equation (6), which assumes constant kilowatt and constant voltage at the load with no harmonics present (the effect of harmonics is addressed in Clause 7).

$$\text{loss ratio} = \frac{\text{loss with capacitors}}{\text{loss without capacitors}} \quad (6)$$

$$= \left(\frac{PF_{old}}{PF_{new}} \right)^2$$

where

PF_{old} is the existing power factor
 PF_{new} is the corrected power factor

This reduction in losses will reduce the generation fuel requirement to supply these losses as well as the system equipment costs to supply the losses at peak load.

4.1.5 Reduced billing charges

A number of utilities use some form of kilovoltampere billing for their large customers (e.g., municipal utilities and large industrial customers). Since the application of shunt power capacitors beyond the meter can result in a reduced kilovolt-ampere loading, this can result in reduced billing charges.

The kilovoltampere billing charge may be calculated in many different ways, including the following:

- a) A fixed charge for each kilowatt plus a fixed charge for each kilovar.
- b) A certain amount for each kilowatt at or above a certain power factor, with additional charges made for each kilovar in excess of that required by a minimum power factor.
- c) A charge per kilowatt demand multiplied by a factor that increases with decreasing power factor.
- d) A fixed charge per peak kilovoltampere.

4.2 Size and number of capacitor banks

The shunt capacitance requirements are determined for a power system by modeling the system for various contingencies and determining the capacitors required to maintain acceptable system voltage. For specific applications, capacitors are applied to optimize the benefits described in 4.1 for a given set of system requirements. Distribution capacitors are often sized to supply the reactive power requirements of the load plus the reactive requirements of the transformer bank(s) at peak load. This provides for power factor correction to unity at the high side of the transformers and effective operation of the transmission or subtransmission system. Transmission substation capacitors are often sized and located based on load flow and stability studies of the transmission network. The capacitors minimize system losses, increase the system voltage, and increase stability margins. After the capacitor requirements are known, the individual capacitor bank megavar sizes and number of steps are determined. To take advantage of the economies associated with standardized equipment, other limitations may influence the maximum and minimum capacitor bank sizes used.

4.2.1 Maximum size

The maximum capacitor bank size is influenced by the following factors:

- a) Change in system voltage upon capacitor bank switching.
- b) Switchgear continuous current limitations.

When a capacitor bank is energized or de-energized, the fundamental system voltage increases or decreases, respectively. In order to have a minimal effect upon customer loads, this voltage change is often limited to a value in the range of 2% to 3%. This voltage change (ΔV) can be estimated by Equation (7).

$$\Delta V = \left(\frac{Q_C \text{ Mvar}}{S_{sc} \text{ Mva}} \right) \times 100\% \quad (7)$$

where

ΔV is the voltage change as a percentage of the fundamental frequency rms system voltage

$Q_C \text{ Mvar}$ is the Mvar size of the capacitor bank

$S_{sc} \text{ Mva}$ is the available three-phase short-circuit MVA at the capacitor bank location

The continuous-current rating of switchgear used for capacitor bank switching may be a factor in choosing the capacitor bank size. The rating is usually determined by multiplying the nominal capacitor current by 1.25 for ungrounded capacitor banks and by 1.35 for grounded-wye capacitor banks. Where currents with substantial harmonic components are likely to be encountered, provision should be made for additional current-carrying capacity in the circuit breakers, fuses, and other auxiliary devices. More detailed information is available in IEEE Std C37.04-1999, ANSI C37.06-2009, IEEE Std C37.012-2005, ANSI C37.66-2005, and IEEE Std 1247-2005.

4.2.2 Minimum size

While there is no absolute minimum capacitor bank size, the practical minimum capacitor bank size may be influenced by the following factors:

- a) The type of capacitor bank used: externally fused, internally fused, fuseless, etc.
- b) The easily available ratings of capacitor units
- c) Capacitor bank unbalance considerations
- d) Fuse performance and/or coordination
- e) The cost of the required switchgear and protection

The principal concerns when installing a small capacitor bank are the proper performance of the proposed capacitor bank (including the protection) and the cost of the installation. Under some circumstances, the cost of the installation may be reduced by installing the capacitor on a lower voltage bus in the same substation.

4.3 Control considerations

Capacitor banks are either switched or fixed, i.e., not switched. Generally, in determining the type of capacitor bank required, consider the following guidelines:

- a) Fixed capacitor banks are sized for minimum load conditions.
- b) Switched capacitor banks are designed for load levels above the minimum condition up to peak load.

The curve shown in Figure 3, which can be determined by a recording kilovar meter or calculated using kilowatt and power factor measurements, illustrates a typical kilovar demand over a 24 hour period. In this figure, the fixed capacitor banks satisfy the base load requirements, and the switched capacitor banks compensate for the inductive kilovar peak during the heavier load periods.

In the operation of a power system, however, it is often desirable to use existing loads to hold down the system voltage during periods of light load (compensate for the excess capacitance of the transmission system). In this case, some of the “fixed capacitors” of this figure should actually be switched to allow the load to hold down the system voltage. In other cases, where excess capacitance can be tolerated during periods of light load, it may be less expensive to leave some of the “switched capacitors” unswitched. In more general terms, the “fixed capacitors” are those that can be left on the system all of the time, and the “switched capacitors” are those that are switched to meet system operating requirements or a billing tariff.

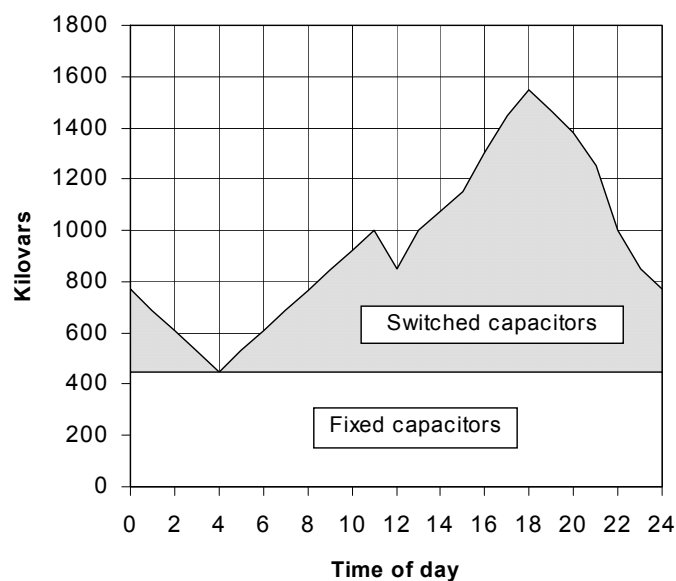


Figure 3— Switching capacitors

5. Capacitor ratings, capabilities, and service conditions

Capacitor ratings and service conditions are specified in IEEE Std 18-2002. Application guidelines for transient, short time and contingency capacitor overvoltages and overcurrents are given in this document. Key aspects of the ratings and service conditions are provided in this clause for easy reference. Short time “momentary” capabilities of capacitors are also explained in this clause.

The life of a capacitor is shortened by overstressing, overheating, chemical change, physical damage, or repeated temperature changes. Life to 90% survival might exceed 20 years when capacitors are applied according to the guidelines of this application guide.

Shunt capacitors cause a voltage rise at the point where they are located and are therefore more likely to operate at overvoltages than other types of equipment. Recognizing this factor, the nameplate voltage ratings of capacitors and permissible overvoltage operation are generally higher than those established for motors and most other equipment.

5.1 Standard ratings

The standard ratings established in IEEE Std 18-2002 are as follows:

- a) Voltage, rms (terminal-to-terminal)
- b) Terminal(s)-to-case (or ground) insulation class
- c) Reactive power
- d) Number of phases
- e) Frequency

5.1.1 Tolerances in ratings

Older capacitors may have tolerances as high as −0% to +15% for capacitance of individual capacitor units at 25 °C uniform case and internal temperature. Beginning with the 2002 edition, capacitors built to IEEE Std 18 have a tolerance of −0% to +10% at 25 °C.

Temperature will affect capacitance measurements. Therefore, the capacitance of capacitor units that are much colder or much warmer than 25°C may measure outside the rated tolerance without having failed elements.

5.1.2 Voltage and reactive power ratings

Typical voltage and reactive power ratings are summarized in Table 3. The reactive power output can be calculated as shown in Equation (8).

$$Q_{OP} = \frac{(2\pi fC)V_A^2}{1000} \quad (8)$$

where

- Q_{OP} is the operating reactive power of the capacitor in kilovoltamperes reactive
- V_A is the applied voltage in volts
- f is the supply frequency in Hertz
- C is the capacitance of the capacitor in farads

The reactive power output will vary according to the actual applied voltage, which may be different than the rated voltage. The operating kvar can also be calculated as shown in Equation (9).

$$Q_{OP} \text{ kvar} = Q_R \text{ kvar} \left(\frac{V_A}{V_R} \right)^2 \quad (9)$$

where

- Q_{OP} is the operating reactive power of the capacitor in kilovoltamperes reactive
- Q_R is the rated reactive power of the capacitor
- V_A is the applied voltage
- V_R is the rated voltage

5.1.3 Insulation classes

The standard basic impulse insulation levels (BIL) of capacitor units are given in Table 3.

Capacitors may be used on circuits of higher voltage than the terminal-to-case insulation class, provided the cases are supported on external insulation suitable for the circuit voltage and provided the terminal-to-terminal voltage limits are not exceeded.

Table 3—Typical voltage and reactive power ratings

Volts, rms (terminal-to-terminal)	kvar	Number of phases	BIL kV ^a
2400	50, 100, 150, 200, 300 and 400	1 and 3	75, 95, 125, 150 and 200
2770	50, 100, 150, 200, 300, 400 and 500	1 and 3	75, 95, 125, 150 and 200
4160, 4800	50, 100, 150, 200, 300, 400, 500, 600, 700 and 800	1 and 3	75, 95, 125, 150 and 200
6640, 7200, 7620, 7960, 8320, 9540, 9960, 11 400, 12 470, 13 280, 13 800, 14 400	50, 100, 150, 200, 300, 400, 500, 600, 700 and 800	1	95, 125, 150 and 200
15 125	50, 100, 150, 200, 300, 400, 500, 600, 700 and 800	1	125, 150 and 200
19 920	100, 150, 200, 300, 400, 500, 600, 700 and 800	1	125, 150 and 200
20 800, 21 600, 22 800, 23 800, 24940	100, 150, 200, 300, 400, 500, 600, 700 and 800	1	150 and 200

^aSee IEEE Std 18-2002 for impulse test specifications.

5.1.4 Frequency

Power capacitors are designed for operation at the device's rated nominal frequency of either 50 Hz or 60 Hz. When capacitors are operated at frequencies lower than rated, both the reactive power and the capacitive current are reduced in direct proportion to the operating frequency as shown in Equation (10) and Equation (11).

$$Q_{OP} \text{ kvar} = \left(\frac{f_{OP}}{f_R} \right) Q_R \text{ kvar} \quad (10)$$

$$I_{OP} = I_{NOM} \left(\frac{f_{OP}}{f_R} \right) \quad (11)$$

where

- Q_{OP} is the operating reactive power of the capacitor, kvar
- Q_R is the rated reactive power of the capacitor, kvar
- I_{OP} is the capacitive current at the applied frequency and rated voltage
- I_{NOM} is the capacitive current at the rated frequency and rated voltage
- f_{OP} is the frequency at which the capacitor unit is to be applied
- f_R is the rated frequency of the capacitor unit

5.2 Related capabilities

5.2.1 Operating and ambient temperatures

Capacitors are designed for switched or continuous operation in outdoor locations with unrestricted ventilation and direct sunlight under the maximum ambient temperatures for each mounting arrangement shown in Table 4.

5.2.1.1 Minimum ambient

Capacitors are designed for continuous operation and switching operations at temperatures not lower than -40°C . The capacitor manufacturer should be consulted for operation below -40°C .

5.2.1.2 Effect of temperature

It is essential that consideration be given to the arrangement of capacitors and complete equipment as an installation to provide adequate ventilation and dissipation of heat. Capacitors are designed to operate at a lower temperature rise than most other types of apparatus for the following specific reasons:

- a) Unlike most other power apparatus, shunt capacitors (whether unswitched or switched) normally operate for relatively long periods of time at full load and, therefore, do not benefit from the lower average temperature rise characteristic of typical daily load cycles.
- b) Capacitors are designed to operate at comparatively high dielectric stresses. The combination of these stresses with operation at high temperature for extensive periods of time will result in gradual deterioration and shortened life.

5.2.1.3 Design considerations

Capacitor ratings are based on maximum ambient temperatures with an allowance for heat dissipation by radiation and convection. The arrangement and mounting of capacitors and the conditions of installations will affect the heat dissipation and thereby limit the ambient temperature in which capacitors may be operated. Capacitors and capacitor equipment operating outdoors in direct sunlight and with unrestricted ventilation will normally operate with lower temperature rise than those operating indoors in still air. The following points are important in relating the operating temperature of a capacitor to the conditions of installation:

- a) An individual non-enclosed capacitor, such as is mounted on an outdoor pole, will dissipate heat with the least temperature rise (the heat dissipation being approximately 45% by radiation and 55% by convection).
- b) The mounting of capacitors in rows side by side or in tiers, or both, increases the temperature rise because of heating of the air stream and because of reduced radiation.
- c) The enclosing of capacitors in a housing or room without forced air ventilation increases the temperature rise because of reduced radiation and restriction of the natural circulation of air.
- d) Capacitors subjected to radiation from the sun or from any surface, the temperature of which is above the ambient, show a higher temperature rise.

Table 4—Maximum ambient

Mounting arrangement	Maximum ambient air temperature, °C ^a
Isolated capacitor	46
Single row of capacitors	46
Multiple rows and tiers of capacitors	40
Metal-enclosed or housed equipment	40

^aThe arithmetic average of the four highest hourly readings during the hottest day expected at the capacitor location

For applications at temperatures higher than indicated in Table 4, consult the capacitor manufacturer.

5.2.2 Continuous operation

Capacitors are suitable for continuous operation at 135% of rated reactive power. This maximum reactive power includes the following factors, the combined effects not exceeding 135%.

- Reactive power due to voltage in excess of nameplate rating at fundamental frequency but within the permissible voltage limitations described in 5.2.2.1.
- Reactive power due to harmonic voltages superimposed on the fundamental frequency.
- Reactive power in excess of nameplate rating due to manufacturing tolerance within the limits specified in 5.1.1.

5.2.2.1 Limitations on continuous operation

Capacitors are intended to be operated at or below their rated voltage and frequency. Capacitors are capable of continuous operation under contingency system and capacitor bank conditions provided that none of the following limitations are exceeded:

- 110% of rated rms voltage.
- 120% of rated crest voltage, i.e., crest voltage not exceeding $1.2 \times \sqrt{2} \times$ rated rms voltage, including harmonics but excluding transients (see Clause 7 for more on harmonics).
- 135% of nominal rms current based on rated kvar and rated voltage, including fundamental and harmonic currents (see Clause 7 for more on harmonics).
- 135% of rated kvar (see 5.2.2).

The continuous and short-time overvoltage capabilities (without loss of life) of any series element of a capacitor unit shall be considered to be its share of the total capacitor unit voltage capability. (In internally fused capacitor units, capacitor elements in parallel with blown fuses sometimes are operated beyond their normal capability, accepting the possibility of shortened life. Similarly, in some externally fused capacitor banks and in some capacitor banks without capacitor unit fuses, capacitor units with failed elements are allowed to remain in service with the remaining healthy capacitor elements in those capacitor units

operating above their normal capability, accepting the possibility of shortened life.) Capacitor units without failed elements are intended to be operated within the guidelines a) through d) shown previously.

5.2.3 Momentary capabilities

Capacitors are capable of withstanding with full-life expectancy switching transients having peak voltages up to $2 \times \sqrt{2}$ times rated voltage rms and other transient disturbances inherent in the operation of power systems.

Capacitors may be subjected to both high voltage and high current under certain conditions associated with switching. The magnitude of the permissible current and voltage peaks depends on the frequency of occurrence. In the case of a frequently switched capacitor, current and voltage peaks must be held to relatively low values. Comparatively high values may be tolerated on a capacitor bank switched infrequently. Figure 4 through Figure 6 provide a guide for the evaluation of service conditions from the standpoint of peak currents and voltage.

The capabilities indicated in these figures may be increased, upon recommendation by the manufacturer, when fewer overvoltages are expected or when less severe temperature conditions exist.

5.2.3.1 Momentary power frequency overvoltage

A capacitor, tested in accordance with IEEE Std 18-2002 may reasonably be expected to withstand, during normal service life, a combined total of 300 applications of power frequency terminal-to-terminal overvoltages without superimposed transients or harmonic content, of the magnitudes and durations shown in Figure 4.

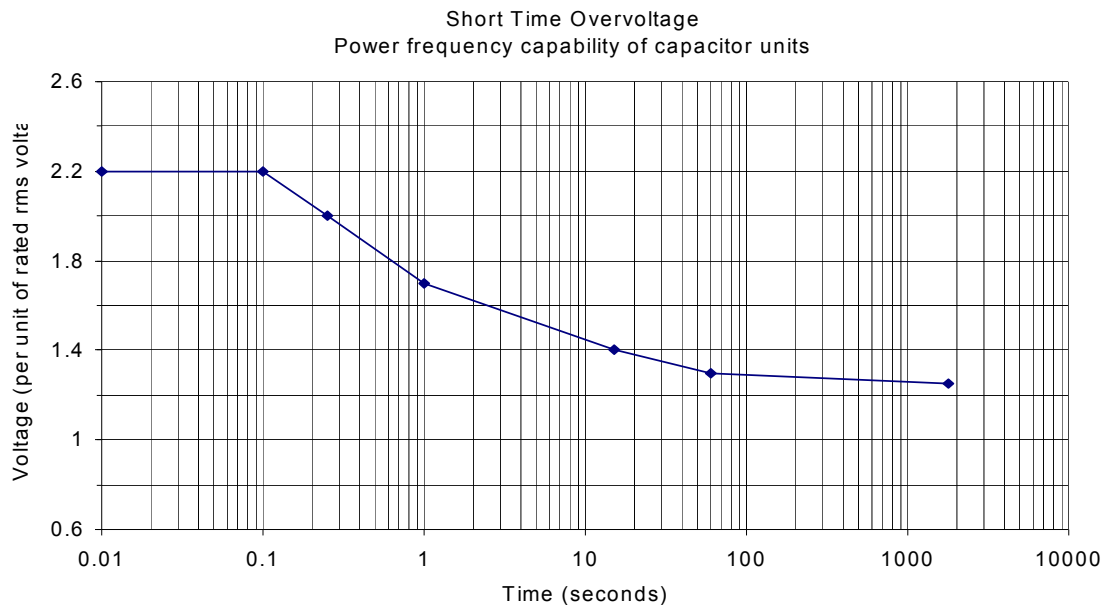


Figure 4— Maximum contingency power frequency overvoltage capability of capacitor units

NOTE—Figure 4 is based on straight line segments between the following points on semi-log coordinates: (0.01, 2.2), (0.1, 2.2), (0.25, 2.0), (1.0, 1.7), (15.0, 1.4), (60, 1.3), and (1800, 1.25).

In using Figure 4, the overvoltage capability is for the capacitor unit, not the capacitor bank. Evaluation of capacitor unit overvoltage exposure should include allowance for any voltage unbalance in the capacitor bank.

Overvoltages may cause localized damaging discharges (partial discharge) in a capacitor unit. Trapped charges and gas generated in the first half cycle make the discharge more severe in the second half cycle. The accumulation of damage makes the severity of the overvoltage event increase with the time of the event. When the overvoltage is eliminated, the trapped charges and accumulated gas tend to dissipate and be absorbed. This improves the dielectric capability of the capacitor from what it was at the end of the overvoltage event.

The time axis of Figure 4 indicates the maximum time for a single event. Capacitor unit damage tends to escalate during an event, so that damage is happening more rapidly at the end of the event than at the beginning. Two continuous seconds at 1.73 per unit is much more severe than two separate events of 1 s each, with a time in between to allow for localized cooling, absorption of corona gasses accumulated gas, etc. The curve should not be used to estimate the effect of contingency overvoltage events exceeding the maximum time indicated by the curve.

For event times shorter than those indicated by the curve, the times of the individual events can be accumulated to estimate the effect of the shorter events. For example, ten 1.73 per unit events of 0.1 s each (shorter than the allowable one second limit of the curve) would create equal or less damage to the capacitor unit than one 1.73 per unit event of 1 s duration.