

V.G
PJM DESIGN AND APPLICATION OF SHUNT CAPACITORS
500 KV, (345V) AND 230 KV
SHUNT CAPACITOR BANKS
PENNSYLVANIA-NEW JERSEY-MARYLAND (PJM)
INTERCONNECTION ASSOCIATION
PLANNING AND ENGINEERING COMMITTEE (P&E)
TRANSMISSION AND SUBSTATION DESIGN
SUBCOMMITTEE (TSDS)

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PREFACE

This second revision of the guide has been updated to recognize the viability of fuseless capacitor banks.

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1.0 **SCOPE**

This document presents guidelines and considerations for application of 500 kV and 230 kV shunt capacitor banks in transmission substations and switching stations. It covers the recommended capacitor bank configurations, capacitor unit ratings, associated switching devices and methods of protection. The individual companies will be responsible for the specific design of their installations. Three essential references for capacitor banks installations are the latest revision of ANSI/IEEE C37.99 "Guide for Protection of Shunt Capacitor Banks," NEMA CP1-1988, "Shunt Capacitors," "IEEE 1036 Guide for the Application of Shunt Power Capacitors." Guidelines for protective relaying and control are the responsibility of the Relay Subcommittee.

2.0 **BACKGROUND**

Voltage and reactive limitations have historically restricted PJM's ability to achieve full economic operation and take full advantage of economically-attractive imports especially from systems to the west of PJM. The P&E Committee's analysis of the 1983 PJM System in the early 1980's resulted in the installation of economically-justified, high-voltage, shunt capacitor banks at various locations in eastern PJM to reduce off-cost penalties. A similar analysis of the projected 1992 PJM System produced the accepted recommendation to install additional high-voltage, shunt capacitor banks on the PJM System to improve reliability of west-to-east transfer from ECAR to PJM and VP.

3.0 **BANK ARRANGEMENT**

Externally fused or fuseless arrangements may be used.

3.1 **500 kV**

At 500 kV, the capacitor bank shall be arranged in a single wye (or multiple wye if fuseless) with the neutral solidly grounded at a single point. Since the 500 kV system operates well above 525 kV, it is recommended that the capacitor banks be designed with a nominal voltage rating of at least 550 kV.

3.2 **230 kV**

At 230 kV, the capacitor banks shall be arranged in a single or double-wye (or multiple wye if fuseless) with the neutral solidly grounded at a single point. It is recommended that the capacitor banks be designed with a voltage rating of at least 242 kV.

4.0 **EQUIPMENT**

4.1 **Shunt Capacitor Equipment**

4.1.1 **Capacitor Unit Configuration**

The capacitor banks can be arranged in single or double-wye fuseless, or externally fused, and can be switched in steps of approximately 100, 150, 200 or 250 MVAR's. Externally fused arrangements previously installed are listed in Table 1.

Nominal Voltage	Grounded-Y Configuration	Capacitor Unit Rating		Series Groups per Phase	Parallel Units per Group	Bank Nameplate MVAR	Effective Bank MVAR @ Nominal Volt
		kvar	kV				
500	Single	300	19.92	16	21	302.4	250
500	Single	300	19.92	16	12	172.8	141.8
500	Single	200	19.92	16	17	163.2	133.9
500	Single	200	19.92	15	12	108.0	101.0
230	Single	200	13.8	10	18*	108.0	100.0*
230	Double	200	19.92	7	14	117.6	106.7

Table 1 Capacitor Unit Configuration

* A failed can and its fuse will see approximately 3,150 kvar of effective capacitance from the other 17 parallel units.

4.1.2 Capacitor Unit Fuse (for externally fused arrangement)

Each capacitor unit shall be protected by an expulsion-type fuse of the proper rating to assure coordination and to minimize the possibility of case rupture. See Table 2 for recommended fuse ratings. Generally less than 4,650 kvar* of effective capacitance at nominal voltage (15,000 watt-seconds of energy) should be connected in parallel. This should assure that the energy withstand capability of the expulsion fuse is not exceeded as well as assure a low probability of can rupture. In installations where two or more capacitor banks are connected to a common bus, additional energy will be contributed by the adjacent equipment (see Reference 37). The historical bank configurations listed in Table 1 either assure that this energy is within the capabilities of expulsion fuses or have proven operating experience; therefore, current limiting fuses are not necessary. 6300 kvar in parallel has been used successfully since 1993 with standard expulsion fuses. The unbalance caused by the blowing of a single fuse should cause the unbalance protection relay to operate and initiate an alarm. It is recommended that the capacitor bank be serviced as soon as possible following the fuse blowing. When more than one fuse blows in the same series group, the switching device on the capacitor bank should be tripped and an alarm initiated, when overvoltage on the remaining capacitor units exceeds 10%.

<i>Capacitor Unit Rating</i>		<i>Line Current Amperes **</i>		<i>Fuse Current Amperes**</i>		<i>Fuse</i>		
<i>kvar</i>	<i>kV</i>	<i>500 kV</i>	<i>230 kV</i>	<i>500 kV</i>	<i>230 kV</i>	<i>Type Link</i>	<i>Cont. Current Amperes</i>	<i>Max. Melt Current @ 300 sec. Amps</i>
300	19.92	204.7	-	17	-	15T	-	-
200	19.92	145.5	334.6	12.1	12.0	10T-SN 10T-AG 12K-SN	15 14 18	24.5 22 31.8
200	13.8	-	313.8	-	17.4	15T-SN 15K-AG 15K-SN	22.5 21.0 22.6	38.0 35.5 40.0

Table 2 Capacitor Unit Fuses

** Assumes 1.25 multiplier for capacitor unit overvoltage, tolerance and harmonics.

4.1.3 Capacitor Rack

The rack shall be designed and constructed for the arrangement specified. It shall provide adequate capacitor unit separation to prevent flashovers caused by voltage surges or fuse operation. Racks shall be supplied with capacitor units (and fuses, when required). All racks shall be balanced for impedance and adequately identified to facilitate the location of each rack in the assembly. Consideration should be given to providing space in the racks for future additions of capacitor units. The rack and substructure must be designed in accordance with the environmental requirements for 230 kV and 500 kV substations listed in PJM Technical Requirements (See Section II Design Criteria).

4.1.4 Capacitor Bank Insulators

The base, bus and stacking insulators are connected line-to-ground in parallel with the capacitor units. These insulators shall provide adequate BIL and creepage insulation for the application. Insulators shall be of adequate mechanical strength to withstand the capacitor rack loading. All insulators shall conform to current ANSI standards.

4.2 Capacitor Bank Switching Device

Each capacitor bank step shall be switched with a device which has the capability to make and break capacitive current a sufficient number of times so that the switching device will not require maintenance more than once a year. The switching devices capable of this duty utilize vacuum or SF6. Switching devices shall not be reclosed before any trapped charge on the capacitor bank has decayed to an acceptable level (usually 5 minutes). The current rating of the switching device shall include the effects of overvoltage (1.1 pu), capacitor tolerance (1.15 pu) and harmonic component (1.1 pu). The recommended multiplier is 1.25, rather than the 1.35 which assumes simultaneous application of the maximums of the three factors. Transient current limiting devices may be required and are discussed in Section 4.4 of this document.

Dedicated SF6 gas insulated circuit breakers are recommended for use in switching 500 kV capacitor banks. In addition to transient current limiting reactors, the circuit breakers shall be equipped with adequately sized preinsertion resistors or use controlled closing, or a combination. The preinsertion resistors shall not limit the reclosing capability of the circuit breakers.

4.3 Power Circuit Breaker

4.3.1 Capacitor Bank Circuit Breaker

When a new circuit breaker is to be used for short-circuit protection, it shall be a Definite Purpose circuit breaker per the latest revision of ANSI/IEEE C37.06, Preferred Ratings and Related Required Capabilities for AC High Voltage Circuit Breakers Rated on a Symmetrical Current Basis. IEC 62271-100 refers to this as a Class C2 circuit breaker. Where an existing circuit breaker is to be used on the capacitor bank for short-circuit protection, the manufacturer should be consulted to determine the capacitive current switching capabilities of this circuit breaker under normal and short-circuit conditions. See Reference 42 for power circuit breaker application. Circuit breakers are usually derated for capacitor switching to a value well below their continuous current rating. See Appendix A of this guide for capacitor bank inrush and discharge currents.

4.3.2 Other Circuit Breakers

When capacitor banks are installed in substations, the circuit breakers on existing power transformers or transmission lines should be checked to ascertain their respective momentary, close-and-latch, outrush capabilities when closing into a fault and capacitor switching capabilities for a short-circuit on the protected equipment. In addition, the associated disconnecting switch momentary ratings should be checked. Oil circuit breakers are particularly vulnerable to outrush di/dt.

4.3.3 Reclosing

Following an opening operation of the capacitor bank circuit breaker, it should not be reclosed until all capacitor bank switching devices connected to that circuit breaker have opened. When the capacitor bank is connected to a transmission line, the local and remote circuit breakers should not be reclosed until all capacitor bank switching devices connected to that line have opened.

4.3.4 Switching Surges

TNA studies of a typical 230 kV system with 300 Mvar connected to the bus have shown that the reclosing of a 230 kV transmission line with a one per unit trapped charge would result in somewhat higher switching surge voltages at the remote end when the remote end power transformer is out of service. With the power transformer connected, no trapped charge would be present on the transmission line and the switching surge voltage would be essentially the same with and without the 300 Mvar of capacitance. Based on these studies, the installation of capacitor banks of the 230 kV system should not cause switching surge problems. One method for minimizing switching surges is to re-energize a transmission line from a terminal which does not have capacitor banks. This also applies to the 500 kV system. It is recommended that a transient switching study be conducted for any new capacitor installation.

4.4 Transient Current Limiting Device

The energizing of a capacitor bank will result in a transient inrush current. The magnitude and frequency of this inrush current are a function of the applied voltage, the circuit inductance and damping due to resistance in the circuit. Also, in a substation where large capacitor banks are installed, the capacitor bank discharging into a short-circuit will result in a high magnitude, high frequency transient current. Equipment ratings should be checked to determine that their capabilities are not exceeded. Refer to Appendix A of this guide. This discharge current will determine the inductance and momentary rating of transient current limiting reactors that may be required.

4.4.1 **Isolated Banks**

The transient inrush current to a single isolated bank is not a concern because it is less than the available short-circuit current. However, the capacitor bank discharge current should not exceed the momentary rating of the switching device.

4.4.2 **Parallel Banks**

When capacitor banks are in parallel and are switched back-to-back, transient currents of high magnitude and high frequency will flow between energized banks and the one being energized. This high magnitude transient current is limited by:

- the impedance of the capacitor banks and of the circuit between them.
- The instantaneous voltage difference between the banks just prior to the instant of energization of the subsequent capacitor bank.

The magnitude will be greatly reduced by the use of series reactors or a capacitor switching device utilizing properly sized pre-insertion resistors, or controlled closing. Preinsertion inductors may also be considered. The thermal capability of the pre-insertion resistors should be checked to ascertain at what time intervals a capacitor bank can be re-energized. The capacitor bank inrush and discharge currents should not exceed the ratings of the switching devices.

4.5 Surge Arresters

Overvoltage protection from lightning or switching transients with surge arresters should be considered. Existing surge arresters should be checked for adequate thermal capability during capacitor bank discharge. High energy metal oxide arresters should be applied to protect the capacitor bank and any gapped arrester in the same substation.

4.6 Current Transformers

When used in the detection/protection scheme for the capacitor bank, the voltage class of the current transformer should be suitable for its location in the circuit. High magnitude currents can saturate and/or thermally overload the transformer causing misoperation of the relays. Suitable ratios and primary and secondary surge protection will tend to reduce the problems associated with high primary currents. Transient inrush currents through a circuit breaker may cause secondary flashover of bushing current transformers (CT) or voltages damaging to protective relays. CT voltage crest should be determined by calculation.

4.7 Voltage Devices

When used in the detection/protection scheme, the voltage devices can be transformers or CCVTs, and should be suitable for the proposed location. Because the capacitor banks can be subjected to lightning/switching surges, the primary and/or secondary of the voltage device should be provided with suitable protection. If intermediate tap point voltages and bus voltages are used for unbalanced protection for single bank design, it is recommended that mid-tap and dedicated bus CCVTs be used.

5.0 DESIGN CONSIDERATIONS

5.1 Grounding

Two industry recognized grounding methods, single point and peninsula, are acceptable. Each method requires that the neutral of each step be brought to a common point and connected to the station ground grid at only one point. This will minimize the severity of the recovery voltage across the switching device and also minimize the severity of the voltage transients induced in control wiring near the capacitor banks. Single point grounding and peninsula grounding are not compatible with one another. All capacitor banks of the same voltage rating in the same substation must use the same grounding scheme; however, the existing ground grid design may strongly influence which grounding scheme, single point or peninsula, is used. See the latest revision of IEEE 1036 "Guide for the Application of Shunt Capacitors", and IEEE C37.99 "Guide for the Protection of Shunt Capacitor Banks".

5.2 Control and Power Cables

The switching of capacitor banks can initiate high frequency, high magnitude transients in control and power cables. In addition to the recommendations outlined in Section 5.1, devices used for the control station equipment should be reviewed. Many systems installed in substations, such as telecommunications, UPS protective relaying, etc., rely on solid-state components. If not properly coordinated, surge protected, or optically isolated, failure of these devices can occur. Particular attention, including the use of shielding, should be given to the installation of control and power cables in the capacitor bank area, with special emphasis on shield grounding.

5.3 Resonance and Harmonics

The grounded configuration of capacitor banks provides a path for harmonic currents. Also, switching devices can initiate transients with multiple harmonic content and may cause resonance with inductive components and result in high magnitude transient voltages, particularly if the switching device has long arcing time and multiple restrike characteristics. These harmonic voltages may be induced in the control circuits by the current transformers and/or the voltage devices but can be reduced effectively by installing harmonic suppression device. Problems with resonance usually can be resolved by the addition of reactors (or reactors and resistors in parallel) in series with the capacitor bank, or relocation or change in capacitor bank rating.

5.4 Environment

5.4.1 RIV

As with much high voltage equipment, RIV may be a problem with these capacitor banks. Shielding of the capacitor racks and associated equipment may be required to reduce RIV levels to acceptable limits as defined by applicable standards.

5.4.2 Audible Noise

Some switching devices used on capacitor banks can generate audible noise. Installations near residential areas and those subject to frequent operations may require switching devices especially designed with low noise levels.

5.4.3 Flammability

Flammability of the capacitor fluid should be considered when locating the banks in the station.

5.5 Physical Arrangement

Within the design limitations of insulators and other structural components, a compromise must be reached on the height of each capacitor bank. Generally it is more economical to install the capacitor racks in a single stack; however, such an arrangement results in a high profile. The importance of aesthetics must be evaluated for each installation. In addition, the impact of wind seismic events as well as loads imposed by strain conductors must be considered.

Need for vehicular access between phases should be considered in the initial layout,

5.6 Capacitor Bank Protection

5.6.1 Short-Circuit Protection

Protection against short-circuits in the capacitor bank shall be provided on each step. The guidelines for short-circuit protection will be formulated by the Relay Subcommittee.

5.6.2 Unbalance Protection

Unbalance protection shall be provided by one of the following methods:

- a. Neutral Current Unbalance
- b. Neutral Current Differential Unbalance
- c. Summation of Intermediate Tap Point Voltages
- d. Voltage Difference

6.0 Maintenance

See Section V.L.2.G for maintenance requirements.

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APPENDIX A. INRUSH CURRENT AND FREQUENCY DURING ENERGIZATION OF CAPACITOR BANKS

TABLE A1

Single Bank

System Short - Circuit Current – kA	Capacitor Bank Load Current – A	Inrush Current – KA Peak	Inrush Current Rate-of-Rise A/μ sec	Freque ncy Hz
I_{sc}	I_L	i_{max}	di/dt	F
<i>230 kV, 106.7 Mvar Bank</i>				
30	266	4	16.1	637
35	266	4.3	18.5	681
40	266	4.9	21.4	728
50	266	5.2	26.7	822
63	266	5.8	33.6	913
<i>500 kV, 101 Mvar Bank</i>				
20	116	2.1	10.6	787
30	116	2.64	15.7	964

$$i_{max} = 1.41 \sqrt{I_{sc} \times I_L}$$

$$f = \frac{1}{2\pi} \sqrt{\frac{I_{sc}}{I_L}}$$

$$di/dt = \frac{2\pi f \times i_{max}}{10^6} = \frac{E_{crest}}{L}$$

I_L = rms Load Current (without harmonics, etc.)

I_{sc} = rms short circuit current

f_s = system frequency (60 Hz)

i_{max} , I_{sc} , I_L in amperes

f , f_s in hertz

di/dt in amperes per microsecond

APPENDIX A (Cont'd)

**INRUSH CURRENT AND FREQUENCY DURING ENERGIZATION OF
CAPACITOR BANKS**

TABLE A2

Two Banks

Impedance on Each Bank - μH	Equivalent of Impedance Between Banks - μH	Capacitor Bank Load Current - A	Inrush Current - kA Peak	Freque ncy kHz
L/Bank	L_{eq}	I_L	i_{max}	f
<i>230 kV, 106.7 Mvar Banks</i>				
50	100	266	30.8	9.5
75	150	266	25.2	7.8
100	200	266	21.8	6.8
125	250	266	19.5	6.0
150	300	266	17.8	5.6
<i>500 kV, 101 Mvar Banks</i>				
100	200	116	21.1	15
150	300	116	17.2	12.3

$$i_{max} = 1,235 \sqrt{\frac{V_{L-L} \times I_L}{L_{eq}}}$$

$$f = 13.5 \sqrt{\frac{f_s \times V_{L-L}}{L_{eq} \times I_L}}$$

i_{max} in amperes

L_{eq} in microhenries

f in kilohertz

f_s in hertz

V_{L-L} in kilovolts

I_L in amperes

APPENDIX A (Cont'd)

**INRUSH CURRENT AND FREQUENCY DURING ENERGIZATION OF
CAPACITOR BANKS**

TABLE A3

Three Banks

Impedance on Each Bank - μH	Equivalent of Impedance Between Banks - μH	Capacitor Bank Load Current - A	Inrush Current - kA Peak	Frequen cy kHz
L/Bank	L_{eq}	I_L	i_{max}	f
<i>230 kV, 106.7 Mvar Banks</i>				
65	100	334.6	39.5	7.5
100	150	334.6	32.3	6.1
130	200	334.6	28.0	5.3
160	250	334.6	25.0	4.7
200	300	334.6	22.8	4.3
260	400	334.6	19.8	3.7
<i>500 kV, 101 Mvar Banks</i>				
130	200	145.5	27.2	11.8
200	300	145.5	22.2	9.6
260	400	145.5	19.2	8.3

$$i_{max} = 1,426 \sqrt{\frac{V_{L-L} \times I_L}{L_{eq}}}$$

$$f = 11.6 \sqrt{\frac{f_s \times V_{L-L}}{L_{eq} \times I_L}}$$

i_{max} in amperes

L_{eq} in microhenries

f in kilohertz

f_s in hertz

V_{L-L} in kilovolts

I_L in amperes

APPENDIX A (Cont'd)

DISCHARGE CURRENT FOR CLOSE-IN SHORT-CIRCUIT

TABLE A4

Impedance from Each Bank to Fault μH	SINGLE BANK Discharge Current – kA Peak
L	I_{max}
<i>230 kV, 106.7 Mvar Banks</i>	
100	43.6
200	30.8
300	25.2
400	21.9
600	17.8
1000	13.9
<i>500 kV, 101 Mvar Banks</i>	
200	30
300	24.6
400	21.2

$$i_{max} = 1,747 \sqrt{\frac{V_{L-L} \times I_L}{L}}$$

The total discharge current for multiple banks is the product of the single bank discharge current times square root of the number of banks in parallel (for portions of the circuit with a common path).

i_{max} in amperes

L_{eq} in microhenries

V_{L-L} in kilovolts

I_L in amperes

For portions of the circuit with independent paths, the currents will add by superposition. This quickly becomes a complex circuit analysis. Because of the high frequencies, the mutual coupling between conductors cannot be ignored.