V. Design, Application, Maintenance & Operation Technical Requirements

V.G PJM Design and Application of Shunt Capacitors

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 100 kV and above 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 “IEEE Guide for the Protection of Shunt Capacitor Banks”, NEMA CP 1 “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. 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. Beginning about 2010, with the increase in generation retirements, shunt capacitors have been deployed more frequently on a case-by-case basis to mitigate the short term loss of generation.

3.0 Bank Arrangement and Voltage

Externally fused or fuseless arrangements may be used.

3.1 Single vs. Multiple Wye

Capacitor banks will be designed for a voltage rating of at least 5% higher than the nominal voltage of the bus, or, the maximum anticipated operating voltage whichever is greater.

Single or double wye solidly grounded neutral banks shall be used. Banks switched by a single device shall have their neutrals grounded at a single point.

Specific bank design shall be coordinated with the Transmission Owner.

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. 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*
kV		*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 - PJM Historical Examples of Capacitor Unit Configurations

* Note that a failed can and its fuse will see the energy associated with the other 17 parallel units, approximately 3.15 MVAR.

4.1.2 <u>*Capacitor Unit Fuse (for externally fused arrangement)*</u> - 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%.

The following show examples of capacitor bank fuses installed in the early 1980s and 1990s.

Capacitor Unit Rating		*Line Current Amperes *****		*Fuse Current Amperes***		*Fuse*		
kvar	*kV*	*500 kV*	*230 kV*	*500 kV*	*230 kV*	*Type Link*	*Cont. Current Amperes*	*Max. Melt Current at 300 s Amps*
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 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 distance for the application. Insulators shall be of adequate mechanical strength to withstand the capacitor rack loading. All insulators shall conform to current ANSI/IEEE 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 shall utilize SF6 gas. Switching devices shall not be reclosed before any trapped charge on the capacitor bank has decayed to an acceptable level (usually 5 min). The continuous 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) multipliers. The recommended multiplier is 1.25, rather than the 1.35 sum, 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. Consideration shall be given to the preinsertion resistor so as not to limit the reclosing capability of the breaker.

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/IEEEC37.06, 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 (peak and short-term withstand capability), 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 (peak and short-term withstand capability) should be checked. Oil circuit breakers are particularly vulnerable to outrush high frequency current (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* - It is recommended that a transient switching study be conducted for any new capacitor installation.

Transient studies of a typical 230 kV system with a 300 MVAR capacitor bank 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 capacitor bank. 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 other system voltages.

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 (peak and short-term withstand capability) 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 bank(s) 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 Equipment 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, relocation, or change in capacitor bank rating.

5.4 Environment

5.4.1 *<u>Radio Interference Voltage (RIV)</u>* - As with much high voltage equipment, RIV may be a problem with capacitor banks. Corona 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 *<u>Audible Noise</u>* - 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 *<u>Flammability</u>* - Flammability of the capacitors' dielectric 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.

Need for fencing of capacitor banks should be considered in the initial layout. Fencing requirements for each Transmission Owner shall be adhered to as applicable.

5.6 Capacitor Bank Protection

5.6.1 *Short-Circuit Protection* - Protection against short-circuits in the capacitor bank shall be provided on each individually switchable section. 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 Document V.L Substation Operation and Maintenance, section 2.G for maintenance requirements.

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Appendix A. Inrush Current & Frequency During Energization of Capacitor Banks

Table A1

Single Bank

System Short-Circuit Current (kA)	Capacitor Bank Load Current *(A)*	Inrush Current Peak (kA)	Inrush Current Rate-of-Rise *(A/μ sec)*	Frequency *(Hz)*
I_{SC}	I_L	i_{max}	di/dt	F
230 kV, 106.7 MVAR Bank				
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**
500 kV, 101 MVAR Bank				
20	**116**	**2.1**	**10.6**	**787**
30	**116**	**2.64**	**15.7**	**964**

$i_{max} = 1.41\sqrt{Isc \times IL}$ $\quad f = S \times \sqrt{\frac{Isc}{IL}}$ $\quad \frac{di}{dt} = \frac{2\pi f \times imax}{10^6} = \frac{Ecrest}{L}$

- 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

Table 2

Two Banks

Impedance On Each Bank (μH)	Equivalent of Impedance Between Banks(μH)	Capacitor Bank Load Current (A)	Inrush Current kA Peak	Frequency (kHz)
L/Bank	**L_{eg}**	**I_L**	**i_{max}**	**f**
230 kV, 106.7 MVAR Banks				
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**
500 kV, 101 MVAR Banks				
100	**200**	**116**	**21.1**	**15**
150	**300**	**116**	**17.2**	**12.3**

$$i_{max} = 1.235 \sqrt{\frac{VL-L \times IL}{Leq}} \qquad f = 13.5 \sqrt{\frac{fs \times Vl-L}{Leq \times Il}}$$

- i_{max} in amperes
- L_{eq} in microhenries
- f in kilohertz
- f_s in hertz
- V_{L-L} in kilovolts
- I_L in amperes

Table A3

Three Banks

Impedance on Each Bank (μH)	**Equivalent of Impedance Between Banks (μH)**	**Capacitor Bank Load Current (A)**	**Inrush Current (kA Peak)**	**Frequency (kHz)**
L/Bank	**L_{eq}**	**I_L**	**i_{max}**	**f**
230 kV, 106.7 MVAR Banks				
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**
65	**100**	**334.6**	**39.5**	**7.5**
500 kV, 101 MVAR Bank				
130	**200**	**145.5**	**27.2**	**11.8**
200	**300**	**145.5**	**22.2**	**9.6**
260	**400**	**145.5**	**19.2**	**8.3**

$$i_{max} = 1.426\sqrt{\frac{V_{L-L} \times I_L}{L_{eq}}} \qquad f = 11.6\sqrt{\frac{f_s \times V_{L-L}}{L_{eq} \times I_L}}$$

- i_{max} in amperes
- L_{eq} in microhenries
- f in kilohertz
- f_s in hertz
- V_{L-L} in kilovolts
- I_L in amperes

Table A4

Impedance from Each Bank to Fault (µH)	**Single Bank Discharge Current (kA Peak)**
L	$\mathbf{I_{max}}$
230 kV, 106.7 MVAR Banks	
100	**43.6**
200	**30.8**
300	**25.2**
400	**21.9**
600	**17.8**
1000	**13.9**
500 kV, 101 MVAR Banks	
200	**30**
300	**24.6**
400	**21.2**

$i_{max} = 1{,}747 \sqrt{\frac{VL-L \times IL}{L}}$

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).

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.

- I_{max} in amperes
- L_{eq} in microhenries
- V_{L-L} in kilowatts
- I_L in amperes