POWER FACTOR CORRECTION AND STATIC REACTIVE COMPENSATOR SYSTEMS

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1.0 SCOPE

This data sheet discusses the relation of power factor to alternating current systems, the effect of low power factor on a transmission system or an industrial distribution system, and the methods employed in industry to correct power factor.

The primary purpose of this data sheet is to be informative. The static reactive compensator systems are relatively new and thus far they have been installed in only a few of FM insured plants in the United States, although a number of installations have been made in Europe, Iran, Japan and South America. It is expected that their use will increase because of the many advantages over the old methods of compensating for the erratic reactive current swings in electric furnace circuits.

This equipment is available in the U.S. from the following manufacturers under the names indicated:

- General Electric Co. - Static Var Control
- Westinghouse Electric Corp. - Static Var Generator
- ASEA, Inc. - Static Var Systems

The Japanese likewise employ a static reactive compensator using thyristors for the suppression of flicker in two 100 ton arc furnaces.

1.1 Hazards

The most common hazard associated with Power Factor Correction and Static Reactive Compensator Systems is overheating and insulation breakdown, causing rupturing of capacitor cases and leaking of electrolyte oils, with fire following.

1.2 Changes

January 2024. Interim revision. Updated and consolidated oil-filled capacitor recommendations from Data Sheet 5-24, *Miscellaneous Electrical Equipment*.

2.0 LOSS PREVENTION RECOMMENDATIONS

2.1 Introduction

2.1.1 Use FM Approved equipment, materials, and services whenever applicable. For a list of FM Approved products and services, see the *Approval Guide*, an online resource of FM Approvals.

2.2 Construction and Location

2.2.1 Locate oil-filled capacitor banks outdoors, taking care not to expose other valuable equipment.

2.2.2 If oil filed capacitor banks are installed indoors, place them in detached buildings or cut-off rooms as described in Figure 2.2.2 and Table 2.2.2-1.

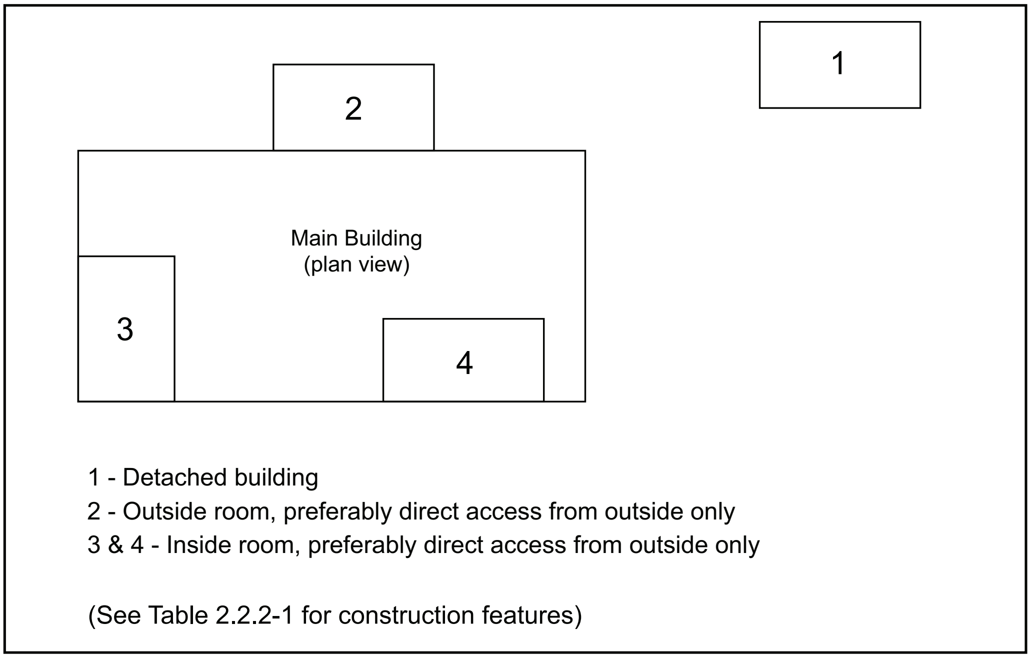

Fig. 2.2.2. Locations for oil-filled capacitor buildings and rooms

Table 2.2.2-1. Recommended Construction for Oil-Filled Capacitor Buildings and Rooms

Total Fluid Volume	*Room or Building Fire Rating*	*Fire Protection for Oil-Filled Capacitors*
Less than 100 gal (380 L)	One-hour fire-rated	Per Section 2.4
100 gal or more (380 L)	Three-hour fire-rated with subdivision between capacitor banks	None[Note 1,2]

Note 1. Sprinkler protection is always desirable over oil-filled equipment. However, in this case omission is tolerable.
Note 2. See Section 2.2.3 for large capacitor bank installations.

2.2.3 Provide subdivided cut-off rooms for large capacitor installations. Consider the arrangement of the cut-off rooms based on process impact if a capacitor fire were to occur. Install fire rated subdivisions aligned with downstream processes to limit the extent of a possible shutdown due to a fire.

2.2.4 Arrange oil-filled capacitor rooms to allow for direct access from outdoors.

2.2.5 Provide normally closed FM Approved fire doors. Keep all interior fire doors normally closed. Alternatively, FM Approved automatic closing fire doors are acceptable.

2.2.6 Design ventilation systems to minimize potential smoke damage.

2.2.7 Provide FM Approved fire stops for all penetration with fire resistance equivalent to 1 hour or to the rating of the construction, whichever is greater.

2.3 Occupancy

2.3.1 Where the surrounding occupancy could be exposed to nonthermal damage due to an indoor oil-filled capacitor fire, provide one of the following:

A. Locate the oil-filled capacitors in rooms with suitable construction so the surrounding occupancy will not be exposed or

B. Equip the oil-filled capacitor room with a mechanical ventilation system designed to vent smoke to outdoors. Provide power for the ventilation system from an emergency source that will not be deenergized as part of the pre-fire plan.

2.3.2 Install FM Approved smoke detection in electrical/capacitor rooms, with alarms arranged to sound at constantly attended location, regardless of any automatic sprinkler protection or heat detection that may exist. The presence or absence of smoke detectors does not change the need for sprinklers. Provide Smoke detection spacing in accordance with Data Sheet 5-48, *Automatic Fire Detection*.

2.3.3 Keep capacitor banks and their associated equipment clean, cool and dry, and all connections tightened in accordance with the relevant industry standard or to the manufacturer's recommendations.

2.4 Fire Protection

2.4.1 Provide indoor oil-filled capacitor installations with automatic sprinklers or water spray above the capacitors and for 20 ft (6 m) in all directions. Design sprinklers to meet a discharge density of 0.2 gpm/ft^2 (8 mm/min) over and 20 ft (6 m) beyond in all directions to a maximum operating area of 3000 ft^2 (279 m^2).

2.4.2 Provide liquid-filled capacitors other than those filled with Askarels with internal pressure and/or thermally actuated interrupting devices set or adjusted to prevent case rupture in the event of an internal fault.

2.4.3 Provide protection for reactors as identified in Data Sheet 5-4, *Transformers*.

2.4.4 Provide protection for grouped cables as identified in Data Sheet 5-31, *Cables and Bus Bars*.

2.4.5 Provide Carbon Dioxide portable fire extinguishers in accordance with Data Sheet 4-5, *Portable Extinguishers*.

2.5 Equipment and Processes

2.5.1 Electrical

2.5.1.1 Operate capacitor banks within their designed specifications and ratings, including working voltage, overcurrent and short circuit protection, temperature ratings, and when installed outdoors weather resistance.

2.5.1.2 Protect capacitors with surge arrestors when connected to exposed overhead lines or when subjected to other transient voltage surges in accordance with Data Sheet 5-11, *Lightning and Surge Protection for Electrical Systems*.

2.5.1.3 For operation and control of oil-filled capacitors which are part of a larger power supply, see occupancy specific Data Sheets such as Data Sheet 7-33, *Molten Metals and Other Materials*.

2.5.2 Water-Cooled Equipment and Conductors

When encountering water cooled electrical equipment or conductors, first consult the occupancy or equipment specific Data Sheets such as but not limited to Data Sheet 6-3, *Induction and Dielectric Heating Equipment* or Data Sheet 5-12, *Electric AC Generators*. In the absence of occupancy or equipment specific Data Sheets follow the guidance below.

2.5.2.1 Provide method or a system to interrupt the power supply upon high temperature.

2.5.2.2 Provide an emergency water supply where the loss of cooling water due to a power failure would result in a serious exposure.

2.5.2.3 Arrange the equipment so that it will not be damaged by leakage or condensation.

2.5.3 Static Reactive Compensator System Recommendations

2.5.3.1 Use FM Approved dielectric fluid in the capacitors.

2.5.3.2 Protect the system in accordance with Section C.5.2 of this data sheet.

2.5.3.3 Provide surge protection for the transformers and switchgear as outlined in Data Sheet 5-11, *Lightning and Surge Protection for Electrical Systems*.

2.5.3.4 Provide air cooling or a freon cooling system for thyristors. Avoid using water for cooling.

2.5.3.5 Provide carbon dioxide handheld extinguishers in the control building.

2.5.3.6 Arrange the air core reactors which are located outdoors with the capacitors to prevent induction heating of iron parts.

2.5.4 Motor-Capacitor Applications

When considering the connection of capacitors to induction motors, the guidelines listed below should be followed:

2.5.4.1 Use motors selected for the application of capacitors that are not subject to inching, plugging or jogging duty.

2.5.4.2 Do not restart motors selected for the application of capacitors while still spinning and generating close to normal voltage.

2.5.4.3 Do not equip crane or elevator motors (where the load may drive the motor) and multi-speed motors with power factor correction capacitors.

2.5.4.4. Do not apply capacitors on the load side of contactors involved in open-circuit transition for voltage change or speed change.

2.5.4.5 Do not use capacitors on the load side of solid state starters and NASA-NOLA power factor controlled motors. The NASA-NOLA controller is a device that senses the load on a motor and varies the terminal voltage in proportion to the motor load. Motors operate very inefficiently at light loads because the constant excitation portion of the stator current is maintained even while the motor is unloaded mechanically. The NASA-NOLA controller improves efficiency at light loads by reducing the motor terminal voltage during light loading period. The controller response time is sufficiently short so that a sudden load increase is easily met by a rapid rise in voltage.

2.6 Operation and Maintenance

2.6.1 Power Factor Correction System

2.6.1.1 Establish and implement a power factor correction system inspection, testing and maintenance program. See Data Sheet 9-0, *Asset Integrity*, for guidance on developing an asset integrity program.

2.6.2 Maintenance of Static Reactive Compensator Systems

2.6.2.1 The static var control systems in general require little maintenance and are very reliable. Occasionally a diode may fail, but its replacement poses no difficulties. The thyristor switches and the electronic control equipment should be cleaned periodically to prevent the accumulation of any dust or dirt.

2.6.2.2 If the thyristor heat sinks are the water-cooled type, the motors and pumps on the cooling system should be inspected and lubricated periodically. Water filters and deionizing cartridges should also be replaced about every six months.

2.6.3 Water-Cooled Equipment and Conductors

2.6.3.1 To prevent water leaks, check the connections on the water-cooling loop in accordance with the manufacture's recommendations for tightness. In some cases, a weekly check may be needed if frequent movement occurs under normal operating conditions.

2.6.3.2 Manufacturer instructions may recommend parts be replaced even if those parts do not show wear and tear or any damage. Maintain a schedule to track replacement of these parts.

3.0 SUPPORT FOR RECOMMENDATIONS

3.1 Loss History

A study of the loss experience for the ten-year period from 2012 to 2022 shows 46 incidents in which the loss was due to the use of capacitors.

Static reactive compensators are highly reliable. One manufacturer quotes an expected forced outage time of only 11 hours per year.

The records show that the capacitor failures were due to many different causes. The most common cause was internal insulation failure resulting in ground faults or short circuits. Other causes of failure were over-voltage due to lightning, overheating, loose connections, flood and harmonic peaks.

4.0 REFERENCES

4.1 FM

Data Sheet 3-26, *Fire Protection for Nonstorage Occupancies*
Data Sheet 4-5, *Portable Extinguishers*
Data Sheet 5-11, *Lightning and Surge Protection for Electrical Systems*
Data Sheet 5-12, *Electric AC Generators*
Data Sheet 5-19, *Switchgear and Circuit Breakers*
Data Sheet 5-48, *Automatic Fire Detection*
Data Sheet 6-3, *Induction and Dielectric Heating Equipment*
Data Sheet 9-0, *Asset Integrity*

4.2 Other

The National Electrical Code.

APPENDIX A GLOSSARY OF TERMS

FM Approved: Product and services that have satisfied the criteria for FM Approval. Refer to the *Approval Guide*, an online resource of FM Approvals, for a complete listing of products and services that are FM Approved.

APPENDIX B DOCUMENT REVISION HISTORY

January 2024. Interim revision. Consolidated power factor capacitor recommendations from Data Sheet 5-24, *Miscellaneous Electrical Equipment*.

January 2001. The recommendation for smoke detection for electrical rooms was revised to provide consistency within 5-series data sheets.

January 2000. This document was reorganized to provide a consistent format.

APPENDIX C SUPPLEMENTARY INFORMATION

C.1 General

C.1.1 Power Factor

Power factor may be defined as follows:

$$\text{Power Factor} = \frac{\text{Sum of Watts per Phase}}{\text{Sum of Volt-Amperes per Phase}} = \frac{\text{Active Power}}{\text{Apparent Power}}$$

Volt-amperes per phase is the product of the phase voltage and the phase current. The sum of these phase volt-amperes is the *apparent power. Apparent power* is made up of both active and reactive (nonworking) kVA.

Watts per phase constitute that portion of the volt-amperes per phase that is expended in doing work, normally in the form of heat, light or mechanical power. The sum of the phase values of watts per phase is the *active power.*

Power factor as defined above is sometimes multiplied by 100 and expressed as a percentage.

C.1.2 Low Power Factor

A low power factor is an indication of less than an optimum use of electrical energy. In an industrial plant this means increased power costs. The contract with the power company often specifies that the owner must maintain a certain power factor and, if it falls below this figure, the owner is penalized. A power factor of 90% is usually considered a good one. Not only does low power factor cause an increase in the cost of electricity, but it can result in overloaded transformers and cables and reduced voltage level, resulting in sluggish motor operation and lower illumination from the lighting system.

The electrical equipment of the power company and the consumer must be sized to carry both the reactive current and the active current. The correction of power factor will reduce the magnitude of the reactive current and could permit the use of smaller sized generators, transformers, transmission lines and cables. The resulting decrease in capital equipment costs of the smaller equipment is frequently reflected in the price of the electrical energy supplied by the power company.

C.1.3 Effect of Low Power Factor on AC Apparatus

At low power factor, the effective capacity of a transformer is reduced because it is rated in kVA, and its kilowatt carrying capacity is directly dependent on the power factor of the load.

Generators are usually rated at 0.8 to 0.9 power factor in order to accommodate some lagging (reactive current flow to load) power factor load. If the power factor of the load is low, the generator kilowatt capacity may have to be reduced because of the increase in total kVA resulting from the larger reactive kVA component.

The size of the conductors in a power system is selected to safely carry a certain amount of current. At low power factor, the conductors are required to carry higher total current due to a large reactive component, in addition to the active component. Therefore, they must be larger for a specific kilowatt load with a low power factor than they would be at a higher power factor. The line losses also vary as the square of the current; therefore, these losses increase per kilowatt of load as the power factor decreases. Low power factor also causes a higher voltage drop at the load ends of distribution lines due to the larger current for a given kilowatt load.

C.2 Methods for Improving Power Factor

The use of synchronous motors, synchronous condensers and power factor correction capacitors can correct the low power factor of a system. In many industrial plants, the most practical method of improving the power factor is by the use of synchronous motors with either unity (1.0) or leading (0.8) (reactive current flow from motor to distribution system) power factor.

When a plant has many large induction motors, they should be operated at their maximum load to keep the power factor as high as possible. The power factor is low in a lightly loaded induction motor because the power component (kW) of the input varies almost directly with the load, but the magnetizing (reactive kVA) component decreases only slightly with decrease in load. Consequently, the high ratio of the lagging reactive kVA component to the power component kW results in a low power factor.

Synchronous condensers, which are synchronous motors operated without load and an overexcited or underexcited field, are generally used by electric utility companies and by very large industrial plants to stabilize the system voltage and improve the power factor. By increasing the field excitation to overexcite the synchronous condenser, reactive current flows from the condenser to the system and raises system voltage. By reducing the field excitation to underexcite the synchronous condenser, reactive current flows to the condenser from the system and lowers system voltage.

For general use in industrial plants the most practical and economical method of correcting power factor is usually the installation of capacitors. Capacitors are also used by the electric utilities on their systems where the cost of installing an expensive synchronous condenser is not warranted.

Capacitors improve the power factor because, when added to an inductive circuit, the effects of capacitance are exactly opposite to the effects of inductances. The inductance is cancelled out, the reactive kVA reduced and the power factor increased.

The use of capacitors over other means of power factor correction offers the following advantages.

A. They are substantially lower in cost.

B. They can be easily moved from one location to another.

C. They require practically no maintenance.

D. The correction capability of a bank of capacitors can be easily increased.

C.3 Power Factor Correction Capacitor Application

C.3.1 Introduction

There are two methods of power factor correction when using capacitors. The first method is the installation of a number of capacitors in a bank at a central point of the system, such as at a switchboard or a distribution panel. The second method is the installation of individual capacitors on each motor circuit at the source of poor power factor.

Power factor correction is most effective when the capacitors are connected directly to the terminals of the inductive apparatus such as induction motors. When so connected, the motor and capacitor are switched on and off as a unit, thus ensuring that the capacitor is in service only when needed. It is important that the capacitors be disconnected when the inductive equipment producing the low power factor is out of service; otherwise, the capacitors may be furnishing an excessive amount of leading current, which is more undesirable than too much lagging current.

C.3.2 Harmonic Resonance

When power factor correction capacitors are used on systems having static power converters, the development of resonance is possible between the capacitors and the system inductive reactance. As this condition is approached, the magnitude of the harmonic current in the system increases. The consequences of the flow of excessive amounts of harmonic current include the overheating of electrical equipment and telephone interference. This current may be high enough to blow capacitor fuses. Blown capacitor fuses or capacitor cell failures are an indication of the *possibility* of resonance. Blown capacitor fuses can be attributed to other causes, including the following:

a) Arcing ground faults in the system
b) Misadjusted switches or motor starters that close two poles sooner than the third pole
c) Lightning surges
d) System short circuits
e) Emergency transfers of power
f) Utility transients, such as those caused by throwing on large nearby banks of capacitors

The calculation of the harmonic resonance point of a system is useful in determining if a resonance problem is probable. To find the resonance point, the short circuit MVA at the capacitor must be known. An approximation of the resonance point on a radial system is given by the following formula:

$$h_r = \sqrt{\frac{MVA}{MVAR_c}}$$

Where h_r = order of the harmonic, (Harmonic Resonance Point);

MVA = short circuit MVA available at the capacitor bank;

$MVAR_c$ = capacitor rating.

The 5th and 7th harmonics are characteristic of 6 pulse converters; therefore, harmonic resonance points near 5 or 7 indicate potential trouble on systems utilizing 6 pulse converters.

Another useful quantity for determining the probability of resonance problems is called the short circuit ratio (SCR). This is the ratio of the short circuit MVA available at the converter to the MW of the converter. It is defined as follows:

$$SCR = \frac{\text{Short Circuit MVA at Converter}}{\text{MW of Converter}}$$

If the total MW rating of the converter is more than 5% of the system available short circuit MVA (SCR<20), significant system voltage distortions can occur on unfiltered systems. If the converter rating is less than 5% (SCR>20), the probability of harmonic problems is low.

Specifically, for a six pulse converter, if the SCR is above 20 and the harmonic resonance point is greater than 8.5, the probability of resonance problems is low. If the SCR is below 20 and the harmonic resonance point is near one of the converter characteristic harmonics, there is a high probability of producing excessive harmonic voltage and high harmonic current.

If harmonic resonance is believed to be a problem, a harmonic resonance study should be undertaken by a qualified engineering firm.

C.4 Capacitor Installation

Capacitors should not be installed in proximity to each other since the heat from one affects the other. Mounting methods provided by the manufacturer consider this factor. Under normal operating conditions the capacitor case temperature should not exceed 131°F (55°C). Overheating at the normal operating voltage is unlikely, but if voltage exceeds 110% of the capacitor rating, damage can occur.

Capacitors are usually filled with an insulating liquid and are rated in vars or kilovars, one var equal to one reactive voltampere and one kilovar equal to 1000 reactive voltamperes. A capacitor rated at 15 kvar will cancel out 15 kVA of inductive reactive kVA, but it must also be rated at the same frequency and voltage as the system.

The *National Electrical Code* requires that overcurrent protection be provided for capacitors. To protect in case of an internal short circuit, fuses rated from 165% to 250% of the rated kilovar current, are usually used. This range allows for maximum operating conditions including momentary surges of current. The fuses should be rated as low as practical to clear a faulted capacitor from the circuit quickly. Otherwise, a buildup of gas pressures can rupture the case.

The ampacity of the circuit conductors is required to be not less than 135 percent of the rated current of the capacitor.

Capacitor banks rated at more than 1000 volts should be provided with the following electrical protection:

1. Overcurrent protection for major equipment faults.
2. Means for identifying the failure of an individual capacitor within a bank.
3. Protection for arcing faults within the capacitor rack.
4. Overvoltage protection.
5. Lightning protection.

Where the capacitors are connected to the conductors on the load side of the starter for an induction motor, separate fuses and disconnects are not required since the starter will afford the required disconnecting means and the overcurrent protection.

It should be noted that wye-connected power factor correction capacitors used in industrial and commercial power systems should be *ungrounded.*

C.5 Static Reactive Compensator Systems

C.5.1 Introduction

In recent years, the synchronous condenser has been superceded by a continuously controlled solid state device that will compensate for the random variations of reactive power so characteristic of arc furnace loads. This solid state equipment (static reactive compensator) is the most economical means of furnishing high speed var control. It has no moving parts to wear, is easy to maintain, and its installation cost is low.

These static reactive compensators have the following uses:

1. Improve the stability of long transmission lines.
2. Compensate for the reactive power swings of large motor drive systems that utilize thyristor converters for main and auxiliary drives.
3. Regulate the voltage of a high voltage ac bus.
4. Minimize voltage flicker or voltage fluctuations in electric arc furnace installations.

The application of these systems for arc furnace control has resulted in higher productivity and significant savings in the cost of electric power.

The principal components of the static reactive compensator equipment consist of the following (as illustrated in Figure C.5.1-1).

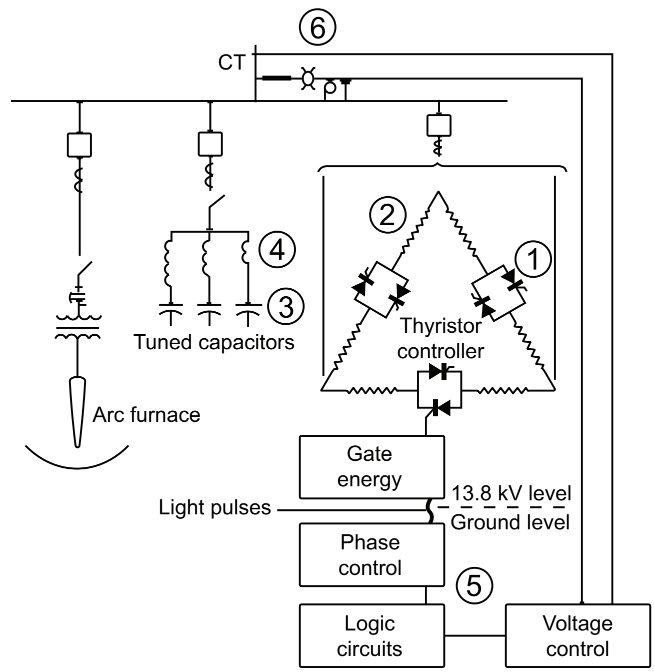

Fig. C.5.1-1. Var control power circuit and block diagram for arc furnace application (Courtesy of General Electric Co.)

1. A thyristor controller.
2. Dry type, linear-air-core shunt reactors.
3. Capacitor banks.
4. Filter reactors, when necessary for reducing system harmonic current.
5. Control equipment, for processing system information received from the sensors.
6. Equipment for controlling leading or lagging vars, as required to provide the desired system performance.

These systems have a very high speed of response; the reactive compensation can be changed in 0.5 to 2 cycles of the power frequency. Depending upon the type of static var system and how they are connected into the system, they can provide reactive compensation or control voltage differently in each phase. They are ideally suited to compensate for the lagging current of an arc furnace and to minimize voltage flicker.

Figure C.5.1-2 shows a typical layout of the equipment used in a static reactive compensator system; Figure C.5.1-3 shows the arrangement when var support for an arc furnace installation is supplied through a 75 MVA, 220 kV-56 kV transformer with a delta tertiary rated at 50 MVA and 14 kV. In the installation of Figure C.5.1-3, the control scheme is one of power factor control with sensors installed at the 220 kV primary so that the power factor is controlled to unity at this point in the system. Thus, the 220 kV bus is not required to furnish vars to the furnace load.

Figure C.5.1-4 shows an actual installation of the capacitors, reactors and filters used with this system.

Electric arc furnace loads are generally unbalanced with poor lagging power factor. They are subject to large, erratic, reactive current swings which cause corresponding voltage drops across the reactive impedance of the ac system. These drops or this voltage variation cause fluctuation of the terminal voltage at the ‘‘critical bus’’ common to the arc furnace load and other customers of the utility. The utility companies are concerned with this voltage variation because of flickering of the light output of incandescent lamps and the effect on voltage sensitive equipment. To reduce the flicker, some utilities may require that the arc furnace load be complemented with a system that will supply a controlled reactive kVA.

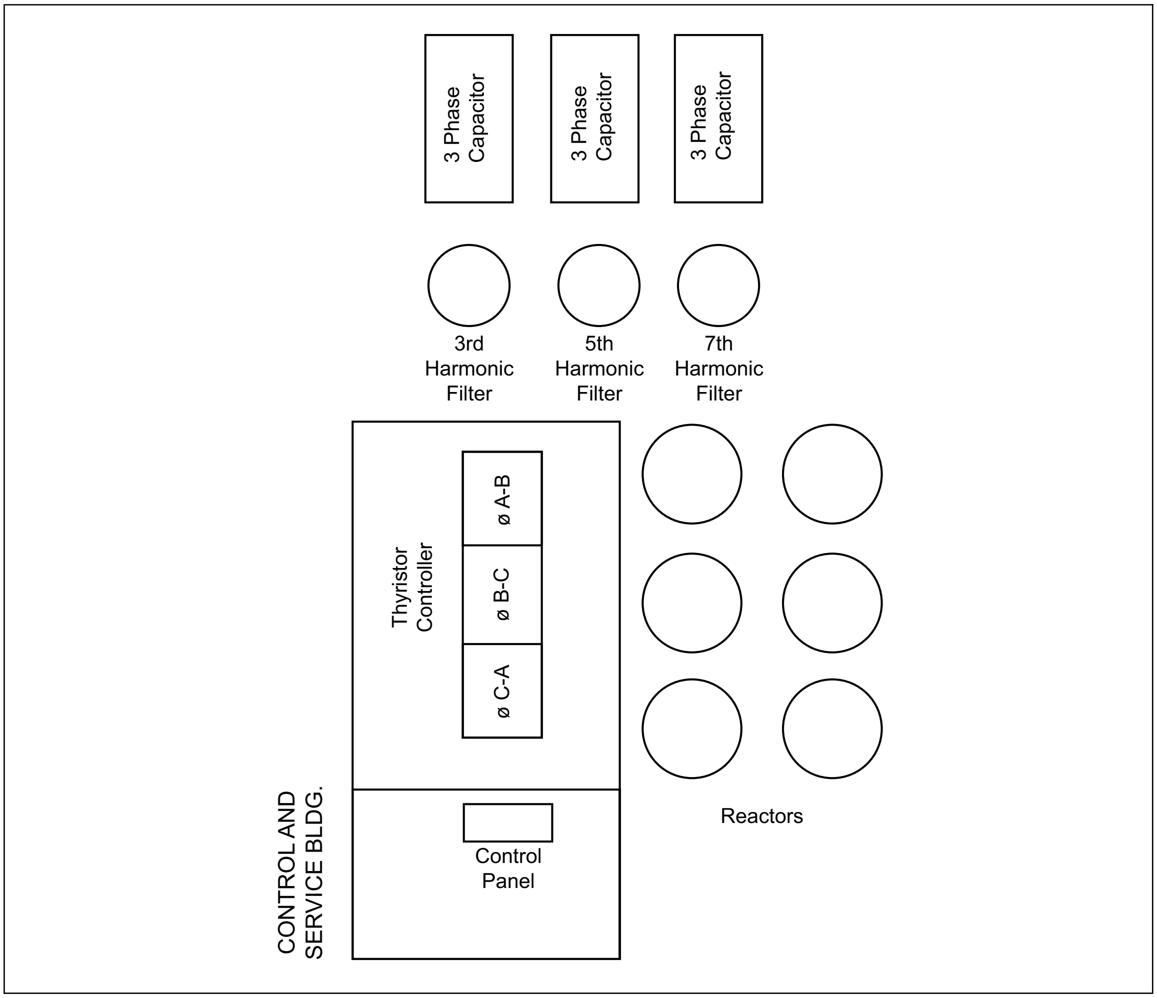

Fig. C.5.1-2. Typical layout of a 25 MVA static reactive compensator system.

Traditionally, a rotating synchronous condenser and fixed or switched capacitor banks have been employed to improve the power factor of arc furnace installations. However, fixed or switched capacitor banks are ineffective for flicker reduction. Although synchronous condensers have been used for voltage dip reductions to some extent, their high initial capital costs, slow response time and frequent maintenance have interfered with their more extensive use.

C.5.2 Protection

Electrical protection for a static reactive compensator system such as that shown in Figure C.5.1-3 would typically include differential relaying on the 220 kV and 14 kV buses with overcurrent backup protection. The capacitor banks employ neutral current unbalance detection to protect against capacitor unit over voltages that could be caused by the failure of individual capacitor elements. Capacitor fault protection is provided by fusing as described in Section C.4 and by inverse time overcurrent relays. Ground fault protection is also included.

Fault currents associated with the power reactors and thyristor controller are detected by inverse time overcurrent relays. If the thyristor controller is unable to turn itself off and clear the fault, upstream circuit breakers are tripped. Overload protection for the thyristor controller includes continuous monitoring of the coolant temperature and the use of thermal overload relays which monitor the thyristor junction temperature.

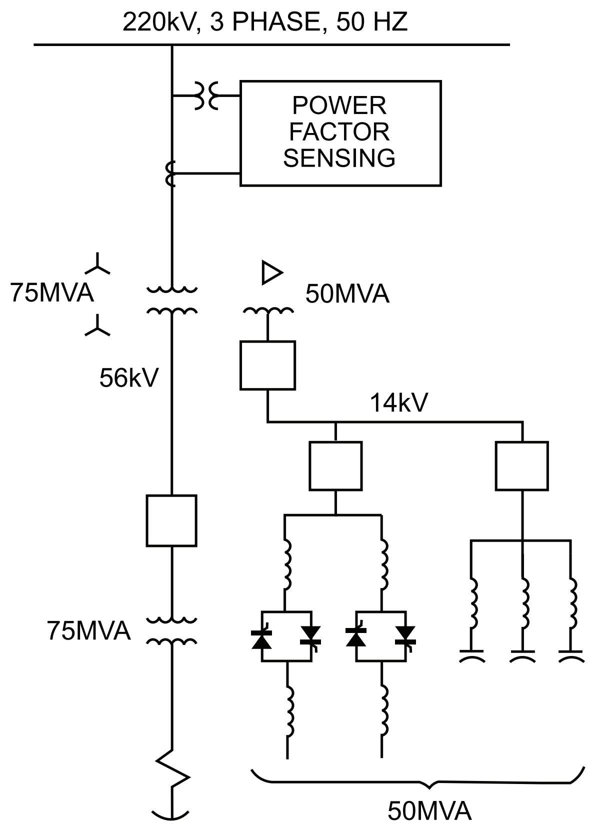

Fig. C.5.1-3. Arc furnace application (Courtesy of General Electric Co.)

Fig. C.5.1-4. Capacitors, reactors and filters for a static reactive compensator system

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