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CAPACITOR BANK CHARGING SYSTEM*

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Power Supply Requirements

In order to charge a large dc capacitor bank rapidly and safely from an ac power supply, certain power supply characteristics are desirable.

Some of the less obvious ones with associated explanations follow:

1. The power supply should not be damaged by shorted output leads. With large capacitor banks containing hundreds of condensers, a shorted capacitor or capacitor bank prefire is not uncommon.
2. The power supply should be capable of rapidly charging the bank with the capacitors being at the 90 - 100% voltage range for a minimum of time. (The life of a capacitor is inversely proportional to the voltage and time it is applied - $\text{Cap life} = K \frac{1}{VT}$).
3. The power supply and regulating system should be quite efficient to reduce cooling problems as well as energy costs.
4. The power supply should be able to handle a high forward voltage drop. Due to the inductive nature of the capacitor bank load, ringing and reverse voltage on the bank is common.

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5. The power supply should be able to run for long periods with a pulse repetition frequency of 2 times a minute. If the characteristics of the power supply are such that it must be turned off for each pulse, the contactor must be good. This is particularly true since turn-off occurs at maximum voltage on the capacitor bank and presumably maximum power of the power supply.
6. The power supply should not create electrical interference during any part of its cycle. Electrical measurements on the experiments operated by the capacitor bank are difficult enough without adding electrical noise from other sources.
7. The power supply should be simple to operate and have few moving parts. This reduces human error and component failure.
8. The power supply should have variable voltage and current capabilities. The nature of the load will determine precise requirements.

Power Supply Components

1. Rectifier: The rectifier should probably be a tungsten filament-type diode. These tubes have high voltage capabilities, long life, and are not greatly damaged by overvoltage. Emission-limited operation is permissible if x rays are not a problem. Thoriated tungsten-type filaments are best but may be damaged by overvoltage. Solid-state rectifiers and mercury vapor rectifiers are all subject to damage due to overvoltage when the capacitor bank rings (reverses polarity) and they may need carefully constructed series strings of

rectifiers, resistors, and capacitors to get the voltage and pulse characteristics required. The overvoltage problem due to ringing can be reduced by series inductance and resistance with a shunt capacitor.

2. Voltage Supply: The voltage supply will be line voltage (120, 208, 240 or 460). Since large capacitor banks are being considered, a three-phase, 208-V, or three-phase, 460-V supply is required. The number of parts required for any voltage-multiplying scheme to replace a three-phase transformer is large and will not match the transformer's reliability. Therefore, a three-phase, liquid-filled (inflammable or noninflammable per local conditions) transformer will be used. Dry-type transformers may be used below 15 kV.
3. Current-Voltage Control: There are many methods of controlling the output of a rectifier. Some of them will be listed below with feasibility comments:
 - a) Controlled firing ignitrons, thyratrons, or silicone control rectifiers on the line side of the rectifier-transformer with electronic control signals from the dc load (capacitor bank) circuit. This system would give excellent control but the complexity of control, the electrical noise produced by the system, and the instantaneous short circuit current rule it out.
 - b) Reactance - capacitance charging system where the charging current is limited by reactance in the primary circuit of the rectifier-transformer or resistance in the dc charging circuit (Fig. 1). With linear resistance or reactance elements, this

system pulls a heavy charging current at the beginning of charge requiring oversized rectifiers but charges slowly at the end of charge holding the capacitors at high voltage for longer periods than desired. By using nonlinear impedances, some of these difficulties can be overcome. They will be considered later.

- c) Constant $\frac{dV}{dt}$: By means of a three-phase variable voltage transformer (Inductrol, Powerstat, Variac, etc.), the input voltage to the rectifier-transformer can be increased with the capacitor bank voltage (Fig. 2). This gives a high efficiency and quick final charge time but guarantees high fault currents in the case of capacitor bank malfunction. This circuit will not be considered further.
- d) Monocyclic Circuit: This is a constant-current circuit wherein any attempt to decrease the load current is automatically countered with an increase in load voltage (Fig. 3). Essentially, the load detunes one element of a series-tuned circuit. This circuit gives a fast charge at the end of the charging cycle and can handle shorted outputs with no problem. A variable voltage transformer must precede the monocyclic network and rectifier-transformer if variable charging current is desired. The disadvantages of this circuit are:
1. The large size of the components.
 2. The extremely high voltage developed if the power supply

load is open-circuited or the rectifier filaments are cold.

3. The need for a line contactor to open the circuit primary at the end of charge (maximum power).

e) Saturable Reactor Control: This is a reactance-capacitance charging system which is easily programmed from an essentially "off" mode to full current at any particular voltage desired. It is essentially an "on-off" control and a current control. The drawback of this circuit is the fault current which can be drawn for a few cycles (even with current feedback control) when maximum charging current and high voltages are required (end of the capacitor bank charging cycle). The saturating reactor is at minimum reactance and cannot change its reactance in less than a few cycles if trouble occurs on the capacitor bank circuit. By modifying the saturating control circuit, the saturable reactor can also hold a pre-set current in the load from zero load resistance to a load resistance corresponding to about 80% of the supply voltage.

Choice of Control

Of the types of control outlined, the saturable reactor control has been chosen for recent capacitor charging circuits. It meets the following requirements:

1. It is not damaged by open or short circuits.
2. It provides rapid charging without oversized components.
3. It is efficient with no moving parts or excessive heat.
4. It has on-off control (except for maintenance purposes) by turning

the saturating current on or off.

5. It produces no transients on power line due to turn-off.
6. It has variable current and voltage capability.

Saturable Reactor Control

Figure 4 shows a schematic diagram of a saturable reactor control and power supply used on a small capacitor testing bank.

This unit controls a 12.5-kW load with less than 100 watts of dc power. A contact in the powerstat circuit turns the saturating reactor on and off; the magnitude of the saturating current, (and thus the bank charging current) is manually set by adjusting the powerstat.

Figure 4(a) shows the actual performance of the charging system. The drop-off as the voltage approaches the rated supply voltage is largely due to the decrease in available voltage drop across the rectifiers as the sum of the capacitor bank and charge resistor voltages approaches the peak of the ac supply voltage.

In this system the drop-off of current is permissible so no correction was attempted. Raising the supply voltage or power supply transformer turns ratio would maintain the flat current characteristics up to the desired voltage.

Theory of Operation

Figure 5 shows a simplified single-phase saturable reactor control system diagram. The output voltage can never exceed the supply voltage and the system, as shown, requires about 5 seconds to turn on or off. The contact R_1 is used as a safety device, on-off control is accomplished by turning the saturating supply on and off with Switch S_1 . Capacitor C_1 determines the ac impedance of

the control circuit and through the reactor turns ratio the saturated impedance. It also bypasses induced ac currents around the saturating current source.

Figure 6 shows the equivalent circuit of the control system in the unsaturated condition where L_m is the magnetizing inductance of the rectifier-transformer and S_R is the unsaturated reactance of the saturable reactor. Generally, the reactance of S_R and L_m are about equal and the voltage on the capacitor bank C^1 will gradually build up to half voltage unless switch S_2 is closed to short the bank. However, the current into the system in this condition is never more than the magnetizing current of the saturable reactor (about 5% of the full load current). This can be greatly reduced by parallel resonating S_R with a small capacitor.

Throwing switch S_1 (Fig. 5) applies dc to the saturating winding of the saturable reactor. With ac applied to the system by closing R, the dc saturating current and the ac magnetizing current aid each other and saturate one of the reactor cores each half cycle. The time at saturation or the firing angle for each half cycle is determined by the dc saturating current.

After one core saturates, the other core and control winding act as a transformer. Figure 7 shows the equivalent circuit during saturation with the control circuit impedance Z_1 modified by the reactor turns ratio and placed in series with the capacitor bank charging rectifiers.

There are two distinct modes of operation plus a transition during each half cycle of capacitor bank charging current, 1) the unsaturated mode as the ac and the dc magnetizing currents build up the core flux to the saturation value in one core (Fig. 6), and 2) the saturated mode where the current is limited by the series equivalent impedance of the saturating circuit and the voltage on the capacitor bank C^1 (Fig. 7).

The transition between the two modes as the iron core saturates can be long or short timewise in relation to a half cycle of the system frequency, depending upon the type of iron in the core. It is this indeterminant which eliminates accurate calculations.

Due to the fact that a pulse arrives every half cycle in the saturating circuit during charging, and the saturating windings of the reactor buck the fundamental power frequency, only second and higher harmonics are induced into the dc saturating current circuit from the load circuit. By allowing only filtered dc to flow in the saturating winding, a square wave of charging current will flow in the capacitor bank rectifier system. Adding capacitor C_1 (Fig. 5) allows a larger load current to flow for a given saturating current.

In all cases, except for the magnetizing current, the current in the load circuit will be mirrored in the saturating circuit modified only by the turns ratio. This is invalidated when both cores are saturated and the transformer action between load and saturating circuit is eliminated.

The analogy for a three-phase saturable reactor control system is similar except that two reactors are saturated during saturation mode (Fig. 7), the other reactor of the three-phase system (Fig. 4) acts as a transformer reflecting the saturating circuit impedance into the rectifier circuit.

The above has been a simplified treatment of saturable reactor control systems. A more complete explanation can be found in Magnetic Amplifiers by Storm.

Design Criteria

Since this system is to be competitive with other control systems,

commercial reactors (or transformers) must be purchased. The reactors should operate with only one leg saturated at a time which is at about 80% the commercial kVA rating. Consequently, one must order an "off-the-shelf" reactor of about 125% the kVA rating of the load at the line to neutral voltage. Due to the long response time of parallel-connected load coils, series-connected load coils must be specified. A single three-phase reactor is quite acceptable and presents fewer ac voltage problems to the saturating supply than three equivalent single-phase units.

Engineering refinements increase the cost of the unit and should be avoided unless space and weight are a problem. The saturating current and voltage, as well as the turns ratio, are set by the manufacturer.

REACTANCE - CAPACITANCE CHARGE SYSTEM

Z OR R MUST LIMIT THE SHORT CIRCUIT CHARGING CURRENT TO RECTIFIER RATING I

$$Z = \frac{FE}{I/A} = \frac{EAF}{I}$$

$$R = \frac{EF}{IA}$$

F = FORM FACTOR
DC TO AC AMPERES

FIG. 1

K=DV/DT CHARGE SYSTEM

$$I = \frac{dQ}{dt}$$

F = FORM FACTOR

$$V = \frac{Q}{C}$$

$$Q = CV$$

$$\frac{dQ}{dt} = C \frac{dV}{dt}$$

$$I = C \frac{dV}{dt} \quad \text{if } \frac{dV}{dT} = K$$

$$\therefore I = CK \quad \text{A CONSTANT}$$

WITH 30 SEC
RISE TIME

$$Q = IT = CV$$

$$I = \frac{CV}{30}$$

C = CAPACITY $\mu\text{fd.}$

V = CAPACITOR VOLTAGE

F = FORM FACTOR

FIG. 2

MONOCYCLIC NETWORK CHARGING

$$i_1 = \frac{E_1}{X_L + \frac{X_C Z_L}{X_C + Z_L}}$$

$$X_L = -X_C$$

$$i_2 = i_1 \frac{X_C}{Z_L X_C} = E_1 \frac{X_C}{X_L X_C + X_L Z_L + X_C Z_L}$$

$$i_2 = E_1 \frac{X_C}{X_L X_C + (-X_C) Z_L + X_C Z_L} = \frac{E_1}{X_L - Z_L + Z_L} = \frac{E_1}{X_L}$$

i_2 IS DEPENDENT UPON SUPPLY VOLTAGE AND X_L ONLY

THE VOLTAGE TO THE TRANSFORMER RECTIFIER IS LIMITED ONLY BY THE LINEARITY OF X_L OR INSULATION BREAKDOWN OF COMPONENTS

FIG. 3

208/120
3 ϕ 60~

FIG. 4

Fig. 4(a). Performance Curves of Saturable Reactor Control

UNSATURATED EQUIVALENT CIRCUIT
CONTACT R_1 AND SWITCH S_1 NOT SHOWN

A
SATURATED EQUIVALENT CIRCUIT

B
SATURATED EQUIVALENT CIRCUIT WITH
NEGLECTIBLE QUANTITIES ELIMINATED

FIG. 7

Z CONTROLS THE CHARGING CURRENT UNTIL THE CAPACITOR VOLTAGE V APPROACHES ABOUT 80% OF THE SUPPLY VOLTAGE