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TRADEOFFS IN CAPACITOR BANK DESIGN

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Summary

When designing a capacitor bank for energy storage,
the engineer should not use more capacitors, voltage,
or energy than necessary to supply the load and to
overcome losses. Universal curves presented in this
paper aid the designer in making intelligent choices.
For example, there is a minimum stored energy to be
achieved, but no minimum voltage at which to store it.
Included in the curves are the effects of series losses
such as voltage drops in regulator tubes or in current-
limiting resistors. Capacitor bank designs for the
neutral-beam power supplies on 2XIIB and TMX are com-
pared using the developed criteria.

Introduction

The formulas for the design of a capacitor bank
are well known and the procedures well established.
However, the process of balancing costs is not quite so
straightforward. Although there is no single most
economic design, it is possible to define a good
design. This paper attempts to provide those
guidelines.

Analysis

A general diagram of a capacitor bank connected to
a load by some series element is shown in Fig. 1(a).
Assume that the series element regulates the load volt-
age and current to some value V_L and I_L for a period
of T seconds and that the initial voltage on the bank
V_{CO} decays away to some value V_{CT} at the end of the
pulse duration T. These relationships are shown in
Fig. 1(b).

Three ratios can now be defined that are indica-
tors of how economically a bank has been designed. The
first ratio is

$$E_r = \frac{\text{energy stored in the bank}}{\text{energy used by the load}} .$$

This ratio can be calculated using the relationship for
energy stored in a capacitor ($\frac{1}{2} CV^2$) and the energy
used in the load (IVT):

$$E_r = \frac{\frac{1}{2} C(V_{CO})^2}{V_L I_L T} .$$

The second ratio,

$$V_r = \frac{\text{bank voltage}}{\text{load voltage}} ,$$

can be calculated as

$$V_r = \frac{V_{CO}}{V_L} .$$

The third ratio,

$$C_r = \frac{\text{bank capacitance}}{\text{minimum capacitance needed}} ,$$

is hard to visualize, but it is calculated as the
ratio of the actual bank capacitance to an arbitrary
reference capacitance. The reference capacitance is
found by equating the load energy $V_L I_L T$ to the energy
stored in a capacitor at V_L and solving for C_{ref}

$$\frac{1}{2} C_{ref} V_L^2 = V_L I_L T ,$$

$$C_{ref} = \frac{2 I_L T}{V_L} ,$$

$$C_r = \frac{C V_L}{2 I_L T} .$$

A discussion of these ratios will be delayed until two
equations are derived relating voltage V_r and energy E_r
to C_r, the capacitance ratio.

Referring again to the waveforms of Fig. 1, we see
that

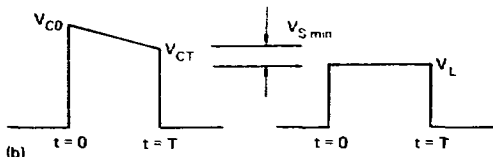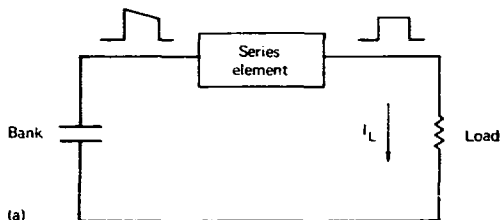$$V_{CT} - V_L = V_{ST} = V_{S\,min} .$$

(a)

(b)

Fig. 1. The equations for the curves are derived from
this generalized circuit diagram (a) and from the
wave forms representing the bank decay and the load
voltage (b).

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V_{ST} is given a special symbol because it represents the minimum voltage drop necessary across the series element. Now the voltage drop across the capacitor bank is related to the charge stored by

$$V_{CO} - V_{CT} = \frac{Q}{C} \ .$$

In this circuit, $Q = I_L T$; therefore,

$$V_{CO} - V_{CT} = \frac{I_L T}{C} \ . \qquad (1)$$

From Fig. 1(b), the voltage on the bank is also seen to be

$$V_{CO} = V_L + V_{S\ min} + (V_{CO} - V_{CT}) \ . \qquad (2)$$

Substituting Eq. (1) into Eq. (2) gives

$$V_{CO} = V_L + V_{S\ min} + \frac{I_L T}{C} \ . \qquad (3)$$

Returning to the definitions of C_r and E_r,

$$C_r = \frac{CV_L}{2I_L T} \ ,$$

$$E_r = \frac{\frac{1}{2} C (V_{CO})^2}{V_L I_L T} \ ,$$

we can express E_r in terms of C_r as

$$E_r = C_r \frac{(V_{CO})^2}{V_L} \ .$$

Now, the expression for V_{CO} found in Eq. (3) can be substituted into this relation, and one of the equations sought appears:

$$E_r = \left[\sqrt{C_r}(1 + \rho) + \frac{1}{2\sqrt{C_r}} \right]^2 \ , \qquad (4)$$

where the ratio of the minimum voltage drop in the series element to the load voltage drop is given the symbol ρ; i.e.,
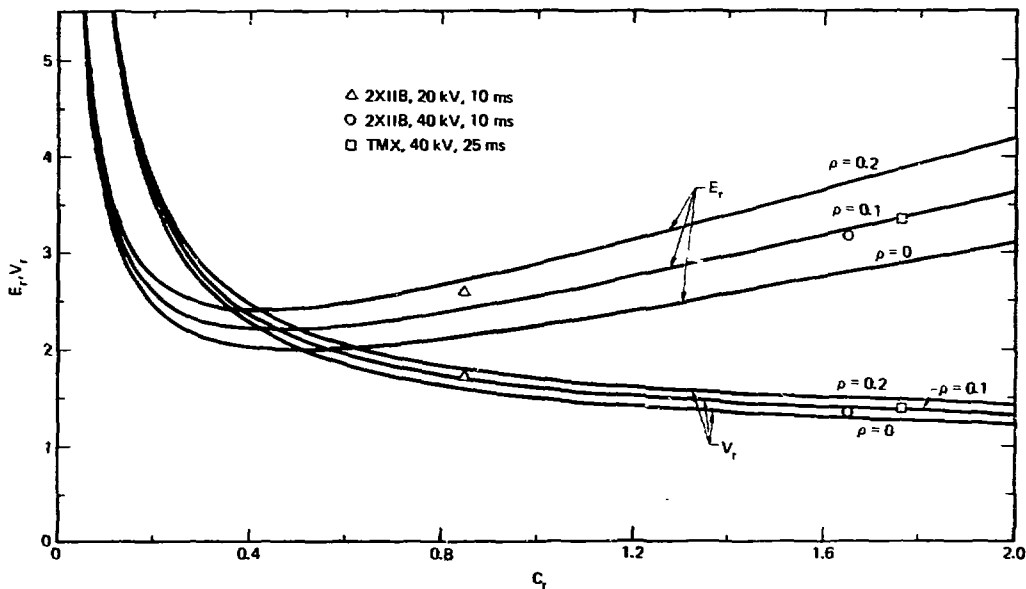

Fig. 2. These curves can be used to evaluate the design of a capacitor bank.

$$E_r = \frac{\text{energy stored in bank}}{\text{energy used by load}}$$

$$V_r = \frac{\text{bank voltage}}{\text{load voltage}}$$

$$C_r = \frac{\text{bank capacitance}}{\text{minimum capacitance needed}}$$

$$\rho = \frac{\text{minimum voltage drop in the series element}}{\text{load voltage}}$$

Capacitor bank designs for the neutral-beam power supplies on 2XIIB and TMX are plotted.

$$o = \frac{V_{S\ min}}{V_L} .$$

Equation (4) is plotted in Fig. 2 with o as a parameter.

The second equation for the graphs in Fig. 2 is obtained from the definition of V_r:

$$V_r = \frac{V_{CO}}{V_L} ,$$

$$V_r = (1 + \rho) + \frac{1}{2C_r} . \tag{5}$$

Evaluating the Design

Using the curves in Fig. 2, we can evaluate the relative cost of a capacitor bank design. For example, a minimum energy can be stored, but there is no minimum voltage at which to store it. If one chooses to build a bank with $C_r = 0.5$, he will store minimum energy but will pay for it by using 2.5 times the voltage required by the load. For example, if 40 kV is needed at the load, one must charge the bank to 100 kV.

Since it costs money to isolate high voltage, a good design will keep V_r as small as possible. E_r should also be as small as possible in order to store no more energy than is needed. The larger E_r is, the greater is the energy wasted. The further to the right on the curves a design falls, the more must be paid for the capacitors to go into the bank. In other words, the greater C_r is, the higher the cost because one chooses to charge at low voltage. Finally, since one would like no voltage drop in the series element, the curves for $o = 0$ are the best one can do.

On the Tandem Mirror Experiment (TMX) and 2XIIB, the series element is a tetrode (4CW100000E) that does not regulate when the voltage drop across it is less than 3 kV. This means that for a 20-kV load, $o = 0.15$ or that the series element drop is 15% of the load voltage. The tetrode is a better choice for 40-kV loads because the losses in it are only 7.5% of the load voltage.

Also shown on Fig. 2 are some design points for 2XIIB 20-kV and 40-kV operation as well as for TMX 40-kV operation. The bank design for 20-kV operation was a good one, but the 40-kV designs were not as good, as shown by their position too far to the right on the curves. *The 40-kV 2XIIB and TMX designs were redesigns of the 20-kV 2XIIB bank and not new designs.*

Conclusion

The design of an energy-storage capacitor bank is not straightforward because there is no one best design. Because capacitors are expensive and occupy valuable room, the engineer wants to keep the total capacitance small. However, to do so he must store at higher voltages than he would if he made the capacitance large. He must then pay for isolating this voltage. A small capacitance also means he must store much more energy than he actually uses, and energy is expensive too.

Acknowledgments