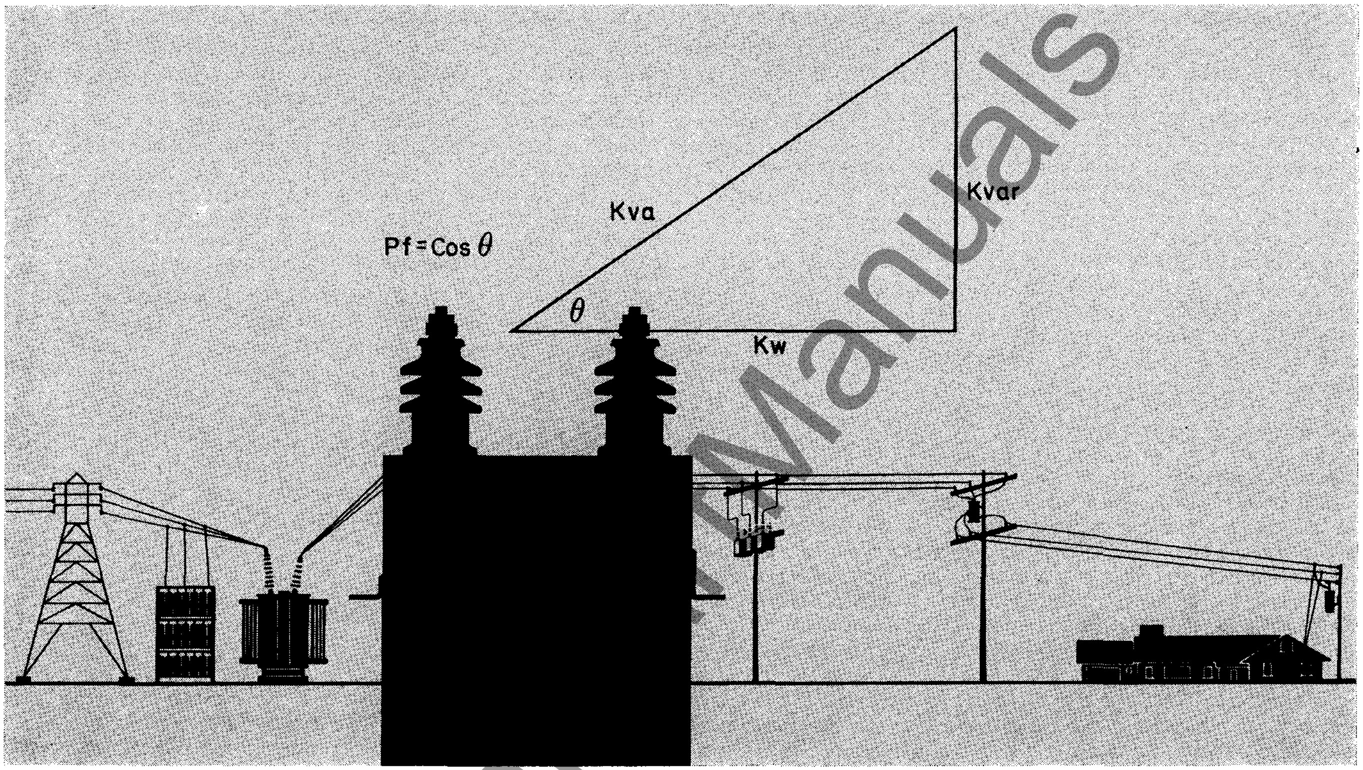
Westinghouse

Shunt Capacitors

Application to Electric Utility Systems



In This Application Data

General Application Information

The capacitor, when connected in shunt on the electric utility system, is a static source of reactive current. It is used to supplement the system generators, which cannot practically or economically supply the overall reactive load.

Theoretically, all load, both real and reactive could be carried by the system generation. However, the high voltage required to maintain adequate VAR flow, increased losses, and increased capacity required, would create an intolerable situation both from an operating and economic standpoint. Therefore, the shunt capacitor has proven itself to be an invaluable item of equipment to the electric utility – providing a source of reactive current which can be installed close to the load. This allows full appreciation of the reduced current in the system up to the point of application, resulting in increased voltage level at the load, and decreased line losses because transportation of a large percentage of the system's reactive load is eliminated.

The effect of a shunt capacitor on a simple radial system is shown in fig. 1.

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General Application Information, Continued

Shunt Capacitor Vs Synchronous Condenser

The same general effect could be obtained from a synchronous condenser at the load bus. However, the economic size of synchronous machines prohibits their use close to reactive loads unless the load is large and highly concentrated. A comparison between the shunt capacitor and the synchronous condenser is shown in table 1. The use of synchronous condensers has decreased markedly in recent years largely because of costs/kvar obtained from rotating sources has been increasing and the cost/kvar using capacitors has been decreasing. Other important advantages of the shunt capacitor are shown in table 1.

System Location

The optimum location of a capacitor bank on the power system can only be determined from a complete, thorough analysis of the power system, both from an operating and economic viewpoint. The majority of utility planners do not, however, seek the optimum in power capacitor application. Initially, a utility in need of reactive compensation will install fixed or switched capacitor banks on distribution feeders. The capacitor banks range in size from 150 to 1800 KVAR and are pole mounted in prewired frames. A typical installation is shown in fig. 2. Where capacitor banks of this type are required, but it is undesirable to locate them on top of a pole, similar equipments can be pad mounted in metal enclosures as shown in figure 3.

Where load from a distribution substation is sufficiently concentrated, such as a business area or where industrial loads emanate directly from the substation, a switched bank can be installed on the substation bus. These are either open racks or enclosed banks as shown in fig. 4 and usually range in size from 600 to 10800 KVAR.

Three-fourths of the typical power system's reactive load comes from customer's magnetizing requirements. Maximum benefit from capacitor application will be obtained when the reactive source is located as close as possible to the reactive load. This does not mean categorically that all capacitors should be located on the distribution feeders. The power system itself, in its generation, transformation, transmission, and distribution equipment, creates a large reactive load. In particular, the transmission system, operating fully loaded and at power factors well below unity, can in many cases use reactive compensation directly at transmission voltage to: (1) correct for its own VAR load, and (2) compensate for accumulated VAR load on distribution circuits.

The installation of distribution system capacitors, both feeder and bus type, is usually the first step in raising the power factor of a power system to unity. Once saturation is reached at this level, determined by light load voltage level and economics, the installation of capacitors to supply reactive current is carried back to the subtransmission and transmission voltage level. The installation of large high voltage banks of capacitors such as shown in fig. **5** have become quite common, although the engineering time and precautions which accompany an application of this type are more involved than that required on lower voltage banks.

Due to the higher cost/kvar of capacitors in the secondary voltage class, power factor correction by utilities at the load itself has been a relatively small part of the total installed capacitors. Economic studies have indicated, however, that there are some

Table 1 – Comparison of Shunt Capacitor with Synchronous Condenser

Application Factors	Synchronous Condenser	Shunt Capacitor
Voltage ratings	Requires transformer above 18 KV	Directly applicable to any voltage class
KVA ratings	Minimum economic size, 15000 KVAR	Available in units, 50 KVAR and up
Control	Stepless control inherent – fully adjustable	Usually switched in large discrete steps
Output VARS	Varies inversely with terminal voltage	Varies directly as square of terminal volts
Effect on voltage regulation	Instantaneous voltage regulation	Switched units provide delayed regulation in steps
Supply of lagging VARS	Inherent supply up to 50% of rating	No supply
Installation	Complicated and expensive installation – location sometimes prohibits use	Very simple and versatile – no location problem
Maintenance	Expensive procedure as with any rotating machinery	No maintenance
Protection against internal fault	Standard relaying dependent on size of machine	Individual fuses and unbalance protection dependent on size
Protection against external fault	Breakers and relays normally associated with synchronous equipment	None required
Function during system emergency –need for additional KVAR	Additional KVAR obtained for short time by raising excitation	KVAR output varies as square of system voltage – usually of no value under emergency
Correction of light flicker	Cost usually too high to justify small unit, but can be used for correction of large loads	Cannot be switched fast enough to be effective
Correction of power factor	Installation too costly to justify for this use alone	Low cost installation makes this practical
Aid to system stability	Automatically aids system during swings by supplying VARS	Output varies as square of terminal voltage

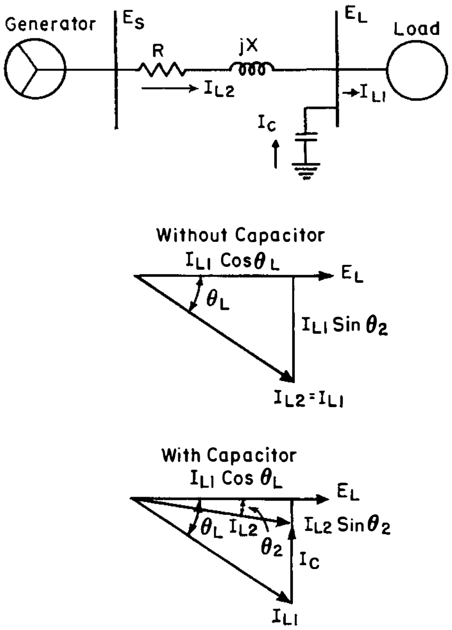

Figure 1. Fundamental vector diagrams showing effect of shunt capacitors.

locations where load characteristics and released transformer capacity will justify the use of secondary units. These are usually single phase capacitors pole mounted at the service drop.

A different secondary capacitor has been used for some time in low voltage network systems, where the special requirements of underground sealed entrances, and submersion preclude the use of standard units.

In addition, the high load densities encountered in secondary networks usually dictate the use of banks directly at the network transformer vault for maximum economic benefit.

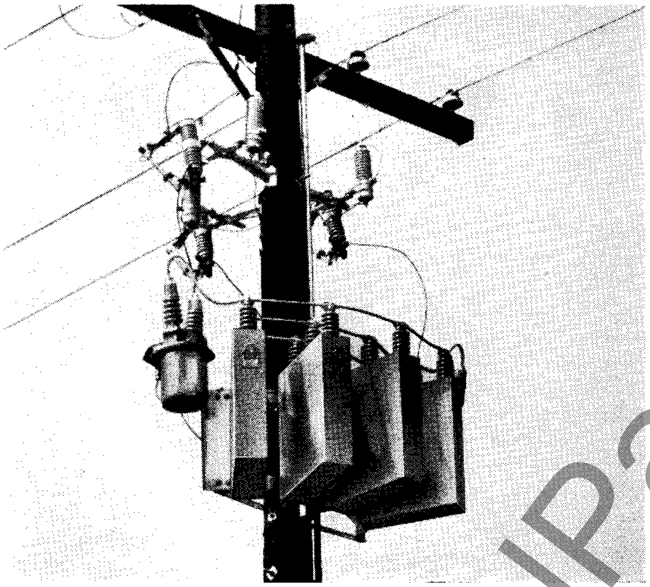

Figure 2. 1200 KVAR 3 phase 7200/12470 volt switched TRI-VAC® capacitor equipment.

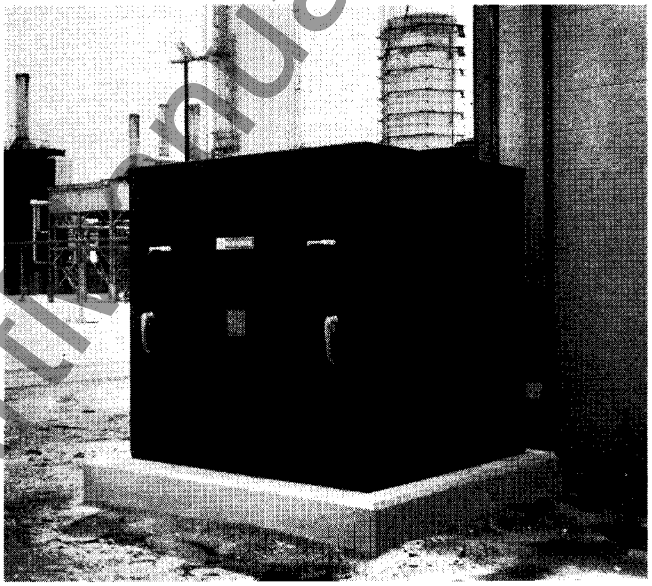

Figure 3. 600 KVAR, pad mounted metal enclosed capacitor bank.

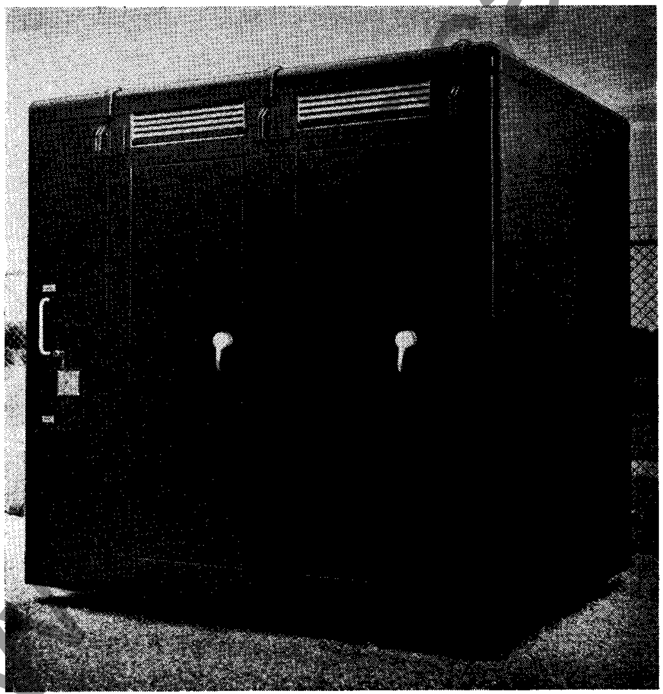

Figure 4. Enclosed substation capacitor bank of 2400 KVAR

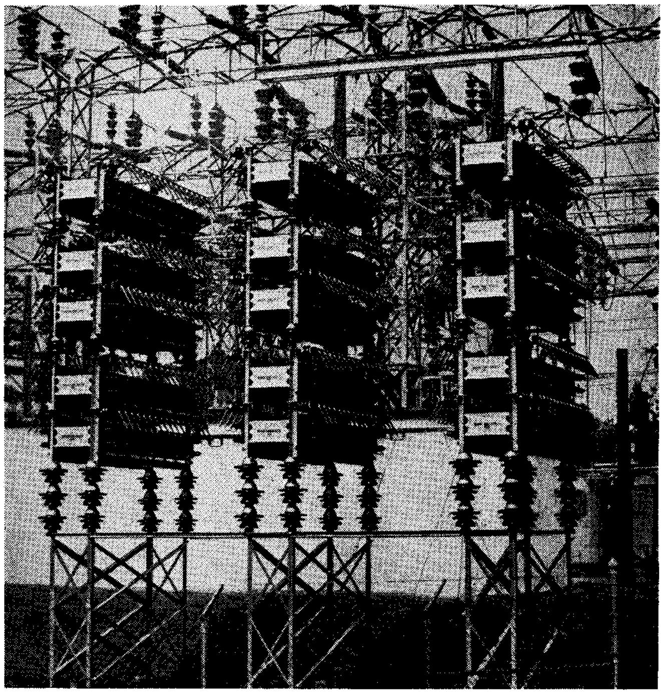

Figure 5. 2400 KVAR, 3 phase, 60 Hertz, 115 Kv edge mounted stack type capacitor bank including elevating substructures.

Fundamental Effects of Shunt Capacitors

As pointed out in previous paragraphs, the shunt capacitor is a static source of reactive current. Fig. 1 shows how it reduces the reactive current required from the generating source, by supplying a reactive current proportional to the capacitor size to the power system load. All the benefits obtained from shunt capacitor installation are derived from this basic fact. Because the power system planner must evaluate all the effects of shunt capacitors in order to determine whether capacitors are economically feasible, and where on the system they should be located, complete understanding of this basic principle is necessary.

Reduction of Line Current

The reactive current from the source circuits is reduced in direct proportion to the capacitor current, however, the total line current is reduced a considerably smaller amount since it has two components, one of which remains fixed. Inspection of fig. 1 verifies this on the assumption that the load remains the same after capacitor installation.

The expression for current I_{L2} in fig. 1 is:

$$I_{L2} = I_{L1}\cos\theta_L - jI_{L1}\sin\theta_L + jI_C \quad (1)$$

where I_{L1} = line current without capacitors

I_{L2} = line current with capacitors

$\cos\theta_L$ = initial power factor

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Example A:

What is the reduction in total current and reactive current respectively on a 4160 V circuit with 1000 KVA of load at 80% power factor when 500 KVAR of capacitors is added?

$$I_{L1} = \frac{1000}{\sqrt{3}\ (4.16)}\underline{/36.8^\circ} = 139\ \underline{/36.8^\circ} =$$

111 −j84 amps

$$I_C = \frac{500}{\sqrt{3}\ (4.16)}\underline{/90^\circ} = +j70 \text{ amps}$$

$I_{L2} = 111 - j84 + j70 = 112$ amps

Thus, the reduction in reactive current from the source is 70/84 × 100 or 83% while the total current is reduced 27/139 × 100 or 19.3%.

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While the reduction in total current is important when considering released capacity, it is also true that in many cases the greatest part of the system voltage drop is caused by reactive current. The components of voltage drop in any circuit can be expressed as follows:

$$\%\ E_R = \frac{\text{KVA} \times R \cos\theta_L}{10 \times (\text{KV})^2} \quad (2)$$

$$\text{and } \%\ E_X = \frac{\text{KVA} \times X \sin\theta_L}{10 \times (\text{KV})^2} \quad (3)$$

where R = resistance of source circuits

X = reactance of source circuits

From inspection of equations 2 and 3, it can be seen that the reactive portion of the voltage drop is greater than the resistive drop whenever

$X \sin\theta_L > R \cos\theta_L$

Since for typical power systems, X ranges from 2 to 15 times R, it is evident that at most operating power factors below 90%, with normal conductor sizes, the reactive drop will exceed the resistive drop.

Practically, this means that the reduction in the lagging component of current, as accomplished by shunt capacitors, will compensate for a large percentage of the voltage drop, thereby improving system voltage levels, and extending voltage regulator range.

A per unit expression for the line current after adding capacitors can be obtained from equation 1 by dividing by I_{L1}.

$$\text{then } \frac{I_{L2}}{I_{L1}} = \cos\theta_L - j\ (\sin\theta_L - \text{ckva}) \quad (4)$$

$$\text{where ckva} = \frac{I_C}{I_{L1}} = \frac{\text{KVAR}}{\text{KVA}}$$

If no additional load is added after the capacitors are installed, the per unit reduction in total line current can be obtained by subtracting equation 4 from unity.

$$\text{then p. u. } |\ I_L\ | = 1 - \sqrt{\cos\theta_L{}^2 + (\sin\theta_L - \text{ckva})^2} \quad (5)$$

This relationship is plotted in fig. 6 as a function of capacitor bank size and original load power factor.

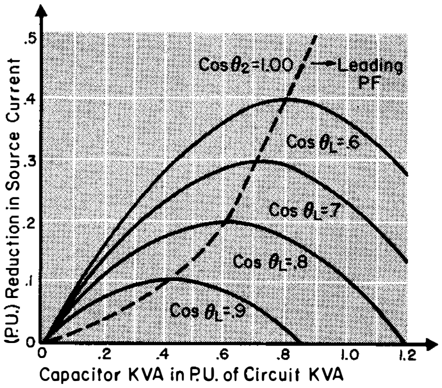

Figure 6. Reduction of line current as an effect of shunt capacitors.

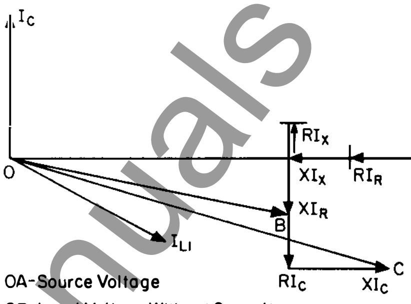

Figure 7. Components of system voltage drop.

All benefits from shunt capacitor installation are a direct function of the reduction in lagging current, however, the effects on power system operation may vary, depending on how they are considered. The following paragraphs discuss briefly each of these contingent benefits and how they affect operation and economics.

Increased Voltage Level at the Load

For the simple radial system shown in fig. 1, the complete expression for voltage drop at the load would be

$$E_L = E_S - I_{L1}\ Z \quad (6)$$

$$E_L = E_S - I_{L1}\ (R\cos\theta_L + X\sin\theta_L) - j\ I_{L1}\ (X\cos\theta_L - R\sin\theta_L)$$

where

E_L = voltage at load

E_S = source voltage

R = line and source resistance

X = line and source reactance

other symbols as previously defined. In equation 6 let

$I_R = I_{L1}\cos\theta_L$

$I_X = I_{L1}\sin\theta_L$

then

$$E_L = E_S - RI_R - XI_X - j\ XI_R + j\ RI_X \quad (7)$$

This relationship is shown in the vector diagram of fig. 7 and E_L is the vector OB.

If capacitors are added to the circuit, the equation for voltage at the load becomes

$$E_L = E_S - RI_R - XI_X - jXI_R + jRI_X - jRI_C + XI_C \quad (8)$$

In fig. 7 the voltage at the load bus with shunt capacitors added to the circuit is vector OC. The voltage at the load is increased because the voltage drop to that point in the circuit is less, due to the decreased magnitude of line current.

A simplified expression for the load voltage on any circuit is:

$$E_L = E_S - RI_R - XI_X + XI_C \quad (9)$$

Equation 9 is obtained from equation 8 by neglecting the quadrature voltage drop. This results in a much simpler and sufficiently accurate solution for practically all cases.

From equation 9 it can be seen that if I_C is sufficiently large, the effect of both the resistive and reactive drop can be cancelled.

Also, since the components of load current I_R and I_X are dependent on the load itself, during light load periods XI_C could be larger than both the RI_R and XI_X voltage drops. The line would then be overcompensated, and the resulting power factor would be leading. Leading power factor as an isolated condition on a distribution feeder is unimportant, however, as a general system condition it would be undesirable. Operating at leading power factor lessens the static stability margin and increases losses above that obtained at unity power factor. Figs. 6 and 9 illustrate that the reduction in current and losses is maximum at a resultant power factor of unity.

A fixed capacitor, therefore, does not change the basic regulation of a radial feeder since the capacitor affects an increase in voltage at both light and full load. It is necessary to investigate the rise in voltage and the system VAR requirements during light load periods to determine if the condition is tolerable to the associated electrical equipment. Switching of the capacitor bank may be necessary in some installations to alleviate an undesirable condition.

Since the rise in voltage at the load is approximately proportional to XI_C, the percent voltage rise for a given capacitor installation is approximately

$$\% \text{ rise} = \frac{\text{KVAR} \times X \times d}{10 \times (KV_{L-L})^2} \qquad (10)$$

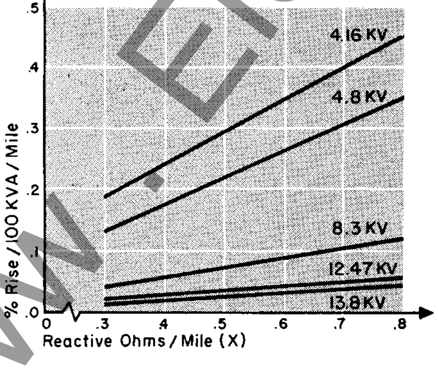

Figure 8. Typical voltage rise curves for various distribution system voltages.

where X = reactance of source up to installation of capacitors in ohms/-mile

KVAR = capacitor bank size

d = miles from regulated bus to installation

KV_{L-L} = line-to-line voltage

Generally, this formula is used to find the voltage rise caused by a capacitor at a specific location, which in turn is superimposed on the feeder voltage profile to obtain net voltage characteristics.

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Example B:
What voltage rise is expected if a 500 KVAR bank is installed 2 miles from a substation on a 4160 volt circuit using 5/0 ACSR?

KVAR = 500
X = 0.681 Ω/mi
d = 2 mi
KV = 4.16

$$\% \text{ rise} = \frac{500 \times .681 \times 2}{10 \times (4.16)^2} = 3.92$$

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Voltage rise curves for typical distribution voltages are illustrated in fig. 8.

Reduced System Losses
Losses on any portion of a power system are a function of the square of the current and the system inductance and resistance. The losses are usually considered as two components, the I^2R power loss and the I^2X var loss. Since the shunt capacitor installation reduces the reactive component of line current, the loss reduction due to capacitors is a function of reactive current only. The real component of current need not be used in the calculation.

The reduction in I^2R power loss due to adding shunt capacitors is:

$$LR_R = (I_X)^2 R - (I_X - I_C)^2 R = 2 I_C I_X R - (I_C)^2 R \qquad (11)$$

Likewise, the reduction in I^2X var loss is:

$$LR_X = 2\, I_C\, I_X\, X - (I_C)^2 X \qquad (12)$$

In equations 11 and 12, I_C is the capacitor current, I_X is the reactive current in the circuit before capacitors are added, R is the circuit resistance and X is the circuit reactance.

The effect of shunt capacitors on system losses is plotted in fig. 9 as a percent of original circuit losses and as a function of the percent capacitor installation. Note that losses are a minimum when ckva = sin θ_L.

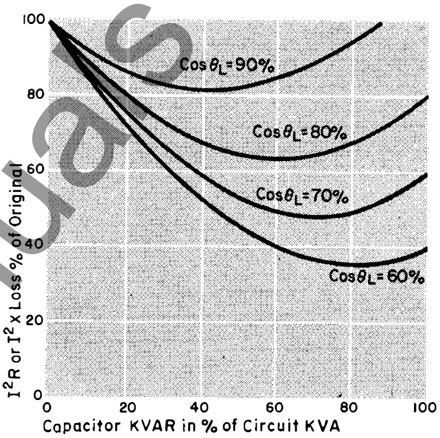

Figure 9. Reduction in circuit losses from adding capacitors.

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Example C:
What is the loss reduction in a 4160 V circuit with a load of 1000 KVA when 500 KVAR of capacitors are added Circuit parameters are as follows:

source imp Z = 0.6 + j0.8 ohms
load power factor = 80%

$$I_L = \frac{1000}{\sqrt{3}(4.16)} = 140 \text{ amps}$$

$$I_X = 140 \times \sin\theta_L = 140 \times .6 = 84 \text{ amps}$$

$$I_C = \frac{500}{\sqrt{3}(4.16)} = 70 \text{ amps}$$

from equation 11
$LR_R = 2 \times 70 \times 84 \times .6 - (70)^2 \times .6$
$LR_R = 4120$ watts

from equation 12
$LX_X = 2 \times 70 \times 84 \times .8 - (70)^2 \times .8$
$LX_X = 5480$ vars

The original system losses calculated are 11760 watts and 15380 vars. If the loss reductions calculated in the above example are subtracted from the original system losses, the final losses are about 65% of the original. This agrees with the result obtained from fig. 9 for this example.

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Increased Power Factor of Source Circuits
Since the capacitor can be considered a generator of vars, any shunt capacitor installation reduces the var burden on the system generation. This reduced var demand from the source generators allows the excitation level to be changed so the machines may be operated nearer unity power factor if desired.

For an indication of how the source power factor increases, refer to fig. 10. The result-

Fundamental Effects of Shunt Capacitors, Continued

ant source power factor is plotted as a function of initial power factor and shunt capacitor installation in percent of circuit loading. These curves are derived on the basis that the load on the source is held constant after the capacitors are added. The resultant power factor would be higher if the circuit loading was reduced by the amount of KVAR added. For instance, if 500 KVAR is added to a 1000 KVAR circuit operating at 60% power factor, the resultant power factor, if no new load is added, would be 89%. If the source loading is held constant by adding more load at the same original power factor, the resultant power factor according to fig. 10 would be 81%.

Reduced Loading on Source Generators and Circuits

The increase in the source power factor, due to reduced lagging component of current, decreases the kva loading of each source generator and circuit. This may relieve an existing overload, delay purchase of new equipment, or release capacity needed for additional load growth on some circuits. The reduction in loading is proportional to the reduced line current discussed previously, and illustrated in fig. 6.

If the capacitor benefits are considered because of released capacity for increasing load, the amount of capacitors necessary for a required load increase is a valuable yardstick. The allowable load increase is calculated on the basis of adding load at the original power factor until the source circuits are loaded to the same point as before adding capacitors. The capacitor KVAR per KVA of load increase is plotted in fig. 11 as a function of percent capacitor KVAR and original power factor. If this quantity is multiplied by the cost per KVAR of installed capacitors, the product is the average cost of supplying each additional KVA of load. This cost, neglecting other advantages of the capacitor, can be compared with other methods of adding circuit capacity – such as reconductoring, higher rated transformers, or increased generation.

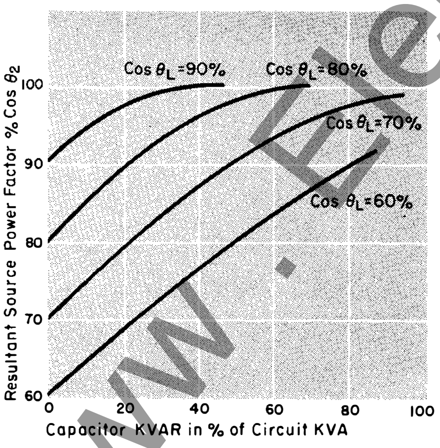

Figure 10. Increase in source power factor as an effect of shunt capacitors.

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Example D:
If the original load power factor is 80%, and 50% capacitor KVAR is added, the capacitor KVAR required per KVA increase in load is 2.2 from fig. 11. If the installed cost of capacitors is **$10** per KVAR, the increase in ability to supply load is obtained at a cost of **$22** per KVA.

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The cost per KVA of adding transformer to accommodate increased load may be much greater than by adding capacitors. Note from fig. 11 that the number of capacitor KVAR required per KVA of increased load carrying ability increases rather sharply with the higher original power factor.

Reduced Demand on Interchange and Purchase Power Locations

The benefit derived from capacitor installation on tie lines, and purchase power locations is essentially as described in previous paragraphs except that it is completely economic in nature. The cost of purchased power is usually based on a KVA demand charge plus incremental charges for real power. Since a capacitor installation will reduce the KVA demand through the tie line, a corresponding reduction will occur in the cost of purchased power. In some cases, it can be proven that correction to 100% power factor is economical.

Relatively few interchange contracts have actual power factor clauses – except in the case of a large industrial plant with generation, connected to an electric utility. However, the economic benefit to be gained from keeping VAR interchange to a minimum is usually quite apparent.

Reduced System Investment per Kilowatt of Load

The typical electric utility arrives at a cost per kilowatt of delivered load by considering its total investment in system facilities and property plus the cost of production. If there were an accepted method of obtaining a cost per KVAR delivered, the reduced system investment from a capacitor installation could be directly equated. Unfortunately, many utilities allot no cost to KVAR supply, others derive a cost related to system losses and still others use a cost obtained from exciter losses.

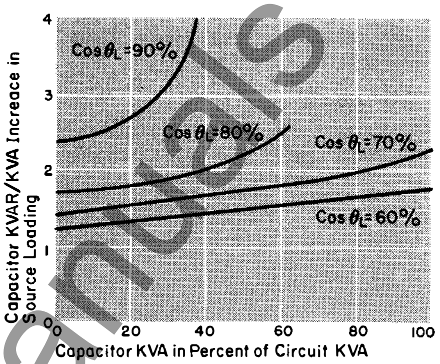

Figure 11. Allowable load increase due to adding shunt capacitors.

If capacitors are installed to release system capacity or improve voltage conditions, it is generally accepted that the reduction in overall system investment is a direct function of the ratio of cost per KVA for different methods of obtaining the same results.

As discussed previously, the increase in source power factor may allow increased loading of the source generators. One practical method of determining the effect on system investment is to consider this benefit as a deferred investment for system facilities.

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Example E:
If a capacitor installation of 50% KVAR rating allowed a 15% increase in load carrying ability, the capacitor KVAR required per KW of load increase is 3.32. Therefore, at **$10** installed cost per KVAR, the cost per KW of load increase is **$33.20.** If an average cost of **$500** per KW of delivered power is assumed, and the annual charge is 15%, the deferred investment savings would be (.15 × 500) – **$33.20** = **$41.80** per KW per year.

Calculation and Evaluation of Shunt Capacitor Economic Benefits

In the installation of shunt capacitors on utility systems the utility planning engineer must, as in the case of any other equipment addition, justify the purchase of the equipment. Initially, justification of capacitors was considered primarily on the basis of released capacity in feeder equipment plus some compensation for reduced feeder losses. It was generally felt that correction above 90% was not practical.

Recent system studies indicate that in addition to considering the same factors, that of released capacity and reduced feeder copper losses, the utility engineer should consider the reduced I^2X kilovar losses, reduced losses in generating and transmission equipment, and the reduced system investment carrying charges.

These studies also emphasize another factor which has become important in the economic comparison, that is, the location of the capacitor bank with respect to the overall system rather than to its position on the individual feeder. Substantially different results can be realized depending upon whether the capacitor is installed on the secondary of the distribution transformer, or on the distribution substation bus. It is these factors which are now considered in addition to the others in making the economic comparison.

Due to the lower cost per KVA of capacitors compared to the higher cost per KVA of generation, transmission, and distribution equipment, the generally recognized theory that correction above 90% power factor was uneconomical, has been disproven. Correction to near unity power factor is commonplace, and it can be shown that it is economical.

The study of any particular utility must be based on the system as a whole rather than a particular section. The overall efficiency of operation is dependent on each portion of the system operating as near unity power factor as possible. The determination of location of the units is an economical derivation, and one must consider that the efficiency of the system must be weighed along with the effectiveness of the capacitor when determining its relative location.

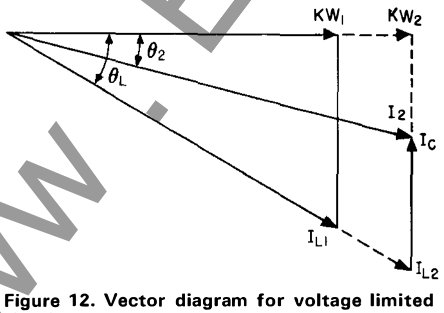


Figure 12. Vector diagram for voltage limited circuits.

There are four criteria on which economic comparisons involving shunt capacitors are based. They are as follows:

1. Released system and equipment capacity
2. Reduced system and equipment losses
3. Increased revenue from higher secondary voltage
4. Capital gains from reduced system investment

Each of the above criteria can be applied several times in any single economic study. The exact formula used and the extent to which the study is carried out is dictated by the proposed location of the capacitors on the utility system.

Released System and Equipment Capacity

The load carrying ability of transmission and distribution equipment is limited in some cases by voltage drop, and in other cases by thermal capacity. Generally speaking, voltage drop is the limiting factor on distribution feeder loading, and occasionally transmission line capacity is determined by maximum voltage drop. Equipment such as generators and transformers are limited by their thermal capacity, and any benefit to be gained therein from the installation of shunt capacitors should be considered on this basis.

Voltage Drop Limitation

When the reactive load current is supplied by capacitors instead of a source which possesses inductive reactance, we have shown, as a fundamental effect, that the voltage at the load side is higher than it is without the capacitors. It is higher by an amount which is equal to the inductive reactance of the source times the load current supplied by the capacitor. It is obvious, then, that if the connected load is limited by the voltage drop, a larger load can be tolerated if shunt capacitors are applied which reduce the line voltage drop. To determine the released capacity obtained by the addition of shunt capacitors, consider the allowable increase in KW loading as the released capacity. The calculation is based on the assumption that the voltage drop after capacitor installation must be the same as before adding the capacitors.

The vector diagram for this condition is shown in fig. 12.

If the voltage is constant, kilowatts and kva are directly proportional to current, and therefore, in per unit notation, they are considered equal to current. From fig. 12,

$$I_C = (\text{capacitor KVAR}) = KW_2(\tan\theta_L - \tan\theta_2) \qquad (13)$$

where I_C = shunt capacitor current
I_{L1} = initial load current
I_{L2} = final load current
I_2 = final source current
other symbols as previously described

The increase in capacity is:

$$\frac{KW_2 - KW_1}{KW_2} = \frac{I_2\cos\theta_2 - I_{L1}\cos\theta_L}{I_2\cos\theta_2} = 1 - \frac{I_{L1}\cos\theta_L}{I_2\cos\theta_2} \qquad (14)$$

Since the voltage drop after adding capacitors must be equal to the original drop, the respective voltage drops can be equated as in equation 15, omitting reactive drop.

$$I_{L1}(R\cos\theta_L + X\sin\theta_L) = I_2(R\cos\theta_2 + X\sin\theta_2) \qquad (15)$$

therefore

$$\frac{I_2}{I_{L1}} = \frac{R\cos\theta_L + X\sin\theta_L}{R\cos\theta_2 + X\sin\theta_2} \qquad (16)$$

substituting in equation 14

$$\frac{KW_2 - KW_1}{KW_2} = \frac{\tan\theta_L - \tan\theta_2}{R/X + \tan\theta_L} \qquad (17)$$

if equation 13 is divided by $KW_2 - KW_1$

$$\frac{\text{capacitor KVAR}}{KW_2 - KW_1} = \frac{KW_2}{KW_2 - KW_1}(\tan\theta_L - \tan\theta_2) \qquad (18)$$

By substituting equation 17 in equation 18, an expression for capacitor KVAR per increase in KW is obtained.

$$\frac{\text{capacitor KVAR}}{\Delta\ KW} = R/X + \tan\theta_L \qquad (19)$$

This analysis indicates that the kilowatts gained, where the circuits are voltage limited, depends only on the load power factor and the ratio of the system resistance to reactance.

The relationship is best plotted in terms of capacitor KVAR per gain in KW versus R/X ratio for several typical power factors. This family of curves is shown in fig. 13.

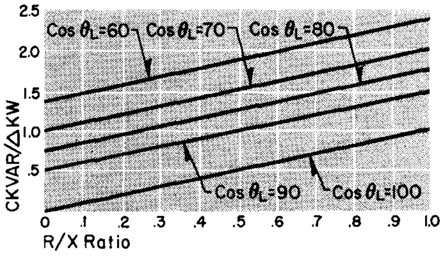


Figure 13. Released capacity on voltage limited circuits based on system R/X ratio.

Calculation and Evaluation of Shunt Capacitor Economic Benefits, Continued

Voltage Drop Limitation, Continued

Example F:

If 500 KVAR in shunt capacitors is added to a circuit of 1000 KVA load at 60% initial power factor, what is the released capacity? The system X/R ratio at the point of installation is 1.0.

from equation 19

$$\frac{KVAR}{\Delta KW}=1.0+\tan\theta_L=1.+1.32$$
$$=2.32$$
$$\Delta KW=\frac{500}{2.32}=215\ KW$$

There is somewhat of a paradox to be noted here since it is apparent from equation 19 that the gain in kilowatts is greater for a given capacitor bank, the higher the initial load power factor. Of course, the thermal capacity of the source equipment involved will limit the extent to which the gain in kilowatts can be carried. Practically speaking, transmission lines, feeders, and secondary circuits seldom exceed their thermal ability and therefore voltage drop limits the load carrying ability. In these cases, the preceding formula and curves should be used to determine the KW gained from capacitor installations.

Thermal Ability Limitation

To determine the released capacity where thermal ability is the limiting factor, a different approach must be taken. In this case, the line current or KVA is increased, after adding capacitors, to the value assumed before capacitor installation.

The additional KVA needed to load the source circuits back to the original loading, is the amount of capacity gained due to the effect of shunt capacitors.

In deriving an expression for the increase in KVA or released capacity, the additional load is assumed to be at the original power factor angle θ_L. This may be pessimistic, but it is more accurate than adding load at the resultant power factor angle θ_2.

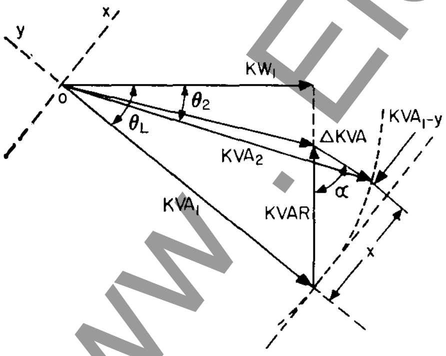


Figure 14. Vector diagram for current limited circuits.

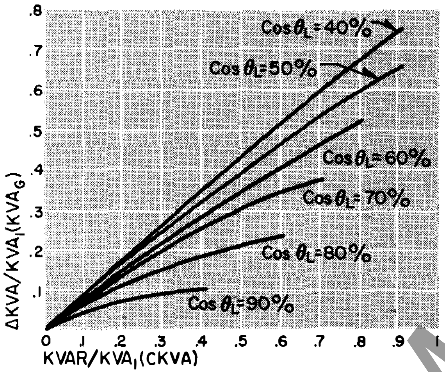


Figure 15. Released capacity on current limited circuits due to capacitor installation.

The vector diagram for this condition is illustrated in fig. 14. Where

ΔKVA =load added at original power factor after capacitor installation

KVAR =capacitor bank size

KVA_1 =original source loading

KVA_2 =final source loading

other symbols as defined previously

If KVA_1 is designated as the radius of a circle with center at 0, and X and Y are coordinates of a point on the circle, the equation for that circle is:

$$X^2+Y^2=KVA_1{}^2 \qquad (20)$$

from fig. 14

$$X=KVAR\ \sin\alpha \qquad (21)$$
$$=KVAR\ \cos\theta_L$$

substitute equation 21 in equation 20

$$(KVAR\ \cos\theta_L)^2+Y^2=KVA_1{}^2Y \qquad (22)$$
$$=\sqrt{(KVA_1)^2-(KVAR\ \cos\theta_L)^2}$$

from fig. 14

$$\Delta KVA=KVAR\ \sin\theta_L-(KVA_1-Y) \qquad (23)$$

substitute equation 22 in equation 23

$$\Delta KVA=KVAR\ \sin\theta_L-KVA_1+\sqrt{(KVA_1)^2-(KVAR\ \cos\theta_L)^2} \qquad (24)$$

The rather cumbersome expression of equation 24 can be simplified by converting to per unit quantities for both the gain in source KVA and capacitor bank size. This is accomplished by dividing equation 24 by KVA. Then KVA_G and ckva are per unit values for the released capacity and installed capacitor respectively.

$$KVA_G=ckva\ \sin\theta_L-1+\sqrt{1-(ckva\ \cos\theta_L)^2} \qquad (25)$$

This relationship is plotted in fig. 15, and only requires the per unit value of capacitors added, and the original source power factor to obtain the released capacity directly.

The resultant power factor of the source circuit is:

$$\cos\theta_2=\frac{KW_1+\Delta KW}{KVA_1} \qquad (26)$$

$$\cos\theta_2=\cos\theta_L\ (1+KVA_G) \qquad (27)$$

. . . .

Example G:

How much load can be added to a circuit already at its thermal limit with a load of 4000 KVA at 60% power factor by adding 2000 KVAR in shunt capacitors?

from equation 25

$$KVA_G=.5\times.8-1+\sqrt{1-(.5\times.6)^2}$$
$$KVA_G=.4-1+.95=.35$$
$$\Delta KVA=.35\times4000=1400\ KVA$$

The resultant power factor of the source circuits from equation 27 is:

$$\cos\theta_2=.6\ (1+.35)=.81$$

. . . .

The relationships illustrated by equations 19 and 25 are useful in determining the released circuit capacity for economic evaluation. Inspection of these two expressions reveal the following:

On voltage limited circuits the released capacity is:

1. Dependent on original source power factor
2. Dependent on source X/R ratio
3. Independent of circuit loading

On current limited circuits the released capacity is:

1. Dependent on original source power factor
2. Independent of source X/R ratio
3. Dependent on circuit loading

Reduced System and Equipment Losses

Calculation of the reduction in system losses due to shunt capacitor installation can be made directly from equations 11 and 12, where the results are expressed in single phase watts, and vars.

A per unit expression for loss reduction is obtained from these same equations by substitution of equivalents as follows:

I_C=KVAR=capacitor bank size

$I=KVA_1$=initial load

ckva=capacitor bank in per unit of initial load

θ_L=initial load power factor angle

from equation 11 or 12,

ΔPL=p.u. peak loss reduction= (28)

$$2\ ckva\ \sin\theta_L-(ckva)^2$$

This expression is valid for either I^2R real or I^2X reactive loss reduction. If reduction in peak losses is desired, the per unit capacitor bank size should be on the peak load base. If evaluation is to be determined using kilowatt hours, the load current or KVA should include the reactive load factor. This would result in a modification of equation 28 as follows:

$$\Delta EL = \text{p.u. energy loss reduction} = (2\ \text{ckva}\ \sin\theta_L)\ LF - (\text{ckva})^2 \quad (29)$$

Use of these equations is valid only if there are no loads which vary the reactive component of current in the section being considered. Therefore, the calculation of loss reduction is only as accurate as the extent to which the system is sectionalized for the purposes of calculation.

Example H:
Using the same circuit parameters as in example c, the peak loss reduction is:

$\Delta PL = 2 \times .5 \times .6 - (.5)^2$
$\Delta PL = \text{p.u. peak loss reduction} = .35$

Therefore the final losses would be 65% of the original as found from the curves of fig. 9.

If the load factor of this circuit is 70%:

$\Delta EL = 2 \times .5 \times .6 \times .7 - (.5)^2$
$\Delta EL = \text{p.u. energy loss reduction} = .17$

After calculation of the loss reduction, there are three economic benefits to evaluate. These are:

1. Peak KW load reduction
2. Peak KVAR load reduction
3. Energy savings due to KW hr loss reduction

The reduction in peak load kilowatts (demand) is an important economic benefit to utilities.

The value assigned to it varies from utility to utility depending on specific situations. The most common evaluation is to assign the average cost per kilowatt of system generation although many use the average cost per kilowatt of the last plant or last unit.

Conversely, most utilities do not give any economic credit for the reductions in the I^2X loss or KVAR load reduction. Where evaluation has been made, in the past, the maximum credit is the cost of the capacitors necessary to supply an equivalent amount of KVAR. There have been attempts by some utilities and manufacturers to arrive at a cost per KVAR generated, however, this has not been universally accepted. If such a cost figure is available, it should be used.

The third benefit derived from loss reduction is easily evaluated once the initial calculation is made. For this cost analysis, most utilities use the delivered cost per kilowatt of energy. This value will deviate among utilities and, in truth, will vary within a utility from plant to plant. The savings, regardless of cost used, is the calculated per unit reduction times original peak loss times the hours for the period considered, multiplied by the cost accounted.

Example I:
What are the savings affected due to loss reduction using the same circuit parameters as examples c and h with cost figures as follows?

e =16% (annual charge)
s =500 $/KW of system generation
v =5 $/KVAR of system generation
c =.0035 $/kwhr of system losses

from example c:

$L_R = 11.76$ KW – initial real loss
$L_X = 15.38$ KVAR – initial reactive loss

1. Peak KW load reduction
$.35 \times L_R = .35 \times 11.76 = 4.11$ KW
savings $= 4.11 \times 500 \times .16 =$ **$330** annually

2. Peak KVAR load reduction
$.35 \times L_X = .35 \times 15.38 = 5.39$ KW
savings $= 5.39 \times 5 \times .16 =$ **$4.30** annually

3. Energy savings due to loss reduction
savings $= .17 \times 11.76 \times .0035 =$ **$70** annually

Increased Revenue from Higher System Voltage

Evaluation of the higher voltages resulting from shunt capacitor installation, concerns two effects. They are:

1. The immediate rise in system voltage at the metering point caused a proportional increase in registration of kilowatt hours.
2. The reduced slope of the feeder voltage profile. This is illustrated in fig. 16.

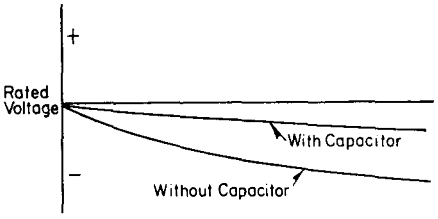


Figure 16. Voltage profile on feeder with distribution load.

The relationship of equation 10 can be used to calculate the voltage rise at a given point. Since this benefit generally is related to residential voltage levels, it can be assumed that the load characteristic will be primarily resistive. Therefore, the increase in kilowatts used will be proportional to the increase in voltage. To keep the evaluation conservative, the following relationship is generally used:

$$\Delta KW = .5 \Delta E \quad (30)$$

where both quantities are expressed in percent

This expression can be converted to KW hours by using the total hours in the period to be considered. The gain in kilowatt hours is usually considered on an annual basis, therefore:

$$\Delta KWHR = 8760 \times .5 \Delta E \times KW \times LF \quad (31)$$

Example J:
What is the economic value of the increase in metered energy if a 100 KVAR capacitor bank is installed on a 4.16 KV feeder with an average load of 200 KW? The feeder is 4 miles long with a reactance of .7 ohm/mile and the average cost of energy is 2 cents/KWHR.

from equation 10

$$\Delta E = \%\ \text{voltage rise} = \frac{100 \times .7 \times 4}{10 \times (4.16)^2} = 1.618$$

from equation 31

$\Delta KWHR = 8760 \times .5 \times 1.618 \times 200 = 14000$
increased revenue $= .02 \times 14000 = 280$ $/year

The second condition of economic gain results because the fixed shunt capacitor bank reduces the voltage gradient along a feeder with distributed load, as shown in fig. 16. Effectively – since the reactive voltage drop is reduced – the ratio of receiving end voltage to sending end voltage is nearer unity. This may allow omission of a feeder voltage regulator, and any resultant reduction in system equipment investment should be credited to the shunt capacitor installation.

Calculation and Evaluation of Shunt Capacitor Economic Benefits, Continued

Summary of Evaluation of Shunt Capacitor Benefits

The main economic benefits of shunt capacitors to electric utilities have been briefly discussed. More detailed analysis and comments can be found in articles listed in the bibliography.

The system planner has the option of evaluating all of the economic benefits listed, or he may use only those which apply to his specific case.

Suggested Procedure

Step 1: Obtain system cost data listed below where available.

s = cost of system generation/KW or KVA
v = cost of system generation/KVAR
c = cost of system losses/KWHR
e = cost of money in percent (annual charge)
r = metered energy rate/KWHR

Step 2: Evaluate the gain in system capacity using equation 19 or 25 whichever is applicable.

gain ($) = ($\Delta$KW or ΔKVA) (s)

Step 3: Evaluate the effect of loss reduction from equations 28 and 29.

Convert to economic gain as follows:

1. Peak KW load reduction gain ($) = ($\Delta$PL) ($L_R$) (s)
2. Peak KVAR load reduction gain ($) = ($\Delta$PL) ($L_X$) (v)
3. Energy loss reduction gain ($/yr) = ($\Delta E_L$) ($L_R$) (8760) (c)

Step 4: Evaluate the effect of higher system voltage using equation 31. gain ($/yr) = ($\Delta$E) (8760) (r) (average load KW)

Step 5: Since shunt capacitor installation can often defer or eliminate investments in equipment or circuits, the capacitor installation should be credited with saving the cost of the reduced system investment.

gain ($) = (reduced capital invest) (e)

Determination of System Shunt Capacitor Requirements

The original concept of shunt capacitor installation on utilities' systems was somewhat of a hit or miss proposition, governed by "rule-of-thumb" methods. Strangely enough, while system-wide engineering analysis, economic comparisons and computer programs have become recommended procedures in capacitor application, these same new methods have verified the basic accuracy of some of the original guides and precepts.

All the preceding information in this application guide has concerned itself with investigation of the fundamental effects of shunt capacitors and calculation of the economic gain or credit established by installation of this type of reactive correction. The system planner must determine, using this fundamental data and his system characteristics, how much reactive correction should be purchased, and where on the system it should be installed.

Estimate of Magnitude of System Reactive Needs

Accurate estimates of the system-wide reactive requirements are necessary to assure that improper distribution of shunt capacitors does not occur. The reactive load in each major section must be considered, the ultimate aim being to operate each part of the system as near unity power factor as is economically and practically possible.

The data which must be collected for this analysis is identical to that necessary for a load flow study on the a-c network calculator. This will include such things as:

1. Transmission and subtransmission line characteristics.
2. Transformer sizes, impedance range and available taps
3. Generator characteristics and reactive capability
4. Magnitude and location of present reactive sources such as synchronous motors and generators, and shunt capacitors
5. Typical distribution feeder line constants and loading
6. Power factor and magnitude of major load taps

Past trends of reactive requirements should be studied particularly with relation to load growth. This will aid in determining future KVAR needs which should be predicted on system peak load trends. A network analyzer load flow study can then be utilized in predicting reactive requirements, generally informing the system planner as to how much KVAR is needed in various sections of the system, based on voltage levels at peak load. This same load study can specifically tell him how much reactive load can be supplied from generators without creating intolerable system voltage conditions.

If a network calculator study cannot be made, capacitor needs must be determined from the same data, by calculating how much KVAR is necessary to raise the power factor of each operating section to unity. The simplest way to arrive at this figure is to resolve the system into an equivalent radial circuit.

This radial circuit will have the combined characteristics of each section assuming implicitly that the characteristics of circuits and load in various sections of the system are similar, and can be lumped together on the common basis of voltage. The operating power factor of each section of the system is dependent on the succeeding section, in the direction of load. Consequently, if correction is begun at the load end, the operating power factor of each preceding section must be adjusted upward before correcting to unity.

Location of Capacitors on System-wide Basis

After obtaining a figure or figures for the total or sectional KVAR requirements, it is necessary to lay out an orderly program of installation. The most typical system locations of shunt capacitors are shown in fig. 17. There are three common plans for determining which of these locations is to be used and the distribution of capacitors in each. They are:

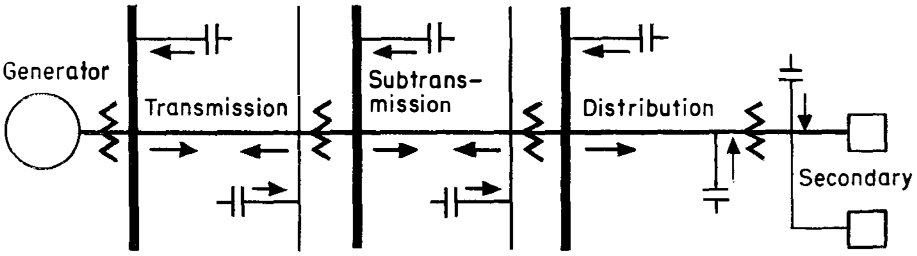


Figure 17. Typical system capacitor bank locations (arrows indicate direction of VAR flow for minimum system losses).

1. Distribution system saturation
2. Economic comparison
3. Emergency priority

1. Distribution System Saturation is the first and still the most common method employed by utilities in applying capacitors. Basically, as the need for reactive correction accumulates, fixed shunt capacitors are installed on distribution feeders until the operating power factor equals or exceeds unity at light load levels. To correct to unity at peak load, switched capacitor banks – either pole mounted or substation bus banks – are installed.

This program is continued each year with a fixed relation between the overall system load growth and the capacitors to be added to the distribution system. If it is found that installation at this voltage level will not fulfill reactive requirements, consideration is then given to installation at the next higher voltage level. In this way, a system will end up with about 75-85% of its shunt capacitors at the distribution voltage level, and the remainder at random locations on the subtransmission circuits.

2. Economic Comparison involves use of system cost figures to obtain the cost/KVAR of installed shunt capacitors for each section of the system. These figures are then compared to cost/KVA of source equipment which will yield the same system benefits such as higher voltage, increased capacity, and lower losses.

There are many ways of obtaining, and comparing these cost figures. Almost every utility has a preferred method tailored to its own system operating or accounting method. One preferred philosophy is to consider that shunt capacitors can be installed in a given section of the system until the $ cost/KVAR installed exceeds the $ gain/KVAR of the last KVAR installed. As pointed out previously, the $ gain/KVAR decreases as the original power factor increases. Therefore, as each KVAR is added, the ratio of $ gain to $ cost will decrease. When the ratio is unity, the economic balance of shunt capacitor installation has been reached. Since the $ cost/KVAR will vary between sections of the system, this comparison must be done on a sectional basis, thereby arriving at an optimum capacitor installation for that section, whether it be transmission, subtransmission, distribution or secondary.

Suggested procedure for making a comparison in this way is as follows:

Step 1: Obtain the $ cost/KVAR installed for each section of the system being considered.

Step 2: Using procedure outlined under the heading "summary of evaluation of shunt capacitor benefits," page 10, calculate the $ gain per KVAR for each section of the system.

Step 3: Calculate the ratio of $ gain/KVAR to $ cost/KVAR and continue installing capacitors in a given section until this ratio becomes unity.

Since the decrease in $ gain/KVAR is a function of the change in source power factor, it is necessary to recalculate the source power factor after each increment of shunt capacitors is added. Table 2, page 12, simplifies this procedure since the resultant power factor for any increment of shunt capacitor addition can be obtained providing the initial power factor is known.

……

Example K:

Suppose 3000 KVAR has been added to a circuit with 11250 KVA load at 80% power factor. What is resultant power factor?

$$\text{correction factor} = \frac{3000}{11250 \times .8} = .333$$

from table 2, resultant power factor = 92.4%

If this is to be used in an economic comparison, all $ gain/KVAR for additional banks would then be evaluated on the basis of an original power factor of 92.4%.

……

Another accepted and proven philosophy of economic comparison is to base the limit of capacitor installation on minimum system cost. The following analysis (bibliography reference 6) correlates the amount of capacitor installation to minimum system investment – certainly a worthwhile goal of system planning. The formulas are derived for general application to any section of the system.

The following quantities are used:

P_L = KW supplied to the load
U_L = KVA supplied to the load
U_R = resultant system KVA
Q_L = KVAR supplied to the load
Q_C = KVAR supplied by capacitor
Q_S = KVAR supplied by source
θ_L = initial load power factor
θ_2 = resultant power factor
R = annual cost/KVAR of capacitor
S = annual cost/KVA of source circuits
C = total cost of system/KW of system capacity

The vector relationship between kilowatts, kilovars, and total KVA at any point on the system is shown in fig. 18 for the simplified system shown in the same figure.

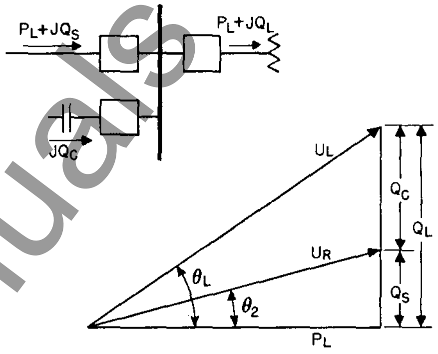


Figure 18. Vector diagram for derivation of minimum cost formula.

The real power required by the load and system is P_L, and the vars of the load and system beyond any particular point is Q_L. The vars are supplied partially from the source generators and the remainder from the capacitor. The part of Q_L that comes from the source is Q_S and the portion supplied from the capacitors is Q_C. The system and load beyond the point of installation of the capacitors draw U_L KVA at an initial power factor angle of θ_L of which the source supplies U_R KVA at a resultant power factor angle of θ_2. The source power factor is called resultant because if the capacitors were not in the circuit, the source would have to supply all the reactive and operate at the same power factor as the load.

Annual capital investment charges required to supply the load, including costs of all sections of the system up to the capacitor installation in terms per unit kilowatts is designated as **C.** Since the cost of each of the energy sources is expressed in per unit values, the total investment charges can be shown as:

$$C \times P_L = S \times U_L + R \times Q_C \quad (32)$$

It is possible to convert this expression with trigonometric equivalents so that the total cost is in terms of a single variable quantity cos θ_2 – the resultant power factor of the source circuits. This is desirable since the ultimate aim of any capacitor installation is to reduce the source reactive demand to a minimum. It should be pointed out that the load power factor is considered fixed and is therefore treated as a constant in the derivation. Therefore:

$$C = \frac{S\dfrac{P_L}{\cos\theta_2} + R \times P_L\,(\tan\theta_L - \tan\theta_2)}{P_L} \quad (33)$$

or

$$C = \frac{S}{\cos\theta_2} + R\,(\tan\theta_L - \tan\theta_2) \quad (34)$$

Determination of System Shunt Capacitor Requirements, Continued

Table 2 – Power Factor Correction Factors in Per Unit KW

Note:

To obtain required capacitor KVA:

1. Get PF correction factor from table below
2. Required capacitor KVA = $KW_{load} \times$ factor

To obtain resultant power factor:

1. Calculate correction factor $= \frac{KVAR}{KW_{load}}$
2. Enter table at present power factor using calculated correction factor and obtain resultant PF

Present Power Factor	Resultant or Desired Power Factor in Percent																				
	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
50	.98	1.01	1.03	1.06	1.09	1.11	1.14	1.16	1.19	1.22	1.25	1.28	1.30	1.34	1.37	1.40	1.44	1.48	1.53	1.59	1.73
51	.94	.96	.99	1.01	1.04	1.07	1.09	1.12	1.15	1.17	1.20	1.23	1.26	1.29	1.32	1.36	1.39	1.43	1.48	1.54	1.69
52	.89	.92	.95	.97	1.00	1.02	1.05	1.08	1.10	1.13	1.16	1.19	1.21	1.25	1.28	1.31	1.35	1.39	1.44	1.50	1.64
53	.85	.88	.90	.93	.95	.98	1.01	1.03	1.06	1.09	1.12	1.14	1.17	1.20	1.24	1.27	1.31	1.35	1.40	1.46	1.60
54	.81	.83	.86	.89	.91	.94	.97	.99	1.02	1.05	1.07	1.10	1.13	1.16	1.20	1.23	1.27	1.31	1.36	1.42	1.56
55	.77	.79	.82	.85	.87	.90	.93	.95	.98	1.01	1.03	1.06	1.09	1.12	1.16	1.19	1.23	1.27	1.32	1.38	1.52
56	.73	.76	.78	.81	.83	.86	.89	.91	.97	.97	1.00	1.02	1.05	1.08	1.12	1.15	1.19	1.23	1.28	1.34	1.48
57	.69	.72	.74	.77	.80	.82	.85	.87	.90	.93	.96	.99	1.01	1.05	1.08	1.11	1.15	1.19	1.24	1.30	1.44
58	.65	.68	.71	.73	.76	.78	.81	.84	.86	.89	.92	.95	.98	1.01	1.04	1.08	1.11	1.15	1.20	1.26	1.40
59	.62	.64	.67	.70	.72	.75	.77	.80	.83	.86	.88	.91	.94	.97	1.00	1.04	1.08	1.12	1.16	1.23	1.37
60	.58	.61	.64	.66	.69	.71	.74	.77	.79	.82	.85	.88	.90	.94	.97	1.00	1.04	1.08	1.13	1.19	1.33
61	.55	.57	.60	.63	.65	.68	.71	.73	.76	.79	.81	.84	.87	.90	.94	.97	1.01	1.05	1.10	1.16	1.30
62	.51	.54	.57	.59	.62	.64	.67	.70	.72	.75	.78	.81	.84	.87	.90	.94	.97	1.01	1.06	1.12	1.26
63	.48	.51	.53	.56	.59	.61	.64	.67	.69	.72	.75	.78	.80	.84	.87	.90	.94	.98	1.03	1.09	1.23
64	.45	.48	.50	.53	.55	.58	.61	.63	.66	.69	.72	.74	.77	.80	.84	.87	.91	.95	1.00	1.06	1.20
65	.42	.44	.47	.50	.52	.55	.58	.60	.63	.66	.68	.71	.74	.77	.81	.84	.88	.92	.97	1.03	1.17
66	.39	.41	.44	.47	.49	.52	.54	.57	.60	.63	.65	.68	.71	.74	.77	.81	.85	.89	.93	1.00	1.14
67	.36	.38	.41	.44	.46	.49	.51	.54	.57	.60	.62	.65	.68	.71	.74	.78	.82	.86	.90	.97	1.11
68	.33	.35	.38	.41	.43	.46	.49	.51	.54	.57	.59	.62	.65	.68	.72	.75	.79	.83	.88	.94	1.08
69	.30	.32	.35	.38	.40	.43	.46	.48	.51	.54	.56	.59	.62	.65	.69	.72	.76	.80	.84	.91	1.05
70	.27	.30	.32	.35	.37	.40	.43	.45	.48	.51	.54	.56	.59	.62	.66	.69	.73	.77	.81	.88	1.02
71	.24	.27	.29	.32	.35	.37	.40	.42	.45	.48	.51	.54	.56	.60	.63	.66	.70	.74	.78	.85	.99
72	.21	.24	.26	.29	.32	.34	.37	.40	.42	.45	.48	.51	.53	.57	.60	.63	.67	.71	.75	.82	.96
73	.19	.21	.24	.26	.29	.32	.34	.37	.40	.42	.45	.48	.51	.54	.57	.61	.64	.68	.73	.79	.94
74	.16	.18	.21	.24	.26	.29	.32	.34	.37	.40	.42	.45	.48	.51	.55	.58	.62	.66	.70	.77	.91
75	.13	.16	.18	.21	.24	.26	.29	.31	.34	.37	.40	.43	.45	.49	.52	.55	.59	.63	.67	.74	.88
76	.10	.13	.16	.18	.21	.23	.26	.29	.31	.34	.37	.40	.43	.46	.49	.53	.56	.60	.65	.71	.85
77	.08	.10	.13	.16	.18	.21	.24	.26	.29	.32	.34	.37	.40	.43	.47	.50	.54	.58	.62	.69	.83
78	.05	.08	.10	.13	.16	.18	.21	.24	.26	.29	.32	.35	.37	.41	.44	.47	.51	.55	.59	.66	.80
79	.03	.05	.08	.10	.13	.16	.18	.21	.24	.26	.29	.32	.35	.38	.41	.45	.48	.52	.57	.63	.78
80	.00	.03	.05	.08	.10	.13	.16	.18	.21	.24	.27	.29	.32	.35	.39	.42	.46	.50	.54	.61	.75
81	...	.00	.03	.05	.08	.10	.13	.16	.18	.21	.24	.27	.29	.33	.36	.39	.43	.47	.51	.58	.72
82	...	...	.00	.03	.05	.08	.10	.13	.16	.19	.21	.24	.27	.30	.33	.37	.41	.45	.49	.56	.70
83	...	...	...	.00	.03	.05	.08	.10	.13	.16	.19	.22	.24	.28	.31	.34	.38	.42	.46	.53	.67
84	...	...	...	...	.00	.03	.05	.08	.11	.13	.16	.19	.22	.25	.28	.32	.35	.39	.44	.50	.65
85	...	...	...	...	....	.00	.03	.05	.08	.11	.14	.16	.19	.22	.26	.29	.33	.37	.42	.48	.62
86	...	...	...	...	....	....	.00	.03	.05	.08	.11	.14	.17	.20	.23	.26	.30	.34	.39	.45	.59
87	...	...	...	...	....	....	....	.00	.03	.05	.08	.11	.14	.17	.20	.24	.27	.32	.36	.42	.57
88	...	...	...	...	....	....	....	....	.00	.03	.06	.08	.11	.14	.18	.21	.25	.29	.34	.40	.54
89	...	...	...	...	....	....	....	....	....	.00	.03	.05	.09	.12	.15	.18	.22	.26	.31	.37	.51
90	...	...	...	...	....	....	....	....	....	....	.00	.03	.06	.09	.12	.15	.19	.23	.28	.34	.48
91	...	...	...	...	....	....	....	....	....	....	....	.00	.03	.06	.09	.13	.16	.21	.25	.31	.46
92	...	...	...	...	....	....	....	....	....	....	....	....	.00	.03	.06	.10	.13	.18	.22	.28	.43
93	...	...	...	...	....	....	....	....	....	....	....	....	....	.00	.03	07	.10	.14	.19	.25	.39
94	...	...	...	...	....	....	....	....	....	....	....	....	....	....	.00	.03	.07	.11	.16	.22	.36
95	...	...	...	...	....	....	....	....	....	....	....	....	....	....	....	.00	.04	.08	.12	.19	.33
96	...	...	...	...	....	....	....	....	....	....	....	....	....	....	....	....	.00	.04	.09	.15	.29
97	...	...	...	...	....	....	....	....	....	....	....	....	....	....	....	....	....	.00	.05	.11	.25
98	...	...	...	...	....	....	....	....	....	....	....	....	....	....	....	....	....	....	.00	.06	.20
99	...	...	...	...	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	.00	.14
100	...	...	...	...	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	.00

2. Economic Comparison, Continued

This final equation for C is an expression of the combined annual cost of the source circuits and capacitor in terms of the resultant source power factor angle. The power factor angle obtained when this annual cost is a minimum, is a measure of the most economical proportion between capital invested in source circuits and in capacitors. The minimum value of C can be obtained by taking the first derivative of C with respect to θ_2, and setting this derivative equal to zero as follows:

$$\frac{d\,c}{d\,\theta_2}=\frac{S\sin\theta_2}{\cos^2\theta_2}+R\left(0-\frac{1}{\cos^2\theta_2}\right)=0 \tag{35}$$

$$\text{therefore } S\sin\theta_2-R=0 \tag{36}$$

$$\text{or} \quad \sin\theta_2=R/S$$

This mathematical analysis, in effect, relates the monetary definitions set forth originally to the vector relationship shown in fig. 18.

since $\cos\theta=\sqrt{1-\sin^2\theta}$
the power factor can be expressed directly as:

$$\cos\theta_2=\sqrt{1-\left(\frac{R}{S}\right)^2} \tag{37}$$

The power factor determined from this formula then, is the optimum power factor which can be reached by applying shunt capacitors to the utility system. Typical results are plotted in fig. 19.

By substitution back in the original formula for total cost, an expression for minimum cost can be obtained.

$$C=\sqrt{S^2-R^2}+R\tan\theta_L \tag{38}$$

Since these formulas are derived on the basis of using a system cost/KVA for thermally limited equipment only, there is a slight error involved where portions of the system included have their capacity limited by voltage drop.

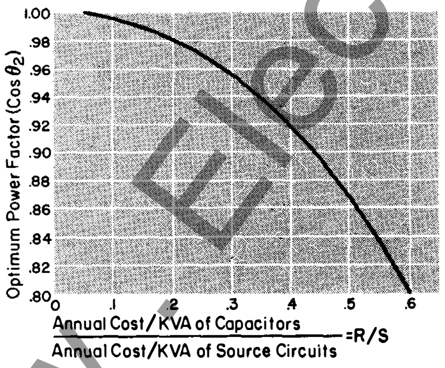


Figure 19. Optimum system power factor as a function of minimum system investment.

Using the optimum power factor derived in equation 37 as the ultimate operating power factor for any section of the system, the optimum amount of shunt capacitor installation can be determined as follows:

1. Determine the $ cost/KW or $ cost/KVA for source equipment or lines. This should be calculated for each section of the system. It is recommended that this cost exclude the generator. The reason for leaving the generator cost out of the calculation is because of the variable nature of its effect. Many utilities will not allot any cost for generation of KVAR since it is largely a matter of initial rated power factor and hydrogen pressure. If the capacitors prove economic without the generator cost being included, the system planner is using the most conservative approach.
2. Determine the $ cost/KVAR for installed shunt capacitors, also on a sectional basis.
3. Using equation 37 or fig. 19, calculate the optimum operating power factor for the section of the system being considered.
4. From table 2, obtain the appropriate correction factor. When the load KW is multiplied by this factor, the value of the optimum capacitor installation for that particular section of the system is obtained.

If the same procedure is to be applied to other sections of the system, it should be remembered that the operating power factor of any section will be modified by any capacitor installation between it and the load.

……

Example 1:
What is the optimum capacitor installation on a 4160 V distribution feeder with the following characteristics?

$KW_1=3000$
$\theta_L=80\%$
$S=125/KVA$
$R=12.50/KVAR$

from equation 37

$$\cos\theta_2=\sqrt{1-\left(\frac{12.50}{125}\right)^2}=.994$$

……

From table 2

optimum shunt capacitor installation

$=.61\times3000$
$=1830$ KVAR

This example indicates the correction to almost unity power factor is many times economically justified.

Primary Vs Secondary Installation

Some system planners prefer to consider secondary capacitors only on the basis of comparing them to primary units rather than overall system application. This method does save time, since it assumes that the primary capacitors are already economically justified. Since all the benefits that accrue to the primary installation can also be credited to the secondary units, justification of secondary units can be quickly checked by computing the additional gains attained by reduced reactive current through the distribution transformers and secondary circuits.

It might seem that secondary capacitors would always be justified since they offer the greatest loss reduction, higher released capacity, and greater increment of voltage increase directly at the metering point. Economically, however, these increased benefits may be completely offset by the higher cost/KVAR of the capacitor units in the 240 to 600 volt class, compared to 2400–7960 volt units. In addition, the individual units are necessarily small due to the size of the reactive load they are intended to correct. This increases the $/KVAR installation cost considerably.

It is possible to make a complete economic comparison on this special case by either method outlined under "economic comparison" page 11, however, a practical quick check method (from bibliography reference 7) is usually preferred. This procedure recognizes that the major advantage of secondary capacitors over primary units is the released capacity in the distribution transformer. Therefore, if the secondary installation can be justified on this basis only, the other benefits merely increase the economic gain. If, however, they cannot show an advantage over primary units due to released transformer capacity, the additional gain from other benefits is not usually sufficient to warrant further consideration.

The curves of fig. 20 were developed from the vector diagram of fig. 14 which is representative of the released capacity in thermally limited equipment. If voltage is the determining factor, a step-by-step economic comparison as discussed previously would be more accurate.

For the general case, however, it is possible to determine whether secondary units are economical knowing only the initial power factor, desired optimum power factor, ratio of secondary installed capacitor costs to primary costs, and distribution transformer

Determination of System Shunt Capacitor Requirements, Continued

costs/KVA. If the allowable ratio of KVAR (secondary) to KVAR (primary) according to the curves of fig. 20 is just equal to the actual ratio, other economic benefits such as reduced secondary losses and increased revenue from higher secondary voltage could be calculated to validify a positive decision.

……

Example M:
Are secondary capacitors justified on a feeder with the following characteristics?

$\cos\theta_L = 70\%$ (init. pf)
$\cos\theta_2 = 90\%$ (final pf)
$/KVAR (sec) = **$21**
$/KVAR (pri) = **$6**
$/KVA (trans) = **$10**

for use on fig. 20, therefore

$$\frac{\$/\text{KVAR (sec)}}{\$/\text{KVAR (pri)}} = \frac{21}{6} = 3.5$$

also

$$\frac{\$/\text{KVAR (pri)}}{\$/\text{KVA (trans)}} = \frac{6}{10} = .6$$

On fig. 20 enter the left curve at 70% power factor and move vertically to the intersection with the 90% power factor curve. Reading to the right, it is determined that .62 KVA of capacity has been released for each kilovar of capacitors added.

Moving to the right to the intersection with the .6 ratio curve for the installed costs of primary capacitors and the distribution transformer. Reading down from this intersection indicates that the maximum economical ratio of KVAR (sec)/KVAR (prim) is 2.05. Since the actual cost ratio is 3.5, the secondary capacitors are not justified.

……

3. Emergency Priority: Many capacitor installations are justified solely on their benefit to the system during emergency conditions. This is particularly true of large, high voltage banks. For example, a large bank of capacitors might be installed on a 138 KV bus with two incoming lines. The capacitor bank would be unenergized most of the time, however, when a lighting storm is in the area, it would be connected to the bus. Thus, if one line relays out during the storm, the remaining line will be able to carry the full load of the substation, because the reactive current will be supplied by the capacitor. Without the capacitor, the voltage on the bus would be too low and the whole load might be lost.

Another example is a utility which found it desirable to compensate for high reactive losses in an interconnecting transformer, normally not carrying appreciable load. This permitted maximum power interchange by operating at or near unity power factor during emergencies such as the loss of a large generator on the interconnected system.

Switched distribution feeder capacitor banks are sometimes installed strictly on their merit in improving voltage regulation. In this application they are compared economically and operationally with voltage regulators necessary to provide the same function. Only recently, with the advent of successful computer programs for comparing methods of voltage regulation has this practice become commonplace. Previously, the complexity and length of the calculations prohibited widespread studies.

Location of Capacitors Within Sections of System

The capacitor installations shown in fig. 17 indicate optimum locations within each section to give minimum system losses. This may or may not dictate exact placement of the capacitor banks within each section, other consideration often taking priority. This is particularly true on transmission and subtransmission banks, where availability of substation space or emergency conditions may exert greater influence on determining the location than minimum losses.

On secondary installations there are only two possible locations, one of which is a pole from which several service drops may originate as shown in fig. 5. The other is directly at the load itself, recently made possible through the availability of capacitor units which are an integral part of the watthour meter assembly.

Exact location of capacitor banks designated for installation on distribution primary feeders is, however, a problem with many variables, and no all-inclusive solution. In general, the analysis for optimum location on a particular feeder is based on maximum reduction in losses. However, the varying load pattern, changing conductor sizes, and effect of using fixed and switched capacitors on the same feeders, make it impossible to maintain an optimum location. This makes it necessary to continuously analyze individual feeders or to develop optimizing methods which apply to the general case, and consider the application only once – at the time of initial installation.

A practical approach to this problem, which has been verified in operation and theory, is to install the capacitor bank at a point ⅔ of the distance from the source to the end of the feeder. The amount of corrective KVAR and the reactive load factor will determine whether this gives maximum loss reduction – in general, however, results obtained are satisfactory. The overall effect

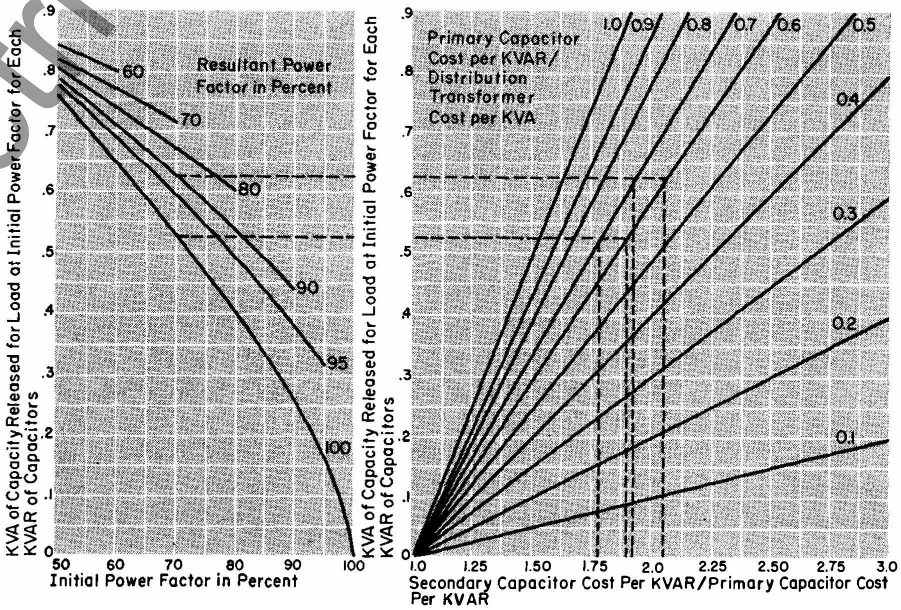


Figure 20. Economic comparison of primary vs secondary shunt capacitor installations.

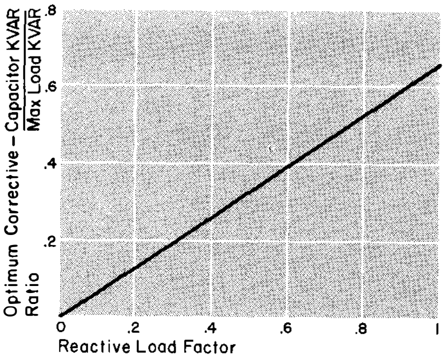


Figure 21. Variation of optimum shunt capacitor installation with reactive load factor.

will be a compromise between the economic capacitor bank size as determined from considering all benefits, and location on the basis of minimum losses.

If the installation is considered only on the basis of minimum losses, it can be shown that the optimum capacitor bank size is ⅔ of the load KVA and that optimum location is as mentioned previously. Results of a recent study (bibliography reference 8) show that this conclusion is valid except where the feeder has a low reactive load factor. Fig. 21 indicates how the optimum capacitor bank size varies with reactive load factor assuming the installation is going to be made at a point ⅔ of the distance between source and load.

The probability that voltage conditions, equipment standardization, or mounting limitations will force installation of more than one bank on a given feeder, add another variable to the problem of optimum size and location.

The following steps are suggested for general use in determining primary feeder shunt capacitor requirements:

Step 1: The optimum installation of shunt capacitors for a particular feeder should be determined either by the minimum cost method or to the limit described when the ratio of $ gain/KVAR to $ cost/KVAR equals unity. Both of these methods were explained under "economic comparison", page 11.

Step 2: The reactive load factor, which is the ratio of average reactive load to maximum reactive load, should be calculated. Using fig. 21, the maximum bank size to be installed at a point ⅔ of the distance from the source to the load can be obtained. If the total to be installed as obtained from step 1 is larger than that determined from fig. 21, the application should be made in two or more banks with the other banks installed back toward the source.

Step 3: When the limit of fixed capacitors is reached, as determined above, switched capacitors should be added until the economic limit is reached. The location of the switched capacitors will be dictated mainly by voltage conditions, however, generally they should be located in the latter ⅓ of the feeder.

Electrical Connection of Shunt Capacitors to Utility Systems

In making the actual connection to the power system, several questions relating to operational conditions must be answered. Such issues as switching, connection and grounding, and bank protection must be settled in advance of installation, and in some cases ahead of purchase. Each of these questions is discussed in the following paragraphs. The bibliography should be consulted if more detail is desired.

Fixed or Switched Capacitor Banks

All shunt capacitor banks must be tied to the utility system through a disconnecting device – at least capable of interrupting the capacitor current. On a switched bank this disconnecting device is operated regularly for system benefit, while on a fixed bank there is only occasional operation for capacitor maintenance.

On distribution circuits, fixed capacitor banks are usually installed until the light load reactive requirements are met. Any additional capacitors are installed with switches, usually pole mounted.

Transmission and subtransmission banks, because of the large block of capacitors, are always switched. The only problem is the maximum amount which can be switched at one time. This is usually limited by the switching equipment rather than the sudden voltage change caused by insertion or removal of the capacitor bank from the system. This is particularly true if load break disconnects or unmodified breakers are used for the switching means.

Very little switching has been attempted with secondary units because of the economics involved. Some use has been made of bimetallic elements responsive to ambient temperature.

Switching Devices

Typical switching devices based on system location are listed below.

Secondary circuits:
1. Bimetallic elements
2. Low voltage relays

Primary distribution feeders:
1. Single or three pole oil switches
2. Oil circuit breakers – 3 pole
3. Air circuit breakers – 3 pole

Transmission or subtransmission circuits:
1. Oil circuit breakers – 3 pole
2. SF_6 interrupter disconnect switches – 1 pole, ganged
3. Vacuum break disconnect switches – 1 pole, ganged

The cost of switching equipment must be included in the installed cost per KVAR of shunt capacitors. Their relatively high cost, particularly in high voltage applications, is sometimes the determining factor in the economic analysis. However, developments in low cost capacitor switching equipment are progressing rapidly, and in the future the economic advantage of large banks will become more apparent.

Switching Device Control

If a capacitor bank is to be switched regularly, a specific method of control must be selected. This control scheme, since it is the basis on which the capacitor bank will be put on and taken off the system, must be tailored to fit, as closely as possible, the system reactive requirements. Typical system parameters used to control capacitor switching devices are listed as follows:

1. Time switch
2. Voltage
3. Current
4. Voltage-time
5. Voltage-current
6. Vars or reactive current
7. Temperature
8. Manual

A recent study (bibliography reference 14) reveals that time switch control has been used in the majority of primary feeder installations, and that voltage control is the most common method on distribution substation banks. The other control schemes are used to a varying degree – usually in special situations. As utilities investigate more fully the var requirements of their systems, it becomes obvious that the more sophisticated control schemes such as current-time and watt-var will gain in usage. They unquestionably can result in a var supply more closely tailored to system requirements, and generally maximum gain from contingent benefits is assured.

Time control, however, has the advantage of being the least expensive to install, and in addition, it is independent of system operation, not requiring coordination with other voltage regulating equipment. Determining whether time control can be used requires study of the load cycle of representative feeders in the system. It is most effective on radial feeders where the load cycle is predictable and consistent. Large banks of capacitors on transmission buses have also been effectively applied using time switch control.

Determination of System Shunt Capacitor Requirements, Continued

Switching a capacitor bank in response to distribution system voltage variation can create a coordination problem with induction or step voltage regulators in the same area. However, using voltage as the switching intelligence is desirable because the sensing element is simple and readily available. Also, in many applications, voltage controlled banks result in gains from all benefits of shunt capacitors, since low voltage is a direct result of reactive current flow, which the capacitor reduces.

To resolve the coordination problem, consideration of the settings of any associated voltage regulator control is necessary. Excessive operations of either the capacitor bank or the regulator may occur due to hunting caused by improper coordination between the two devices. When voltage control is used on a primary feeder bank, the voltage change caused by the capacitor must be calculated from equation 10. The range of the voltage regulator must include or bracket the feeder voltage change calculated, so that operation of one will not cause operation of the other in the opposite direction. If coordination is attained, interaction between the two devices will not occur, and the capacitor bank will be in service the maximum time allowable based on system reactive requirements.

Connection and Grounding of Capacitor Banks

Shunt capacitor banks can be connected to a utility system much the same as a transformer, in that they can be either wye or delta connected. As a further breakdown, if connected in wye, the bank can either be grounded or ungrounded. The majority of present capacitor banks are wye connected. There is still some controversy over whether or not banks should be grounded or ungrounded. The three basic methods of connection are shown in fig. 22. The method used by a utility will depend on the type of system (grounded or ungrounded), fusing practices, economics, location, and possible inductive interference.

Generally, large banks on transmission, subtransmission, and distribution substation buses are wye connected. The size of the bank and protective scheme employed, determines whether the bank is grounded or ungrounded.

On distribution primary feeder banks, the majority of shunt capacitor banks are wye connected with the neutral grounded. Reasons for this preference are as follows:

1. Since the neutral is grounded, the mounting frame and capacitor tanks can be grounded, and the installation is considered safer from an operating viewpoint.
2. If a capacitor unit fails, high fault current results and positive fuse operation occurs.
3. The installation is considered safe if an open conductor occurs ahead of the bank, since the load side of the open circuit will not be above ground potential.
4. The bank is somewhat self protecting from lightning surges, since there is a low impedance path to ground.
5. Neutral inversion or resonant conditions, due to single phase switching between the source and the bank, is less likely to occur.

Many utilities, which use delta or wye ungrounded connected banks, base their practice on the following disadvantages of the wye connected solidly grounded bank.

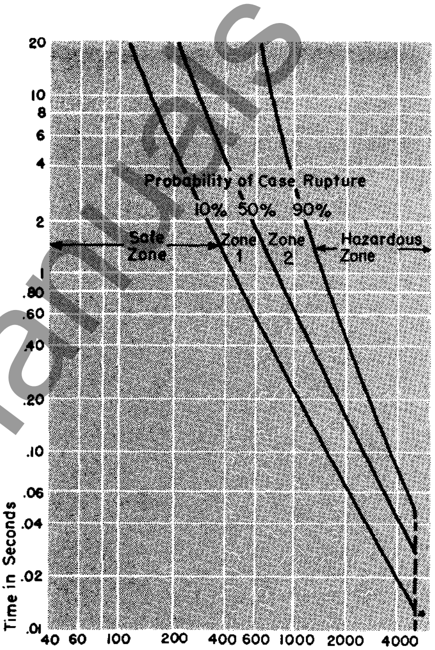
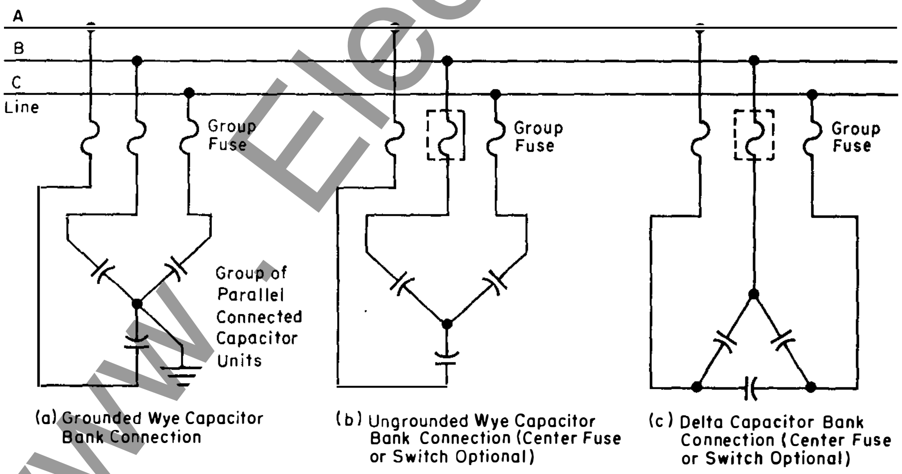


Figure 23. Case rupturing characteristics of 50 KVAR capacitor units.

1. Grounded wye banks may upset ground detection or relay schemes on ungrounded circuits since they provide a low impedance circuit to ground.
2. The capacitor bank, if grounded, provides a path for odd harmonic currents to flow, and inductive or telephone interference may result. Also, these harmonic currents may cause overheating of the neutral wire.

Both delta and wye-ungrounded banks have the advantage that only two switches are needed to de-energize the capacitor bank. Thus a utility may choose this connection for economic reasons in addition to the two disadvantages of the wye grounded connection mentioned above.

Where excessively high fault currents are to be expected, it is sometimes necessary to use the ungrounded wye bank which inherently limits the current caused by a faulted capacitor unit. This is illustrated by examination of fig. 23 which shows that the time to case rupture for 50 KVAR units at 5000 amperes or above is .8 cycle. The minimum clearing time for fuses is also .8 cycle and therefore group fusing coordination is difficult, if not impossible. The use of a wye connected, ungrounded bank which limits the current to 3 times normal, eliminates the necessity for going to expensive current limiting fuses to solve this problem.



(a) Grounded Wye Capacitor Bank Connection

(b) Ungrounded Wye Capacitor Bank Connection (Center Fuse or Switch Optional)

(c) Delta Capacitor Bank Connection (Center Fuse or Switch Optional)

Figure 22. Methods of connecting capacitor banks to utility systems.

To summarize, the most common practices regarding connection of shunt capacitor banks on utility systems are listed below.

1. Transmission, subtransmission, and distribution substation bus installations are usually wye connected, either grounded or ungrounded depending on the type of protection.
2. For delta or ungrounded systems, delta connected banks are usually used, except where fault currents are excessive, then ungrounded wye banks are needed.
3. For solidly grounded, four wire systems, wye connected-grounded banks are used in most locations. If excessive fault currents are expected, ungrounded wye banks are used. Economics may favor use of delta or wye-ungrounded banks since only two switches are required.

Protection of Shunt Capacitor Banks

Shunt capacitors, like other electrical equipment, are subject to failure from external or internal causes. Protective measures, compatible with the investment in the capacitor installation should be taken to protect both the system and the adjacent capacitors from individual unit failure if it occurs.

Large Bank Protection

The protection of large banks of capacitors, made up of series-parallel groups of individual units, and installed on transmission or distribution substation buses is a fourfold problem.

1. Surge protection must be provided to protect insulation to ground from lightning and switching surges. Even though shunt capacitor banks are somewhat self protecting in this respect, particularly the wye-grounded bank, lightning arresters are warranted. Line or intermediate type arresters are considered satisfactory for this use. They should be installed on the source side of any switching device so that the device itself is protected in case it is open. This also removes the necessity for the lightning arrester to discharge trapped energy from the capacitor in case a surge sparks over the arrester.

2. System protection against faults in the capacitor bus structure or leads can easily be provided for by overcurrent relays in the main switching device. These overcurrent relays are usually time delay, induction disc type, so they will override any capacitor bank inrush currents which may occur during switching operations.

3. Individual unit protection: When a capacitor unit fails internally, gases resulting from the arc acting on Inerteen® and other organic material cause extremely high pressures which may rupture the case walls. The damage to adjacent units or personnel from a violent failure is prevented by individual fuses on each capacitor. The manufacturer supplies the proper fuse rating which is coordinated with case rupture characteristics as shown in fig. 23. Only the failed unit is isolated and the rest of the bank remains in service.

This same fuse has an additional benefit in that it serves as an indicator that a unit has failed. Without this type of fusing, it would be difficult to detect a single unit failure on a large bank.

4. Overvoltage protection: When a shunt capacitor bank is made up of series connected groups of parallel units, the removal of one or more units from a group will cause overvoltages on the remaining units. The continuous voltage on any unit should not exceed 110% of rated voltage. The failure rate of capacitor units – normally less than one percent – increases very rapidly if they are subjected to overvoltages. Therefore, some type of protection is desirable on large banks, which will relay the bank off the system or sound an alarm, when a significant number of units have been removed from service due to fuse operation.

Many schemes of protection for this condition have been proposed and used. Actually, as mentioned previously, the type of protection many times dictates the connection and grounding of the capacitor bank. The most common methods of protection, briefly described and illustrated in fig. 24, are:

1. Three potential transformers connected across the lower groups in each phase of a grounded WYE bank with secondaries connected in open delta energizing a sensitive voltage relay. If sufficient capacitor units fail a voltage unbalance will result and the relay will operate on the residual voltage across the delta.
2. The double wye scheme where the capacitor bank is split into two identical wyes and left ungrounded. The neutrals of the two banks are interconnected through a current transformer. If a unit fails in one bank, an unbalance in voltage occurs, and a current will flow between the two banks. This current flow will be detected by a sensitive current relay on the current transformer secondary.
3. Direct resonant overvoltages occuring simply from the incident of connecting the capacitor bank to the circut. neutral current. When a unit fails, the resulting unbalance will cause a residual current to flow which can be detected by a sensitive relay.

Since the overvoltage protection problem is very complex, only brief comments are included here. If further information is required, consult the several references listed in the bibliography.

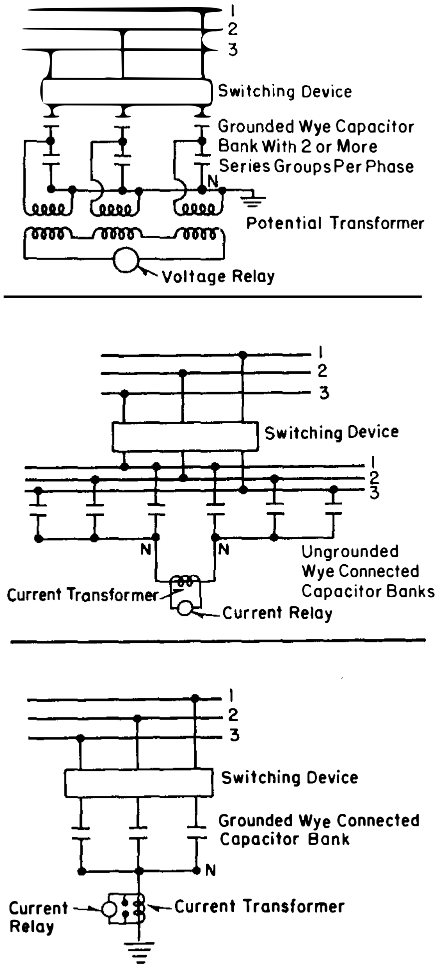


Figure 24. Common methods of overvoltage protection on large shunt capacitor banks.

Distribution Feeder Bank Protection

Because of its smaller size and consequently smaller total investment, the primary feeder bank warrants less protection than its larger counterpart. Fixed banks are generally protected against internal faults by a group fuse which is coordinated with the case rupture characteristics as described previously. This same fuse serves to disconnect the bank from the system – preventing a feeder outage – because of a capacitor bank fault.

Switched primary feeder banks are also protected by group fuses. These fuses are installed ahead of the oil switch and perform the same dual function described above. A typical installation is shown in fig. 2.

Surge protection for the fixed or switched feeder bank is usually a matter of company policy. About 50% of the banks are installed without protection, due to inherent surge ability of the bank and the small investment. If arresters are installed, they should be on the source side of the disconnecting fuse, to protect it in case the bank is de-energized.

Secondary Capacitor Protection

The secondary capacitor is protected by an individual fuse located on the capacitor bushing. This fuse is coordinated with case rupture characteristics.

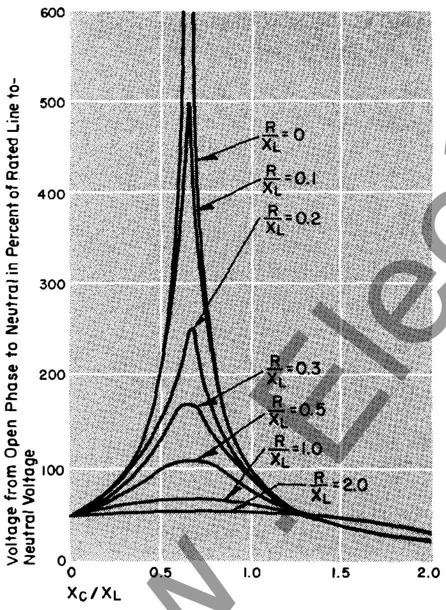


Figure 25. Overvoltages possible due to resonant conditions with one phase open.

Contingent Effects of Shunt Capacitors On Electric Utility Systems

There are several operating problems which may be encountered due primarily to an installation of shunt capacitors. These conditions must be recognized and corrected. The application of shunt capacitor units is still, however, one of the simplest and most straight forward of any electrical apparatus. The problems which arise are usually minor, and can usually be solved without disturbing other system components or the ultimate benefit of the capacitor installation.

Brief discussions of these operating problems and limitations of shunt capacitors are contained in the following paragraphs. More detailed information is found in references listed in the bibliography.

Telephone Interference

Due to the presence of equipment on an electric system which can inherently generate harmonic currents, an inductive coordination problem may exist between electric utility circuits and adjacent telephone lines. While the capacitor unit itself is not a source of harmonic currents, a wye connected-grounded bank can complicate or substantially increase the harmonic currents and voltages associated with any particular portion of the system. This is because the capacitor bank creates a reduced impedance path for harmonic current, since its impedance is inversely proportional to frequency.

Inductive coordination or telephone interference was more troublesome in the past than at present. With the improvement in telephone cables and equipment, very little trouble of this sort has been encountered in recent years. The most typical method of dealing with this problem is to rearrange the connection of the capacitor bank, if a problem does occur. In other words, if the bank is installed as a grounded neutral bank and telephone interference is increased in the area, a reconnection to an ungrounded wye bank can usually be accomplished, and the problem will disappear. In the event a reconnection is not possible, there are other methods of improving the situation such as auxiliary reactors and changes in the telephone circuit or relocation of the capacitor bank.

Effect of Shunt Capacitors On System Stability

As pointed out in a previous section, the installation of shunt capacitors on an electric utility system causes direct increase in the operating power factor of the source generators. Reducing the amount of reactive supplied by the generator reduces the field current magnitude for a given kilowatt load and terminal voltage. The static stability of a given set of load conditions is proportional to the voltage on the air gap line of the generator saturation curve, corresponding to the excitation current. As the exciting current is decreased, the voltage on the generator air gap line is decreased; therefore, the static stability limit is proportional to the generator exciting current. It has been generally observed, on turbine generators, if the operating power factor at full load is maintained at 95% lagging or below, there is no problem with static instability. Operating experiences have also indicated that some generators can be operated between 95 and 100% power factor with no apparent trouble with generator stability.

Any generator, regardless of its type, will be affected by the installation of shunt capacitors on the system, because of the natural decrease in exciting current. It may be necessary, as the operation of various generators on a system approaches unity, to analyze the reactive capability of each generator and determine where its maximum operating power factor should be, from a stability standpoint. The reactive capability curve of each generator can be obtained from the manufacturer, and the static stability limits for the generator plotted on the curve. This will enable the operators to determine the proper operating power factor, and eliminate any stability problems due to the installation of shunt capacitors.

Resonance Problems Encountered With Shunt Capacitors

The capacitor as a circuit parameter has the inherent ability to resonate at some frequency with circuit inductances. It follows, that under certain conditions resonance may occur with the capacitor in combination with shunt reactances to ground in the system or its equipment. Various phenomena of transient over voltages have occurred in the past which can directly be traced to the presence of shunt capacitor banks in the system. The problems generally fall into these following categories:

1. Overvoltages on the primary circuit with shunt capacitor banks installed on multi-grounded distribution circuits using single phase distribution transformers.
2. Transient overvoltages occurring on the secondary of a three phase distribution transformer with capacitors on the primary.
3. Direct resonant overvoltages occurring simply from the incident of connecting the capacitor bank to the circuit.

The transient overvoltages in the first two cases occur when one or two connectors are open, and a resonant circuit is set up between the transformer magnetizing reactances and the capacitor reactance to ground.

Single Phase Distribution Transformer Resonance

Typical overvoltages possible for a specific system condition are shown in fig. 25, for the first category mentioned above. Detailed studies of this phenomena can be found in bibliography references 20 and 21. The conclusions reached, concerning resonance of this type, are:

1. This particular resonance phenomena occurs only on four wire circuits having single phase line-to-neutral loads and ungrounded capacitor banks. The capacitors may be connected either in ungrounded wye or in delta.
2. Resonance occurs when one or two phases become open between the capacitor bank and the voltage source.
3. Serious overvoltage or neutral inversion occurs only during very light load conditions. This type of resonance would be more prevalent and well known except that the necessary values of capacitance, inductance and resistance are outside the range usually found on primay feeder circuits.
4. The resonance condition can be prevented by grounding the capacitor bank neutral, by preventing open phases between the capacitor and the voltage source, or by keeping circuit constants out of the critical range.

Three Phase Distribution Transformer Resonance

The second type of resonance phenomena can occur with a grounded bank of capacitors and on ungrounded wye-delta distribution transformer bank. With one or two phase conductors open, the capacitive reactance and magnetizing reactances of the circuit tend to form a resonant path of low impedance, with certain ratios of these reactances. This allows current to flow with resultant high voltages appearing on the secondary, or on the open phases of the primary. Circuit voltages can reach a magnitude of two to three times normal line-to-line voltage.

The trouble can occur even where shunt capacitors are not installed, due to the line-to-ground capacitance of the circuit, however, the presence of a wye connected shunt bank aggravates the situation. Evidences of the overvoltages possible when this condition occurs have been witnessed in burning out of appliance motors, grounding of low voltage heaters and flashover of secondary outlets.

The fact that a fuse cutout is usually located between the capacitor bank and the transformer increases the possibility of resonance occuring. An analytical presentation of this phenomena is contained in bibliography references 4 and 5 along with detailed methods of calculating the possible overvoltage. The conclusions reached with respect to cause and cure are as follows:

1. The transient voltages encountered may be eliminated by grounding the neutral of the distribution transformers.
2. Use of single phase switching devices between the capacitor bank and the transformer bank should be avoided.
3. Generally, dangerous transient overvoltages due to this type of resonance are limited to systems where the ratio of capacitance reactance to magnetizing reactance is three or less.

Direct Resonant Overvoltages

The phenomena associated with the third condition is an undesirable resonant effect causing high voltages when a capacitor bank is physically connected to a system. These overvoltages are often in locations remote from the capacitor bank, such as a lower voltage circuit inductively coupled through a transformer to the circuit on which the capacitor is located. Generally, the lower voltage circuit has a fixed capacitor bank electrically nearby. For example, high transient overvoltages might be observed near a secondary capacitor when a primary feeder capacitor bank is switched. This is due to a resonant circuit forming with secondary capacitor and the feeder and transformer inductance between the two capacitor banks. When the primary bank is switched, a transient frequency occurs, which triggers the resonant circuit causing the overvoltage. This type of trouble may result in fuse or lightning arrester failure on lower voltage circuits and possible bushing flashover or failure of instrument transformers on the high voltage circuit.

All three of the above mentioned resonant conditions are difficult to recognize and almost impossible to predict. Only after the trouble occurs can it be related to the capacitor banks, since a peculiar set of conditions must prevail before any direct resonance or ferro-resonance such as described can cause abnormal system voltages. If the problem arises, corrective conditions such as moving the capacitor bank, grounding either the transformer or the capacitor bank depending upon which type of trouble is encountered, removing single phase protective devices from between a capacitor bank and a transformer, or adding a damping impedance such as a reactor will usually remove the resonant problem entirely.

Operation of Capacitors Under Abnormal System Conditions

Capacitors are designed to withstand a continuous 60 cycle voltage of 110% of rating. The kvar rating of a particular capacitor at any voltage is found from the expression:

$$\text{KVAR} = \frac{E^2 \times 2\pi f C \times 10^{-6}}{1000} \qquad (39)$$

where

E = rated rms voltage
f = frequency, cycles/second
C = capacitance in microfarads

As the voltage goes up, the kvar increases as the square of the voltage. This will increase the current drawn by the capacitor, and therefore, cause extensive heating and failure of the capacitor, if the condition is prolonged. Therefore, it is important to be sure that no 60 cycle voltages over 110% of the capacitor rating be maintained continuously on the capacitor unit. The capacitor does, however, have designed margin for emergency overvoltage conditions as does most electrical apparatus. Tables 3 and 4 taken from the power capacitor standards indicate the time limit of various overvoltages and currents, to which the standard capacitor unit can be subjected without loss of expected life.

Table 3 – Recommended overvoltage limits for power capacitors

Duration	Multiplying Factor Times Rated RMS Voltage
½ Cycle	3.0
1 Cycle	2.7
15 Cycles	2.0
1 Second	1.75
15 Seconds	1.40
1 Minute	1.3
5 Minutes	1.2
30 Minutes	1.15

Table 4 – Recommended transient voltage and current limits for power capacitors

Probable Number of Switching Operations Per Year	Permissible Peak Transient Values Times Rated RMS	
	Voltage	Current
4	5	1500
40	4	1150
400	3.4	800
4000	2.9	400

Shunt Capacitors

Application to Electric Utility Systems

In the design of capacitors for application to power circuits, it is recognized that the operating voltage wave shape is not a perfect sine wave, and that the operating kvar of the capacitor will be higher than rated, by an amount proportional to the magnitude of harmonics present in the voltage wave. Recognizing again that generators and transformers are suppliers of odd harmonic voltages, it is necessary to design the individual capacitor units to withstand continuously some amount of harmonic voltage.

Capacitor units, therefore, have a thermal margin which is sufficient to allow for 60 cycle overvoltage as mentioned previously and some wave form distortion. The industry standard of 135% rated current must provide for both excessive fundamental 60 cycle voltage and harmonics combined. Thus, if the fundamental voltage is higher than normal, the margin for harmonics is reduced. A basic operating procedure is to limit the overvoltages at 60 cycles to no more than 105% of the rated voltage, so that the harmonic overvoltage margin will not be reduced excessively.

Fig. 26 indicates the effect of wave form on capacitor current and can be used to determine the permissible amount of overvoltages based on the rms measured voltage in percent of rated voltage.

The total rms voltage and rms current may be determined on a particular circuit from a conventional voltmeter and ammeter.

It is possible from the curves of fig. 26 to determine the percent of rated rms current allowable based on 135% permissible working KVA.

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Example N:
What is the maximum rms current (measured) a 100 KVAR, 2400 volt capacitor can be drawing and still be within thermal limits if it is being operated at 105% of rated voltage?

For fig. 26, assume that only 3rd harmonic voltages are at sufficient magnitude to cause overcurrent.

From fig. 26, the measured rms current can be 146% of rated current.

$$I_{RATED}=\frac{100}{\sqrt{3}\times 2.4}=24 \text{ amps}$$

permissible $I=1.46\times 24=35$ amps

This means that if the measured value of rms current does not exceed 35 amperes, the capacitor is operating within its permissible thermal limit.

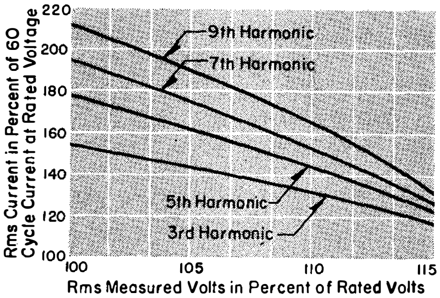

Figure 26. Thermal operating **limits of standard capacitors.**

Further Information

Apparatus	Section
Capacitor units and accessories	39-410
Open rack equipments	39-420
Pole mounted equipments	39-430
Metal enclosed equipments	39-440
Secondary network equipments	39-450
Coupling capacitors and line traps	39-600

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