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Power Factor Correction

By the Engineering Department, Aerovox Corporation

RECENT developments in the use of fluorescent lamps have brought to the fore the disadvantages of low power factor operation on a.c. power lines. The disadvantages are not only of importance to the power companies, who long have known and tried to correct them, but to the users of power as well, who up to now have done very little about low power factor operation.

The widespread use of fluorescent lights, which are low power factor devices, has made the use of power factor correction equipment of importance to both power company and power user. The power companies are concerned because these lamps require about twice as much current as an incandescent lamp of the same power rating. The electric bills, however, are determined not by the current but by the power in watts used. The user of these lamps is concerned because the number of lamps that can be connected to a branch circuit is only one-half the number of Mazda lamps of the same power rating. Moreover, the power lost in the line is four times greater than with an equivalent light load of Mazdas. The actual cost of this power may not be very great, but it does show up in a larger line voltage drop and increased flickering of the lights as lights or other loads are turned off and on.

To explain this, a brief review of the fundamentals of alternating current theory is desirable.

An alternating current or voltage differs from a direct current or voltage insofar as the flow of current, or the force of the voltage, is not always in one direction, but actually reverses itself twice a cycle. This can be observed by the shock received when an alternating voltage is applied to the body. When such a voltage, of sufficiently low value so that it can be endured for some time, is applied to the body, a vibrating or tickling sensation is observed. When a direct voltage is applied to the body, the sensation is not vibratory, but constant.

Graphically this is shown in Figure 1, which depicts the variation of the magnitude of the voltage with time. If the values above the zero line are considered positive, the current can be considered flowing from the generator to the lamp for one-half of the cycle, and from the lamp back to the generator during the second half of the cycle, as shown by the current lying below the zero line. A direct current is represented by the dotted line, which shows a constant current flowing in one direction at all times.

Since the voltage of the generator changes direction twice a cycle, the current will change its direction of flow in step with the voltage. The current, however, may lag behind the voltage, or even lead it depending on the type of circuit connected to the generator or the line. If the load is a coil, the current will lag the voltage, although maintaining the same rate of alternation. When a capacitor is connected to the line, the current through the capacitor will lead the voltage. This is illustrated in Figure 2. It will be noted that the effect of the capacitor is opposite to the effect of the coil, as far as the relative timing of the currents is concerned.

The use of the curves to illustrate the relative timing of the current and

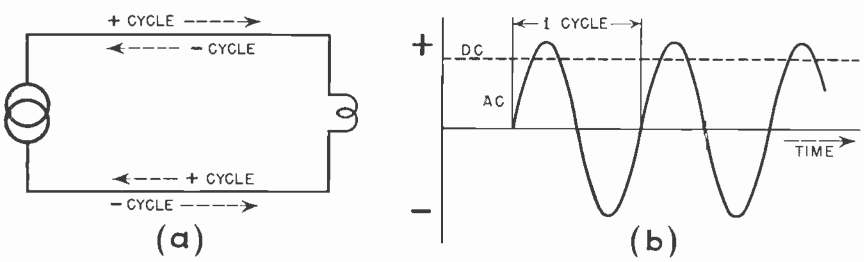

Figure 1

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TABLE 1

POWER FACTOR CALCULATION

P.F.	K.	P.F.	K.	P.F.	K.
20	4.899	47	1.877	74	.909
21	4.656	48	1.828	75	.882
22	4.433	49	1.779	76	.855
23	4.231	50	1.732	77	.829
24	4.045	51	1.687	78	.802
25	3.873	52	1.643	79	.776
26	3.714	53	1.600	80	.750
27	3.566	54	1.559	81	.724
28	3.429	55	1.518	82	.698
29	3.300	56	1.497	83	.672
30	3.180	57	1.442	84	.646
31	3.067	58	1.405	85	.620
32	2.961	59	1.368	86	.593
33	2.861	60	1.333	87	.567
34	2.766	61	1.299	88	.540
35	2.676	62	1.266	89	.512
36	2.592	63	1.233	90	.484
37	2.511	64	1.201	91	.456
38	2.434	65	1.169	92	.426
39	2.361	66	1.138	93	.395
40	2.291	67	1.108	94	.363
41	2.225	68	1.078	95	.329
42	2.161	69	1.049	96	.292
43	2.100	70	1.020	97	.251
44	2.041	71	.992	98	.203
45	1.985	72	.964	99	.142
46	1.930	73	.936	100	

The above table gives K values for each Power Factor. In order to obtain the required KVA, it is only necessary to subtract one K from the other and multiply this by the KW load. Example: Correct a 10 KW load 220V-60 cycle at 64% power factor to 90% power factor.

K at 64% = 1.201
K at 90% = -.484
.717

.717 × 10 KW = 7.17 KVA required

From table below, 220V = 55 mfd. per KVA. The corrective capacity necessary is 55 × 7.17 = 394 mfd.

VOLT	MFD. PER KVA
110V.	219 mfd.
220	55
330	24.3
440	13.8
550	8.76
660	6.09
880	3.42

voltage is rather awkward, and to simplify this, the vector form is used. By definition, a vector is a quantity having magnitude and direction. Thus a wind blowing toward the northeast with a velocity of ten miles per hour could be represented by an arrow ten units long pointing northeast. A wind can be considered more or less constant in magnitude and direction for fairly long periods of time, but alternating currents or voltages change direction rapidly, reversing 120 times per second for a 60 cycle system. For this reason, vectors used to represent or illustrate alternating currents or voltages are considered as rotating, although they are always drawn in a fixed position. The direction of rotation is normally counter-clockwise so that the relative timing of two or more alternating currents or voltages can be represented by the position of their vectors. Figure 3 shows how the currents and voltages of Figure 2 would be depicted.

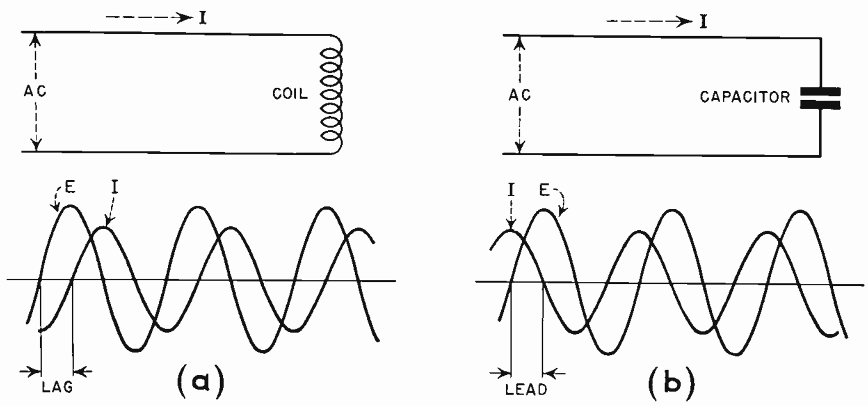


Figure 2

From a power point of view, the alternating current system differs from the direct current system in that the product of current and voltage is not power in watts. To obtain the power in watts for an alternating current system, it is necessary to multiply the product of current and voltage by a factor called "power factor". The value of the power factor can never be greater than "1" and is usually less than "1". In fact, the power factor may be "zero" so that it is theoretically possible to have a circuit in which current is flowing, yet no power (such as would be recorded on a watt-hour meter) would be taken from the line. Or, from the other point of view, a given power load, such as an induction motor operating at 50 per cent power factor, would require twice as much current as a motor driving the same load but operating at 100 per cent power factor. The wire necessary for running the 50 per cent power factor motor would be twice as large in cross-section. The same can be said of any load operating at low power factor. 100 per cent power factor is the ideal condition, but power factors of 85 to 95 per cent usually are considered satisfactory.

Normal devices, such as motors and fluorescent lamps, have lagging power factors; while Mazda lamps and heaters have power factors which are nearly 100 per cent. Capacitors, however, have power factors that are nearly zero (about 1% or less), but leading. Since the current taken by a capacitor leads the voltage, it is possible to use capacitors to cancel out the lagging currents of devices which operate at lagging power factors. Connecting a capacitor of the correct value across the line at the terminals of a motor will cause the line current to decrease.

To determine the current value of capacitor for any given load requires the use of trigonometry, or charts that have been made to eliminate the use of trigonometry as such. Table 1 gives the multiplying factors which are used to compute the voltampere capacity of the capacitor required for the correction of any load.

The Table is based on the following theory:

Figure 4 shows the vector diagram for a single phase load of lagging power factor before and after correction. Note that the actual power is unchanged except for the small amount taken by the capacitor. The total load is considered as consisting of two parts, the power components marked "KW" and the wattless component marked "reactive KVA" or "current". To improve the power factor, it is necessary to reduce the magnitude of the reactive component. The connection of a capacitor across the line at the load terminals will reduce the load reactive component by the value of the capacitor KVA component. The equations are given below.

(1) $$\text{P.F.} = \cos\theta = \frac{KW}{KVA}$$

(2) $$KVA = \frac{KW}{\text{P.F.}}$$

(3) before correction
$$RKVA = KVA \sin\theta = KW \tan\theta$$

(4) after correction
$$RKVA = RKVA - \text{Capacitor KVA}$$

$$\text{New power factor} = \cos\phi = \cos\tan^{-1}\frac{RKVA}{KW}$$

(5) $$\text{Cap. KVA} = \frac{0.377\,CE^2}{1{,}000{,}000}$$

E is line voltage.
C is capacity in microfarads.

$$C = \frac{2{,}650{,}000\ KVA}{E^2}$$

Table 1, however, simplifies the computation as shown by the following example:

A five horsepower single-phase motor operates on a 220-volt line, drawing 4.4 KW and 28 amperes. It is desired to improve the power factor to 95 per cent.

The present power factor:

$$\text{P. F.} = \frac{4400}{220 \times 28} = \frac{4400}{6160} = .715$$

From the Table, the RKVA factor for .715 P.F. is .98, and for .95 P.F. the RKVA factor is .324. The difference between the two RKVA factors multiplied by the power, which is 4.4 KW, gives the capacitor KVA required.

Thus the capacitor KVA = 4.4 (.978—.329) = 4.4 × .649 = 2.86 or the required capacity is:

$$C = 2{,}650{,}000 \left(\frac{2.86}{220^2}\right) = 157 \text{ mfds.}$$

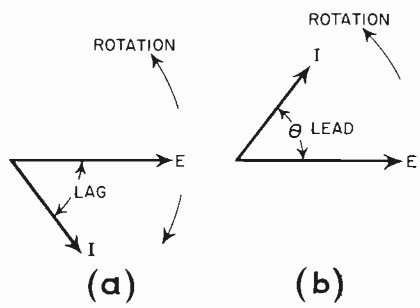


Figure 3

For polyphase systems the capacity will be divided into as many groups as there are phases, and one group will be connected across each phase. The computations will be exactly as outlined above if the KVA and KW values are known. If the current and voltage between lines and the line current are given, the KVA is found by the following equations:

For single phase (2 wire) $\frac{E_L I_L}{1000}$

For two phase (3 wire) $\frac{2E_L I_L}{1000}$

For three phase (3 or 4 wire) $\frac{\sqrt{3}E_L I_L}{1000}$

E_L = voltage between phases or lines
I_L = current in line

THE ECONOMICS OF POWER FACTOR CORRECTION

In addition to the installation of power factor correction equipment, when required by law or power company regulations, it is often economical to install such corrective equipment in existing wiring systems. For example, the wiring capacity of a system can be increased without changing the wire size as was done in the following installation.

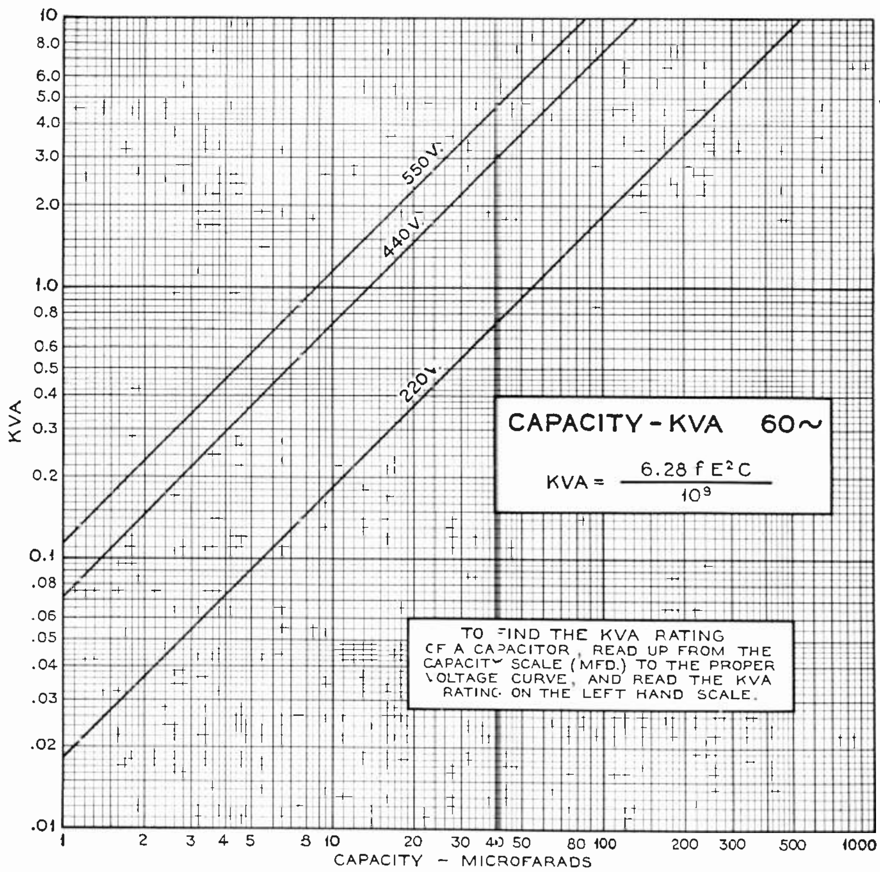


Figure 5

A small plant had a connected load of 73, ¼-horsepower motors, and two 5-horsepower motors. The line feeding the fractional horsepower motors was a 3/o rubber-covered cable with a capacity of 175 amperes. Increased business required the installation of 15 additional machines of the same type. This would require running an additional line from the main panel board. The installation of .25 KVA capacitors across each motor decreased the full load current of each motor from 3.3 amperes to 2.5 amperes and decreased the maximum line current from 168 amperes to 129 amperes. Thus the capacity of the existing line was increased by 30 per cent, allowing the installation of 22 additional machines without interruption of service, and saving the cost of running 350 feet of new conduit and pulling wire.

In addition to the increased capacity, a saving in power resulted from the decrease in line current. This saving amounted to 123 KW hours per month based on 23 eight-hour working days. The voltage drop was also decreased, resulting in better operation of the machines.

The most economical size of capacitor for any installation will depend on the relative saving and the cost of the capacitor. Usually it is not economical to correct the power factor to better than 90 per cent, although there may be cases where 100 per cent correction would be desirable. Such may be the case where the increased line capacity warrants the improvement to 100 per cent.

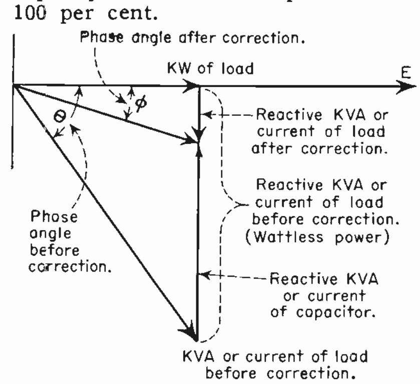
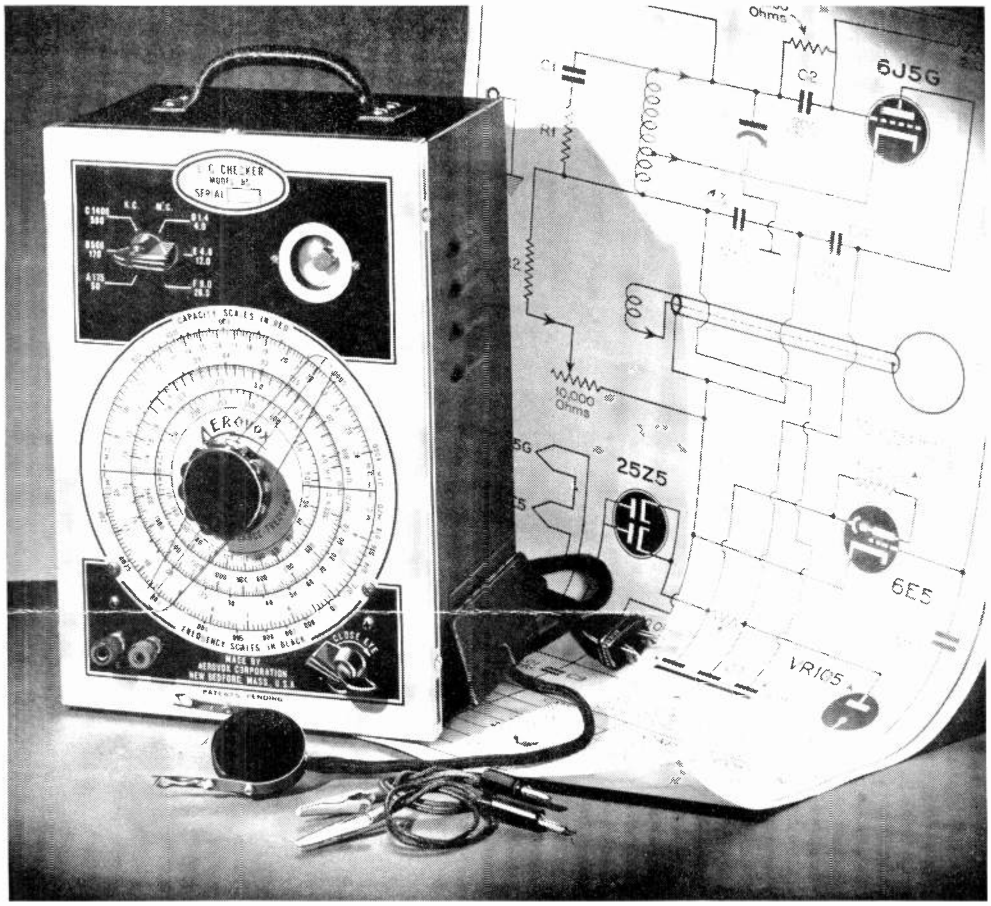


Figure 4

Over-correction of power factor is seldom warranted. As the capacity across any line is increased, the line current will decrease until 100 per cent power factor is reached and then will increase again. The power factor also decreases, but is said to be leading.



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