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The AEROVOX Research Worker

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The Influence of Power Factor and Capacity on Filtering Efficiency

PART 1

By the Engineering Department, Aerovox Corporation

ELECTROLYTIC condensers have become so commonly used that they are taken for granted as efficient components for power packs and similar filters. Economy and conservation of space are some of the main considerations in filter design, hence the use of electrolytics.

When this type of condenser was new, the relative merits of the paper condenser and the electrolytic condenser were widely discussed. The result of many measurements and their interpretation was published in the "Research Worker" for October-November 1931. Here it was amply demonstrated that the cost of an electrolytic condenser, as compared with a paper one of the same capacity and voltage rating was much lower. In the same way, the bulk and weight of the electrolytic is much less. Furthermore, the presence of some leakage and a less favorable power factor was proven to be quite unimportant from the standpoint of filtering efficiency.

This subject is becoming of interest again due to the appearance on the market of paper condensers of the same size and shape as the electrolytic type and labelled as a suitable replacement for 8 microfarad electrolytic condensers. These replacement condensers do not have their capacity marked on the label but they are of the same size as an 8 microfarad electrolytic. Now it is well proven that per microfarad an electrolytic condenser has the smallest volume. How then, can a paper condenser suitable for replacing it, have the same size?

Some measurements of these condensers show that their capacity varies between 4 and 5 microfarads, some being as low as 3.6 microfarads. By this, the manufacturer evidently means to imply that the loss of filtering efficiency due to lower capacity is offset by the better power factor. Or, in other words, that a 4 microfarad paper condenser is equally efficient in filtering as an 8 microfarad electrolytic.

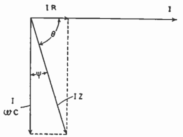

Fig. 1

In order to prove the fallacy of this reasoning we shall show the effect of power factor and capacity on filtering efficiency and shall see what happens to the ripple voltage when such replacements are made.

POWER FACTOR

Before proceeding it would be well to refresh the memory of our readers by defining what is meant by "power factor."

When the power in a d.c. circuit is to be determined, one simply multiplies the voltage and the current and obtains the power in watts. In an a.c. circuit the product so obtained must again be multiplied by a factor in order to arrive at the watts. This factor is called the power factor and is equal to the cosine of the phase difference between current and voltage.

Similarly, the power factor of a condenser equals cost θ, where θ is the angle whereby the current leads the voltage. This is illustrated in the vector diagram of Figure 1. The reference vector, I, represents the current flowing through the condenser and the vector IZ represents the voltage. The angle between the two, θ, is the phase difference and the angle $\psi = 90^\circ - \theta$, is called the phase angle of the condenser. Resolving the vector IZ into its resistive and reactive components, we find IR and $I/\,2\pi fC$.

Trigonometry now tells us that $\cos\theta = \sin\psi = R/Z$. For a good condenser, the phase angle is very small. For such small angles we may write $\sin\psi = \tan\psi = \psi$ (ψ measured in radians) Since it is more practical to us these last equations and the error is negligible, the power factor is usually defined as

$$\text{power factor} = \frac{\text{resistance}}{\text{reactance}}$$

In order to show that the error is very small, the table of Figure 2 has been calculated. Here the first column shows the power factor in percent, the second shows the phase angle in degrees, the third column shows the resistance of an 8 mfd. condenser at 120 cycles calculated from the simplified formula and column 4 as calculated by the correct formula. Note the small difference between the two: for low power factors the difference is so extremely small that we have shown the resistance as being identical. The last column lists the impedance (to close approximation) such a condenser would have at 120 cycles.

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POWER FACTOR	PHASE ANGLE DEGREES	RESISTANCE = Z X POWER FACTOR	RESISTANCE = Xc X POWER FACTOR	IMPEDANCE
.1	0° 3′	.166	.166	166.
.5	0° 17′	.830	.830	166.
1.	0° 34′	1.66	1.66	166.
5.	2° 52′	8.32	8.30	166.2
10.	5° 44′	16.7	16.6	166.8
15.	8° 38′	25.2	24.9	167.9
20.	11° 32′	33.9	33.2	169.3
25.	14° 29′	42.9	41.5	171.4

Fig. 2. The figures in columns 3, 4 and 5 are given for 8 mfd. condensers at 120 cycles ($X_c = 166$ ohms). Note the small difference in columns 3-4.

SHUNT OR SERIES RESISTANCE

A condenser with a power factor of more than zero can be considered as a perfect condenser with a resistance across it or with a resistance in series. There are equations to convert a shunt resistance into an equivalent series resistance and vice versa. Yet, the two types of losses have different causes. A shunt resistance would be caused by leakage in the dielectric while a series resistance is caused by bad contacts, resistance in the foils themselves, etc. The electrolytic condenser has some leakage and the average radio man labors under the erroneous impression that this causes its relatively high power factor. That this is not so easily shown.

The normal leakage of an electrolytic condenser may be .2 ma. per microfarad. An 8 microfarad condenser would have a leakage of 1.6 ma. at 500 volts. This can be considered as a shunt resistance of 500/ .0016 = 312500 ohms. The equivalent series resistance for this leaage would be

$$R_s = \frac{X_c^2}{R_{sh}} = \frac{166^2}{312500} = \frac{27556}{312500} = .09 \text{ ohms approx.}$$

The power factor due to leakage is then resistance/ reactance .09/166 = .00054 or .054 percent.

It is then obvious that the power factor is due to other causes. In order to take the worst possible condition, in future examples we shall use a power factor of 20 percent. A good electrolytic condenser generally has a power factor of 10 percent or less, so by assuming 20 percent and proving this to have negligible effect on filtering efficiency we are on the safe side.

For an 8 mfd condenser at 120 cycles, a 20 percent power factor means a series resistance of 33 ohms and an impedance of 169 ohms.

EFFECT OF POWER FACTOR

Assume a simple power pack as shown in Figure 3 and let it be required to calculate the effect on the residual hum if the three condensers with zero power factor are replaced by three others of the same capacity but of 20 percent power factor.

For purposes of calculation we can consider C1 to be in series with the tube a.c. resistance across the transformer secondary and by neglecting the rest of the filter and the load across C1 no large error is introduced since the reactance of this shunt circuit is very large compared with the reactance of the condenser C1. This will hold true as long as L and C2 together have a resonant frequency far below the rectifier frequency. (The impedance of an 8 mfd condenser at 120 cycles is 166 ohms and of a 30 henry choke 22620 ohms.)

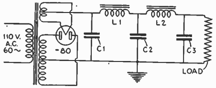

Fig. 3

Now we come to consideration of the effect of power factor on the filtering efficiency of various condensers used in a typical circuit.

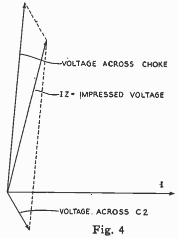

Fig. 4

Let us assume a certain amount of alternating current to be flowing through the tube and through the first condenser and let us determine the ratio of a.c. hum voltage across the first condenser with condensers of various power factor. As mentioned previously, we will consider the cases of a zero power factor condenser and the cases on the condenser with a power factor of 20%.

The hum voltage across condenser C1 will be proportional to the impedance of that condenser assuming a constant or practically constant impedance of that circuit. The impedance of an 8 mfd condenser at 120 cycles is given by the equation

$$Z = \frac{1}{\omega C}$$

substituting values:

$$Z = \frac{1,000,000}{6.28 \times 120 \times 8} = 166 \text{ ohms}$$

This refers to a perfect condenser with zero power factor. Assuming that this condenser is replaced by another one of the same capacity but with a 20% factor, the impedance of this condenser is given by the equation

$$Z = \sqrt{R^2 + X_c^2}$$

$$Z = \sqrt{3.32^2 + 166^2} = 169.3$$

The ratio of increase in hum voltage due to power factor is then

$$\frac{166}{169.3} = 1.02 \text{ or } 2\%$$

Turning our attention now to the second condenser, C2, this can be considered to be connected across a generator delivering a voltage $\Delta E1$, in series with the choke. Assuming again a perfect condenser for the first condition we find the ratio between $\Delta E1$ and $\Delta E2$. The total impedence in the circuit is

$$Z = \sqrt{R^2 + (X_L - X_c)^2}$$

substituting values:

$$Z = \sqrt{400^2 - (22620 - 166)^2} =$$

$$= \sqrt{160000 + 504182116} = \sqrt{504342116}$$

$Z = 22456$ ohms.

Here we assumed a 30 henry choke with a resistance of 400 ohms.

The voltage across C2 is then X/Z times $\Delta E1$ or $\Delta E2 = 166/22546\ \Delta E1$ volts.

When C2 is replaced by a condenser of 20 percent power factor, Z becomes

$$Z = \sqrt{433^2 + (22620 - 166)^2}$$

$$= \sqrt{187489 + 504182116} = \sqrt{504369605}$$

$Z = 22458$ ohms, practically the same as above.

and the voltage across C2 is

$$\Delta E2 = \frac{169.3}{22458} \text{ohms}$$

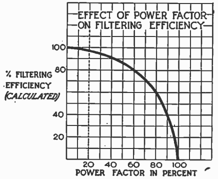

Fig. 5

The ripple voltage has then been changed by the following ratio

$$\frac{169.3 \times 22458}{22456 \times 166} = 1.02 \text{ (nearly)}$$

Finally, it is left for us to calculate the effect of changing the third condenser. This is shunted by the load and the load has an a.c. impedance which is large compared to that of the condenser. Therefore it is permissible to neglect the load and the problem is then the same as the one just solved . The increase in hum across C3 by replacing it with a 20 percent power factor is 1.02 (nearly).

The total increase of replacing all three condensers is the product of the individual ratios, or,

$$1.02 \times 1.02 \times 1.02 = 1.06$$

The case of the second and third condenser can perhaps be visualized best when a vector diagram is drawn of currents and voltages across choke and condenser.

Figure 4 shows such a vector diagram. It is not drawn to scale for in reality the impedance of the choke is about 1500 times the impedance of the condenser and the angles are of such a nature that it cannot be drawn in a small space. It should be remembered then, that the vector representing the voltage across the choke should be much longer. Where this is the case, the voltage across the condenser is practically proportional to the impedance of the condenser. The 20 percent power factor results in an increase of impedance of only 2 percent, so the increase in hum is about the same. When the capacity is halved, however, the impedance becomes twice as high and the hum twice as high but this is another story which we shall discuss in next month's "Research Worker."

So far, a frequency of 120 cycles has been considered. The harmonics cause no difficulty. When the frequency is twice as high the choke impedance is twice as high and the condenser impedance is half as much. The proportion E1/ E2 is then 4 times as good as for the fundamental and the increase of hum due to power factor is the same as for the fundamental.

The engineering department of the Aerovox Corporation has collected figures showing the influence of power factor on filtering efficiency. A curve of the results is shown in Fig. 5. A condenser of zero power factor is assumed to have 100 percent efficiency of filtering. The curve shows that the loss in efficiency is not important for power factors below 20 percent. Moreover, the curve shows clearly the law of diminishing return when trying a better and better power factor.

THE DECIBEL

The effects of power factor have thus far been expressed in voltage ratios, but when a man has replaced a few condensers and judges the result with his ears—as men will—that doesn't mean very much to him. Therefore a unit has been devised which is more in accord with the reaction of the human ear.

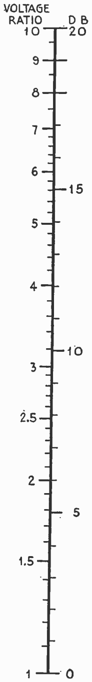

Fig. 6

When someone listens to a continuous sound of fixed intensity and this sound is suddenly increased, the subject cannot judge at all how many watts have been added. Further investigation will show that there is a certain percentage of power increase which represents the lowest change the ear can detect. And to the ear it does not seem like the power has been multiplied by any factor, it just seems that something has been added. The same can also be expressed this way. Suppose that a sound of 1 watt power was increased (multiplied by two) by 1 watt ,then this would seem to a listener as a certain noticeable increase. Then if this same listener would have to judge the increase from ten to twenty watts, he would say that "it's the same difference." The change from 1 to 2 watts is the same to the ear as from 10 to 20 watts.

One can call the least noticeable increase in volume a "sensation unit" and let the factor of power increase be a (greater than 1), then it follows that the addition of one sensation unit to the sound means multiplying the power by a. An increase of two sensation units corresponds to a power ratio of a^2 three sensation units increase mean multiplying the power by a^3, etc. So the response of the ear is proportional to the logarithm of the ratio of power increase (or decrease). This last sentence already gives the definition of the fundamental unit, the bel, named after Alexander Graham Bell. For practical purposes this unit is too large, so one uses the "decibel," equal to one tenth of a bel. The number of db. gain or loss, is then equal to ten times the common logarithm of the power ratio. Since power is proportional to the square of the voltage or the current as long as the impedance is constant, the gain or loss in db. is also given by

$$db = 20 \log_{10} \frac{E_2}{E_1} \quad db = 20 \log_{10} \frac{I_2}{I_1}$$

where E1 and E2 are the voltages before and after the change under investigation and the same goes for I1 and I2.

Figure 6 shows graphically the relation between db. and voltage ratio. The use of this chart can be extended beyond a voltage ratio of 10, by adding 20 db. for every place the decimal point has been moved to the right. For instance, if one wishes to find the db. equivalent to a voltage ratio of 56, look up 5.6 on th evoltage ratio scale, find its corresponding value in db., which is 15, so a voltage ratio of 56 corresponds to 35 db.

Having so defined the unit it is necessary to remark that a difference of 2 db. is about the lowest a listener can detect.

Converting now our voltage ratios into db., we find that the change due to power factor is +.017 db. for C1 and +.017 db. each for C2 and C3 making a total of +.051 db. This is much less than the least noticeable increase.

Changing electrolytic condensers and replacing them with paper condensers will result in a slight—unnoticeable—decrease of hum level. But replacing them with paper condensers of a different capacity is a different story.