Power-Factor Correction

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Users of electric energy, especially in the field of power applications, sooner or later become interested in power-factor and methods used in correcting bad power factor conditions. This interest is usually brought about by the bill presented to the user by the power supplier. On this bill the user will observe an energy charge, a demand charge, and a charge or penalty for low power factor. Usually, he can easily understand the energy charge and the demand charge, but he may not understand the power factor charge or penalty. He may not understand what he is being asked to pay for, what benefit, if any, he has received, or what he has done to justify such a penalty. We shall then consider in some detail the meaning of the term "power factor", why the electric supplier makes a charge on the basis of power factor, and what the user can do to eliminate or reduce this charge.

In defining the term "power factor," we can say that it is a factor by which "apparent power" is multiplied to obtain "real power." This leads to an explanation of the terms "apparent power" and "real power." In a direct-current circuit the power required to supply a given load is determined by multiplying the current in amperes taken by the load by the voltage in volts across the load. This product is expressed in watts, and if this product happens to produce 746 watts, the load is equivalent to one horsepower. However, if instead of using a direct-current voltage, an alternating-current voltage is applied to this same load, we may find that a higher voltage must be applied to produce the same current in amperes. We may observe that the product obtained by multiplying this alternating current by the voltage across the load is 1000. As the load has not changed, we are still supplying 746 watts, since the value in amperes of the current to the load is the same in both cases, but the product of volts multiplied by the amperes in the first case differs from the product of volts multiplied by the amperes in the second case. In the first case we called this product watts; in the second case we shall call this product volt-amperes. Now, watts is the "real power" and "volt-amperes" is called the "apparent power," and to reduce the "apparent power" to "real power," we must multiply the apparent power, in this case, by 0.746. This factor 0.746 is called the power factor.

We shall now examine these two conditions in a more visible manner by the use of vector diagrams. We shall choose a scale for volts and a scale for amperes and shall represent these two quantities by arrows so that the length of the arrow represents the magnitude of the quantity, and the directions of the arrows represent the relative directions of the quantities. Fig. 1 represents the magnitudes and the relative

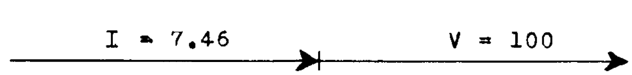

Figure 1

directions of the voltage and the current in the direct-current case, and Fig. 2 represents these same values in the alternating-current case. The voltage vector is designated by the letter V, and the current vector, by the letter I.

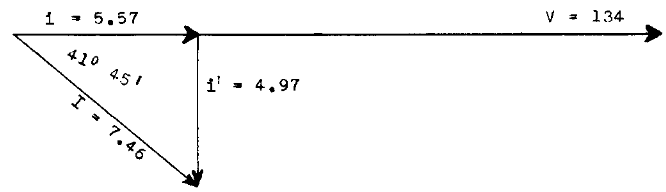

Figure 2

In Fig. 1 the current vector is in phase with, or in the same direction with, the voltage vector so that the product of the two produces watts, but in Fig. 2 the current and the voltage vectors are not in phase; thus their product produces volt-amperes. In order to reduce volt-amperes to watts, we must multiply volt-amperes by the power factor, which is 0.746. We have seen that the in-phase current multiplied by the voltage gives us watts in the direct-current case; thus in the alternating-current case, the in-phase component of the current mulitplied by the voltage should also give us watts. As volt-amperes multiplied by 0.746 gave us watts, the in-phase component of the current in the alternating-current case should be 0.746 I, or the current I is 41°-45' out of phase with the alternating current voltage, since the cosine of 41°-45' is 0.746. From Fig. 2 we see that the in-phase component of the current is represented by the vector i. We also see another component of the current I, which is perpendicular to the voltage vector, and it is designated as i'. The value of i' is equal to I sin 0 or 0.666I, and is called the out-of-phase component, or reactive component.

We have seen that the in-phase component of the current multiplied by the voltage gives real power in watts and that the in-phase component of the current is obtained by multiplying the current of the cosine of the angle between the current vector and the voltage vector. This angle is usually designated by the Greek letter θ. Therefore, to obtain the watts delivered to a single-phase load by an alternating-current circuit, we multiply the voltage by the current by the cosine of the angle between them. Expressed mathematically this becomes VI cos θ.

Electric machinery is usually rated in volts, amperes, and volt-amperes or kilovolt-amperes. In the case of alternating-current machines, the voltage rating is determined by the insulation and the dimensions of the magnetic circuit, the current rating is determined by the machine's ability to dissipate heat, and the kilovolt ampere or kva rating is the product of the volts multiplied by the amperes divided by one thousand. Therefore, the kva rating of an electric machine is determined by its ability to get rid of the heat generated within the machine by the electric current flowing through the resistance of the windings.

This heat is expressed as I^2R, where R is the resistance of the windings and I is the current in the windings. This product I^2R is in watts, and 3413 watts equal one Btu.

Now, since the capacity of an electric machine determines the current it can carry and since only the in-phase component of this current represents real power or real energy, a reduction in power factor reduces the capacity of this electric machine for supplying real power. If the angle between the current and the voltage vectors should approach 90 deg., the real power delivered by the machine would approach zero, with the machine carrying its full kva load, since the cosine of 90 deg. is zero. From this it can be seen that the ability of an electric machine to deliver useful energy or to perform useful work is dependent upon the power factor of the load. If a power supplier is required to furnish a load of 100 kva at unity power factor, or 100 kilowatts, he can do so with a 100-kva transformer, but if the power factor of this load should decrease to 0.5, the power supplier would have to install a 200-kva transformer to supply this load of 100 kw. This not only affects the size of the transformer at the load, but it also affects the capacity of all electric equipment and lines back to and including the generators in the power plant. As the power supplier is required to make a larger investment to supply low-power-factor loads than he would to supply the same loads at a higher power factor, he is legitimately entitled to receive greater compensation for the low-power-factor loads. Low power factor also reduces the useful capacity of the user's equipment. It is, therefore, of interest to the user and to the supplier of electric energy to provide ways and means for preventing low power factor, or for correcting it at the load if the nature of the load is such that it must operate at a power factor other than unity.

Electric lights, electric heaters, and induction motors represent the bulk of the electric load on the average power system. Electric lights and heaters are basically unity-power-factor loads and do not present a power factor correction problem. This leaves the induction motor as the chief offender in the creation of low-power-factor loads. The induction motor must draw from the line or from the source an out-of-phase or reactive component of current for excitation purposes, and the magnitude of this component is practically constant regardless of the load on the motor. The in-phase component of current taken by the induction motor may be called the power component, and it increases or decreases as the load on the motor increases or decreases. From an examination of the vector diagram of Fig. 2, it can be seen that the greater this in-phase component of the current becomes, the out-of-phase component remaining constant, the smaller the angle θ becomes and the greater the cosine of θ becomes. This means that the greater the load becomes on an induction motor the better the power factor will be. This improvement is, of course, limited by the capacity of the motor. An induction motor, when running light, may have a power factor of around 0.2, but when it is fully loaded, this power factor may increase to 0.9. At overloads this power factor will be higher. At loads between no-load and full-load, the power factor will be somewhere between 0.2 and 0.9, depending upon the load, as shown by the curve of Fig. 3.

The first step to take, then, in improving the power factor of an induction motor load is to have the motors operate at or near full-load at all times. This means that care should be taken in choosing the proper size of motor for a given load. It is poor economy to select a 15-hp motor to pull a 10-hp load. This results in a higher purchase price for the

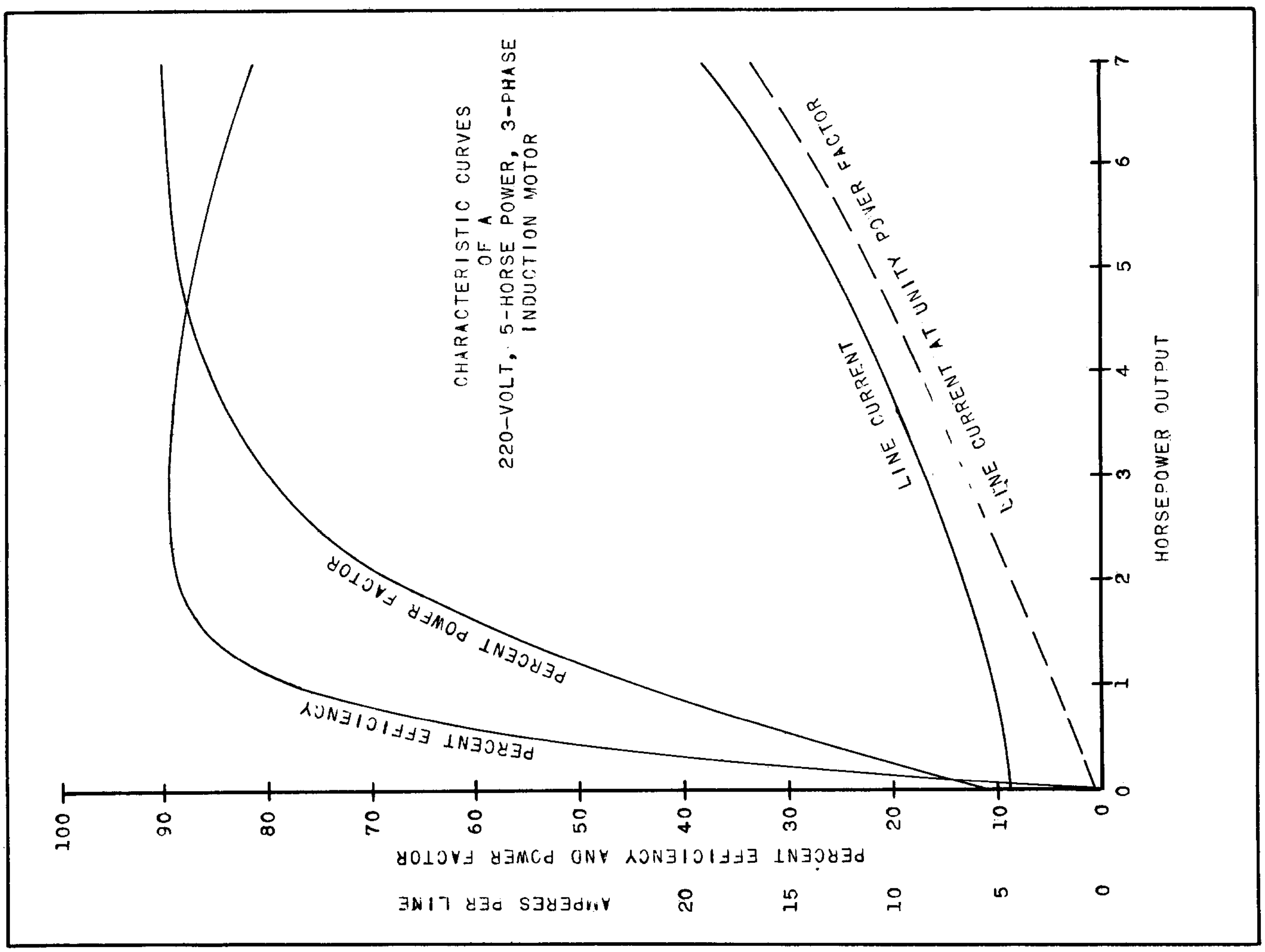

Figure 3

motor, operation at low power factor, and low efficiency. The induction motor is designed to have its maximum efficiency at or near full-load, and as the power factor is better at full-load than at fractional loads, it is quite important that care should be taken to see that all induction motors are properly rated for the loads they are to carry. Moreover, the load should be as constant as possible so that the motor will continuously operate at its maximum efficiency and power factor. For example, if a motor is driving a pump jack with counterbalance weights, these weights should be so adjusted that the motor operates, as nearly as possible, under full-load conditions. Improperly adjusted weights may cause the motor to operate at an overload during one half of the stroke and to regenerate on the other half of the stroke. This not only causes the motor to operate at low efficiency and low power factor, but it also causes very objectional voltage surges to develop on the lines supplying the motor. Thus the first and most economical step to take in improving power factor is to select a motor that has the proper rating for its load and to maintain this load as nearly constant as possible. If the demand of the load is unknown, a motor of ample size should be installed, and by measuring the watts input to the motor, while it is pulling the load, the proper sized motor for the load can be determined. This may appear to be a waste of time and expense; however, it should be a money-saving operation in the long run.

After the above steps have been taken toward the improvement of power factor, further improvement can be made by installing auxiliary equipment for this purpose. The nature of the equipment will depend upon the nature and physical locations of the loads which are creating low-power-factor conditions and upon the operating schedules of these loads. As the induction motor produces a lagging power factor - that is, the current lags behind the voltage in time phase -- as indicated in the vector diagram of Fig. 2, this can be corrected by installing equipment at the same location which operates at a leading power factor.

At the present time, the most economical and trouble-free equipment of this kind is the static-condenser or capacitor. This condenser, or these condensers, should be placed as near the induction motor as possible or practical. This, of course, means that the condensers should be connected to the terminals of the motor. This relieves not only the kva load on the transformers supplying the motor but also all lines and equipment from the terminals of the motor back to and including the generators at the power plant. These condensers are rated in volts and kilovolts amperes reactive, or kvar, and in the selection of the proper rating for condensers to be used for a given application, the line voltage should be specified and the reactive or out-of-phase component of the load current should be determined. The voltage to be applied across the condenser multiplied by the reactive component of the load current divided by 1000 will give the voltage and the kvar rating of the consenser required. As the condenser draws a current from the line that is 90 deg. ahead of the voltage and as the out-of-phase or reactive component of the current to the motor is 90 deg. behind the voltage, these two currents neutralize each other, and the resulting power factor of the current at the terminals of the motor and the condensers is unity. As the out-of-phase component of the current taken by the motor is practically constant at all loads, the proper sized condensers will correct the power factor of the motor at all loads on the motor.

If several motors are installed at one location, an installation of capacitors with sufficient kvar rating to correct the power factor of all motors can be made; however, for obtaining correction to unity power factor, all motors would have to run simultaneously. If some of the motors were shut-down, the effect of the condensers would be to produce a leading power factor of probably objectional magnitude; moreover, as this leading reactive component of current would be drawn over lines and through transformers that have inductive reactance, a rise in voltage could result that might reach dangerous proportions. Condensers automatically controlled to compensate for variations in the load can be obtained, so that the above-mentioned objections can be eliminated.

Another method of power factor correction frequently used at concentrations of induction motor loads is the synchronous motor or synchronous condenser. This, in reality, is a synchronous generator or alternator operating as a motor. Unlike the induction motor, the synchronous motor has a field which is excited with direct current, and this field is the rotating element. By changing the current in the field of this motor, the power factor of the current taken by the armature can be changed from lagging through unity to leading. If the motor is not loaded and is over excited it will draw a leading component of current from the line and will act as a condenser and is, therefore, called a synchronous condenser. If the motor has sufficient capacity, it can carry a load and can also be used to correct the power factor of the near-by induction motors.

The type of power-factor-correcting equipment to be used will depend upon local conditions and, upon the justifiable expense connected with the purchase, the installation, and the operation of this equipment. The choice of this equipment will entail a careful study of the situation by qualified personnel and will involve numerous tests at varying conditions of load before intelligent conclusions can be reached.