ELECTRICAL POWER AS RELATED TO RESISTANCE WELDING MACHINES

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Introduction

The intent of the material presented is to serve as a guide to the understanding of the many excellent sources on the general aspect of electrical power as it is related to resistance welding.

The content has been kept as non-mathematical as possible and generalization, rather than detail, used to explain basic principles. As a result many of the statements made will not apply to exceptional situations.

However, it is hoped that the information given will enable the reader to recognize these and to use the references for additional data when required.

Sample calculations based on a typical standard resistance welding machine have been included.

Concept Of Duty Cycle

Since the resistance welding loads are inherently intermittent, the concept of duty cycle becomes important.

Duty cycle is the percent of time that the load is applied during the integrating period for the device.

The integrating period is the sum of a load and a rest period.

For determining RWMA standard ratings, the integrating period is set at one minute.

The RWMA standard rating is based on 50% duty cycle.

For example, a 150 KVA transformer can carry a 150 KVA load if the load and rest times are equal and if the load time does not exceed 30 seconds. Since welding load cycles are seldom exactly at a 50% duty cycle rate, some method is required to convert loads from any duty cycle to a thermal equivalent at either 50 or 100% duty cycle.

KVA (Kilovolt-amperes) is a unit of apparent electrical power and is a measure of the apparent instantaneous power delivered to or taken from a device.

The heating effect, or real power component, of a given magnitude of KVA is equal to I^2R if the ampere (current) component of the KVA quantity is used and if the effective resistance of the device is used.

Thus I^2R is a measure of the instantaneous electrical power converted to thermal power in a device carrying I amperes with an effective resistance of R ohms.

The electrical energy converted to thermal energy, or heat, is then I^2R multiplied by the time that the current, or load, exists.

Mathematically -

$$E = I^2RT \text{ (Thermal energy)}$$

The basic premise of converting from one duty cycle to another is that the energy remains constant.

Suppose it is required to find the continuous current (100% duty cycle) that will produce the same energy (heating effect) as a current at 50% duty cycle.

Energy at 100% duty cycle -

$$E_{100} = I_{100}^2 \times R \times T$$

Energy at 50% duty cycle -

$$E_{50} = I_{50}^2 \times R \times 0.5T$$

$$I_{100}^2 \times R \times T = I_{50}^2 \times R \times 0.5T$$

$$I_{100}^2 = I_{50}^2 \times \frac{R}{R} \times \frac{0.5T}{T}$$

$$I_{100} = I_{50} \times (0.5)^{1/2}$$

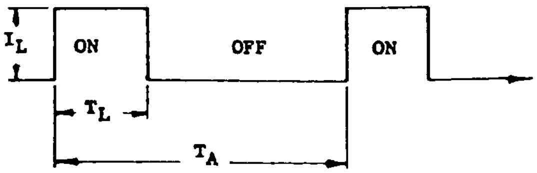
$$= I_{50} \times 0.707$$

Also -

$$I_{50} = I_{100} \times (2)^{1/2}$$

$$= I_{100} \times 1.414$$

Consider the following simple load pattern:



The current I_A which must exist over the interval T_A to produce the same heat energy as current I_L over interval T_L is -

$$I_A^2 \times T_A = I_L^2 \times T_L$$

$$I_A = I_L \left(\frac{T_L}{T_A} \right)^{\frac{1}{2}} \qquad (1)$$

The ratio $\frac{T_L}{T_A}$ is the duty cycle.

If T_A is one minute, I_A is the equivalent continuous current.

Therefore since $I_A = I_{100}$

$$\text{and} \qquad I_{100} = I_{50} \times (0.5)^{\frac{1}{2}}$$

$$I_{50} \times (0.5)^{\frac{1}{2}} = I_L \times \frac{T_L}{T_A})^{\frac{1}{2}}$$

$$I_{50} = I_L \times \left(\frac{T_L}{T_A} \right)^{\frac{1}{2}} \times 2^{\frac{1}{2}} \qquad (2)$$

Using the sample values of 46200 amperes of welding current at 4.36 percent duty cycle, the 50 percent duty cycle current can be found by using (2) -

$$I_{50} = 46200\ (.0436)^{\frac{1}{2}}\ (2)^{\frac{1}{2}}$$

$$= 13650 \text{ amperes}$$

KVA may be substituted for amperes and the required transformer rating found by using the same equation.

$$KVA_{50} = 508KVA\ (.0436)^{\frac{1}{2}}\ (2)^{\frac{1}{2}}$$

$$= 151 \text{ KVA}$$

If the T_L intervals vary, but all load currents are equal, the duty cycle is equal to the sum of all T_L intervals divided by one minute. (T_L and T_A must be expressed in the same units.)

If both the load currents and the load time intervals vary, the equivalent continuous load current can be found as follows: (3)

$$I_C = \left[\frac{(I_{L1}^2 \times T_{L1}) + (I_{L2}^2 \times T_{L2}) + \ldots (I_{LN}^2 \times T_{LN})}{T_A \text{ (One Minute)}} \right]^{\frac{1}{2}}$$

Algebraic manipulation of equation (2) gives other useful forms. Two of these are given below.

Maximum allowable duty cycles, expressed in percent, can be found using the following equations:

$$DC = \left(\frac{\text{KVA (50\% DC Rating)}}{\text{KVA Demand}} \times 7.07 \right)^2 \qquad (4)$$

$$DC = \left(\frac{I_{SO}}{I_L} \times 7.07 \right)^2 \qquad (5)$$

I_{SO} = Secondary Current Rating at 50% D.C.

I_L = Welding Current

The relation between demand, rating and duty cycle can be expressed graphically. Such a curve is shown on the attached chart, Figure 1.

The dashed lines show that at a duty cycle of 4.36 percent, the allowable demand is 338 percent of the 50 per cent duty cycle rating. For a 150 KVA machine this is about 508 KVA.

Machine Secondary Parameters

General

The secondary current output of a resistance welding machine is controlled by the secondary circuit electrical characteristics. An understanding of these is helpful when estimating machine output. If the voltage level is unchanged the magnitude of an alternating current in an electrical circuit is determined by the circuit resistance, inductance, and capacitance. In the case of most resistance welding machines and their power supply, only the resistance and inductance need be considered.

Resistance

Resistance is analogous to friction and its magnitude is determined by the electrical conductor material, section and length, and frequency of the current. (In special cases the resistance is influenced by materials adjacent to the conductor.) It is the mechanism by which electrical energy is converted into thermal energy.

In a circuit composed only of resistance the current varies exactly in time relationship with the supply voltage and the voltage and current are said to be "in phase". The voltage drop is also in phase with the current. The power factor of such a circuit is 100%. See figure 2.

Single point machines with high KVA ratings generally have low resistance secondary circuits. Multi-point machines using cable circuits have higher resistance.

Reactance

A conductor carrying an electrical current always produces an electromagnetic field concentric about the conductor and extending outward with decreasing intensity.

In the case of closed loops, such as the secondary circuits of resistance welding machines, only that portion of the field enclosed by the loop is of interest.

The strength of the field at any point varies with the current and is "in phase" with the current.

Sine wave variation of the current causes the field to change likewise and the changing field generates, or induces, a voltage in the secondary circuit which leads the current by one-quarter of a cycle or 90 degrees. This is the "voltage drop" of an inductive circuit.

In any circuit composed of only one parameter (resistance or inductance) the supply voltage must be in phase with and equal to the voltage drop. For a purely inductive circuit the current therefore lags the supply voltage by 90 degrees and the power factor is said to be zero percent lagging. See Figure 3.

The induced voltage inhibits the passage of current and this property is known as inductive reactance. The value of the inductive reactance is determined primarily by the area enclosed by the circuit conductors, presence of magnetic materials in or closely adjacent to the circuit loop, and the frequency.

The reactance of secondary circuits varies somewhat more than the square root of the ratio of the enclosed areas. Thus if the area is doubled the reactance will increase approximately 150%.

The presence of magnetic materials increses the strength of the electromagnetic field and therefore the reactance of the circuit. For the conditions normally existing the increase seldom exceeds 25%. (The energy losses in the material also increase the resistance component of the circuit slightly.)

Impedance

All secondary circuits contain both resistance and inductive reactance. They are considered to be in series for calculation purposes and the reactance is normally greater than the resistance.

The total restricting effect on the current is equal to the square root of the sum of the squares of the resistance and reactance. This total effect is known as impedance. This implies that the resistance and reactance are the two sides of a right triangle. By convention the resistance is considered to be the lower horizontal side and the reactance the vertical side. The power factor is the cosine of the angle whose tangent is equal to the reactance divided by the resistance. If the resistance and reactance are equal the angle is 45 degrees and the power factor is 70%. This is illustrated in Figure 4.

It is sometimes necessary to estimate the change in output due to a change in throat area. Although the primary change in the parameters is in the reactance, the resistance also usually changes a small amount due to the variation in the length of the conductors. It must be remembered that that part of the machine parameters due to the transformer don't change and the total effect may be estimated by assuming that the impedance changes by an amount equal to the square root of the ratio of the throat areas. Thus an increase in throat area of 100% will increase the machine impedance to about 140% and decrease the output to approximately 70%.

Since the out-of-phase current associated with the reactance does no useful work, it is desirable to keep its value as low as possible. Reducing it also reduces the impedance and therefore the voltage required to produce a given welding current.

Decreasing the secondary voltage for a given output reduces the electrical welding demand a like amount and therefore less power supply capacity is required.

Work Resistance

The parts being welded have resistance. If they didn't, resistance welding would not be possible. Most of the work resistance appears at the mating surfaces of the pieces being welded.

The work resistance adds to the machine resistance and therefore decreases the secondary current. The magnitude of the decrease depends on the change in the machine impedance.

If the machine short circuit resistance were equal to or greater than the reactance (70% power factor or greater) a given value of work resistance will increase the machine impedance more than the same work resistance added to a machine with a lower short circuit power factor. This is illustrated by Figure 5.

For this reason high power factor machines are said to be "resistance sensitive."

As a rule-of-thumb, the welding current is about 85% to 90% of the short circuit current for standard single point machines.

In general, a machine with high power factor is more desirable than one with low power factor. However, this is only true if the higher power factor is due to lower reactance and not higher resistance.

Output Estimate

The electrical efficiency of machines can be compared by expressing their outputs in "amperes per secondary volt".

The machine used as an example has an output per volt of 50,000 amperes divided by 11 volts or 4550 amperes per volt.

As a rule-of-thumb, this figure varies from approximately 1500 for cable circuits of multi-point machines to 12,000 for large flash welders.

Transformers

General

The following comments apply to the majority of resistance welding transformers used with single-phase line frequency pedestal machines and transformers generally known as "package type" used with multi-point machines.

In the interest of non-technical clarity some of the design theory has been over-simplified without changing basic principles.

These transformers have effectively two electrical windings on one iron core. The primary winding is multi-turn and is connected to the supply line. The minimum number of effective turns is equal to the supply line (primary) voltage divided by the maximum rated secondary (output) voltage. The maximum number of turns is equal to the primary voltage divided by the minimum secondary voltage. The number of turns is always a whole number.

The secondary (output) winding is effectively one turn. Since the secondary current ratings are high, the sectional area of the secondary winding must be large and this is most conveniently obtained by using cast or fabricated copper sections.

The following factors influence the transformer design:

Primary Voltage
Primary Frequency
Secondary Voltage Range
KVA Input at 50% DC
Insulation Class
Cooling Method
Type of Core Material to be used

A brief discussion of the effect of these on transformer design and application follows.

Primary Voltage

The primary voltage level determines the dielectric strength of the primary insulation system, the sectional area of the primary copper (for equal KVA ratings), and together with the secondary voltage range, the number of effective primary turns.

The standard primary voltages are 220 and 440 volts. If the actual voltage to be applied to the transformer (line voltage less primary contactor drop) exceeds either of these values by more than 10%, special designs are required.

Units are occasionally required for operation at 2400 or 4160 volts. Although the dielectric strength of the insulation must be increased, the dielectric problems involved are usually easily solved.

The voltage level also determines the conductor section. (For equal KVA ratings). As the voltage decreases the conductor section increases and ratings above 500 KVA are usually not desirable for voltage below 440.

As the number of effective primary turns increases due to increased primary voltage and/or decreasing secondary voltage, the design problems also increase. This is largely due to the space required by the between-turn insulation which can't be decreased below a certain minimum thickness for physical reasons. This in turn leads to the need for using more primary coils and exceeds the usual maximum two to one ratio of primary to secondary coils generally used for efficient cooling of the primary and low leakage reactance.

Frequency

If all other things are equal, the weight of the core iron required is inversely proportional to the primary frequency. Usually, however, the secondary voltage required is somewhat less as the frequency is decreased so that the core weight does not quite double for a 50% decrease in frequency. The usual frequencies encountered are 60, 50, and 25 cycles per second. Although the RWMA standard frequency is 60 Hz, some transformers are designed so that they can be used at both 60 and 50 Hz.

Secondary Voltage Range

The secondary voltage range influences the design to a great extent.

The range (maximum voltage divided by minimum voltage) should not exceed 2.8 since the increased number of primary turns required defeats efficient design.

The maximum secondary voltage determines the size of the core and the section of the secondary winding copper.

Except for increasing the overall size and weight of the transformer, the larger core required for higher secondary voltages does not affect the operating characteristics of the unit.

For a given KVA rating the secondary copper sectional area varies inversely with the secondary maximum voltage. Thus a transformer with a 10 volt secondary has one-half of the secondary copper of one with a 5 volt secondary if both have the same KVA rating. This is important when applying the transformer to a given welding load.

The transformer having an adequate KVA rating with the lowest maximum voltage that will produce the required welding current will result in the highest utilization efficiency.

The secondary current rating is found by dividing the KVA rating by the maximum secondary voltage.

The RWMA standards specify that a transformer shall be capable of carrying the rated secondary current at any primary tap. Use of the secondary current rating results in a convenient method of determining the allowable operating duty cycle for a given welding current.

Equation (5) in the section on Duty Cycle is used.

Equation (4) of the same section is only valid for operation at the primary tap producing the maximum secondary voltage. For any other condition the KVA rating must generally be derated in direct proportion to the secondary voltage.

For example, a transformer rated at 150 KVA at 11 volts maximum will only be rated at 80 KVA when operated at a primary tap giving 5.95 volts.

A numerical example will further clarify this.

Suppose that the welding current of 46,200 amperes used for the example is produced at 5.95 volts rather than at 11.0. This gives a demand of 275 KVA. Using KVA demands as a basis, the transformer rating must be lowered to 150 multiplied by 5.95 divided by 11.0 giving 80 KVA. The maximum allowable duty cycle is then found by equation (4) to be 4.36%.

The transformer rated secondary current is 13,650 amperes, and the welding current is 46,200. Using equation (5) the maximum allowable duty cycle is found to be 4.36%.

KVA Input Rating

The KVA input rating is usually considered by the user to be the most important of the various transformer ratings. The previous discussion has shown that the secondary voltage rating is equally important.

The practice of rating resistance welding transformers at 50% duty cycle is difficult to rationalize by engineering analysis. However, two possible reasons for using this rating method are, first, that the welding load is seldom such that it could be considered as continuous; and, second, that the difference between the rating and welding demand becomes less as the rating duty cycle approaches the actual welding duty cycle.

This reasoning tends to lead to the thought that a standard rating at less than 50% duty cycle would serve the purpose better.

In any event, nothing relating to the design and operation of resistance welding equipment would be different if the rating were changed to a 100% duty cycle basis. To do this all transformer ratings would simply be multiplied by 0.707, making for example, a 150 KVA unit a 106 KVA or, rounded off, a 100 KVA unit.

The RWMA Standard stipulation of one minute as the integrating period (averaging time) for welding equipment means that operating limits and ratings are determined by calculating the duty cycle over a one minute interval.

As an example, a load of 100 KVA existing for 30 seconds will require a transformer rated at 100 KVA (50% DC) as long as the rest time is at least 30 seconds. The standard rating will still be 100 KVA if the rest time is one, two, or any number of hours.

This results in calculated required standard ratings that are not always practical, and will be discussed in more detail later.

Insulation Class

The KVA rating is determined by the thermal endurance of the insulation system used.

Each of the five NEMA insulation classifications has a maximum temperature which should not be exceeded if adequate insulation life (100,000) hours) is to be obtained.

The difference between this maximum and the standard reference temperature (ambient air or water) is the allowable temperature rise.

Since different methods of temperature measurement give different degrees of accuracy with respect to the maximum hot spot temperature, each method (thermometer, resistance, or imbedded detector) has been assigned a rise associated with each insulation system.

Generally, the resistance method is used for the primary windings of water cooled transformers and in this case the allowable rise is 85 for Class B, 110 for Class F, and 130 for Class H, all in degrees C.

Since the KVA rating of a given transformer varies approximately with the square root of the ratio of the rises, the same transformer can have different KVA ratings depending on the insulation system used.

Although other factors are involved which can modify the following observations under certain conditions, it is in general true that a transformer using a high rise insulation system is less efficient than one using a low rise system if both units are designed for the maximum allowable rise. This follows because the resistance of the copper windings increases with temperature and, for the same KVA input, the copper losses are greater with the higher rise systems.

Suppose a 100 KVA transformer has an input of 100 KVA and that the losses are equal to design values. Now increase the transformer rating to 200 KVA by the usual method of doubling the copper sections. This halves the resistance and the losses decrease by 50%. Now increase the input to 200 KVA. Compared with the 100 KVA unit with 100 KVA input, the 200 KVA input to the 200 KVA transformer gives twice the current through one-half of the resistance. The losses are then $(2I)^2$ times one-half of the resistance giving twice the losses. Therefore, for the same class of transformer, loaded to its rating, the losses vary directly with the KVA rating. This means that twice as much heat energy must be removed by the cooling system from a 200 KVA unit as from a 100 KVA unit.

Cooling

Because of the need for compact, high strength construction required to withstand the mechanical forces produced by the intermittent overloads characteristic of resistance welding, it is difficult to provide the air spaces necessary for convection cooling.

Also the heavy secondary sections make it easy to provide water cooling paths.

For these reasons resistance welding transformers are generally water cooled.

The RWMA Standards specify certain usual service conditions under which the transformers are warranted to operate satisfactorily. The most important of these are when the ambient air temperature does not exceed 40 degrees C, the water temperature does not exceed 30 degrees C, or has a pressure less than 30 psi.

The water cooling requirements vary with the transformer design but as a rule-of-thumb 1½ gallons per minute per 100 KVA is generally adequate.

Since the cooling water usually removes from 50 to 75% of the total losses, the remaining losses must be removed by the surrounding air. Thus the temperature of the ambient air has an influence on transformer operation.

Core Material

A core of ferromagnetic material is required to carry the magnetic flux that transfers the electrical power from the primary to the secondary winding.

This flux varies between negative and positive maximums at the frequency of the supply voltage.

Under steady-state conditions the maximum value is directly proportional to the maximum value of the secondary voltage (for effective single turn secondary windings) and inversely proportional to the frequency.

The quotient of the total maximum flux divided by the sectional area of that part of the core that passes through the window of the coils is known as the core flux density.

When the primary winding is energized, a current must exist in the primary winding to establish the flux. For a given type of core material this exciting current varies non-linearily with the flux density at some positive power greater than one.

This is shown by curve "A", on Figure 6, for the core material usually used in stacked core transformers, and for curve "B" for grain oriented wound cores. (A well known trade name for this material is Hipersil).

Note the high values of exciting current associated with densities 10% greater than normal for the wound core.

The RWMA Standards limit the exciting current to 10% of rated primary current for ratings of 100KVA and below and 5% for ratings above 100KVA.

Figure 7 shows the variation of the flux produced by a sine wave of primary voltage, and the maximum flux reached for normal and delayed firing.

At a typical power factor of 70% the primary voltage will terminate at either A or B. (For full sine wave conduction.) Assume that the termination was at A.(Last half-cycle positive). The flux density will have a value of A' and will decay to a value somewhat lower than this in a short time. For stacked cores the final, or residual value, will be at about A_s, and at A_w for wound cores. This residual value, together with the magnetic characteristics of the iron, determine the maximum transient exciting current.

Nearly all welding controls have antipolar firing patterns and the next energization of the transformer will be negative with the firing point at A". The flux change will be less than that for the steady-state condition because the first negative half-cycle is fractional.

However, since the starting point value was either at A_s or A_w, the negative maximum is greater than that during steady-state operation. These transient maximum flux values are shown A_{sm} and A_{wm} with the corresponding exciting currents on Figure 6. Note that the current for the wound core is beyond the values shown on the curve. At this point the exciting current is limited largely by the primary winding resistance.

If the firing point is delayed to about 90 degrees, or at voltage maximum, the flux change for the wound core will be less and the transient maximum will be about equal to the steady-state maximum. The exciting current will then be approximately equal to the steady-state value. This method of controlling the exciting current is known as "delayed firing".

The flux-exciting current curve for the grain oriented core shows that, for the maximum allowable exciting current, the flux density can be greater and the core, therefore, can have less section than for the stacked core. For this reason transformers using grain oriented cores are generally smaller than the stacked core types.[17]

Thermal Capacity

General

The thermal capacity of power supply systems is usually determined by using a current, or KVA, which is the continuous equivalent of the welding load.

If only one load is involved, equation (1) in the Section on Duty Cycle can be used. If there is more than one load and none of the "ON" times overlap, equation (3) can be used. Rules for other conditions will be given later.

For example, consider the load of 508 KVA (1155 amperes) at a duty cycle of 4.36 percent as used for the sample calculations. Equation (1) gives an equivalent continuous load of 106 KVA or 242 amperes. The continuous load arrived at this way is valid for most conditions. However, suppose that the machine were in use for one minute and at rest for one hour. Use of 242 amperes to select the thermal capacity of some power supply components could result in the choice of capacities larger than actually required.

The reason for this is the use of the standard equipment averaging time of one minute to find the continuous equivalent load for apparatus with a thermal time constant considerably longer than one minute.

There is no simple solution to this difficulty since the thermal time constants of power supply components are not readily available. Reference 1 (5 on page 29) and Reference 11 give more information on this.

In any event, use of one minute as the averaging time will usually result in conservative results.

As a rule-of-thumb use of equivalent continuous loads less than one-sixth of the welding demand should be used with caution.

When more than one load is to be supplied by the same power supply system, and if any of the "on" times overlap, equations (1) and (3) can't be used. For these conditions, the methods given in reference 1 (Ref. 6 on p. 53) and 3 must be applied.

If no "on" times overlap, the total equivalent current is equal to the square root of the sum of the squares of the individual equivalent continuous load currents.

The following data will be based on the machine used as the example, operating continuously.

Low Voltage Feeder Selection

(a) Cable - The minimum total required sectional area of each of the two legs of the feeder will depend on the following:

1. NEC requirements
2. Type of insulation
3. Number of cables per leg
4. If in air or conduit
5. Ambient temperature

The National Electric Code is a good reference for all of the above.

NEC Section 630-31 (1) specifies the minimum size of cable that can be used as related to the machine rating and whether the operation is manual or automatic. For this case the size specified is less than other considerations dictate.

NEC Table 310-12 is used to select the cable size using the calculated equivalent current of 241 amperes.

The proper vertical column selected is determined by the insulation type. Table 310-2 (a) lists most of the available insulation systems with a maximum temperature for each. Type THW with a 75 degree Centigrade rating is selected.

Assuming that the maximum ambient temperature is 40 degrees, all values in Table 310-12 must be de-rated to 0.88 of those given.

300 MCM cable when de-rated will carry 250 amperes and is the minimum that can be used for the 241 ampere load.

It is possible that more than one cable per leg will be required to reduce the voltage drop. If so, Note 8 for Table 310-12 will further decrease the ampacity of the cable. If two cables per leg(four total) were required, 2/0 size would be selected.

(b) Bus Duct - The NEC does not list the thermal capacity of bus duct.

The ampacity is given in the technical data provided by the manufacturers of bus ducts.

The required rating will be the next standard rating above 241 amperes. This is 400.

(c) Disconnecting Device - Article 630-32 of the NEC gives rules for determining the minimum rating of the switch or circuit breaker. For this case it can't be less than 241 amperes.

The next standard rating above 241 amperes is 400. This would be the size selected.

(d) Supply Transformer - Since transformers are rated in KVA, it is convenient to express the equivalent continuous load in KVA rather than amperes.

$$KVA_C = 508 \text{ KVA } (.0436)^{\frac{1}{2}}$$

$$= 106 \text{ KVA}$$

Thus the transforming device must have a KVA rating equal to or greater than 106 KVA.

If other loads are being carried by the same bank, the difference between the other loads and the bank rating must be equal to or greater than 106 KVA.

Single Phase Transformer

If a single phase transformer is to be used, the next standard rating above 106 KVA, or 167 KVA, is selected. (See Ref. 1 for standard ratings.)

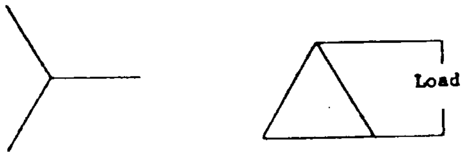
As in all thermal selections, it is possible that the ratings might have to be increased if the voltage drop calculations to be made later require greater capacities.

Three Phase Transformer

The three phase transformer connections normally used are as follows:

Delta - Delta

Star - Delta



Delta - Star

As long as the load is connected to two lines as shown and not line to neutral (for the delta-star connection), the single phase thermal capacity is one-half of the three phase capacity.

Thus, for the example being used, the rating of the three phase bank must be equal to or greater than twice 106 KVA or 212 KVA. The smallest standard rating above this is 225 KVA.

If the load is connected line to neutral in the delta-star arrangement, the three phase capacity must be three times the single phase capacity.

Disconnecting And Overcurrent Devices

General

As in the case of any electrical device some means must be supplied to disconnect the machine from the source of supply. In addition current responsive elements must be provided to protect the machine and that portion of the power supply system on the load side of the protective device from damage due to overcurrents.

The disconnecting means must be thermally and physically able to carry the normal load currents required by the machine and in addition not be damaged by short-circuit or fault currents.

Disconnecting devices can be divided into two basic categories.

One is an air break switch and the other an air circuit breaker.

Switches

Air break switches, or, more simply, switches, are available in three types. These are isolating, general purpose, and motor circuit. These are defined on Page 70-11 of the National Electric Code.

Standards for enclosed switches are given in NEMA Publication KS1 and in UL 98.

The standards are too involved to discuss in detail here but an attempt will be made to point out the parts of the standards that are important when applied to resistance welding machines.

Voltage Rating

Standard alternating current voltage ratings are 120, 240, 480, and 600 volts. Obviously the switch voltage rating must equal or exceed the voltage of the circuit with which it is to be used.

Thermal Rating

All switches which meet UL and NEMA Standards have continuous ampere ratings. Standard ratings are 30, 60, 100, 200, 400, 600, 800, and 1200. These are per pole.

To find the required ampere rating of the switch, convert the load current to the equivalent continuous current and select a rating equal to or greater than this value.

In the case of the example, this current is 241 amperes so the switch rating required would be 400 amperes at 480 volts. This would be a two pole unit.

Interrupting Rating

Switches which have only ampere ratings are required to interrupt 150% of rated current.

Some switches have horsepower ratings. Enclosed switches are divided by NEMA into three classes - HD, MD, and LD. The HD class standard reads in part "---the operator will (can) not restrain the operation of the contacts after they have initially touched or parted---". This style is generally called "Quick-make, Quick-break" and, if it meets NEMA Standards, is capable of interrupting up to ten times the full load current ratings given in the NEC for the horsepower rating of the switch. Unfortunately the present NEMA ratings do not go above 200 ampere switches rated at 480 volts.

In general, a switch should not be used to interrupt current unless the interrupting rating of the switch is fully understood and the maximum possible magnitude of the overcurrent known.

It is general practice not to use fusible switches rated above 600 amperes at 480 volts.

Switches supplied as an integral part of resistance welding controls can be of any type and should not be presumed to have any interrupting ability.

Overcurrent Protection

Overcurrents are currently greater than the rated current of a device or circuit. They can be divided into two categories. One is called an overload current which is due to a device malfunction or improper use. The current path is confined to the normal circuit elements. The other is known as a short circuit, or fault, current which is not confined to the normal current path and which generally has a magnitude much greater than either the rated or overload current.

Fuses are the only devices available for use with switches to give overload and/or short circuit protection.

It is difficult to apply fuses to resistance welding equipment so that they protect against overcurrents and still do not open during the welding operation.

Although both NEMA and UL have written standards relative to the time-current characteristics of fuses rated at 600 volts or less, they are expressed as single maximum or minimum values with no one point having both a maximum and minimum value so as to establish a band of required operation. Therefore, fuses of different manufacture can meet the NEMA and UL Standards and yet have different opening times for the same currents.

For loads equal to five times the fuse rating NEMA Type H and UL Type K time-delay fuses must not open in less than 10 seconds. Most H and K time-delay type fuses will open near this value. Type J fuses and H and K fuses not designated as time-delay or dual element types do not have to meet this requirement and, therefore, may open in less time at this value of overcurrent.

Fuses are normally applied to resistance welding equipment by using the next standard rating above the calculated equivalent continuous current using one minute as the averaging time. The opening time-current curve of the particular fuse to be used is then examined to be sure that it will not open at the demand current for the welding time used.

Since fuse tests are conducted under conditions which limit the temperature of the air around the fuse to 32 degrees C, operation at temperatures above this will cause the operation of the fuse to depart from the published curves. Therefore, for operation in air above this temperature the fuse should be de-rated.

Although Class H and K fuses can have approximately the same characteristics in the overcurrent region, Class K fuses have peak let-through current and I^2T ratings. Thus these fuses are current and energy limiting and help protect the system from damage due to short-circuit currents.

The values of peak let-through current and I^2T energy can be obtained from the fuse manufacturer's data or from References 12 and 13.

Fuses having I^2T ratings give a basis for applying the fuse so as to limit the temperature rise of cables during fault conditions. Reference 14 gives short time-current limits for cables of various sizes. This data can be converted to I^2T ratings that can be compared with the fuse rating.

The 300 MCM cable selected has a calculated I^2T rating of about 250×10^6 amperes squared-seconds. A K-5, 250 ampere fuse has a standard rating of 1.6×10^6 and should give adequate protection provided that the available fault current does not exceed the interrupting rating of the fuse.

I^2T ratings of apparatus other than fuses should be used with caution since these values are only valid for time intervals short enough to confine the heat developed to the device itself. This interval is generally given as ten seconds or less.

A special class of fuses known as "welder limiters" is also available. These have a longer time-delay than time-delay H or K fuses and, since they also have I^2T ratings, they can be used for back-up fault protection. It is recommended that H or K fuses be used on the load side of these special fuses.

Class K fuses may have interrupting ratings of 50,000, 100,000, or 200,000 symmetrical amperes. These ratings are determined by test and are assigned by the fuse manufacturer. They are included in the fuse characteristics data.

The interrupting ratings become important when applying fuses to power systems having high fault current capability. A fuse with an interrupting rating less than the fault capacity of the system at the location of the fuse may not interrupt a short-circuit within its I^2T and peak let-through ratings with resulting damage to the devices to be protected.

The interrupting rating of the 250 ampere K-5 fuse selected for the example is 50,000 symmetrical amperes.

Circuit Breakers

General

A circuit breaker is a device for closing and interrupting a circuit between separable contacts under both normal and abnormal conditions. An air circuit breaker is one in which the interruption occurs in air.

Molded case circuit breakers are available in frame amperage ratings from 100 up to and including 1200 and at alternating current voltages of 600 and below.

The following discussion is confined to molded case air circuit breakers, hereafter spoken of as simply "breakers".

Breakers can be supplied with thermal time-delay and/or instantaneous fixed or adjusted magnetic overcurrent trips, undervoltage trips, or no trips. Operation can be fully manual or electrical closing, and/or electrical opening. (Shunt trip).

Thermal Rating

The basic maximum thermal rating is determined by the allowable temperature rise of the current carrying parts of the "frame" of the breaker. If the breaker is supplied with thermal overcurrent trips all or part of the current must pass through parts of the tripping devices. This limits the rating of the breaker to the thermal capacity of the overcurrent elements. For example, a 400 ampere frame breaker is available with a number of ratings below 400. One is 250 and limits the breaker to a continuous current of 250 amperes even though the same breaker is capable of carrying 400 amperes with a 400 ampere overcurrent unit.

For the example a 400 ampere frame breaker with a rating of 250 amperes could be used. If a thermal-magnetic trip unit is used, the breaker rating is 250 amperes.

Interrupting Rating

All breakers have interrupting ratings. The magnitude generally is a minimum of 5000 symmetrical amperes and increases with increasing frame size, or rating, to a maximum of 100,000 amperes. Thus breakers can be opened or closed with loads which do not exceed their interrupting rating.

Class J, K, or L fuses can have greater interrupting ratings than a breaker of the same continuous thermal ratings. For this reason a current-limiting, high interrupting capacity fuse is sometimes used in series with a breaker so as to allow the breaker to be used on a system with fault currents greater than the interrupting capacity of the breaker only.

The breaker selected for use with the example has an interrupting rating of 30,000 symmetrical amperes.

An approximate idea of the value of the fault current that may be expected can be found by dividing one hundred by the estimated welding load voltage drop expressed in percent and multiplying the quotient by the primary welding current demand.

If the voltage drop for the example is assumed to be 5%, the expected fault current would be 20 multiplied by 1155 or about 23,100 amperes. Although this method can be used for initial estimation, the breaker selection should be based on an actual calculation using the methods given in Reference 14.

Overcurrent Protection

In general breakers are available with overcurrent devices which are responsive to either inverse time-current relationship and/or current magnitude only. Both can be combined in the same breaker.

The thermal inverse-time portion of the time-current curve is shown on Figure 9 and is similar to the time-delay type of fuse in the same percent overcurrent region. This part of the breaker overcurrent curve is not adjustable. (Some change of the lower part of the curve occurs when the magnetic device is adjusted.)

The magnetic portion of the overcurrent characteristic can be supplied as an adjustable unit. The range is usually from 5 to 10 times the rating of the breakers. This is shown by the vertical section of the curves.

Breakers are sometimes applied to resistance welding machines using only magnetic trip units. This provides short-circuit protection and eliminates the possibility of nuisance tripping due to thermal effects but does not provide overload protection for the feeder.

As in the case of all thermally rated apparatus, the rating must be decreased if the ambient temperature exceeds the standard value. For breakers this is 40 degrees C.

Figure 9 compares the time-current characteristics of time-delay fuses, non-time-delay fuses, and breakers with a welding machine. The curves are based on the assumption that all of the devices have equal continuous ratings. For example, if the welding machine were rated at 250 amperes (350 amperes at 50 percent duty cycle) the fuses and the breaker would also be rated at 250 amperes.

The location on the "Welding Machine Thermal Limit" curve shown as "Operating Point" corresponds to the seconds of operating time during one minute for the 4.36 percent duty cycle for the machine used as an example.

Since this point is above the curve for the Class J fuse, the inference is that a non-time-delay fuse would not be satisfactory.

Voltage Drop

General

Consideration must usually be given to three elements of the power supply system. These are:

1. The high voltage transmission or distribution feeder normally owned by the power company.
2. The transformer(s) reducing the transmission voltage to the voltage level required for the welding machine. These may or may not be owned by the power company.
3. The low voltage feeder connecting the transformer with the welding machine.

Methods for determining the voltage drop of each section will be presented after the following discussion on the overall approach.

Two methods for arriving at voltage drops are generally used. The first is the most accurate and involves the use of actual ohmic values and vector manipulations. The second is based on estimates, ratios, charts, and tables, and involves little mathematics. This method is often accurate enough.

Two basic calculated values are used to find voltage drops. These are the drops due to the resistance and the inductive reactance. The ohmic values of either are taken from tables or curves; or, in the case of transformers also from data plates or manufacturer's information if available.

The voltage drop for each parameter is calculated by multiplying the ohmic value of a device or line section by the rms (root-mean-square or effective) current passing through it. Since the resistance voltage drop reaches its maximum at the same time as does the current, and the reactance drop one-quarter of a cycle earlier, the two drops cannot be subtracted arithmetically from the line voltage to find the load voltage.

The methods for combining the two basic drops with the system voltages and the determination of the correct ohmic values to use for the resistance and reactance must be understood in order that voltage drop calculations may be made with acceptable accuracy. A further complication is the fact that most published material gives information on the calculation of three-phase loads on three-phase systems. The methods given in this section will be confined mainly to single-phase loads on either single-phase or three-phase systems.

In alternating current circuits the various voltages involved in a voltage drop calculation often do not reach their maximum or minimum values at the same time. In order to make correct calculations, these time differences must be considered. This can be done by means of a vector diagram such as Figure 10.

Diagrams of this kind may be drawn to scale with the lengths of the arrows, or vectors, representing rms magnitudes. The angular displacements are equal to differences in real time.

Zero degrees, or zero time, is at three o'clock and the rotation, or time lapse, is counter-clockwise. Thus the current vector I_L is shown lagging the load voltage E_L by the angle theta.

The voltage drops represented by the small triangle were made greater than would normally be encountered so that the notations would be legible.

Note the following on Figure 10.

1. The resistance drop is the vector E_R and is always parallel to the load current I_L.
2. The reactance drop is E_X and is always normal to I_L.
3. E_Z is the impedance drop and is the hypotenuse of the right triangle formed by E_Z, E_R, and E_X.
4. The load voltage E_L is the vector sum of E_S and E_Z.
5. The difference between the lengths of E_S and E_L is the voltage drop E_D and may not be equal to E_Z.
6. The angle (time difference) between E_S and I_L may not be equal to the load power factor angle theta.

The significance of these observations will become clear later.

One other condition that is not apparent from the diagram and that influences the accuracy of the usual drop calculations is that the load current is assumed to be constant regardless of the value of the load voltage that is found by the drop calculation. This effect can be compensated for by trial and error calculations.

Calculations Using Ohmic Values

Feeders

The first step is to determine the ohmic values of the resistance and reactance to be used. For feeders these are taken directly from tables or charts such as given in references 1 and 14.

Unless otherwise stated the values given in all such sources are "ohms to neutral". This means that the value is per conductor, or electrical side. When this value is multiplied by the rms value of the current in the conductor, the result is the voltage drop of this conductor only. This drop is called the "drop to neutral". For single-phase loads on either single-phase or three-phase systems, the line-to-line drop is this "drop to neutral" multiplied by two. For three-phase systems with three-phase loads the line-to-line drop is the "drop to neutral" multiplied by the square root of three.

Transformers

Ohms to neutral values can also be found for transformers. The equations below give ohmic values that can be used with the same current as used to find the drop in the feeder supplying the welding machine.

To use the equations the transformer percent resistance and reactance must be known. (If only the percent impedance is available, the estimation method given later should be used).

The R and X percent values will sometimes be given on the data plate. The manufacturers can also supply this data. An easier, and, for standard transformers, an accurate enough way is to refer to tables such as appear in references 1 and 14.

For three-phase transformers, or three single-phase transformers connected as a three-phase unit, with delta-delta, delta-wye, or wye-delta arrangements the equation is:

$$\text{R or X} = \frac{(\text{R\% or X\%}) \times E_{LL}^{2} \times 10^{-5}}{\text{KVA}} \quad \text{(ohms to Neutral)} \qquad (6)$$

E_{LL} = Secondary (feeder) line-to-line voltage

KVA = Three-phase bank rating

For single-phase transformers connected to single or three-phase systems:

$$\text{R or X} = \frac{(\text{R\% or X\%}) \times E_{LL}^{2} \times 10^{-5}}{2\ \text{KVA}} \quad \text{(ohms to neutral)} \qquad (7)$$

E_{LL} = Secondary (feeder) line-to-line voltage

KVA = Single-phase bank rating

For single-phase loads the transformer drop can be found by calculating the "drop to neutral" and multiplying this by two. The calculation is the same for either three-phase or single-phase transformers.

Transmission Line

The percent voltage drop due to the high voltage transmission line is usually much less than either the transformer or feeder drops. A rule-of-thumb sometimes used is to assign a drop of one percent to the transmission line.

If a knowledge of the actual drop is required it is advisable to contact the power company and ask that a calculation be made. However, if it is essential that a calculation be attempted, the following methods can be used.

Obtain the R and X ohmic values from the power company. (These may be given as 0.00 plus j0.00. The first number is the resistance, the second the reactance in ohms to neutral. Multiply these by the square of the quotient of the feeder (transformer secondary) line-to-line voltage divided by the tramsmission line-to-line voltage. These new ohmic values can be used as though they were for a second section of low voltage feeder.

Many times the only data available on the transmission line is the three-phase "fault capacity". This can be given either in amperes or KVA. In this case only an impedance value can be found and this is not usable with an ohmic calculation. Amperes can be converted to KVA by dividing by the line-to-line transmission voltage in kilovolts and then by the square root of three.

A method using the fault capacity for estimating the transmission line drop is given later.

Calculation Of Individual Drops

The approximate voltage drop of a device or line section is given by the following equation:

$$E_D = I_L (R \cos \theta + X \sin \theta) \text{ volts} \qquad (8)$$

(θ = theta = load PF angle)

> If R and X are expressed in "ohms to neutral" the result is in "volts to neutral". For single-phase loads the line-to-line drop is this multiplied by two.

Figure 11 is a vector diagram of voltage drop as calculated by equation (8).

Essentially, this gives the sum of the R and X_L drop projections on the extension of the load voltage vector E_L.

If the total drop is not over 15% of E_S, the angle alpha (a) will be small and the error will be negligible.

If the angle is zero, as when the ratio of X over R of the power supply system equals the X over R ratio of the load, the error is zero.

In the section on Thermal Capacity a 225 KVA three-phase and a 167 KVA single-phase transformer were selected as being thermally large enough for the load used as an example.

The voltage drops of these must now be calculated to be sure that they are not excessive.

From Reference 1 the R and X values for the 225 KVA unit are found to be 1 and 4.9%. (X is calculated by taking the square root of the square of the impedance less the square of the resistance).

Using equation (6) the ohmic values to neutral are calculated at 0.0102 for R and 0.049 for X.

Equation (8) then gives a drop of 55.4 volts to neutral or 110.8 volts line-to-line. This is 23.1% of 480 volts and is about five times too great. Therefore, a 1000 KVA transformer is selected and the drop found as above. This is 28.6 volts or 5.95% of 480 volts and is acceptable.

The calculation for the 167 KVA single-phase transformer is made using the values from Reference 1 and equations (7) and (8). The line-to-line drop is found to be 14.8% and is too large. In order to keep the drop to around 6%, a 500 KVA transformer will be required.

Using the same calculating method the 500 KVA drop is found to be 5.4%.

The drop of the 300 MCM, 480 volt feeder should also be checked.

Using R and X values from Reference 1 (R is interpolated) the ohmic values for an assumed 100 feet of feeder are 0.00434 R and .0046 X. The line-to-line drop is calculated to be 3.03%.

Calculation Of Total Drop

A one line diagram of the assumed power supply system, with ohmic values and calculated drop, is shown on Figure 12.

The total drop is found by adding all of the ohmic R values and then all of the X values and using equation (8) to find the total drop to neutral. This is multiplied by two to find the line-to-line drop for single-phase systems.

The total drop is 47.4 volts giving a load voltage of 432.4 volts. Primary contactor drop should be subtracted from this giving a load voltage at the machine transformer of about 432 minus 20 or 412 volts. At this voltage the demand current would be less than 1155 amperes. This would in turn reduce the drop and the actual voltage at the transformer would have some value between 412 and 440 volts.

The vector diagrams of the data given on Figure 12 is shown on Figure 13.

For better accuracy the equations given on page 233 of Reference 14 may be used.

Machine Output

Another interesting use of ohmic values is the calculation of a machine output that does not involve voltage drop but does require knowledge of the machine secondary parameters. (These can be calculated if the welding demand, power factor, and turn ratio are known).

To do this the R_T and X_T ohmic values are converted to the level of the machine secondary by multiplying them by the reciprocal of the square of the machine transformer turn ratio.

The resultant R and X values are multiplied by two, added to the machine secondary R and X values, and the impedance calculated. The machine open circuit voltage for the turn ratio under consideration (corrected for ignitron tube drop) is divided by the impedance and the quotient is the machine output in amperes.

Power Supply System	Referred to Machine Secondary	
	R	X_L
$\frac{.00828 \times 2}{40^2} =$	1035×10^{-6}	
$\frac{.01893 \times 2}{40^2} =$		23.64×10^{-6}
Machine =	110.50×10^{-6}	212.00×10^{-6}
	120.85×10^{-6}	235.64×10^{-6}

$$Z = 263.5 \times 10^{-6}$$

$$I_S = \frac{\frac{480}{40}}{263.5} \times 10^{+6} = 45{,}600 \text{ amperes}$$

Calculations Using Charts, Etc.

While the methods following are not as accurate as ohmic calculations they are satisfactory in many cases. The drops arrived at are impedance drops and are added arithmetically.

Feeder voltage drop can be read directly using the special slide rule of Reference 15. The drop in this case is given as 14.0 volts.

Transformer drops are found as follows:

For three-phase transformers -

$$E_D = \frac{\text{KVA (demand)} \times Z\% \times 2 \times E_{LL}}{\text{KVA (rating)} \times 100} \quad \text{(volts)}$$

For this case the drop is found to be 23.7 volts. (Transformer Z = 5.75%)

For single-phase transformers -

$$E_D = \frac{\text{KVA (demand)} \times Z\% \times E_{LL}}{\text{KVA (rating)} \times 100} \quad \text{(volts)}$$

For transmission lines -

$$E_D = \frac{(2 \times \text{KVA (demand)} \times E_{LL})}{(\text{KVA (fault capacity)})} \quad \text{(volts)}$$

For this example the drop is found to be 4.88 volts.

The total drop is the sum of 14, 23.7 and 4.88 giving 42.58 volts. The ohmic calculation drop was 47.4 giving an error of 10.2% for the estimated drop.

Reference 2 on page 53 of Reference 1 gives methods for estimating voltage changes on the loaded and unloaded phases.

Drops Due to Multiple Loads

When more than one load is connected to a supply system it is often necessary to determine the effect of the drop produced by one load or loads on other machines.

Reference 5 on page 53 of Reference 1 gives procedures for finding these effects.

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APPENDIX

CHARACTERISTICS OF MACHINE USED FOR SAMPLE CALCULATIONS

General Rating

Type	RWMA Size 2 Proj.
Rating	150KVA (50% DC)
Throat Depth	30 inches
Primary Voltage	440 volts
Frequency	60 Hz
Secondary Voltage-Max.	11.0 volts
Secondary Voltage-Min.	5.95 volts
Rated Secondary Current	13650 amperes

Short Circuit Data

Secondary Output	50,000 amperes
Power factor	27.5%
Demand	550 KVA
Demand	1272 amperes
Impedance(Ref.to Sec.).	220 microhms
Reactance "	212 microhms
Resistance "	60.5 microhms

Welding Data

Secondary Current	46,200 amperes
Secondary Voltage	11.0 volts
Demand	508 KVA
Demand	1155 amperes(Pri.)
Power factor	46.5%
"ON" Time	20 cycles(0.33 sec.)
"OFF" Time	7.32 seconds
Duty cycle	4.36%
Power factor angle theta	62.3 degrees
Continuous equivalent	106 KVA
Continuous equivalent	241 amperes(Pri.)
Impedance(Ref.to Sec.)	238 microhms
Reactance "	212 microhms
Resistance "	110.5 microhms

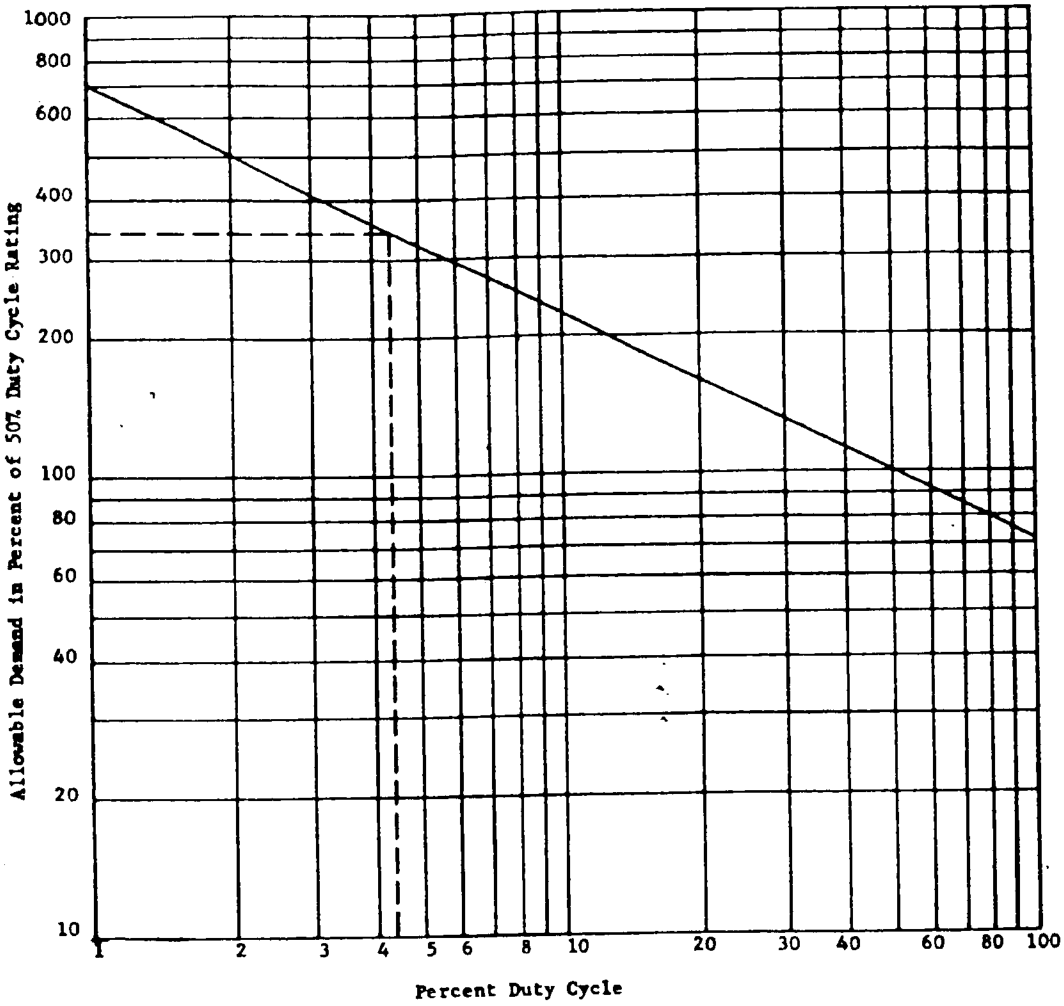


Figure 1

100% POWER FACTOR

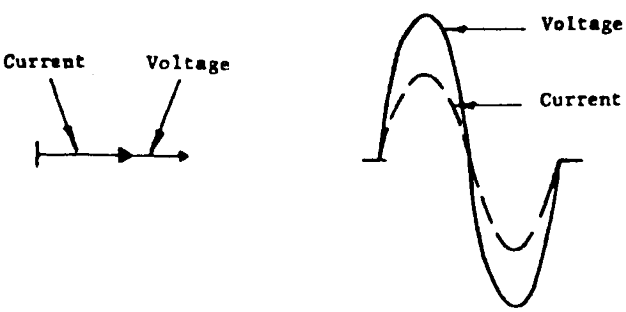


Figure 2

ZERO POWER FACTOR

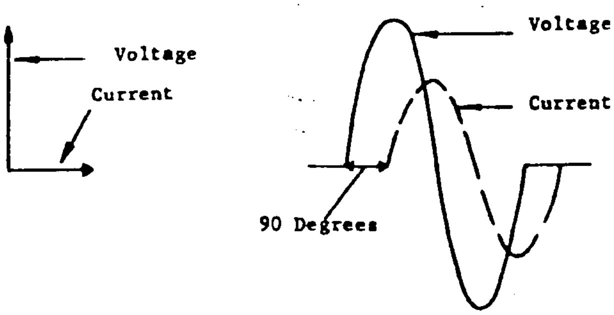


Figure 3

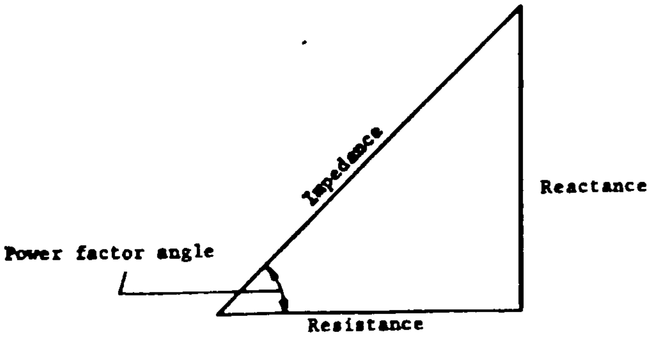


Figure 4

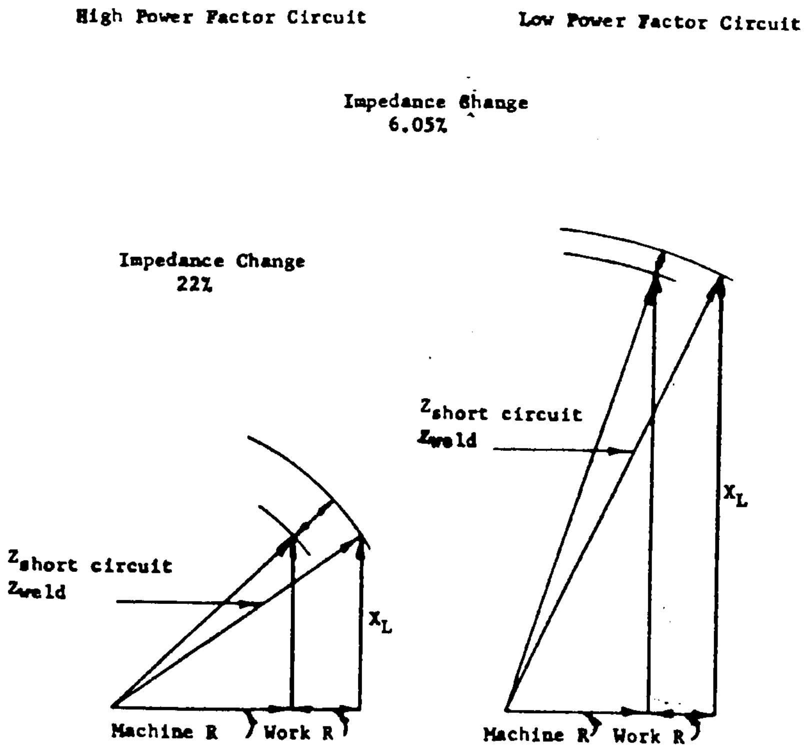


Figure 5

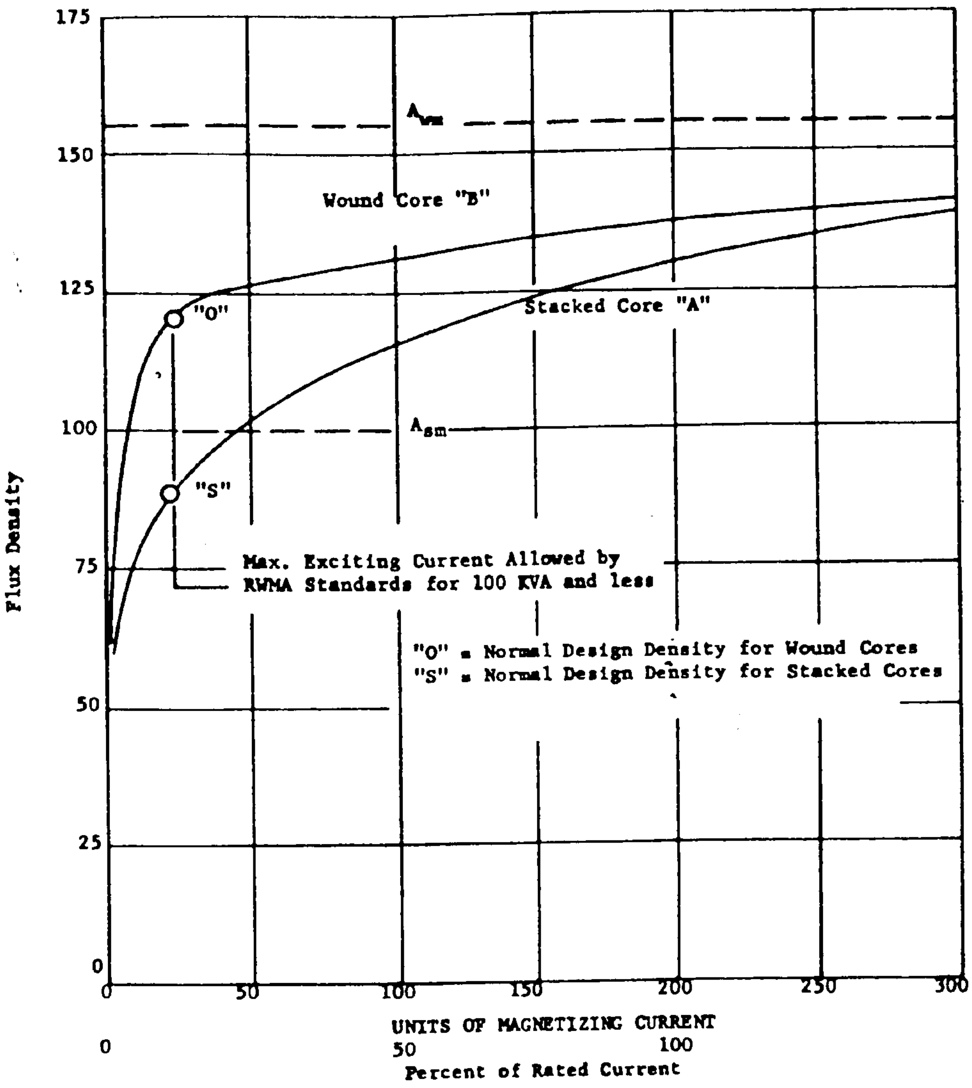
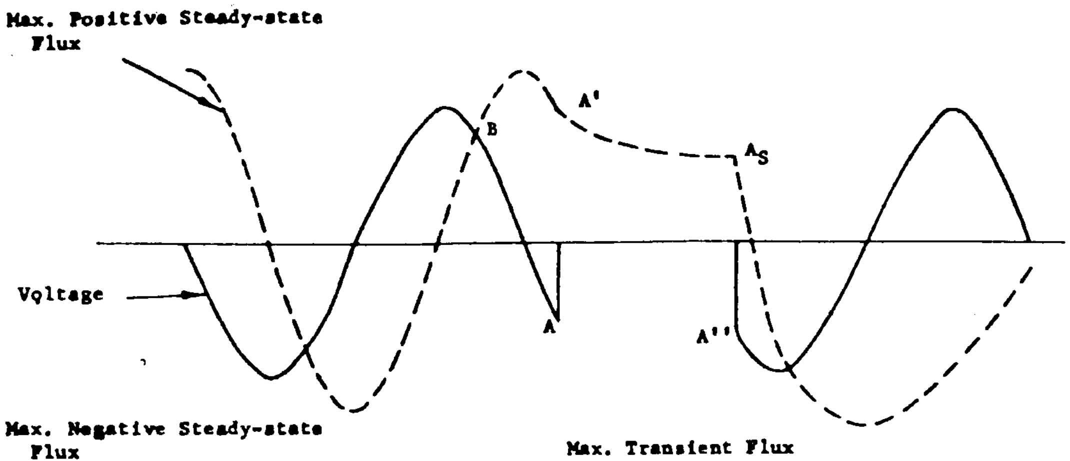
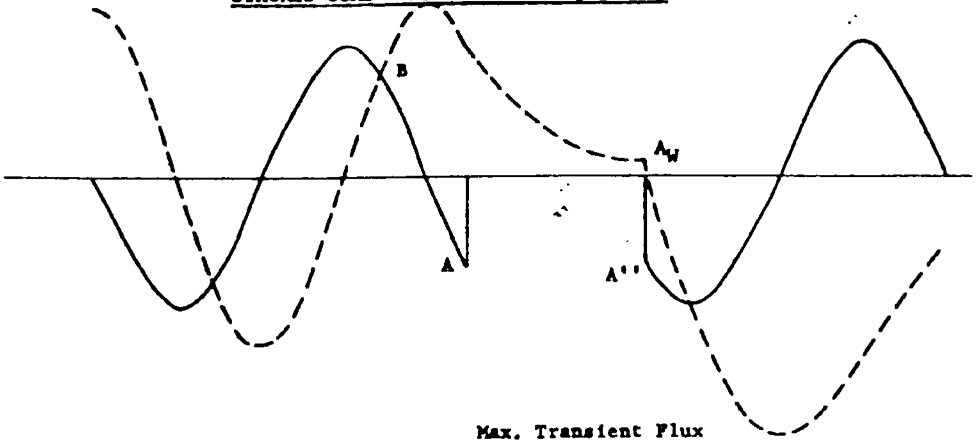

175
150
125
100
75
50
25
0
Flux Density
A_wm
Wound Core "B"
Stacked Core "A"
"O"
"S"
A_sm
Max. Exciting Current Allowed by
RWMA Standards for 100 KVA and less
"O" = Normal Design Density for Wound Cores
"S" = Normal Design Density for Stacked Cores
0
50
100
150
200
250
300
UNITS OF MAGNETIZING CURRENT
0
50
100
Percent of Rated Current

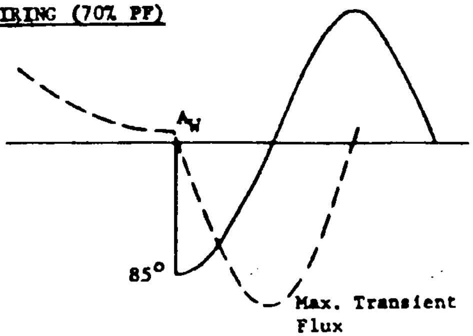
Figure 6



STACKED CORE - NORMAL FIRING (70% PF)



WOUND CORE - NORMAL FIRING (70% PF)



WOUND CORE - 85° FIRING (70% PF)

Figure 7

APPROXIMATE TIME-CURRENT CURVES
FOR
600 VOLT FUSES AND MOLDED CASE BREAKERS

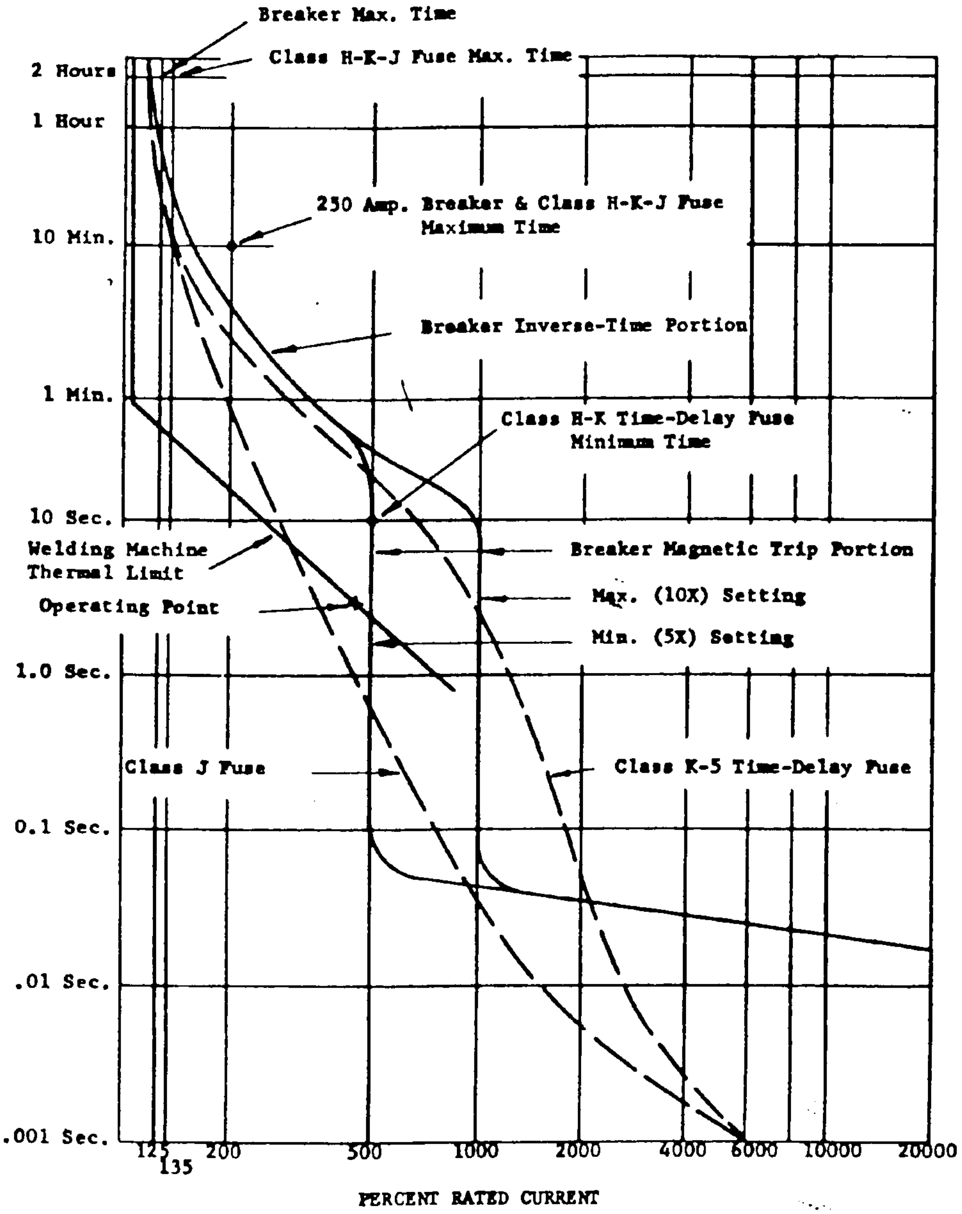


Figure 9

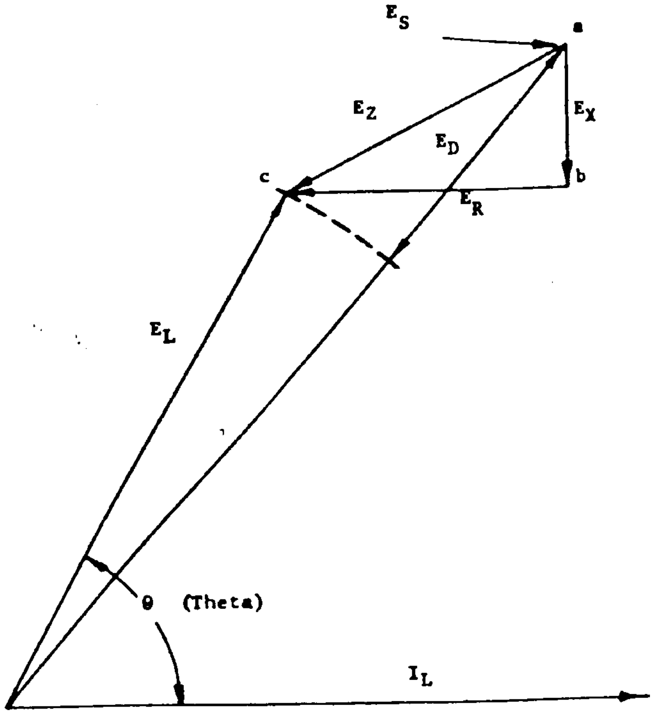


Figure 10

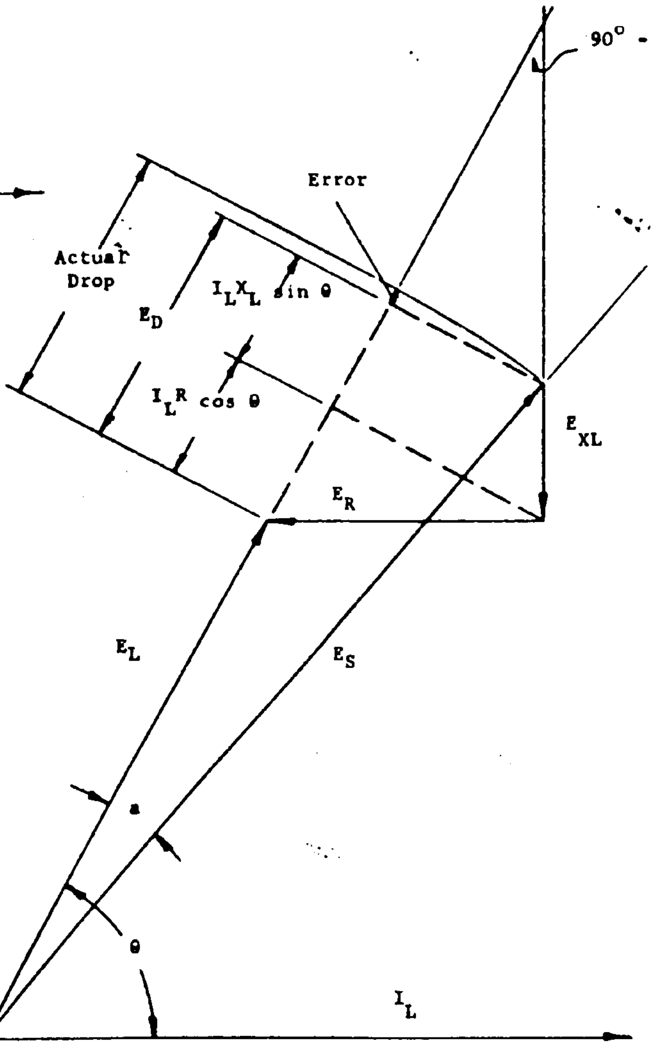
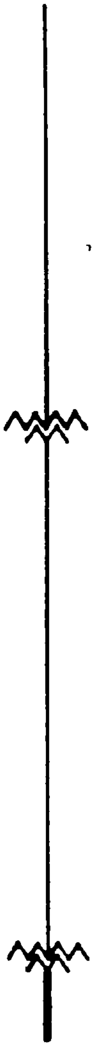
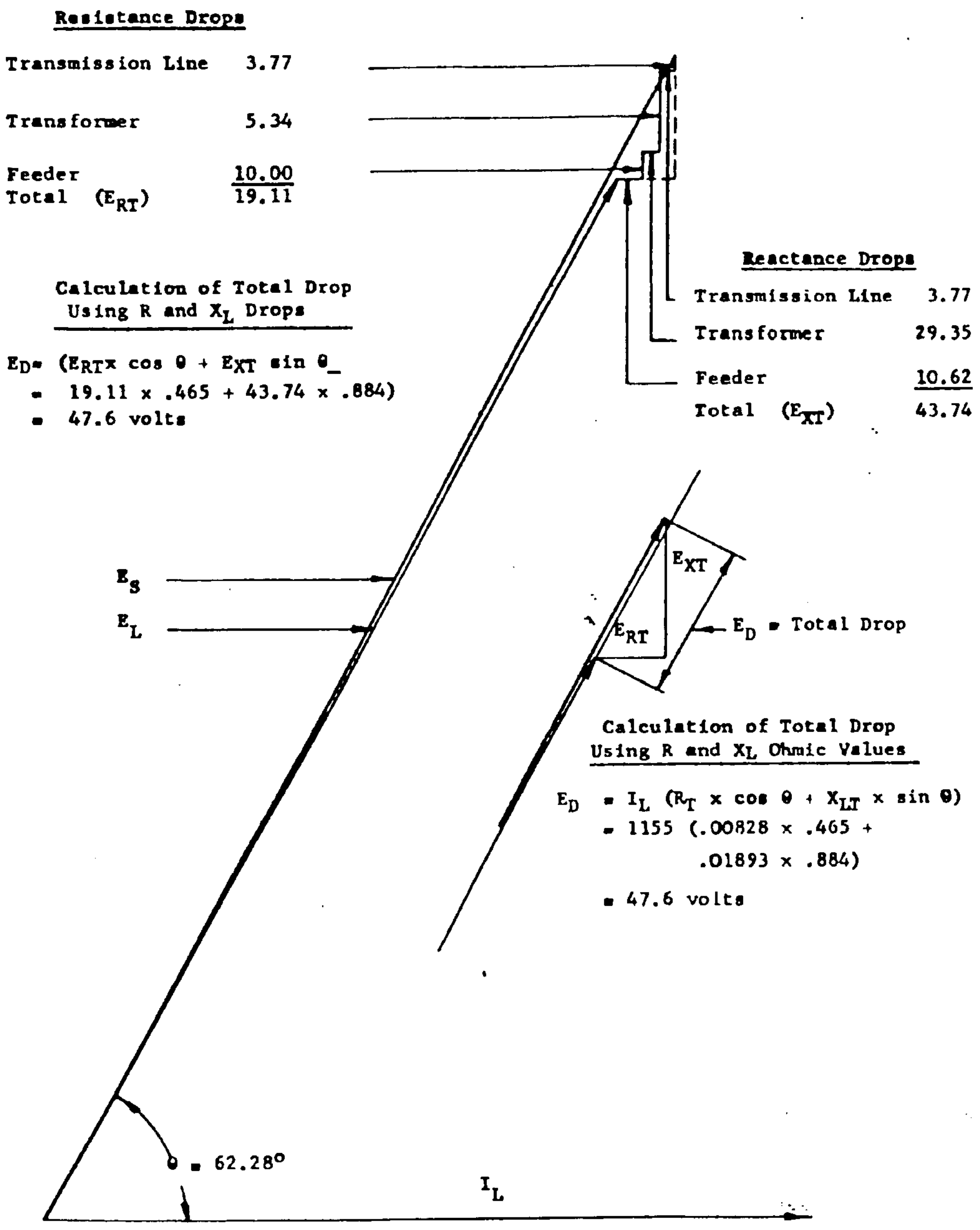


Figure 11



	Ohms to Neutral 480v Base		Line-to-Line Voltage Drop at 480v
	R	X_L	
TRANSMISSION LINE			
4160 volts line-to-line 100,000 KVA Fault Capacity 0.122 + j0.122 ohms			
$R = \frac{0.122}{75} =$	.00163		5.05
$X = \frac{0.122}{75} =$		.00163	
TRANSFORMER			
1000 KVA Three-phase 4160/480 line-to-line			
R = 1%	.00231		28.60
X = 5.5%		.01270	
FEEDER			
1 - 300 MCM/leg 100 feet from transformer to load			
R =	.00434		14.00
X =		.00460	
Total at Machine	.00828	.01893	47.60
LOAD			
508 KVA (1155 Amp.) 46.5% PF			

Figure 12



Resistance Drops

Transmission Line	3.77
Transformer	5.34
Feeder	10.00
Total (E_{RT})	19.11

Calculation of Total Drop Using R and X_L Drops

$E_D = (E_{RT} \times \cos\theta + E_{XT} \sin\theta$_

$= 19.11 \times .465 + 43.74 \times .884)$

$= 47.6$ volts

Reactance Drops

Transmission Line	3.77
Transformer	29.35
Feeder	10.62
Total (E_{XT})	43.74

Calculation of Total Drop Using R and X_L Ohmic Values

$E_D = I_L (R_T \times \cos\theta + X_{LT} \times \sin\theta)$

$= 1155 (.00828 \times .465 +$

$.01893 \times .884)$

$= 47.6$ volts

Figure 13