Preliminary Design of an 18MVA Industrial System

A Major Qualifying Project submitted to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
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Abstract

The purpose of this project was to explore power factor correction in an industrial setting. A theoretical factory is looking to expand its operation. In order to do so, they are opening up a new wing in the factory. In designing the new wing, they need to supply power to the lights and to the various induction motors required to run the machinery. These motors operate with a certain power factor. They manufacturer wants to correct this lower-than-desired power factor so that the motors draw less current, ultimately decreasing losses in conductors and saving them money on their operation.

Acknowledgements

I would like to thank my advisor Professor Emanuel for taking me under his wing when I desperately needed another project, for his guidance and encouragement along the way, and for his patience at times when the project may not have been going as smoothly as we would have liked. Without him, this project would not have been possible.

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1.0 Introduction

Especially in an industrial setting, efficiency is key. It can mean the difference between facing heavy fines and meeting government standards, between being on budget versus being over budget, between on time and past the deadline. An inefficient factory will face problems with costs that could force them to close. One way to reduce inefficiencies in their system and reduce costs, at least for power, is through power factor correction.

Power factor is essentially a measure of how much of the power consumed is actually useable by the equipment. The factory is drawing drawing current for all the power consumed, not just what is used by the equipment. By correcting this power factor, you keep the power actually used by the equipment the same, but decrease the total consumed, reducing the current necessary to get the power to the equipment. In doing so, you decrease the losses in the transmission system and reduce the costs of building because you can build to a lower current.

2.0 Background

2.1 Power

Power is a measure of energy consumed over time. Generally measured in Watts, it represents Joules per second. Power can be mechanical, it can be magnetic, or it can be electric. Motors, for example, convert electric power into mechanical power plus heat losses, such that **Figure 1** is an accurate representation of the input and output powers of a motor.

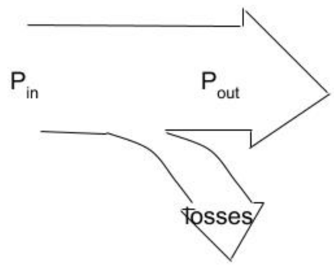


Figure 1 - Basic Power Flow Diagram

Power can be defined by:

$$P = I * V \qquad \text{(Eq 1)}$$

where P is power in watts, I is current in Amperes, and V is voltage in Volts. Using Ohm's Law:

$$V = I * R \qquad \text{(Eq 2)}$$

where R is resistance in Ohms (Ω), Equation 1 can be rewritten in two other forms, depending on what information is available. Given voltage V and resistance R, it can be rewritten as:

$$P = \frac{V^2}{R} \qquad \text{(Eq 3)}$$

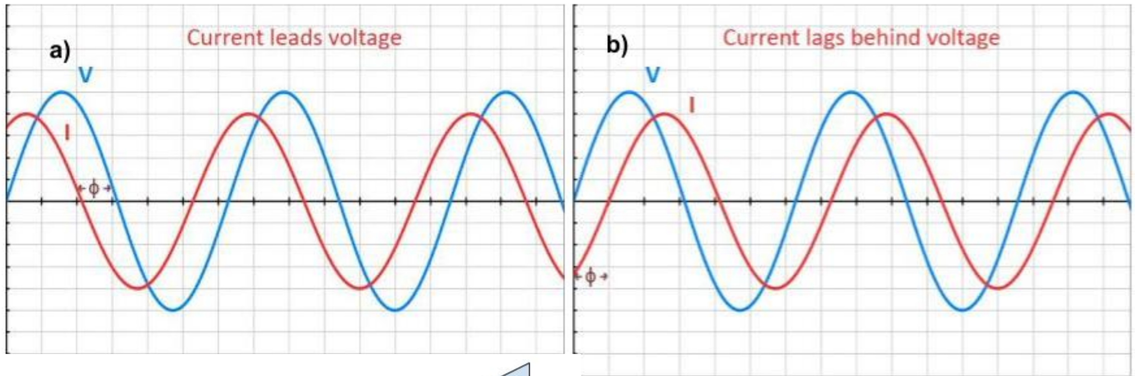
Alternately, when given current I and resistance R, the equation is rewritten as:

$$P = R * I^2 \qquad \text{(Eq 4)}$$

This format is primarily used to calculate losses in a system, such as losses along the length of a conductor.

2.2 The Power Triangle

In inductive or capacitive systems, power is not quite so straightforward. When there are inductive or capacitive loads present in a system, power has multiple components. Power comes three varieties: real power P and reactive power Q, which combine via the Pythagorean theorem into apparent power S. Real power R is the result of resistive loads and uses Watts as a unit. Reactive power Q is a result of lagging or leading current resulting from an inductive or capacitive load. Reactive power is a parasitic value that, while it increases apparent power consumed therefore increasing currents to be designed for, it does nothing to power any sort of



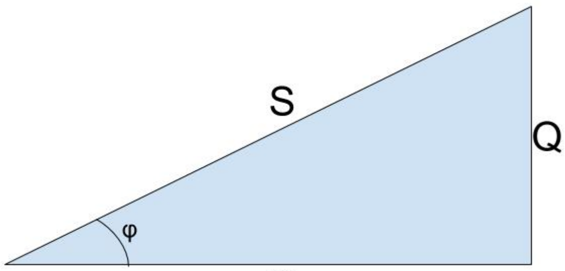


Figure 2 - a) capacitive current lead,
b) inductive current lag,
c) resulting power triangle

machinery or electronics on the system. Capacitors result in a current waveform that "leads" the voltage waveform, meaning that the current waveform is out of phase with the voltage waveform, being ahead by some angle as in **Figure 2a**. Inductors result in a "lagging" current waveform, meaning the current waveform is some angle behind the voltage waveform, as seen in **Figure 2b**. In a system with capacitors, inductors, and resistors, the net lag or lead in the system can be modeled as a literal triangle, aka the Power Triangle, as seen in **Figure 2c**. The angle φ in the triangle is the same the angle by which the current lags or leads the voltage. By taking cos(φ), a relationship between P, Q, and S is formed called the "Power Factor". The Power Factor is essentially a measure of how much of that power is usable, i.e. real power, relative to the apparent power S that gets consumed by the system.

2.3 Power Factor Correction

In order to decrease the value of Q and correct the power factor, an additional inductive or capacitive load is needed. If the original power factor is due to an inductive loads, the power factor can be corrected with the proper capacitance. If the power factor is due to a capacitive load, it can be corrected using the correct size inductor.

The use of inductive loads to correct capacitive loads, and vice versa, is due to the lagging of the current in inductive loads and the leading of current in capacitive loads. If the current is lagging, it can be corrected by adding a capacitive load, cancelling out the lag in the current waveform by adding a lead, in a sense. The same happens when an inductor is used to correct a leading current waveform from a capacitor.

An alternate explanation comes from drawing them as arrows. **Figure 3** shows the current and voltages. **Figure 3a** shows what happens when the power factor is 1, or “unity”, meaning there is no phase shift in the current waveform. **Figure 3b** shows a capacitive load. **Figure 3c** shows an inductive load. Note that one is pointing up, and the other is pointing down. This shows that inductors can be used to correct a capacitive load’s power factor, and that capacitors can be used to correct an inductive load’s power factor.

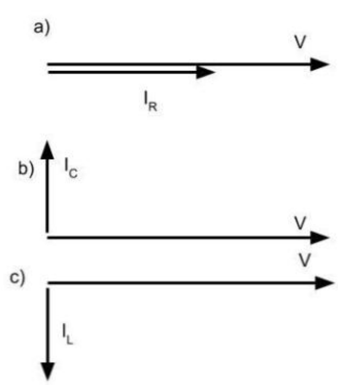


Figure 3 - a) resistive load
b) capacitive load
c) inductive load

In order to correct the power factor, the capacitances and inductances need to be the correct size. They must match so that the reactive power through each is equal and opposite to the original reactive power (assuming a correction to unity, or to a power factor of 1). In order to find the value of a capacitor given an inductive load, use the equation:

$$C = \frac{Q}{2\pi f * V_{LL}^2} \qquad \text{(Eq 5)}$$

where Q is the reactive power, f is the frequency (typically 60 Hz in power systems), and V_{LL} is the line-to-line voltage. Likewise, if the load is capacitive, and the the value of a corrective inductor is needed, use the equation:

$$L = \frac{V_{LL}^2}{2\pi f * Q} \qquad \text{(Eq 6)}$$

Equations 5 and 6 are the necessary equations to calculate the capacitance and inductance needed to correct inductive and capacitive power factors respectively. All that is needed is the uncorrected power factor.

2.4 3 Phase Power

Power is often delivered as what is called "Three Phase Power". Three Phase Power is power delivered as three separate current waveforms of equal magnitude, each 120° out of phase

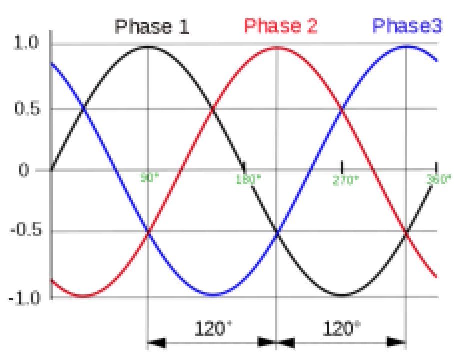


Figure 4 - Three Phase Current Waveform

from each other. This ensures that there is constant power delivery, rather than the on-and-off delivery from single phase. The Three Phase current waveforms can be seen in **Figure 4**.

Notation in Three Phase Power is less straightforward that in single phase. The three phases are labelled I_a, I_b, and I_c. These correspond to voltages V_a, V_b, and V_c. However, whenever voltages are needed for calculations, they are measured in V_{LL} and V_{LN}. V_{LL} is voltage line-to-line. This is the voltage of the phases relative to each other. Likewise, V_{LN} stands for voltage line-to-neutral, or the voltage of one line relative to the neutral wire. The conversion process is quite simple:

$$V_{LN} = V_{LL}/\sqrt{3} \qquad \text{(Eq 7)}$$

This equation is used quite frequently, so it is an important one to memorize.

One last important thing to note is that in calculations involving three phase systems, it is often the case that equations must take into account that there are multiple lines involved, so there needs to be a scaling factor of 3. One such notable equation is calculating line losses, such that equation 4 is changed to:

$$P = 3 * R * I^2 \qquad \text{(Eq 8)}$$

The new coefficient of 3 is because there are three lines, and therefore three times the resistance.

3.0 Problem Statement

A theoretical factory is looking to expand their production a bit by opening a new wing of the factory. The new wing requires power for lights and for induction motors that will run the machines necessary for production. The wing of the factory is supplied by a 3-phase voltage of 14kV RMS, line-to-line at 60 Hz. It runs into a step-down transformer that steps it down to 440 V RMS, line-to-line. Out of that transformer, it runs along a line for 50 meters before it splits into two branches: one running to the factory's induction motors, and one running to the lights. The entire system can be seen in **Figure 5**.

The induction motors run on 440 V_{RMS}, with an efficiency of 90%, and an inductive power factor of 85%. The max power drawn by the motors is 18 MVA, but the load varies in time. It follows a sine wave that runs from 60% load to 100% load (10.8 MVA to 18 MVA) over the period of 24 hours. The lights draw 0.5 MVA, and have a total harmonic distortion of 28%.

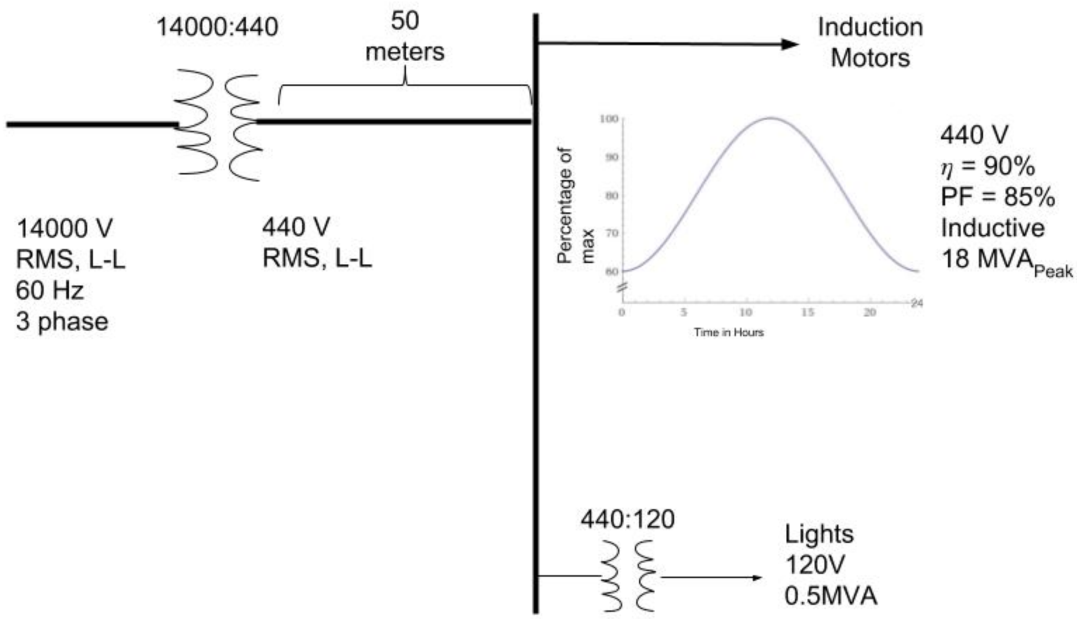


Figure 5 - Initial design of the system

The goal of the project is to correct the power factor of the induction motors to 98%. In order to do this, one must calculate and determine:

- The size of the Circuit Breakers and Fuses
- Transformer ratings
- Capacitors needed to correct the power factor
- Conductor size and material
- Surge and overload protection
- Power lost

4.0 Defining the System

All calculations are compiled for easy checking in **Appendix A.**

4.1 Defining the Conductor

In order to determine the details of the conductor, the current out of the transformer secondary must be found. Given a total of 18.5 MVA that needs to be carried to the lights and to the motors, and given a voltage of 440 V_{LL}, or 254 V_{LN}, the total current carried by the 50 meter conductor running from transformer outside all the way to the new wing of the factory is:

$$I = \frac{S}{3 * V_{LN}} = \frac{18.5x10^6\ VA}{3 * 254\ V} = 24278\ A \qquad \text{(Eq 9)}$$

This is the maximum current to run through each of the conductors, which is the bar minimum that they musteach be able to bear. Note the 3 in the denominator, meaning the power needs to be divided amongst the three conductors of the system. In order to find the necessary cross-sectional area, both the current and current density are needed. The equation for current Density (J) is:

$$J = I / A \qquad \text{(Eq 10)}$$

where A is the cross-sectional area. The given minimum current density is 3 A/mm^2, i.e. $J \geq 3$ A/mm^2. Using this value and rearranging Equation 10, the cross-sectional area can be found:

$$A = \frac{I}{J} = \frac{24278\ A}{3\ A/mm^2} = 8093\ mm^2$$

Bear in mind, this cross-sectional area is meant to be the area of only one single conductor, all of which should be the same size. To make for easier routing throughout the facility, a rectangular cross-section would be ideal for the conductor, as it could be made thinner along one axis, and therefore easier to bend whenever necessary. A good idea for the dimensions may be something along the lines of 130 x 62 mm, making it not too thin in any one direction, but not so thick it would be impossible to bend and route throughout the building. Compare this value to a diameter of roughly 100 mm should a circular conductor be chosen. It would make it significantly more difficult to route this conductor throughout the facility.

The wire, as with all materials, would have some level of resistance along its length. The equation for resistance along the length of a conductor is:

$$R = \rho \frac{l}{A} \qquad \text{(Eq 11)}$$

The length l is given as 50 meters, and the cross-sectional area A was found to be 8093 mm^2, or 0.008903 m^2, so all that is needed is ρ, or the resistivity of whatever material is chosen for the conductor. A common material for the conductor is copper, which has a resistivity ρ_{Cu} of $1.72x10^{-8}$ Ω*m. Given this material's resistivity and equation 11, the resistance is:

$$R = 1.72x10^{-8}\Omega * m * \frac{50\ m}{0.008903\ m^2} = 1.06x10^{-4}\ \Omega$$

Lastly, given this resistance, the losses along the conductor can be calculated. In a three phase system, the losses along the conductor can be calculated using a variation of equation 4 which, similar to equation 9, takes into account that there are three separate but identical conductors. The equation for losses along the three conductors is:

$$P = 3 * I^2 * R$$

Given the calculated current of 24278 A and resistance of $1.06x10^{-4}$ Ω, the losses along the conductor are:

$$P = 3 * (24278\ A)^2 * 1.06x10^{-4}\Omega = 187436\ W$$

In summary, the conductor creates huge losses in the uncorrected system. Unfortunately, the conductor dimensions must remain the same after correcting the power factor.

4.2 Pre-Correction Power Triangle

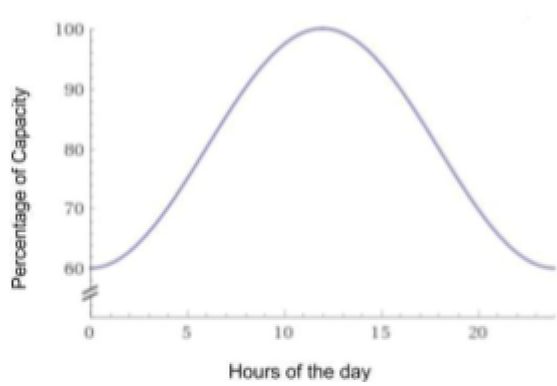


Figure 6 - Graph of Operation Levels throughout the Day

Given the graph of the level of operation throughout the day in **Figure 6**, the maximum power draw of the motors is 18 MVA. The original power factor for these motors is also given as 0.85. Using these values, the sides of the power triangle (S, P, Q) can be calculated for various times throughout the day. In order to correct the power factor of the system, the original S, P and Q must be known at multiple times throughout the day, otherwise the power factor may only be corrected for one single point in the day, which wouldn't make much sense. For simplicity of calculation, the percentages are chosen at the daily minimum capacity the daily average capacity, and the daily maximum capacity, or 60%, 80% and 100% respectively.

At the maximum capacity, it is given that the apparent power S_{max} = 18 MVA. In order to find the real power, 2 of 3 values must be known: S, Power Factor (PF), and Q. S and PF are known, so the equation:

$$P = S * PF \qquad \text{(Eq 12)}$$

is usable. Given S_{max} = 18 MVA and PF = 0.85, equation 12 yields the result:

$$P_{max} = 18\text{ MVA} * 0.85 = 15.3\text{ MW}$$

Which is what drives the motors at their peak levels of operation. This value will stay here even after correcting the power factor, otherwise the motors would not function at the levels necessary for peak operations. Lastly, the value that will be corrected, Q, must be calculated. This can be found simply using the Pythagorean theorem, as it is the last leg of the power triangle, which is a right triangle. The equation to find it given P and S is:

$$Q = \sqrt{S^2 - P^2} \qquad \text{(Eq 13)}$$

Knowing S_{max} and P_{max}, Q_{max} can be found as:

$$Q_{max} = \sqrt{18^2 - 15.3^2} = 9.5\text{ MVar}$$

Q_{max} is the maximum value that will be corrected.

At the average operation levels for the motors, or at 80%, the apparent power S_{ave} = 14.4 MVA. Given the power factor of 0.85 and equation 12, the real power P_{ave} can be found as:

$$P_{ave} = 0.85 * 14.4\text{ MVA} = 12.24\text{ MW}$$

Which will remain after correction. Lastly, the reactive power is:

$$Q_{ave} = \sqrt{14.4^2 - 12.24^2} = 7.6\text{ MVar}$$

Again, this is the value to be corrected.

Lastly, the motors will be operating at 60% at the bare minimum, such as in the middle of the night. This means that the apparent power S_{min} = 10.8 MVA. Given this and equation 12:

$$P_{min} = 0.85 * 10.8\text{ MVA} = 9.18\text{ MW}$$

Yet again, this value will remain the same after correction. Lastly, given S_{min} and P_{min}:

$Q_{min} = \sqrt{10.8^2 - 9.18^2} = 5.7$ MVar

Just a reminder that these values are before power factor correction.

4.3 After Correction

The desired corrected power factor is 0.98. The induction motors at 100%, 80%, and 60% require the input of real power P of 15.3, 12.24, and 9.18 MW respectively. Given the power P and the new power factor, the equation to find the new apparent power S is a variation of equation 12:

$S = P/PF$ (Eq 14)

Once S is found, the equation to find Q stays the same as in Equation 13.

At max, the new S is:

$S_{max} = 15.3 / 0.98 = 15.6$ MVA

Note how much closer the new value to the real power. This means Q_{max} is expected to be much smaller. Now, applying equation 13:

$Q_{max} = \sqrt{15.6^2 - 15.3^2} = 3$ MVar

At the average of 80%, the real power P_{ave} is a constant 12.24 MW. Applying equation 14 again yields:

$S_{ave} = 12.24 / 0.98 = 12.5$ MVA

Again, not too much larger than P_{ave}, so Q_{ave} can be expected to be even smaller. Applying equation 13 again yields:

$Q_{ave} = \sqrt{12.5^2 - 12.24^2} = 2.5$ MVar

Lastly, at the minimum operation level of 60%, the real power P_{min} is 9.18 MW. Applying equation 14 one last time, the apparent power at the minimum is:

$S_{min} = 9.18 / 0.98 = 9.36$ MVA

That, like the last two times, shows that Q_{min} can be expected to be even smaller. Applying equation 13 one final time yields:

$Q_{min} = \sqrt{9.36^2 - 9.18^2} = 1.8$ MVar

At all these levels, the apparent and reactive power are significantly smaller than before. This will, in the long run, save the facility lots of money on power costs, and less of a burden on the system means less maintenance costs.

5.0 Implementation

5.1 Capacitor Banks to Correct the Power Factor

The motors in the facility are inductive motors. This means that the power factor and the reactive powers are all inductive, and require the use of capacitors in order to correct them. In order to determine the proper capacitor size, the difference in the reactive power at each level must be known. The values are shown in **Table 1** to compare them at the old and new power factor, as well as the difference between the two.

Table 1 - Reactive Powers and Corresponding Capacitances

%	Q_{Old} (MVar)	Q_{New} (MVar)	$\Delta Q = Q_{Old}-Q_{New}$ (MVar)	Total Capacitance	Capacitance for Step
100%	9.5	3	6.5	89 mF	17.8 mF
80%	7.6	2.5	5.1	71.2 mF	17.8 mF
60%	5.7	1.8	3.9	53.4 mF	53.4 mF

Using the ΔQ values from **Table 1**, it is possible to know what correction capacitors to use based on the desired change change in Q. In order to correct the power factor at all the chosen points throughout the day, one single capacitor is not enough, otherwise the power factor will be corrected only at that point in the day. As the level of operation increases, so does the change in Q, and therefore so does the capacitance needed. As such, a possible implementation is a capacitor

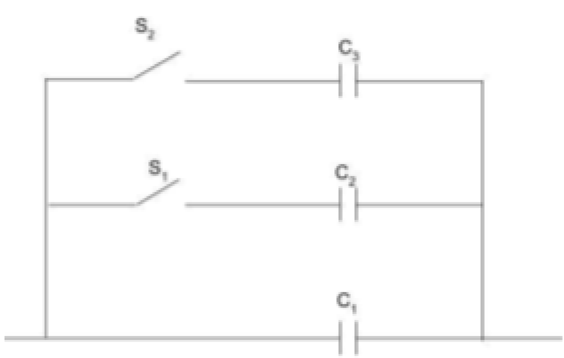


Figure 7 - Switched Capacitor Bank

bank, as seen in **Figure 7**. This capacitor bank contains however many capacitors needed for however many points were chosen. In this case, three capacitors were chosen because only three levels were chosen. The capacitors are connected in parallel, with switches on all but the base capacitor, the minimum capacitance, which corresponds to 60% capacity, the lowest the motors go over the course of the day. The other capacitors are each in series with their own switch, such that they are switched on around the time when the system typically reaches that point. They are in parallel because capacitors in parallel add due to capacitance being a function of the surface area between the plates of a capacitor, and putting them in parallel effectively adds the surface areas. These capacitor banks are implemented in parallel to the motor, with one on each phase, as seen in **Figure 8**.

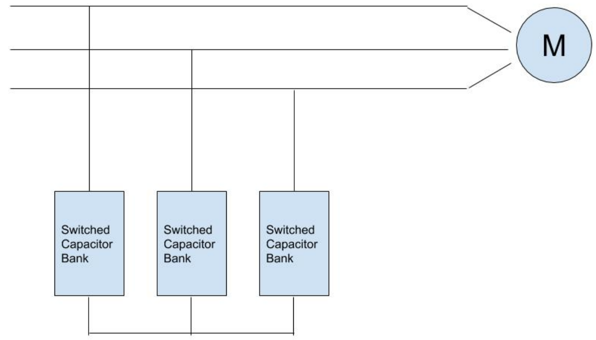


Figure 8 - Capacitor Bank on the Three Phase System

In order to find the size of the total capacitances at each level, equation 5 is used, subbing in ΔQ for Q, so that the desired Q is reached. At max, the total capacitance is:

$$C_{max} = \frac{6.5x10^6\ MVar}{2\pi * 60\ Hz * 440V^2} = 89\text{ mF}$$

At the average:

$$C_{ave} = \frac{6.5x10^6\ MVar}{2\pi * 60\ Hz * 440V^2} = 71.2\text{ mF}$$

And the minimum:

$$C_{min} = \frac{6.5x10^6\ MVar}{2\pi * 60\ Hz * 440V^2} = 53.4\text{ mF}$$

These capacitances, as mentioned, are the total capacitances need to correct the power factor at the given points, assuming a frequency of 60 Hz (f = 60 Hz) and a line-to-line voltage of 440 V (V_{LL} = 440 V). However, the actual values of capacitances need to be found. This is simply done by subtracting them from one another, such that:

$C_1 = C_{min} = 53.4$ mF

$C_2 = C_{ave} - C_{min} = 71.2 - 53.4 = 17.8$ mF

$C_3 = C_{max} - C_{ave} = 89 - 71.2 = 17.8$ mF

These are the values of the capacitors in each capacitor bank. Again, these values assume 60 Hz and 440 Volts line-to-line. Should neither of those be the case, these capacitor values would be wrong.

5.2 Savings

With the new power factor and new Q and S values, various things change. Most notably is the current draw on the conductor from before is lower. The length, resistance, and cross-sectional area remain the same because not only would that incur significant installation costs, but it would spell disaster for the system should the capacitor banks fail. Given the new new maximum apparent power for the motors of 15.6 MVA, and the unchanged apparent power draw of the lights being 0.5 MVA, the total apparent power carried by the conductor is 16.1 MVA. In order to calculate the reduction in losses, using equation 9, the maximum current carried by the conductor is:

$$I = \frac{16.1x10^6 VA}{3 * 254V} = 21128 \text{ A}$$

This reduction in current leads to fewer losses from the conductor's resistance. Given that it stays the same (due to the dimensions and the resistivity of the material remaining constant) at a value of $1.06x10^{-4}\ \Omega$, using equation 8, which was losses in a three phase system:

$$P = 3 * (21128 \text{ A})^2 * 1.06x10^{-4}\ \Omega = 141953 \text{ W} = 141.953 \text{ kW}$$

Remember that the losses before the power factor correction were 187.44 kW. That means that the power saved, the difference between the two values, is:

$$\Delta P = P_{old} - P_{new} = 187436 - 141953 = 45483 \text{ Watts} = 45.5 \text{ kW}$$

Using the power saved from losses alone, the money saved from losses alone can now be determined. Given a price tag of $0.14 per kiloWatt-hour (Cost = 0.14 $/kWh), the money saved is:

Savings/day = ΔP * time * Cost = 45.5 kW * 24h/day * $0.14/kWh = $152.81/day

Assuming the motors were running at their maximum all day, the facility would save $152.81 every day just from losses in the conductor.

6.0 Protection

6.1 Circuit breakers

One simple way to protect against excessive currents, translating to overvoltage protection thanks to Ohm's law, is through the use of basic circuit breakers. For simplicity's sake, a good possible choice for circuit breaker size is 125% of the maximum possible current in that wire. In the 50 meter long conductor, the maximum possible current is roughly 24278 A. The circuit breaker that is roughly 125% the maximum possible current there is 30 kA.

On the primary of the initial transformer, the 14000 V:440 V step down transformer, the current is found with an equivalency given in equation 15:

$$\frac{V_1}{V_2} = \frac{I_2}{I_1} \qquad \text{(Eq 15)}$$

This equivalence can be used to find the current on the primary side of the transformer. That current is:

$$I_1 = \frac{I_2 * V_2}{V_1} = \frac{24278A * 440V}{14000V} = 763 \text{ Amps}$$

Given this current, a circuit breaker placed before the transformer should have a value of 953 Amps.

The transformer leading to the lights is a 440V:120V step down transformer, because lights typically run on 120 Volts RMS. Given that the lights consume 0.5 MVA, applying a rearrangement of equation 1 gives the current on both the secondary and the primary. On the primary side, along side a scaling factor of 3 to account for the three phases, the current is:

$$I = \frac{S}{3 * V} = \frac{0.5x10^6}{3 * 440} = 379 \text{ A}$$

This current means a circuit breaker on the primary of the lights' transformer would need to be rated for 473 A. Meanwhile, the current on the secondary, where the voltage is 120 V:

$$I = \frac{S}{3 * V} = \frac{0.5x10^6}{3 * 120} = 1.39 \text{ kA}$$

The required circuit breaker would need to be rated for 1740 A.

Lastly, the current flowing the conductor directly to the motors needs to be calculated. Given the main conductor's current of 24278 A, the current into the lights' transformer primary of 379 A, and Kirchoff's Current Law (total current into a node equals total current out of the node), the current running in that wire is:

$$I_{motor} = I_{conductor} - I_{lights} = 24278 - 379 = 23899 \text{ A}$$

That means the circuit breaker in that section needs to be rated for 29.9 kA. It is important to note that, much like nearly everything in the calculations, these circuit breakers are meant to go on each phase, such that each point has three circuit breakers in total.

6.2 Lightning Protection

In the event of a lightning strike, the total current and voltage in the system briefly becomes vastly larger than the system is capable of handling, even with the circuit breakers. This is because the spike in current is over far too quickly for the circuit breakers to trip. The key to protecting against this rapid spike is called a lighting arrester. A lightning arrester, as seen in **Figure 9**, is simply two zener diodes placed anode to anode (negative to negative).

Figure 9 - Lightning Arrester

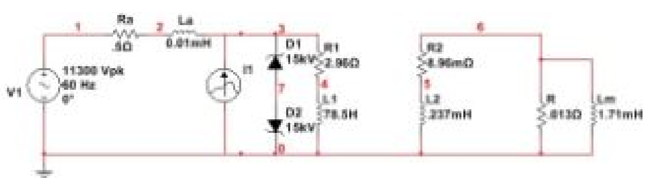


Figure 10 - Circuit with Lightning Protection

A zener diode is a type of diode. Like standard diodes, they let current pass through in one direction with relatively little difficulty. However, zener diodes have a "breakdown voltage", or BV, at which they "break down", or rather the voltage difference between cathode and anode at which they start to let current through the wrong way. By placing two of the anode to anode, if one of them breaks down and lets the lightning's current through, the other lets it pass. By placing the arrester between the line and ground, as seen in the test circuit in **Figure 10**.

This is a basic uncorrected, single phase representation of the circuit, without factoring in the lights, that was simulated in PSPICE. The purpose of simulating this circuit was to show that the lightning arrester did the job and allowed for continued normal operation by routing all the lightning away from the transformer, sending it directly to ground. The PSPICE code is shown in **Appendix B**.

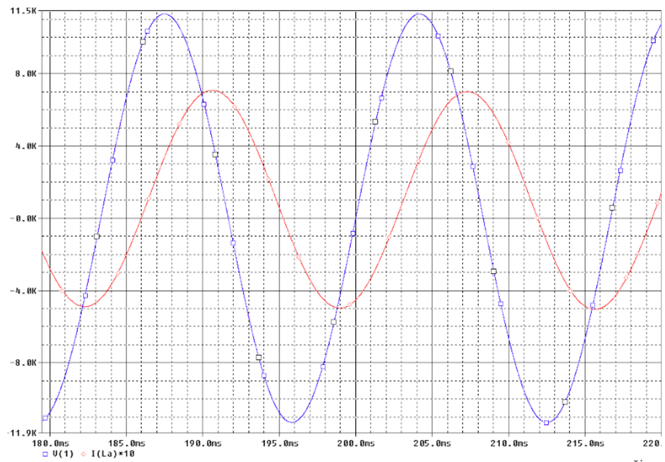


Figure 11 - Source Voltage And Current

The voltage out of the source is shown in **Figure 11**. The blue line is the voltage while the red is the current across a resistor and inductor representing part of the source, multiplied by a factor of 10 to make it easier to read the graph. This graph also shows the lag in current thanks to the inductance. This is before any lightning strikes.

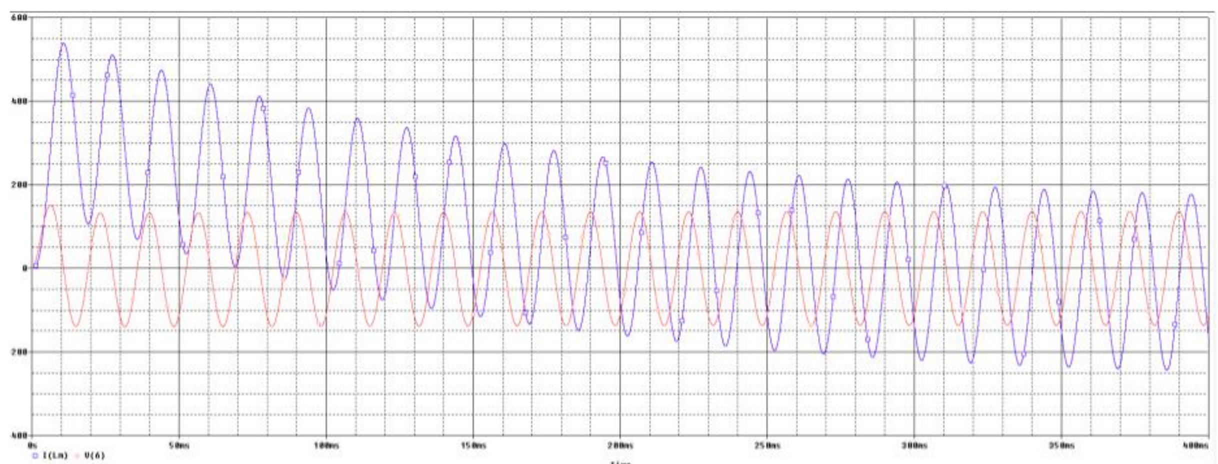


Figure 12 - Current and Voltage across motor with neither lightning nor protection

Next, the current and voltage going into the motor are shown in **Figure 12**. The current is in blue, and the voltage is in red. The current starts higher as the inductors charge and the motor picks up. This is, yet again, without lightning.

When lightning strikes, the current in **Figure 13** is injected into the system. The lightning strike starts at 0 A. It nearly instantaneously jumps to 20 kA. The rise time is only a mere 1 microsecond. It then decreases at a rate of 1 kiloAmp every 5 microseconds, reaching zero Amps at 100 microseconds and staying there indefinitely. The current on the primary of the transformer and through the motor are shown in **Figure 14**. The blue line is through the motor, while the purple line is through the transformer primary. Note that there is a massive spike in current at the beginning. That spike is caused by the lightning when

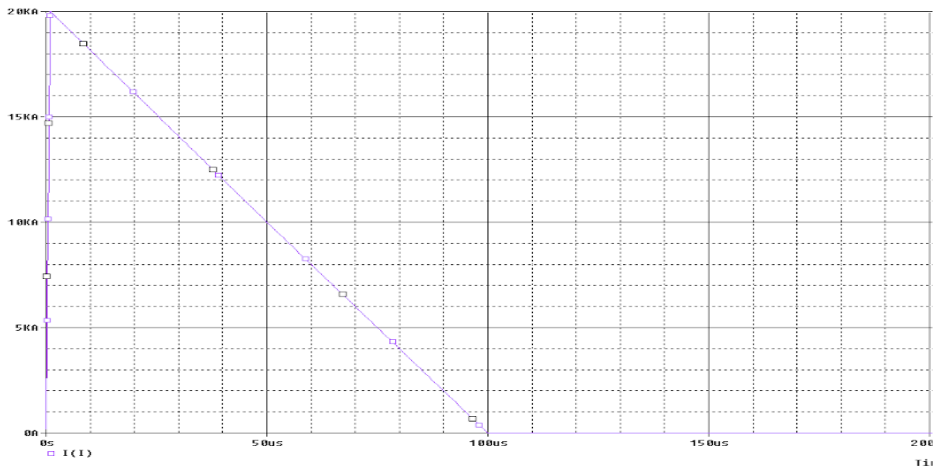


Figure 13 - Lightning Strike Current

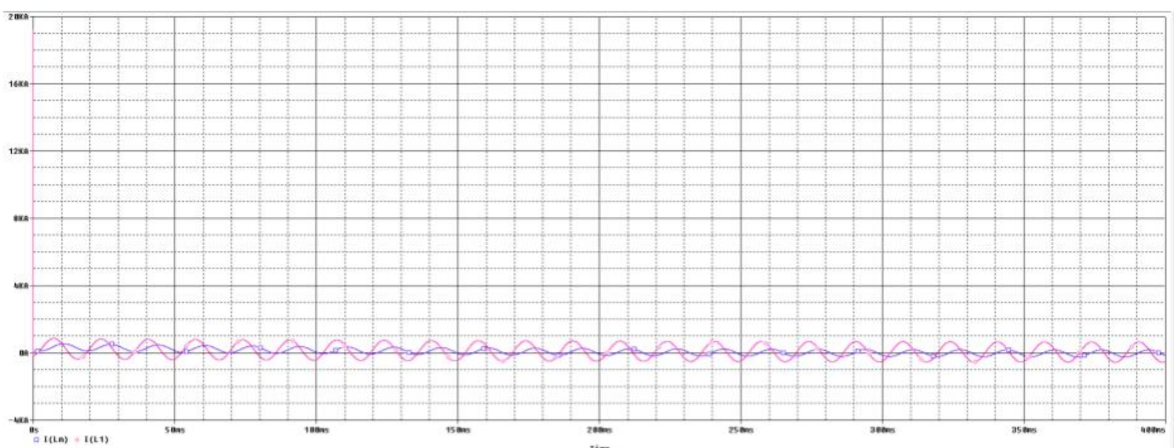


Figure 14 - Effects of lightning on the transformer and motor

there is a lack of protection on the system. Despite being such a small spike as far as duration is concerned, it can result in serious damage to the system because of the drastic increase in power in the system. Overheating will be a major cause for concern, and various circuits could theoretically explode, much like older electronics during power surges. It is spikes like that which the lightning arrester is meant to protect against.

When the lightning strikes, the current in the system increases exponentially for a short period of time. As a result of the resistivity of just about every object conceivable, this also translates into an absolutely massive voltage drop between the source node and ground. Again, this can be protected against using two zener diodes placed anode-to-anode, such that no normal current can get through the diodes, but a very large current, exceeding the breakdown voltage of the diodes can force its way through. This means the lightning can run straight to ground and

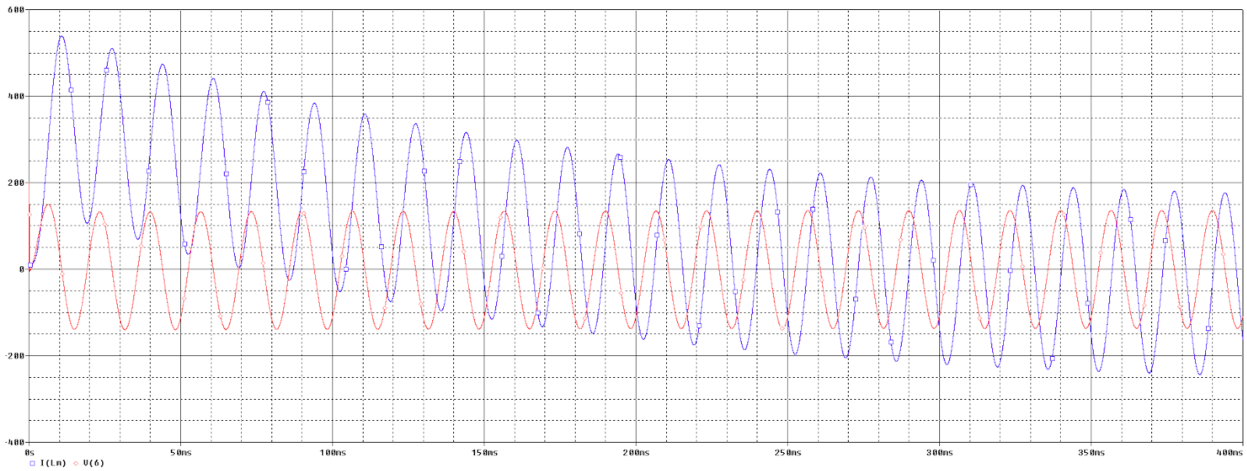


Figure 15 - Transformer and motor current with protection

avoid hitting anything. **Figure 15** shows the transformer primary and the motor with the protection. The motor current is blue and the transformer primary current is in red. Note that the spike is now missing. This is because the lightning arrester did the trick and redirected the lightning straight to ground.

7.0 Conclusion

The preliminary design for the facility started with the total apparent power S drawn to run induction motors. The apparent power for the motors at peak was 18 MVA, and the graph of the operation levels throughout the day is a sinusoidal waveform going from 60% capacity up to 100%. Using this info, and the given power factor of 0.85, the current in the original conductor was found to be 24278 Amps. When corrected to a power factor of 0.98, that current turns out to be 21128 A. However, the resistance and cross-sectional area remain the same because those properties are not dependent on other properties. This correction is done using a capacitor bank made up of switched capacitors. As the operation levels increase and decrease, more and more capacitors will gradually switch on and off, raising and lower the total capacitance as needed based off the reactive power draw expected at that time. These capacitor banks will parallel to the motor, with one on each phase to compensate for each individual line's current. Using this, the power saved in losses decreased, resulting in saving of about $150 per day at the maximum. To protect the system, circuit breakers should be put in place at various points in the system, and should be rated for roughly 125% the maximum possible current. Lastly, a lightning arrester should be put in place across the primary side of the transformer in order to protect the transformer and the motors from potential damage in the event of a lightning strike. By implementing this design, the new wing of the facility will not only expand the manufacturing capabilities, but will will be much more cost efficient

Appendix A - Calculations

A.1 Conductor Specifications

Given:

$S_{lights} = 0.5$ MVA $\quad$ $S_{motors} = 18$ MVA $\quad$ $V_{LL,RMS} = 440$ V

$l = 50$ meters $\quad$ ρ_{Cu} = resistivity of copper = $1.72 \text{x} 10^{-8}\ \Omega/\text{m}$

J = current density $\geq 3\ \text{A/mm}^2$

$V_{LN} = V = V_{LL,RMS} / \sqrt{3} = \frac{440}{\sqrt{3}} = 254$ V

$S = S_{lights} + S_{motors} = 0.5$ MVA + 18 MVA = 18.5 MVA

$$I = \frac{S}{3 * V} = \frac{18.5x10^6\ VA}{3 * 254\ V} = 24278 \text{ A}$$

$$A = 1 / J = \frac{24278\ A}{3\ A/mm^2} = 8093 \text{ mm}^2 = 0.008093 \text{ m}^2$$

$$R_{wire} = \rho\frac{l}{A} = 1.72x10^{-8}\Omega \cdot m * \frac{50\ m}{0.008093\ m^2} = 1.06 \text{x} 10^{-4}\ \Omega$$

$\Delta P = 3RI^2 = 3*(1.06 \text{x} 10^{-4}\ \Omega)*(24278\ \text{A})^2 = 187435$ W

A.2 Power Triangle at Old Power Factor

Given:

S_{motors} = 18 MVA   PF = cosθ = 0.85

B_{max} = 100% capacity = 1.0

B_{ave} = 80% capacity = 0.8

B_{min} = 60% capacity = 0.6

At minimum:

$S_{min} = S_{motors} * B_{min}$ = 18 MVA * 0.6 = 10.8 MVA

$P_{min} = PF * S_{min}$ = 0.85 * 10.8 MVA = 9.18 MW

$Q_{min} = \sqrt{S_{min}^2 - P_{min}^2} = \sqrt{10.8^2 - 9.18^2}$ = 5.7 Mvar

At average

$S_{ave} = S_{motors} * B_{ave}$ = 18 MVA * 0.8 = 14.4 MVA

$P_{ave} = PF * S_{ave}$ = 0.85 * 14.4 MVA = 12.24 MW

$Q_{ave} = \sqrt{S_{ave}^2 - P_{ave}^2} = \sqrt{14.4^2 - 12.24^2}$ = 7.6 Mvar

At max

$S_{max} = S_{motors} * B_{max}$ = 18 MVA * 1.0 = 18 MVA

$P_{max} = PF * S_{max}$ = 0.85 * 18 MVA = 15.3 MW

$Q_{max} = \sqrt{S_{max}^2 - P_{max}^2} = \sqrt{18^2 - 15.3^2} = 9.5$ Mvar

A.3 Power Triangle at New Power Factor

Given:

PF = 0.98

P_{min} = 9.18 MW P_{ave} = 12.24 MW P_{max} = 15.3 MW

At Minimum

$S_{min} = P_{min}$ / PF = 9.18 MW / 0.98 = 9.36 MVA

$Q_{min} = \sqrt{S_{min}^2 - P_{min}^2} = \sqrt{9.37^2 - 9.18^2} = 1.8$ Mvar

At average

$S_{ave} = P_{ave}$ / PF = 12.24 MW / 0.98 = 12.5 MVA

$Q_{ave} = \sqrt{S_{ave}^2 - P_{ave}^2} = \sqrt{12.5^2 - 12.24^2} = 2.5$ Mvar

At maximum

$S_{max} = P_{max}$ / PF = 15.3 MW / 0.98 = 15.6 MVA

$Q_{max} = \sqrt{S_{max}^2 - P_{max}^2} = \sqrt{15.6^2 - 15.3^2} = 3$ Mvar

A.4 Correction Capacitor Values

Given:

$V_{LL} = V = 440$ V   f = 60 Hz $w = 2\pi f = 120\pi$

$Q_{0,min} = 5.7$ Mvar $Q_{1,min} = 1.8$ Mvar

$Q_{0,ave} = 7.6$ Mvar $Q_{1,ave} = 2.5$ Mvar

$Q_{0,max} = 9.5$ Mvar $Q_{1,max} = 3$ Mvar

$\Delta Q_{min} = Q_{0,min} - Q_{1,min} = 5.7$ Mvar $- 1.8$ Mvar $= 3.9$ Mvar

$$C_{min} = \frac{\Delta Q_{min}}{w\, V_{LL}^{\;2}} = \frac{3.9x10^6\ Mvar}{120\pi(440\ V)^2} = 53.4 \text{ mF}$$

$\Delta Q_{ave} = Q_{0,ave} - Q_{1,ave} = 7.6$ Mvar $- 2.5$ Mvar $= 5.1$ Mvar

$$C_{ave} = \frac{\Delta Q_{min}}{w\, V_{LL}^{\;2}} = \frac{1.91x10^6\ Mvar}{120\pi(440\ V)^2} = 71.2 \text{ mF}$$

$\Delta Q_{max} = Q_{0,max} - Q_{1,max} = 9.5$ Mvar $- 3$ Mvar $= 6.5$ Mvar

$$C_{max} = \frac{\Delta Q_{min}}{w\, V_{LL}^{\;2}} = \frac{6.5x10^6\ Mvar}{120\pi(440\ V)^2} = 89 \text{ mF}$$

A.5 Loss Changes

Given:

$S_{max} = 15.6$ MVA $\quad S_{lights} = 0.5$ MVA

$R_{wire} = 1.06x10^{-4}\ \Omega$ $\quad V_{LN} = 254$ V $\quad \eta = 0.9$

$\Delta P_{old} = 187435$ W $\quad$ Cost = \$0.14/kWh

$S_{new} = S_{lights} + S_{max} = 0.5$ MVA + 15.6 MVA = 16.1 MVA

$$I = \frac{S_{new}}{3 * V_{LN}} = \frac{16.1x10^6\ VA}{3 * (254\ V)} = 21128\ \text{A}$$

$\Delta P_{new} = 3 * R * I^2 = 3 * (1.06x10^{-4}\ \Omega) * (21128\ A)^2 = 141953W$

$\Delta P_{saved} = \Delta P_{old} - \Delta P_{new} = 187435$ A - 141953 A = 45482 W = 45.48 kW

Savings = ΔP_{saved} * 24h * Cost = 45.48 kW * 24h * \$0.14/kWh = \$152.81/day

A.6 Circuit breakers

Given:

$I_2 = 24278$ A $\quad V_1 = 14000V$ $\quad V_2 = 440V$ $\quad V_{light,1} = 440V$

$V_{light,2} = 120V$ $\quad S_{light} = 0.5MVA$

$$I_1 = \frac{I_2 * V_2}{V_1} = \frac{24278A * 440V}{14000V} = 763 \text{ A}$$

$I_{1,CB} = 1.25 * I_1 = 1.25 * 763 \text{ A} = 953.75 \text{ A}$

$I_{2,CB} = 1.25 * I_2 = 1.25 * 24278 \text{ A} = 30.35 \text{ kA}$

$$I_{light,1} = \frac{S}{3 * V} = \frac{0.5x10^6}{3 * 440} = 379 \text{ A}$$

$I_{light,1,CB} = 1.25 * I_{light,1} = 1.25 * 379 \text{ A} = 473 \text{ A}$

$$I_{light,2} = \frac{S}{3 * V} = \frac{0.5x10^6}{3 * 120} = 1.39 \text{ kA}$$

$I_{light,2,CB} = 1.25 * I_{light,2} = 1.25 * 1.39 \text{ kA} = 1.74 \text{ kA}$

$I_{motor} = I_2 - I_{light,1} = 24278 - 379 = 23899 \text{ A}$

$I_{motor,CB} = 1.25 * I_{motor} = 1.25 * 23899 = 29.9 \text{ kA}$

Appendix B - PSPICE Code

```
00 lightning_protection.cir
01
02 V 1 0 sin(0 11300 60); 8000V RMS = 11300 Vpeak
03 Ra 1 2 0.5; source resistance
04 La 2 3 0.04; source inductance
05 R1 3 4 7.85m; transformer primary resistance
06 L1 4 0 78.5m IC=0; transformer primary inductance
07 L2 5 0 .237m IC=0; transformer secondary inductance
08 R2 5 6 8.93m; transformer secondary resistance
09 R 6 0 0.013; motor resistance
10 Lm 6 0 1.71m IC=0; motor inductance
11 K L1 L2 0.99 ;transformer inductor coupling
12 I 0 3 PWL(0s,0 1u,20000 50u,10000 100u,0 1000u,0) ;lightning strike
13 D1 7 0 Dix ;lightning arrestor diode
14 D2 7 3 Dix ;lightning arrestor diode
15 .MODEL Dix D(RS=0.14 BV=15000) ;model diodes
16 .PROBE
17 .TRAN 400u 400m 0 1u UIC
18 .END
```

This code was used to test the lightning arresters. In order to test before the lightning strike, lines 12 through 14 were commented out. In order to test the unprotected system, the lightning strike in line 12 was uncommented back in. Then in order to protect the system, the diodes in lines 13 and 14 were also uncommented back in.

Works Cited

Fitzgerald, A. E., Kingsley, C., & Umans, S. D. (2014). *Fitzgerald & Kingsleys electric machinery*. New York: McGraw-Hill.

Hart, D. W. (2011). Power electronics. New York: McGraw-Hill.

Pictures Used

Figure 2 - https://www.electricaleasy.com/2015/11/understanding-power-factor.html

Figure 4 - https://commons.wikimedia.org/wiki/File:3_phase_AC_waveform.svg

All other pictures were created by hand through Google Draw, NI Multisim, or were taken from PSPICE simulations.