

Calculating the savings

Summary

This report summarizes how savings are calculated and benchmarked in evaluating our Power Optimization System (POS).

Data collection

All the data that is used for calculating the savings are gathered in two steps, monthly electricity bills from a consecutive 12-month and an energy audit.

The electricity bills are used as a baseline to calculate the potential savings and also to measure the real savings after the system has been installed. The variables we use from the electricity bills are kilo Watt hours (kWh), kilo Watt (kW) and the monthly expenses (\$).

We also conduct an energy audit where we gather pertinent information about every electric load in the facility. To develop our customized solution, we need to know certain properties of the load, which vary depending upon the type of load as shown on table 1 below. Other values will be gathered during the energy audit, but the properties shown in Table 1 are essential to calculate the potential savings.

Table 1: The most important properties gathered in the energy audit.

Load\Property	Voltage	Current	Watts	Model #	Make	Ballast	Refrigerant	Run hours / week
Lighting	x		x	x		x		x
Refrigerator	x	x	x	x	x		x	x
HVAC	x	x	x	x	x		x	x
Electric motor	x	x	x					x
Resistive load	x	x	x					x

The results of the energy audit are compared electronically with the electricity bills to ensure that all electric loads are identified and that the audit is complete. This is accomplished by comparing the total kWh consumption according to the audit with the kWh from the electricity bills.

The equation used for calculating the kWh usage for each component is the following:

$$Quantity \cdot Load \cdot Hours \text{ per week} \cdot \frac{52}{12} \cdot Months \cdot UtilityFactor = Annual \text{ kWh}$$

Each component's annual kWh is calculated with equation above and then added together. The final value of kWh will then be compared to the kWh from the electricity bills. These values will most likely

not be exactly the same and therefore we use a utility factor¹. Say for example that all refrigerators in facility are on 24/7. In fact it's more likely that the pump and compressor will only be on 2/3 of the time. In this case we use a utility factor of 66.66% to get a more accurate value of kWh for the refrigerators. The utility factor will depend on two variables, the type of load, as mentioned above, and the type of facility², e.g. office building or an industry.

The calculated consumption of kWh, adjusted for the relevant utility or load factors should equal the kWh usage known by the electricity bills. This will give us a much more accurate calculation of the savings we can provide and also show our customer how much each type of load consumes.

Savings

The results are then processed using a proprietary predictive model developed by our vendor, the output of which includes information regarding the loads to be treated, the sizes and technologies needed, a guaranteed savings percentage, defined in kWh and guaranteed by a performance bond underwritten by Lloyds of London, and a return on project investment defined as the payback period.

In determining which loads will be treated, we evaluate whether we can effectively treat the load and whether the return on investment (ROI) is sufficient. Since we provide a whole facility approach, we generally treat all loads that are used on a regular basis, except electric motors below 0.5 HP and resistive loads (e.g. computers, printers, microwave, etc.).

For electric motors, refrigerators and HVAC the savings will range from 2% and 25%. These are general values based on the type of load and on how the load will be treated (e.g., an electric motor that is treated with a capacitor will generally save 7.5% for a variable frequency drives (VFD) and generally 10% for standard motors). If an HVAC unit is treated with a capacitor, optimizer and improved refrigerant the savings can be up to 25%. Potential savings estimates shared with customers are conservative since we never promise higher savings than we can provide.

For lighting, the savings will vary from 10% up to 80% depending on the treatment. These values will depend upon whether the lighting is treated with retrofitting or voltage regulation. If voltage regulation is used, the typical savings are around 20% while the savings for retrofitting will depend on the lighting type before and after treatment according to the following equation:

$$\frac{\text{Lighting usage after treatment [W]}}{\text{Lighting usage before treatment [W]}} \cdot 100\% = \text{Savings}[\%]$$

¹ Utility factor is sometimes known as load factor.

² Utility factor based on type of facility comes from the Commercial Buildings Energy Consumption Survey (CBECS). The Energy Information Administration (EIA) provides this database <<http://www.eia.doe.gov/emeu/cbecs/>>.

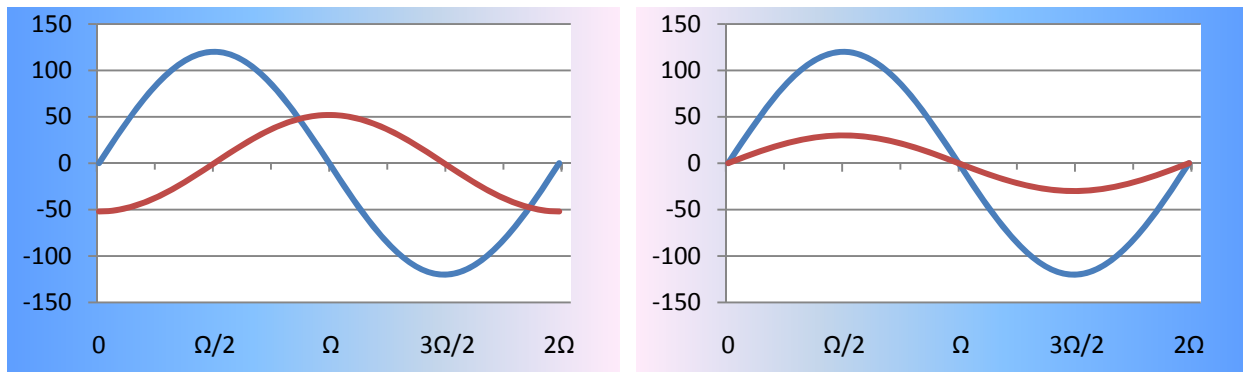
How does the capacitor work?

The power (P) that is needed to use an electric motor is calculated by the following equation:

$$P = \underbrace{U(I_{active} + I_{reactive}) \cos \varphi}_{\text{motor usage}} + \underbrace{(I_{active} + I_{reactive})^2 R}_{\text{line losses}}$$

The first part of the equation represents the power usage that must be sustained to operate the motor at the appropriate level of torque. The second part of the equation depicts the line losses that will occur between the motor and the main. What we do by introducing a capacitor is that we lower the reactive current; decreasing line losses, which depend on both active and reactive current.

The charts below show an example of how the voltage and current changes from before and after the motor has been treated with a capacitor. The blue line is the voltage and the red line is the current multiplied 10 times.



An electric motor needs reactive current to magnetize the armature and this current is taken from the power outlet. When a capacitor is connected to the motor the reactive current is taken from the capacitor instead of the power outlet. Since reactive current is taken from the power outlet the total current will be higher. and this will decrease the total current.

Figure 1: Voltage and current plot before and after the capacitor is connected.

When the motor has been treated the reactive current will decrease and the value of $\cos \varphi$ will increase. These two parameters will cancel each other out in the first part of the equation and therefore provide the same amount of power to the motor. But when the reactive current is lower, the line losses will decrease in the second part of the equation and therefore kWh will be saved.

Sizing the capacitor

For each electric motor that will be treated we calculate the size of the capacitor to get the most savings. To calculate the right size of the capacitor we need to know the voltage level, the power, the current and the phase lag between the voltage and the current.

Figure 2 below shows the simplified model of how an electric motor is connected before and after a capacitor is added. And as stated in the previous section the power consumed by the motor can be calculated by the following equation,

$$P = \underbrace{U(I_{active} + I_{reactive}) \cos \varphi}_{\text{motor usage}} + \underbrace{(I_{active} + I_{reactive})^2 R}_{\text{line losses}}$$

where the resistance in the line losses are $R = Z_l$.

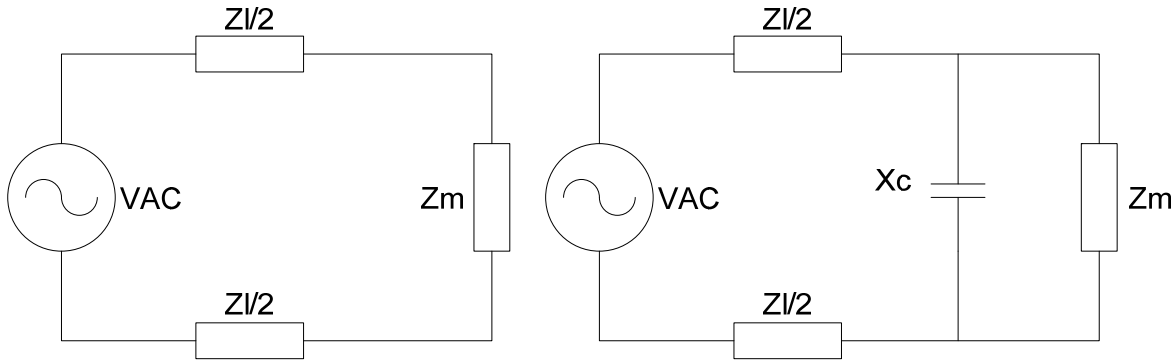


Figure 2: Equivalent circuit of an induction motor with cables between the mains and the motor. The left circuit is without a capacitor and the right circuit is with a capacitor.

In this case we want to size the capacitor by first calculating the impedance for the motor using the following equation:

$$\left. \begin{aligned} Z_m &= |Z_m| \cos \varphi + j|Z_m| \sin \varphi \\ |Z_m| &= \frac{U^2 \cos \varphi}{P} \end{aligned} \right\} Z_m = \frac{U^2 \cos \varphi}{P} \cos \varphi + j \frac{U^2 \cos \varphi}{P} \sin \varphi$$

where φ is the phase angle between the voltage and the current.

The total impedance of the motor change when we connect the capacitor and we'll call this value Z_{tot} which is equal to:

$$Z_{tot} = \frac{Z_m + jX_c}{Z_m \cdot jX_c}$$

By implementing Z_m from the equation above the result will be:

$$Z_{tot} = \frac{\frac{U^2 \cos^2 \varphi}{P} + j \left(\frac{U^2 \cos \varphi}{P} \sin \varphi + X_c \right)}{-\frac{U^2 \cos \varphi}{P} \sin \varphi X_c + j \left(\frac{U^2 \cos^2 \varphi}{P} \right)} \sqrt{\frac{\tan^{-1} \left(\frac{\frac{U^2 \cos \varphi}{P} \sin \varphi + X_c}{\frac{U^2 \cos^2 \varphi}{P}} \right)}{\left[180 - \tan^{-1} \left(\frac{\cos \varphi}{\sin \varphi} \right) \right]}}$$

To get the most efficient motor the angle of the new impedance should be equal to zero. Extracting the two angles from the equation above and setting them equal to each other, the reactive capacitance X_c can be calculated using the following equation:

$$\tan^{-1} \left(\frac{\frac{U^2 \cos \varphi}{P} \sin \varphi + X_c}{\frac{U^2 \cos^2 \varphi}{P}} \right) = 180 - \tan^{-1} \left(\frac{\cos \varphi}{\sin \varphi} \right)$$

If tan is added to both sides X_c can be extracted and calculated with the following equation:

$$X_c = \frac{U^2 \cos^2 \varphi}{P} \tan \left(180 - \tan^{-1} \left(\frac{\cos \varphi}{\sin \varphi} \right) \right) - \frac{U^2 \cos \varphi}{P} \sin \varphi$$

From this equation the size in Farads (F) can easily be calculated by the following formula:

$$C = -\frac{1}{2\pi f X_c} = -\frac{1}{2\pi f \left(\frac{U^2 \cos^2 \varphi}{P} \tan \left(180 - \tan^{-1} \left(\frac{\cos \varphi}{\sin \varphi} \right) \right) - \frac{U^2 \cos \varphi}{P} \sin \varphi \right)}$$

Since we don't want to assume the risk of over-compensating any motors, we will always have a conservative approach. Therefore, the size of the capacitor installed will always be smaller than the value calculated with the equation above.

How are savings gained by using a capacitor?

The previous chapter showed how the capacitor is sized to fit each motor that will be treated. This section will continue the calculations to show how the savings are gained by installing a capacitor next to the motor.

The first equation in the previous chapter shows how the power consumption is calculated for an electric motor.

$$P = \underbrace{U(I_{active} + I_{reactive}) \cos \varphi}_{motor\ usage} + \underbrace{(I_{active} + I_{reactive})^2 R}_{line\ losses}$$

When a capacitor is installed next to a motor the reactive current ($I_{reactive}$) will decrease. If the reactive current decreases, the value of $\cos \varphi$ will increase proportionately and the power for the *motor usage* will be the same. But the total power usage will decrease, pursuant to the second part of the equation, since the *line losses* decrease when the reactive current decreases.

So how does the reactive current decrease when a capacitor is connected?

In the equation above the current is equal to the sum of the active and reactive current. The current can also be calculated by dividing it into a real part and an imaginary part. The real part is the active current and the imaginary part is the reactive part. This will give the following equation:

$$I = \underbrace{\frac{U}{|Z|} \cos \varphi}_{=I_{active}} + j \underbrace{\frac{U}{|Z|} \sin \varphi}_{=I_{reactive}}$$

Before the capacitor have been installed the impedance will be equal to $Z_m = R_m + jX_m$ and $\cos \varphi$ will have a value lower than 1. When the capacitor is connected in parallel with the motor, the impedance will change to $Z_{tot} = R_{tot} + jX_{tot}$ and $\cos \varphi$ will be close to 1. The reactive part of the impedance, Z_{tot} , will almost be zero since the capacitor has been connected. This will affect the angle between the voltage and the current and therefore raise $\cos \varphi$ so it will be close to 1 and $\sin \varphi$ will be close to 0.

After adding the capacitor the active current (I_{active}) will stay the same and the reactive current ($I_{reactive}$) will almost be eliminated. Since the reactive current decreases so dramatically there will be savings in the line losses according to $(I_{active} + I_{reactive})^2 R$.

Savings from other losses

So far we only mentioned losses occurring in the lines between the main and electric motor. In reality there are more than line losses and they are all related to the magnitude of current. The following sections will briefly describe other types of losses, which will be substantively remediated by the introduction of a POS system. None of the following sections have calculations included since it would be too time consuming to calculate the size of these losses.

Hysteresis losses

Hysteresis loss is a heat loss caused by the magnetic properties of the armature in an AC motor. When an armature core is in a magnetic field, the magnetic particles of the core tend to line up with the magnetic field. When the armature core is rotating, its magnetic field keeps changing direction. The continuous movement of the magnetic particles, as they try to align themselves with the magnetic field, produces molecular friction. This, in turn, produces heat. This heat is transmitted to the armature windings and this heat will cause the armature resistances to increase. When the armature resistance is increased the RI^2 will rise.

Skin effect losses

The apparent resistance of a conductor is always higher for AC than for DC. The alternating magnetic flux created by an alternating current interacts with the conductor, generating a back electromotive force, which tends to reduce the current in the conductor. The center portions of the conductor are most affected because it has the greatest number of lines of force, the number of line linkages decreasing as the edges are approached. The EMF produced in this way by self-inductance varies both in magnitude and phase through the cross-section of the conductor, being larger in the center and smaller towards the outside. The current therefore tends to crowd into those parts of the conductor in which the opposing EMF is a minimum; that is, into the skin of a circular conductor or the edges of a flat strip, producing what is known as 'skin' or 'edge' effect. The resulting non-uniform current density has the effect of increasing the apparent resistance of the conductor and gives rise to increased losses.

Harmonic loading increases skin effect losses by the square of the increase in frequency above nominal line frequency, and so is responsible for a substantial lost wattage in any facility with large populations

of nonlinear equipment loads, such as VFDs, DC drives, rectifiers, induction heating or other arcing or switching power supply devices.

Proximity effect losses

Proximity effect losses exist when conductors are close together, particularly in low voltage equipment, where a further distortion of current density results from the interaction of the magnetic fields of other conductors.

In the same way as an EMF may be induced in a conductor by its own magnetic flux, so may the magnetic flux of one conductor produce an EMF in any other conductor sufficiently near for the effect to be significant.

If two such conductors carry currents in opposite directions, their electromagnetic fields are opposed to one another and tend to force one another apart. This results in a decrease of flux linkages around the adjacent parts of the conductors and an increase in the more remote parts, which leads to a concentration of current in the adjacent parts where the opposing EMF is a minimum. If the currents in the conductors are in the same direction the action is reversed and they tend to crowd into the more remote parts of the conductors.

This effect, known as the 'proximity effect' (or 'shape effect'), increases the apparent AC resistance. If the conductors are arranged edgewise to one another the proximity effect increases. In most cases the proximity effect also tends to increase the stresses set up under short-circuit conditions and this may therefore have to be taken into account.

Transformer losses

The two primary types of transformer losses are core losses and load losses. The core loss of a transformer arises because the core must be taken through its alternating cycles of magnetization. Core losses occur because there exist a magnetizing current in the primary winding of a transformer, which is additional to that current which balance the current in the secondary winding. The magnetizing current is required to take the core through the alternating cycles of flux at the rate determined by the system frequency. In doing so, energy is absorbed, and this is known as the core-loss. The core-loss is present whenever the transformer is energized.

Transformer load losses occur because the flow of a current in any electrical system also generates loss dependent upon the magnitude of that current. Transformer windings are no exception and these give rise to the load loss of the transformer. Load loss is, of course, present only when the transformer is loaded and its magnitude is proportional to the current squared.

There are three categories of load loss which occur in transformers:

- Resistive losses often referred to RI^2 losses.
- Eddy-current winding losses due to the alternating leakage-fluxes.

- Stray losses in leads, core-framework and tank due to the action of load-dependent stray alternating fluxes.

Resistive losses, as the term implies, are due to the fact that the windings cannot be manufactured without electrical resistance and are therefore a "fact of life" which cannot be eliminated for the transformer designer.

The leakage-flux occurring in transformer windings is greatest at the winding ends, but is present throughout the entire winding body. Consequential eddy currents are set up that oppose the natural direction of current flow and greatly increase the transformer's apparent AC resistance. Stray losses exist in all transformers, but present more of a problem on larger transformers because the physical size of the leads and the currents they carry is greater.

Eddy-current losses

With any electrical system component comprising an iron or steel frame and an electrical coil, flux will flow in the steel as a result of the alternating current in the coil. The flux in the steel will itself induce an EMF in the material following the basic laws of induction. Since the material is essentially an electrical circuit closed on itself, the induced EMF will cause a circulating electrical current called an eddy-current. Its value is dependent on the value of EMF and on the resistivity of the path of current. As in any other electrical circuit the power loss is the product of RI^2 . In a similar manner to hysteresis losses, the eddy-current loss manifests itself as heat, contributing to the maximum operating temperature limit of the device.

Eddy current losses occur in protective circuit breakers, lighting ballasts, power supply transformers, magnetic motor starters, voltage reducing or isolation transformers, current overload relays, control contactors and relays, all motor windings, and even building wiring, when the wiring is in circular proximity to steel or iron structures, such as electrical enclosures, distribution panels, or terminal or distribution blocks.

Calculating the total savings

After all load data is collected in the energy audit we decide which loads will be treated. All treated loads treated will save a certain percentage and this is used in the equation below.

The following equation is used for every load that is treated to calculate the savings in kWh. Table 2 further down contains explanations of all the parameters used in the equation.

$$Quantity [N] \cdot Load [kW] \cdot Hours\ per\ week [h] \cdot \frac{52}{12} \cdot Months [1 - 12] \cdot Savings [\%] \cdot UtilityFactor [\%] = Annual\ savings [kWh]$$

Table 2: Explanation of parameters used in the saving equation

Parameter	Explanation	Unit
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Quantity	Number of loads of this type that are treated	N
Load	kW rating for the component	kW
Hours per week	Hours the load/loads are running per week	h/week
Months	Months per year the load/loads are being used	months
Savings	Percentage of savings for the specific load	%
Utility Factor	This value is based on a the type of load and type of facility	%
Annual savings	This is the annual savings that the specific load/loads will save	kWh

When all the potential savings have been calculated it will be compared to the annual kWh usage. This will give an overall saving that based on the whole electric system for the specific facility. The equation below is used to calculate the overall savings.

$$\frac{\text{Total kWh usage} - \text{Total kWh savings}}{\text{Total kWh usage}} \cdot 100\% = \text{Overall savings } [\%]$$

Economical review

To calculate the return of investment (ROI) we need to know the total cost of installing our POS and the savings per year gained by our system. The ROI will be calculated as follows:

$$\frac{\text{Cost of installing POS}[\$]}{\text{Overall savings}[\%] \cdot \text{Total kWh usage}[\text{kWh}] \cdot \text{Cost per kWh}[\$/\text{kWh}]} = \text{ROI}[\text{years}]$$