APPLICATION OF MOTOR CAPACITORS TO IMPROVE FACILITY POWER USAGE IN THE INDUSTRIAL SETTING

A Thesis

by

WILLIAM JEFFREY HILLHOUSE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2005

Major Subject: Electrical Engineering

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Approved by:

Chair of Committee,	Prasad Enjeti
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ABSTRACT

Application of Motor Capacitors to Improve Facility
Power Usage in the Industrial Setting. (August 2005)
William Jeffrey Hillhouse, B.S., Texas A&M University
Chair of Advisory Committee: Dr. Prasad Enjeti

As deregulation of the electric power system in the United States unfolds, many customers are experiencing changes in their billing rate structure. Some face the addition of power factor penalty tariffs, and seek ways to minimize the added burden. The installation of entrance capacitor banks is the common response, but fails to take complete advantage of capacitor abilities. Other project designs exist that can harness these advantages to the full benefit of the customer.

This work will show that distributing shunt capacitors in parallel with induction motors will elevate power factor and voltage, and also decrease ohmic losses in the wiring and protection devices that supply the motor. This reduction often produces a better overall economic solution due to energy savings.

The distribution of capacitors at induction motors reduces the reactive current in the branch of the distribution system that supplies them. A reduction in the total current flowing to the motor along the distribution system results in smaller losses throughout the system. As losses diminish, the total real power drawn through the distribution system is lessened, and electric bills are reduced. This alternative to entrance capacitor banks is not as commonly implemented. A misconception that the resistance in facility distribution systems is relatively low has discouraged distributed motor capacitor installation for overall facility power factor correction, in favor of entrance capacitor banks. We will show that the resistance in the distribution system is higher than typically thought, that motor capacitors can exploit this fact, and can often economically outperform entrance capacitor banks which are terminated at the point of incoming utility power.

Motor capacitors are not a new technology. They are commercially available off the shelf technology, suitable for power factor correction for induction motors. Distributed capacitors can be utilized for all significantly sized induction motors in a facility. The elevation in power factor and voltage, reduction in reactive current and real power are calculated, and trends are observed. The matter is considered from both the standpoint of engineering and economics to provide an integrated study.

For my lovely wife Claire,

and for Jackson

ACKNOWLEDGMENTS

Many people helped with this work. In particular I would like to thank my parents. My father Mike – an accomplished electrical engineer himself – provided guidance and countless hours to help critique and improve the thesis. My mother, Diana, offered encouragement throughout the long process of preparation and revision. I want to thank my wife, Claire, for putting up with all the time apart while I wrote the paper. Dr. Sebastien Gay – my classmate in the Department of Electrical Engineering at Texas A&M University – offered useful and informative advice on the behavior of induction machines as well as general comments to improve the paper. Dr. Michael Bryant of the University of Texas Mechanical Engineering Department kindly explained the phenomena of fretting corrosion and its effects on contact resistance. I want to recognize my advisor, Dr. Prasad Enjeti. He sponsored my enrollment into the graduate program, and has encouraged my development as an engineer.

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CHAPTER I

INTRODUCTION

In this chapter the concept of power factor will be introduced. The causes of and problems resulting from low power factor in industrial facilities will be explored. The conventional power factor correction method for industrial facilities will be presented, and limitations described. The composition and needs of the modern industrial facility will be examined, and the phenomenon of fretting that increases electrical resistance in distribution systems will be investigated, motivating a better method for correcting industrial power factor.

1.1 Power Factor Defined

Power factor (PF) is a parameter that ranges from zero to unity. It is an electrical quantity that characterizes the power that flows to a reactive circuit, describing the ratio of real (or useful) power to the total (apparent) power.

Table 1 – Basic power parameters

FUNDAMENTAL POWER FACTOR QUANTITIES		
Quantity	Symbol	Unit
Voltage	V or v	volt
Current	I or i	amp
Resistance	R	ohm
Reactance	X	ohm
Impedance	Z	ohm
Real Power	P	watt
Reactive Power	Q	volt amp reactive (VAR)
Apparent Power	S	volt amp (VA)
Phase Angle	ϕ	degree or radian
Inductance	L	Henry
Capacitance	C	Farad
Power Factor	PF	none

This thesis follows the style of *IEEE Transaction on Industry Applications.*

The PF can be defined for any electrical load, but we will focus on those with sinusoidal waveforms. Purely resistive circuits have a PF of unity, while inductive or capacitive loads have a sub-unity PF. Basic parameters relevant to PF are listed in Table 1.

1.1.1 The Power Triangle

The total power in a circuit is comprised of the real power (P) and the reactive power (Q). They are related by the power triangle (see Figure 1). The hypotenuse is the apparent power (S). The angle separating P and S is the displacement phase angle, ϕ.

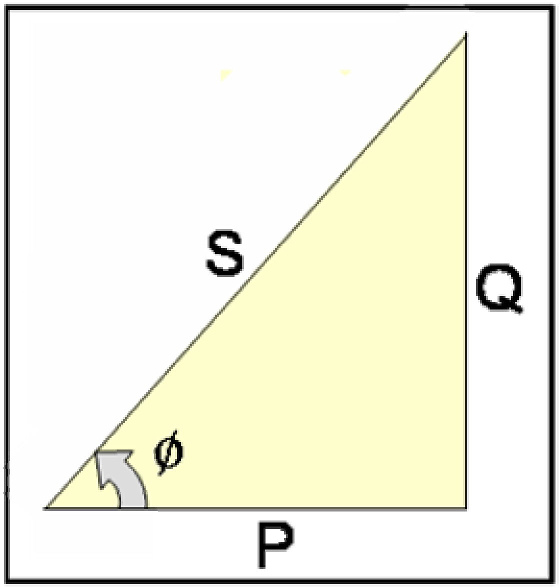

Fig. 1. The power triangle

Real Power - The real power for three-phase systems is given by Equation 1.1.

$$P = \sqrt{3} VI \cos(\phi) \qquad 1.1$$

Where I is the root mean square (RMS) magnitude of the current, V is the RMS magnitude of the voltage, and ϕ is the displacement phase angle. Real power is the quantity that produces useful work. It is dissipated across a circuit's resistance (R). In the case of a motor it performs the work on its surroundings. The unit for real power is the watt.

Reactive Power - The reactive power for three-phase systems can be calculated by Equation 1.2.

$$Q = \sqrt{3} VI \sin(\phi) \qquad 1.2$$

The reactive power is interchanged from the reactive element of the load to the power supply and back. For an induction motor, it creates the excitation magnetic field. It is dissipated across a circuit's reactance (X). For a lightly loaded motor the displacement phase angle is large, and Q is large compared to P. The unit for reactive power is the volt-amp-reactive, or VAR.

Apparent Power - The apparent power for three-phase systems can be obtained by Equation 1.3 or 1.4.

$$S = \sqrt{3} VI \qquad 1.3$$

$$S = \sqrt{(P^2 + Q^{2)}} \qquad 1.4$$

For a wholly resistive load S = P, and for a completely reactive load S = Q. The apparent power is dissipated across a circuit's impedance (Z). The unit for apparent power is the volt-amp, or VA.

1.1.2 Displacement Phase Angle

The PF can be expressed by several methods. It can be obtained from Equations 1.5 and 1.6.

$$PF = \frac{P}{S} \qquad 1.5$$

$$PF = \cos(\phi) \qquad 1.6$$

Equation 1.5 is the general formulation for PF. It gives the ratio of the real power to the total power drawn by a load, including the reactive power, and also harmonic currents for loads where they are present. Equation 1.6 is the case for sinusoidal loads, where harmonics are absent. This equation is also referred to as the displacement power factor. It relates the displacement phase angle ϕ to the PF.

The angle also conveys the displacement between the current and voltage waveforms, as they are shifted by reactive elements in the circuit. The angle is given in degrees or radians. In Figure 2, for example, the displacement phase angle $\phi = 30^\circ$. This means that the current lags the voltage by 30º.

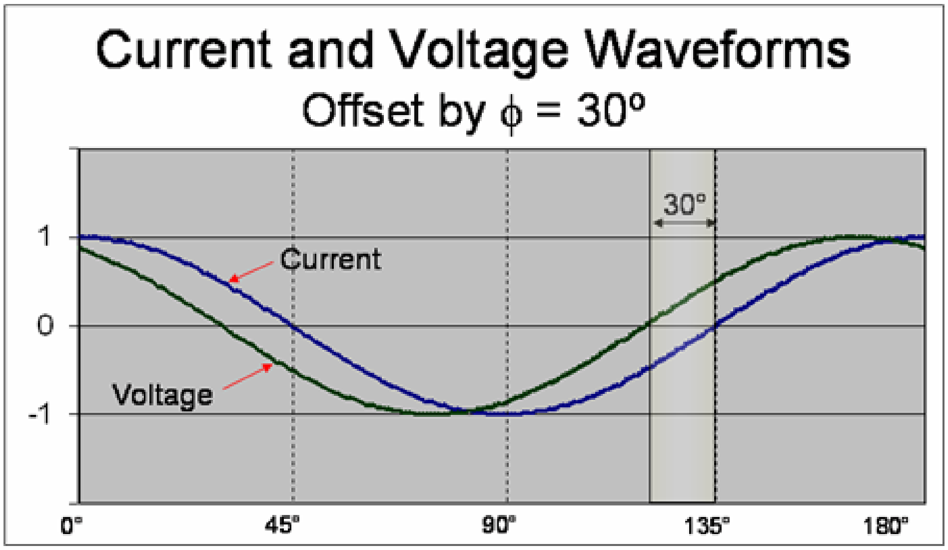

Fig. 2. Displacement phase angle ϕ, voltage and current waveforms

1.1.3 Leading and Lagging Power Factor

For capacitive loads the reactive power is negative, and the PF is referred to as leading; the current leads the voltage by the displacement phase angle. For inductive loads the reactive power is positive, and the PF is referred to as lagging; the current lags behind the voltage by the displacement phase angle. We will deal almost entirely with lagging PF, except for instances where the PF is over-corrected to a leading condition.

1.1.4 Distortion Power Factor

In most cases the loads in a facility are not purely resistive. This is due in part to the proliferation of electronics equipment that generates harmonics. This results in distorted current in the facility. Equation 1.6 is not valid for these situations, and must be enlarged to include the effect of harmonic distortion. The distortion power factor is given by Equation 1.7.

$$PF_{dist} = \frac{I_1}{I_{total}} \tag{1.7}$$

Where PF_{dist} is the distortion power factor, I_1 is the fundamental frequency component of the line current, and I_{total} is the total current. The higher frequency components occur at integer multiples of the fundamental frequency, which in the United States is 60 Hertz. PF_{dist} describes the distortion that occurs when harmonic currents are present, as a result of adjustable speed drives, electronic equipment in offices, and other non-linear elements.

The total PF accounts for the displacement of the current and voltage due to reactive circuit elements, and also for the distorting characteristics of harmonics. We combine Equations 1.6 and 1.7:

$$\begin{aligned} PF_{total} &= PF \cdot PF_{dist} \rightarrow \\ PF_{total} &= \cos(\phi) \cdot \frac{I_1}{I_{total}} \end{aligned} \tag{1.8}$$

1.2 Causes of Low Power Factor

The PF in industrial facilities is lowered primarily by induction motors. It can vary between two identical motors, depending on the loading behavior. The same motor will exhibit a different PF from one moment to the next as the loading varies. Even at rated conditions, induction motors operate at a PF below unity.

1.2.1 Motor Loading

As the loading on a motor declines below rated value, the PF falls off as well (see Figure 3). At zero loading a relatively low real power is required to overcome losses in the stator and rotor windings, and losses in the core, so the bulk of the total apparent power is used to maintain the field. Equation 1.5 shows that PF is low for this condition.

Motors are often designed larger than the application requires to insure that the motor can deliver the required torque during all operating conditions. For this reason, most induction motors in a facility operate with a PF that is below rated value.

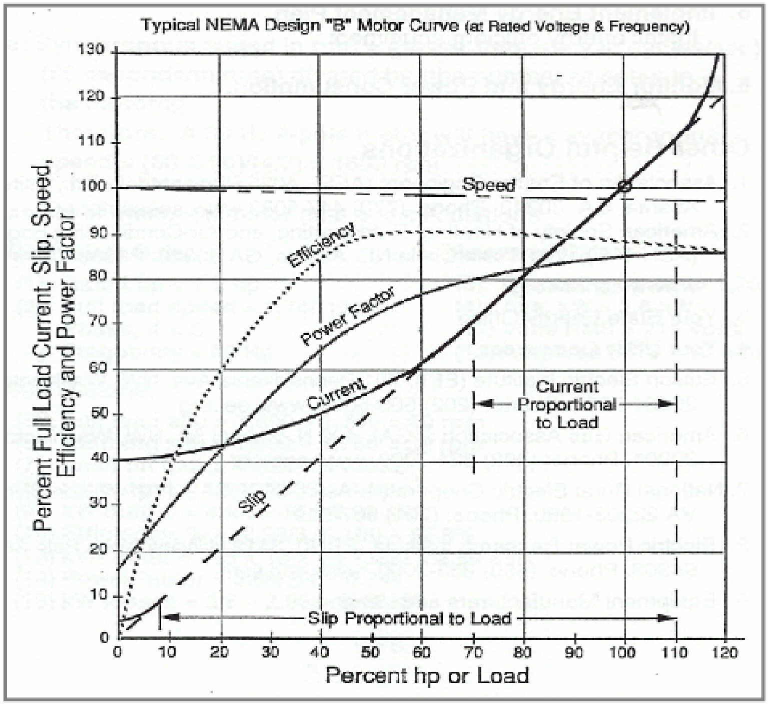

Fig. 3. Motor behavior as a function of load[1]

1.2.2 Oversized Transformers

Transformers are often purposely designed with future expansion in mind. They are sized with a larger capacity than needed at present, which can influence the PF adversely. From the viewpoint upstream of the transformer, the impedance of a circuit with an oversized transformer will be larger than if the transformer were sized for the existing load. The reactance, which occurs in the transformer's magnetizing inductance, will shift the current by a larger angle than it normally would. This causes the PF to decline to a lower value. This should be considered when designing a system transformer.

1.2.3 Power Factor vs. Efficiency

Power factor is a wholly electrical quantity. By contrast, efficiency is a measure of the ability of the motor to convert electrical power into mechanical power. Efficiency and PF are proportional, as shown in Figure 3.[1] The figure is from the National Electrical Manufacturers Association (NEMA). It is a plot of power factor, efficiency, and other parameters as a function of motor load, for Type B motors. Both efficiency and PF are low for a motor at low load. We will discuss induction motors in greater detail in section 1.5.1.

1.3 Capacitors

The reactive power required by an induction motor prevents it from ever achieving unity PF. To elevate the PF at the motor, external assistance is needed. The reactive power can be provided locally by a capacitor. This will bring the current and voltage waveforms closer to being in phase. For the half-cycle of the waveform when the motor requires reactive power, the capacitor can provide most of it. The roles are reversed for the remaining half-cycle. This elevates the PF at the termination point of the capacitor, while leaving the motor attributes essentially unchanged.

A capacitor, in its most simple form, is a set of parallel metal plates. It is a passive device that stores energy by holding electrostatic charge. See Equation 1.9.

$$C = \varepsilon \frac{A}{d} \qquad 1.9$$

Where C is the capacitance, ε is the dielectric permittivity, A is the surface area of the plates, and d is the distance separating the plates. Capacitors liberate electrical system capacity, raise voltage levels, and lower power costs by reducing distribution system losses.[2] They act as an open circuit for low frequency signals and as a short circuit for high frequency signals. Capacitors are simple to install and require very little maintenance. They have very low resistance and low associated losses. And happily, they elevate PF.

Capacitors have been widely used in power system designs since the 1930s.[2] Although they are passive elements in a distribution system, capacitors inject reactive power at the point of coupling, thereby elevating lagging PF. This reduces the reactive power that must flow to the area in the distribution system from upstream. The amount of reactive power produced by a capacitor is given in Equation 1.10.

$$Q = 2\pi f C V^2 \tag{1.10}$$

Where f is the frequency (in Hz), C is the capacitance (in Farads), V is the RMS voltage (in volts), and Q is the capacitance (in VARs).

Capacitors typically elevate the steady-state voltage by about 1-2% (see Equation 1.11). This is a useful characteristic for voltage control, when the voltage sags due to excessive loading.

$$\% \Delta v = \frac{(Q_{cap} Z_{tx})}{S_{tx}} \tag{1.11}$$

Where Q_{cap} is the capacitor reactive power rating (in VARs), Z_{tx} is the impedance of the upstream transformer (in %), and S_{tx} is the rated apparent power capacity of the transformer (in VAs).

Now we turn from the steady-state to the instantaneous behavior of capacitors. When a voltage potential is applied across a capacitor, energy is stored. This energy provides electrical inertia that prevents the voltage across a capacitor from changing rapidly.

$$i = C\frac{\Delta v}{\Delta t} \tag{1.12}$$

$$\Delta v = i\frac{1}{C}\Delta t \tag{1.13}$$

Where Δv/Δt is the change in voltage with change in time, and i is the instantaneous current that flows across the capacitor. In Equation 1.13 we solve for the rate change in voltage. One can see that for short time periods, or for large capacitance the capacitor will resist sudden large changes in voltage. This property of capacitors causes a flattening of the voltage. This allows a capacitor to dampen sudden increases in the voltage which sometimes occur during a transient. For this reason, when capacitors are located near equipment they provide some protection from voltage surges that could otherwise damage delicate controls and other electronics.

1.4 Entrance Capacitor Banks

It is a common practice to correct the PF for an entire facility with a capacitor at one central location. This can be accomplished with a large, fixed capacitor, or by arranging capacitor stages into an automatic switching bank. The stages can be switched into and out of service as the facility reactive power requirement fluctuates. A feedback control based on PF directs the switching action. It is usually located at the entrance, but must be terminated downstream of the billing meter in order to avoid a utility PF tariff (see Figure 4).

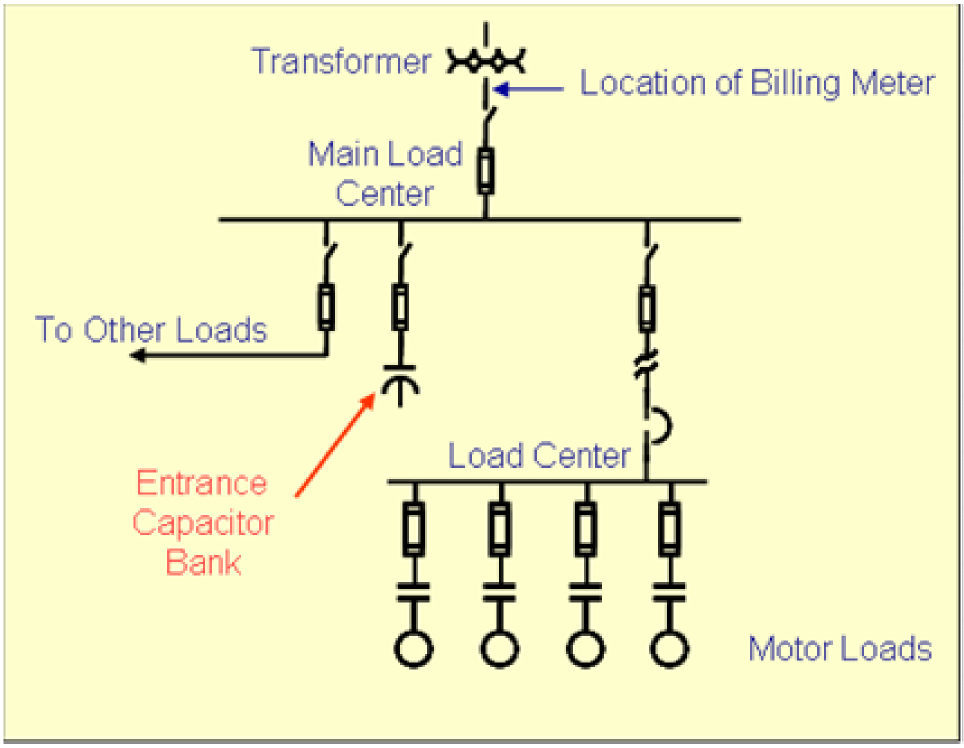

Fig. 4. Capacitor bank terminated near entrance of the facility

Electrical demand varies in a facility over time – such as a daily cycle. Reactive power needs vary as a result. This can make a fixed entrance capacitor undesirable, since it may provide too much reactive power during times when inductive load is inactive, so automatic staged banks are the more common method for correcting poor industrial facility PF when load varies significantly.

For the example in Figure 5, the amount of reactive power that must be supplied by the entrance bank to maintain a PF of 0.95 is represented by the blue line.

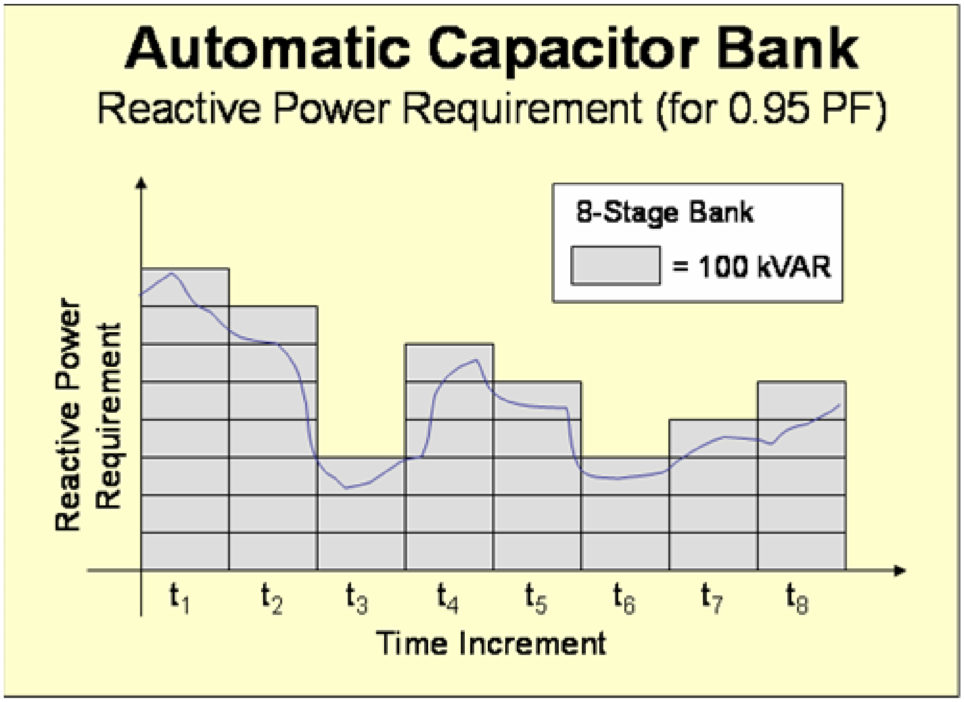

Fig. 5. Automatic capacitor bank switching operation

There are several factors that encourage entrance capacitor projects. A number of electric utility providers penalize customers for poor PF (below 0.95, for example, as defined by the utility company tariff). Capacitor banks can elevate the PF above the threshold where the penalty is accessed. Other customers may be serviced by transformers that are loaded above rated value. Capacitor banks are often installed downstream of the transformer at the customer’s site to decrease loading through the transformer. This method increases the capacity margin of upstream equipment, rather than requiring that transformers and other equipment be replaced to accommodate growth.

Automatic entrance capacitor banks are able to improve the PF for an entire facility with one device, have low maintenance, and switch out excess capacitance when it is not needed. Due to economy of scale, a large capacitor bank placed at the service entrance can be purchased at lower cost than the sum of smaller capacitors placed at individual loads. Although entrance capacitor banks are widely used, they have several important shortcomings.

When multiple stages of a capacitor bank are switched on, termed back-to-back switching due to the proximity of capacitor units with a small amount of impedance, the system can experience a high in-rush current until the capacitors reach a steady-state regime.[3] To avoid the problem, line inductors must be installed in series with the capacitor units at extra cost.

Capacitors offer a low impedance path to ground for high frequency currents. For those facilities containing significant harmonics, a capacitor bank must be de-tuned to avoid capacitor damage. Filtered capacitor banks are significantly more costly than standard banks.

An entrance capacitor bank alleviates overloading on upstream transformers and other equipment, but does not reduce the downstream current. This prevents entrance banks from decreasing losses downstream of the bank. To reduce the reactive current in the plant itself, smaller capacitors must be distributed near the load level. This feature, in particular, is a drawback that will motivate distributed capacitors which do reduce losses in the plant.

1.5 Modern Industrial Facilities

A tremendous amount of energy is consumed by modern industrial facilities to manufacture the material goods that are used in daily life. A typical industrial facility may demand from a fraction to hundreds of megawatts of power. This enormous quantity of electricity is primarily used by induction motors, and because of their widespread presence, the average plant will operate below unity PF.

1.5.1 The Induction Machine

An induction machine can operate in three conditions: motoring, generating, and braking. When operated in the motoring condition, the induction machine is the workhorse of industry. It provides the motive force for countless processes. Estimates suggest that motor driven equipment consumes over two-thirds of all electricity in the United States industrial sector.[4] Induction motors are rugged, provide high torque, and operate at high efficiency. A typical motor at rated load operates at about a 0.87 PF,[5] and because they comprise most of the load in a standard industrial facility, the overall PF for the facility itself is dominated by the inductive portion.

An induction motor can be modeled by an equivalent circuit. The stator, rotor, and air-gap performance is described by the circuit components. Equations result, which can predict motor behavior (see Figure 6).

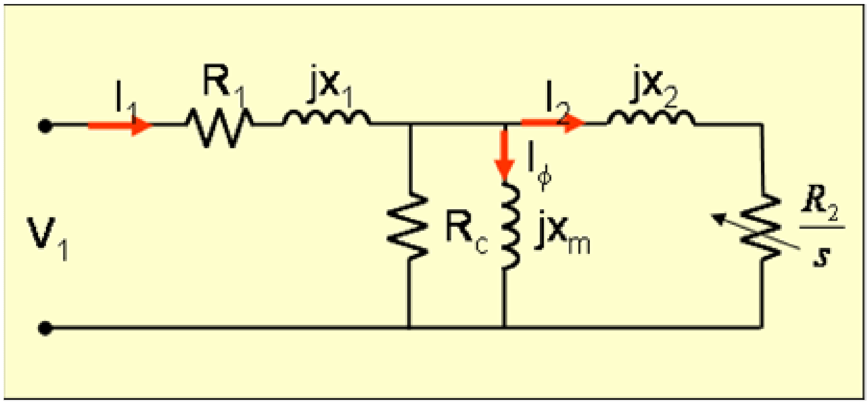

Fig. 6. Induction motor equivalent circuit

Where V_1 is the input terminal voltage, I_1 is the stator current, I_2 is the rotor current, and I_ϕ is the excitation current. The variable R_1 is the stator winding resistance, where copper losses are dissipated. R_c is the core loss resistance, which accounts for hysteresis and eddy current losses in the iron core. The variable X_1 is the stator leakage inductance, and X_2 is the rotor leakage inductance. These inductances account for the quantities of stray flux that fail to bridge the motor air gap, therefore wasting reactive power. The variable X_m is the magnetizing inductance, the quantity that magnetically couples the stator and rotor, and finally R_2/s is load resistance. It is dependent on s, the slip, which itself is determined by the motor speed.

When the windings in the rotor are magnetized, pairs of magnetic poles are formed in the rotor. The rotor spins to keep the poles lined up with the stator field. The number of poles determines synchronous motor speed, as shown in Equation 1.14.

$$n_s = \frac{120 \cdot f}{p} \tag{1.14}$$

Where p is the number of poles, f is the line frequency (typically 60 Hz in the United States), and n_s is the synchronous motor speed (in rpm). Along with the synchronous speed, the motor speed determines the slip, as shown in Equation 1.15.

$$s = \left[\frac{n_s - n}{n_s} \right] \tag{1.15}$$

Where s is the slip, and n is the motor operating speed (in rpm). As the slip increases, the motor speed decreases, and the power developed at the load grows larger. As the load increases, PF gets larger. The relationship of the PF to the motor speed is shown in Figure 7.

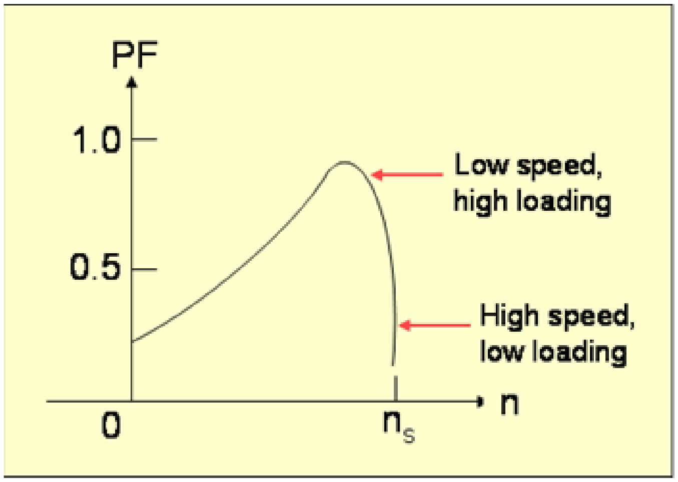

Fig. 7. Dependence of motor power factor on motor speed

The input power (for three-phase motors) is given by equation 1.16.

$$P_{input} = \sqrt{3} V_1 I_1 \cos(\phi) \tag{1.16}$$

Due to losses in the stator windings, rotor windings, and core, not all the power that is delivered to motor input terminals is actually developed at the load. The losses in the stator and rotor windings, respectively are:

$$P_1 = I_1^2 R_1 \tag{1.17}$$

$$P_2 = I_2^2 R_2 \tag{1.18}$$

The losses in the core are caused by hysteresis and eddy currents. Hysteresis is a phenomenon that occurs in ferromagnetic objects. As the motor rotates through a cycle the flux density increases. When the field is relaxed, the flux does not fall off as quickly as it developed. This is due to stiffness in the magnetic dipoles, and is a source of energy loss. Eddy currents occur when a ferromagnetic object passes through a changing magnetic field. Currents are induced in the object by the changing field, but they in turn induce magnetic fields which oppose the original magnetic field, with associated energy loss.

The mechanical power that is developed at the load R_2/s can be found by Equation 1.19. The slip, and hence motor speed determine the power that is developed at the load.

$$P_{load} = \frac{I_2^2 R_2}{s} \qquad 1.19$$

The efficiency of a motor is reduced by the losses mentioned above. It is expressed in Equation 1.20 and 1.21.

$$Eff = \frac{P_{out}}{P_{in}} \rightarrow \qquad 1.20$$

$$Eff = \frac{\frac{I_2^2 R_2}{s}}{\sqrt{3} VI \cos(\phi)} \qquad 1.21$$

1.5.2 Facility Distribution Systems

The network of cables and nodes that deliver power to electrical loads in a facility is the distribution system. The upstream, electrical entry for an industrial facility is called the service entrance. This is a common location for a transformer, which provides power to the entire facility at a desired voltage level. The transformer steps down the primary voltage to a lower voltage for consumption in the facility.

The service entrance usually feeds one or more main control centers, which branch to supply secondary and sometimes tertiary panels. The panels often support multiple branches, which supply one or more loads.

These points separate the path between the service entrance and the load into numerous line segments. At each segment, and the connections that link them, the voltage drop between the service entrance and load is increased. This happens because each individual element in the conduction path contributes a modicum of resistance, which all sum linearly.

The branch from entrance to load is usually divided into line segments, connected by devices that safeguard the load, allowing the load to be isolated from the distribution system. These devices include breakers, fuses, disconnect switches, motor starters, and others. The branch resistance can be minimized with good soldering, proper mechanical connections, and sufficiently large conductor cables. Beyond these measures, only reduction to the branch current remains as an opportunity for ohmic loss reduction (and thereby demand reduction and energy savings, as we will explain in greater detail in Section 1.6.3).

Line Resistance - The resistance in a wire can easily be calculated, given the length and thickness of the cable. The National Electric Code (NEC) handbook lists the resistance per 1000 foot for a range of wire sizes (see Table 2)[6]. If properly sized, the resistance in the wire itself will not significantly increase with the passage of time and accumulated wear.

Table 2 – Line resistance values[6]

OHMS TO NEUTRAL (PER 1000 FT)	
Wire Size (AWG or kcmil)	AC Resistance (milliohms)
14	3100
12	2000
10	1200
8	780
6	490
4	310
3	250
2	190
1	150
1/0	120
2/0	100
3/0	77
4/0	62
250	52
300	44
350	38
400	33
500	27
600	23

Contact Resistance – The same cannot be said for the resistance due to protection devices that connect the lengths of wire, however. Associated with every connection point between a wire and protection device (or between two wire segments) is a quantity of contact resistance. The resistance is initially low, but even for a properly installed connection, the resistance at a connector can exceed that of the wire segment to either side. This resistance cannot easily be projected, as a number of factors affect the magnitude. In addition, the resistance increases over time due to a process known as fretting.

1.6 Fretting and Contact Resistance

Fretting is the degradation of a metal contact that occurs due to micro-motion at the boundary between the two surfaces. As the number of cycles of operation increases, the contact corrodes, and a gradual increase in the contact resistance occurs.

During the fretting process, the contact resistance increases as corrosion introduces insulating material at the contact. Counteracting this is fritting, a process whereby conducting material breaks through these resistive films to reestablish a good conduction pathway. This phenomenon repeats as the contact resistance steadily increases until a critical point where a good conduction cannot be reestablished and the boundary at the contact point can essentially become an open circuit.[7]

1.6.1 Causes of Fretting

The rise in contact resistance from fretting corrosion results from two phenomena: A) Chemical processes that cause an insulating film of oxides or sulfides up to hundreds of nanometers thick to develop at the boundary that impedes the flow of electricity, and B) Geometric processes associated with surface undulations and asperities, that segment the apparent area of contact into islands of contact, leaving the real contact area a fraction of the apparent area. Here electrons must funnel through the geometric constriction formed by contacting asperity hills through so-called a-spots, and across the contact. Conduction is limited due to the constriction of the contacting area. In extreme cases, this can cause open circuits.[7]

A number of phenomena can bring about fretting, including vibrations present in the environment which cause relative motions between contacting members of the electrical connection, resulting in long-term metal fatigue of the members. Other catalysts include the presence of corrosive agents such as oxides, sulfides, or ozone, thermal cycling, high temperatures, high humidity, disparate metals at each side of the contact, advanced age of the connector, and frequent power cycling of nearby equipment (and associated in-rush currents and heat). If insufficient normal force is used to secure the contact, or no lubricant is used, a dramatic increase in contact resistance can occur over time.

The typical contact resistance in a new connector can range from 10^{-2} to 10^{-3} ohms. However, for aged equipment operating in hostile conditions like those mentioned above, connectors can experience contact resistances of up to several ohms apiece.[8]

1.6.2 Buildup of Circuit Resistance Due to Fretting

The conditions that stimulate fretting and the resulting rise in contact resistance are straightforward, but how does one model the behavior to predict the increase in contact resistance? Such a method would provide useful insight into the future operation of a circuit connection point. Unfortunately, no standard yet exists that can accurately predict individual contact resistances.[8] However, one can observe the attributes of an electrical contact and estimate future behavior based on such parameters as the contact wipe, fretting vibration frequency, plating thickness, normal pressure, electrical load, and lubrication.[7]

The wipe distance is the amplitude between a contact point's average and maximum positions as the contact oscillates during the fretting process. If the wipe distance is increased, the contact resistance will increase considerably, as more asperity surface area is uncovered. Greater exposure results in a rapid increase in contact resistance. The fretting vibration frequency plays an important role.

At low frequencies, asperities in the contact are vulnerable to corrosion for extended periods during each cycle. This allows the insulating film that forms due to oxidation to grow thicker. For lower vibration frequencies, fewer cycles are needed to produce a given contact resistance.

The presence of a thick plating depth over conducting wires can safeguard a contact from escalating resistance. The plating can protect the underlying connector from corrosion, but is itself susceptible to harmful mechanical effects. The best approach is to layer a hard plating material such as nickel between an inactive exterior such as gold, with a soft underlying substrate like copper.

The normal pressure at the contact point determines how easily the two surfaces can slide past one another. Higher normal force locks down the oscillations, maintaining a stable, low contact resistance. If normal pressure is low, however, the fretting mechanism can more easily occur.

The electrical load usually has a modest effect on contact resistance. The formation of an insulating film is not affected by the electrical load, with the exception of high voltage. If high voltage is present, the healing process of fritting is facilitated, breaking down the film, and reducing contact resistance.

In Figure 8, a graphic representation of the fretting contamination process is presented. Panel A illustrates the contact of 2 asperity hills. Multiple a-spots like this form the actual conduction pathway between two surfaces of a metal contact. In Panel B, fretting oscillation has forced the displacement of the asperity hills by the wipe distance. The exposed surfaces of the asperities are subjected to corrosive attack. An insulating film begins to form. Panel C shows the return of the asperities to proper alignment, but the point of connection is enveloped by corrosive film. In Panel D, the oscillation continues, and additional corrosion occurs. Panel E shows alignment once again, but the movement has caused deformations which break up the film and combine the corrosive product with the contacting metal itself. This increases the contact resistance. Finally in Panel F, insulating material has completely blocked the asperity connection. The conduction of electrons continues, however, as they tunnel across the blockage. But when the film reaches a thickness of over 20nm, electrons can no longer tunnel and the connection may become an open circuit.

The presence of a lubricant can help reduce contact resistance. A lubricant can shelter the contact from the ambient environment, impeding the formation of corrosive materials. In addition, lubricants diminish friction, and thereby reduce wear.

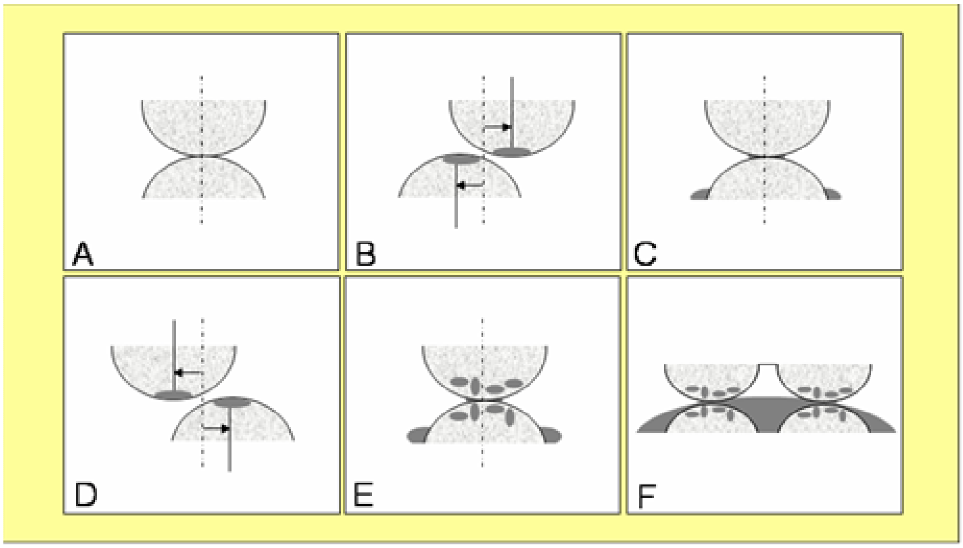

Fig. 8. Development of fretting corrosion[7]

As mentioned above, contact resistance fluctuates as fretting cycles increase. The resistance grows, with periodic decreases due to the healing process of fritting. A typical new contact can exhibit a resistance of about 10^{-3} ohms, but after a period of about 10^3 to 10^4 cycles, the contact resistance can increase by several orders of magnitude.

Figure 9[9] shows an example of a tin-lead contact. The contact was established in a lab, with a normal load of 30-300g, a wipe of 10-240μm, a frequency of 0.17 to 8.00 Hz, and standard temperature and humidity. The contact resistance was measured under dry conditions with a maximum potential of 20mV. The contact resistance was observed for the conditions: A) unlubricated, B) lubricated with a 5% solution of mineral oil (1,1,1-trichloroethane) C) lubricated with a 10% solution, and D) lubricated with a 20% solution. The contact resistance increased from 10^{-3} ohms to over 1 ohm in all cases except the 20% solution.

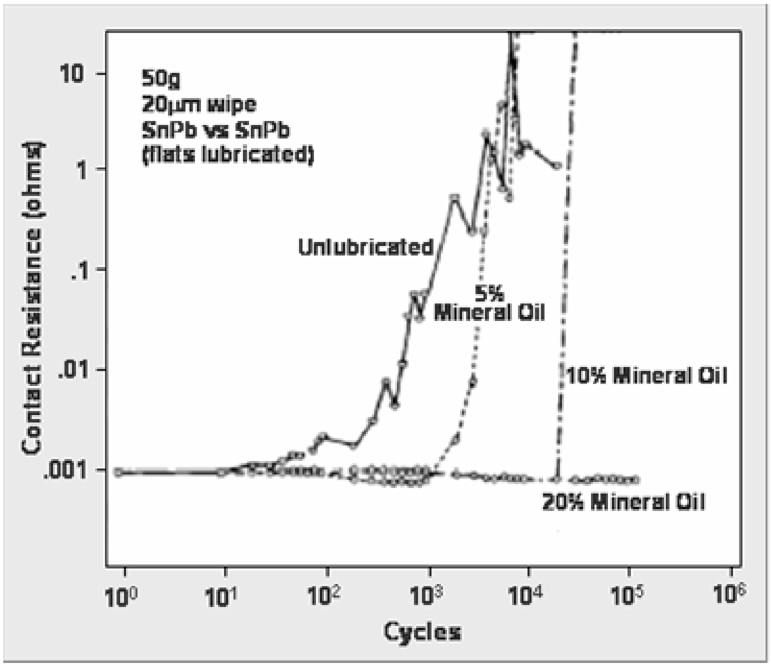

Fig. 9. Contact resistance vs. number of cycles[9]

1.6.3 Branch Resistance and Ohmic Losses

The branch resistance in a circuit is a series of resistances, summed to obtain the total resistance. In this model, the resistance of the branch connectors would come to dominate the total resistance as the contacts at each connector age and are exposed to the fretting process and resulting corrosion.

When contact resistance from connectors is included, the branch resistance is often much larger than the contributions from wire segments alone. The higher resistance results in larger ohmic losses. Due to logistic issues, it is difficult to measure branch resistance directly. We will consider a method for calculating the branch resistance, based on the response of a circuit to changing electrical conditions.

When a circuit experiences a decrease to RMS current, and an associated real power decline is observed, one can calculate the branch resistance. We begin with the basic description for ohmic loss (see Equation 1.22)

$$P_{loss} = I^2 R \qquad 1.22$$

Where P_{loss} is the real power loss due to heating in the wires and at the connectors, I is the total RMS current flow along the pathway to the load, and R is the sum of the resistances along the branch. This relation can be expanded to describe the effect that modification to the circuit current has on the ohmic loss for the circuit. For a three-phase load, ohmic losses must be considered for all 3 phases. We revise Equation 1.22, substituting for the initial current and final current (Equation 1.23 and 1.14).

$$P_{loss_1} = 3{I_1}^2 R \qquad 1.23$$

$$P_{loss_2} = 3{I_2}^2 R \qquad 1.24$$

Where P_{loss1} and P_{loss2} are the ohmic losses in the system before and after the total current is reduced.

Assuming the current is reduced ($I_1 > I_2$), we subtract Equation 1.24 from Equation 1.23 to account for the change in ohmic loss that occurs when the current is reduced:

$$\begin{aligned} & P_{loss_1} - P_{loss2} = 3{I_1}^2 R - 3{I_2}^2 R \rightarrow \\ & \Delta P_{loss} = 3R\left({I_1}^2 - {I_2}^2\right) \end{aligned} \qquad 1.25$$

Now we solve for the branch resistance,

$$R = \frac{\frac{\Delta P_{loss}}{3}}{{I_1}^2 - {I_2}^2} \qquad 1.26$$

So if the currents I_1 and I_2 are known, as well as the change in the ohmic loss when the current is reduced, one can back-calculate the branch resistance with Equation 1.26.

It is also instructive to determine the percentage of ohmic losses that are eliminated by reducing the RMS current. We form the relation, using Equations 1.23 and 1.24.

$$\begin{aligned} & \% \Delta P_{loss} = \frac{P_{loss1} - P_{loss2}}{P_{loss1}} \rightarrow \frac{3I_1^2 R - 3I_2^2 R}{3I_1^2 R} \rightarrow \\ & = \left(1 - \frac{{I_2}^2}{{I_1}^2}\right)\% \end{aligned} \qquad 1.27$$

Due to the squared dependence of ohmic losses on the current, the reduction in losses that results from a decrease in the system current is not linear. A 50% decrease in the current produces a 75% reduction to the ohmic loss, for example.

Despite the considerable decreases in ohmic loss that can be accomplished with modest current reduction, the importance of the ohmic loss reduction is only valuable if the loss itself is significant. This is determined by the magnitude of the branch resistance. We will now consider an example.

1.6.4 Example of Circuit Resistance

To illustrate the dominance of the contact resistance in a circuit, we will examine an air conditioner motor from a facility that will be considered in more depth later in Chapter IV. See Figure 10 for a picture of Condenser Fan 1.

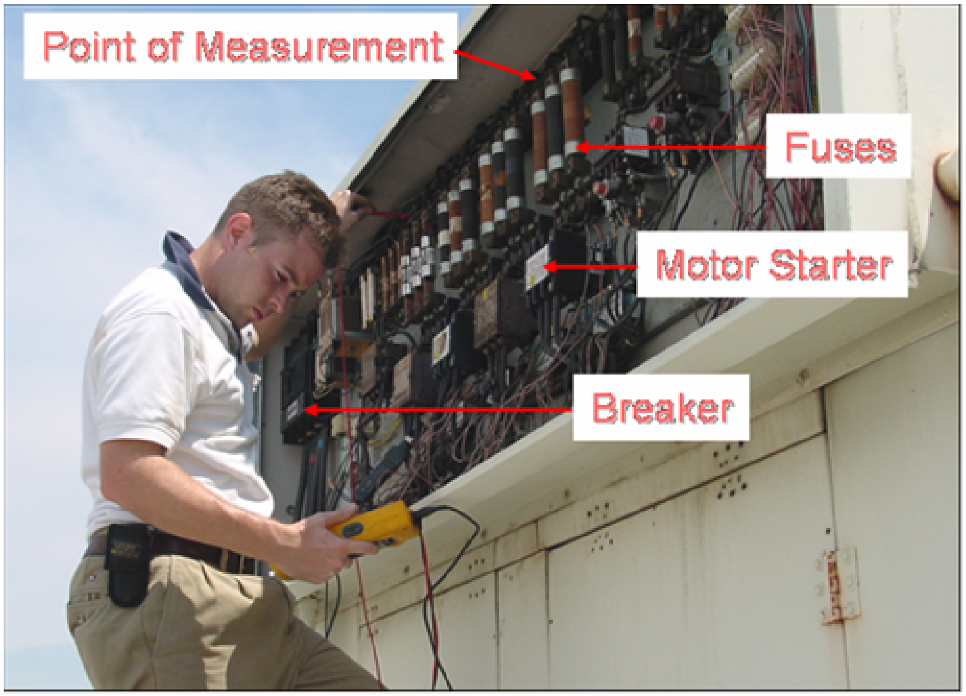

Fig. 10. Motor control panel

The one-line diagram for Condenser Fan 1 is shown in Figure 11. As depicted in the figure, there are two #14 gauge line segments between the motor terminals and the point of measurement. In addition, there are two protective devices: a 70 amp fuse and a motor starter. Each device includes multiple connection points, such the positive and negative terminals, and potentially more contacts within each device.

We will calculate the branch resistance using Equation 1.26. The measured values for I_1, I_2, and ΔP were measured:

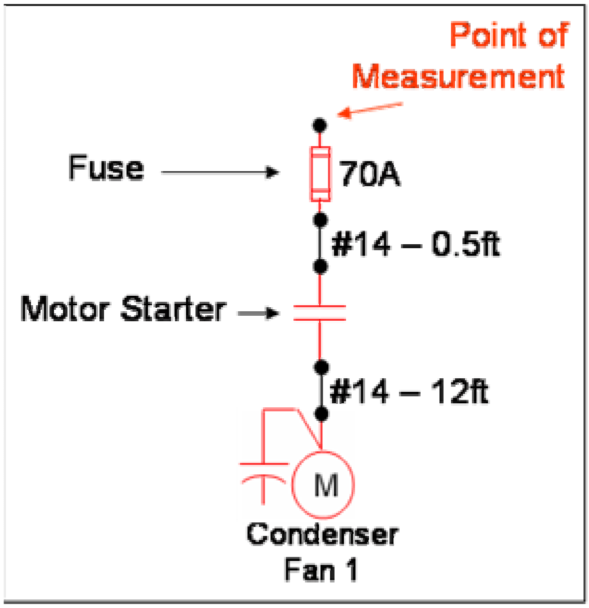

Fig. 11. One-line diagram: Condenser Fan 1

$I_1 = 4.01$ amps

$I_2 = 2.62$ amps

$\Delta P = 170$ watts

$$R = \frac{\frac{\Delta P}{3}}{\left(I_1^{\,2} - I_2^{\,2}\right)} \rightarrow \frac{\frac{170 watts}{3}}{\left((4.01)^2 - (2.62)^2\right)} = 6.1196 \text{ ohms}$$

So the branch resistance is 6.1196 ohms. Now we will determine the predicted resistance due to only the line segments, using the coefficients from Table 2.

$$R = (length) \cdot (resist./length) \rightarrow$$

$$R_1 = (0.5 ft) \cdot \left(\frac{3100 m\Omega}{1000 ft}\right) = 1.6 m\Omega$$

$$R_2 = (12 ft) \cdot \left(\frac{3100 m\Omega}{1000 ft}\right) = 37.2 m\Omega$$

The resistance in line segment 1 and 2 were found to be 1.6 mΩ and 37.2 mΩ, respectively. These values sum to a total line resistance of 3.88 mΩ (see Table 3).

Table 3 – Circuit resistance for Condenser Fan 1

BRANCH RESISTANCE EXAMPLE			
Line Segment	Comment	Length (ft)	Resistance (milliohms)
1	#14 awg	0.5	1.6
2	#14 awg	12	37.2
Total	-	12.5	38.8

Now we determine the contact resistance:

- Branch Resistance, Measured * 6119 mΩ (* Calculated from measurement)
- Predicted Line Resistance 39 mΩ
- Contact Resistance (6119-39) mΩ = 6080 mΩ

We observe that well over 95% of the resistance in this example resides in the contacts. Now we calculate the reduction to ohmic loss that occurred.

$$\%\Delta P_{loss} = \left(1 - \frac{I_2{}^2}{I_1{}^2}\right) \rightarrow \left(1 - \frac{(2.62)^2}{(4.01)^2}\right)\% \; = 57.3\%$$

So the current was reduced by 35%, but the ohmic losses were decreased 57%.

We have examined the influence of resistance on ohmic losses. In the next chapter, we will present a method for lowering the branch currents, as a means of reducing ohmic losses.

CHAPTER II
DISTRIBUTED MOTOR CAPACITORS

In this chapter we will investigate distributed motor capacitors that are installed at the load level to improve power factor and reduce reactive current flow in the facility distribution system. We will consider the reduction of ohmic losses and the associated decrease in the real power flowing to the load. The engineering and economic considerations involved in a successful distributed motor capacitor project will be presented.

2.1 Characteristics

As mentioned in Chapter I, capacitors provide many benefits if installed in a distribution system where PF and/or voltage is below rated level. Examples include load control centers or individual motor loads. Capacitors can free up current capacity on the upstream branch of the distribution system, and can dampen transient voltage surges.

We will show that distributing capacitors is often a better approach than placing them at the service entrance. The treatment of individual motor loads not only corrects the PF, but also affords additional advantages that are not possible with entrance capacitor banks.

Motor capacitors are located locally, in parallel with the motor, and often terminated downstream of the motor starter. When the motor is energized, the capacitor is activated and begins to generate reactive power that is directly absorbed by the motor. The capacitor is sized to produce a significant portion of the reactive power required by the motor. When the motor turns off, the capacitor is isolated from the facility distribution system. This prevents the flow of excess reactive power. By placing a capacitor at each motor, PF is individually corrected to around 0.96 to 0.98. The entire facility PF is improved when many loads are treated this way.

2.1.1 Reduced Ohmic Losses

A distributed motor capacitor elevates the individual PF for a motor by locally producing most of the reactive power that would otherwise be supplied by the electric utility provider. This results in a reduction of the total current flowing across the facility distribution system to the load (see Figure 12). In the figure, a portion of the facility current (represented by the large red arrows) is provided by the capacitor which is terminated adjacent to the motor.

In Equation 1.22, we observed that reduction of the current can impact ohmic losses considerably. If each significantly sized induction motor in a facility is individually treated with a capacitor, the reactive current flowing throughout the distribution system is generally constrained to the immediate region near the motors. A great deal of ohmic losses can be avoided by this method, which are reflected in the monthly utility bills.

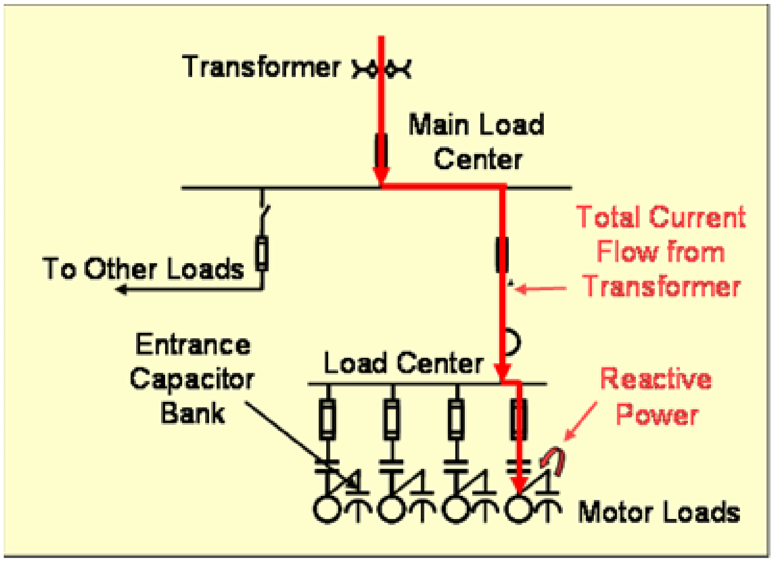

Fig. 12. Distributed motor capacitors terminated at load level

2.1.2 Transient Damping

Another advantage of a distributed motor capacitor is the ability to provide added protection to the motor from voltage transients. While an entrance capacitor bank protects downstream loads from upstream disturbances, it cannot guard against surges that originate inside the plant (downstream of the bank). Internal voltage surges account for many events, making the issue significant. By contrast, distributed motor capacitors provide individual protection to each load.

2.1.3 Reduction of In-Rush Current

When a motor is initially energized, the current magnitude increases to a high level for a brief time. This transient is required to accelerate the motor from rest to operating speed: the in-rush current. In-rush current can typically attain 5-6 times rated current levels, with duration lasting 0.1 to 5.0 seconds. The addition of a distributed motor capacitor to the motor reduces the in-rush current level, attenuating the current with a slight lengthening of the starting time. This reduces stress on the motor, and on the lines and devices that supply and protect it.

2.2 Design Considerations

Motor capacitors provide many benefits, but caution should be observed during the design. The capacitor must be properly sized, and the nearby distribution system should be evaluated for harmonic currents. If harmonic generating equipment is present in the facility, the harmonic frequencies where resonance can occur must be avoided. The voltage level on the distribution system should also be considered. Capacitors are manufactured by tolerance to voltage level, and the correct rating must be observed.

2.2.1 Sizing the Capacitor

Ideally, the capacitor should provide slightly less than the total reactive power required by the motor. If too much reactive power is supplied, the lagging PF will become leading as the capacitive element comes to dominate the circuit. In addition, excessive capacitance can cause an over-voltage on the motor. This can damage the motor during re-closer operations following a power outage, if the capacitor remains connected to the motor following the outage.[5] The amount of reactive power required to improve the PF from the original to the desired level, for a given motor loading level is given by Equation 2.1.

$$\begin{gathered} Q = P \cdot \left[\tan\left(a\cos(PF_1)\right) - \tan\left(a\cos(PF_2)\right)\right] \\ Q = P \cdot k \rightarrow k = \left[\tan\left(a\cos(PF_1)\right) - \tan\left(a\cos(PF_2)\right)\right] \end{gathered} \qquad 2.1$$

Where PF_2 is the corrected value, PF_1 is the original value, P is the real power drawn by the motor at PF_1, and k is the indexed coefficient that is multiplied by the motor load. The most common approach is to set the corrected PF to a value in the range 0.96 to 0.98. If the corrected value is designed lower than 0.96, it may dip to unacceptable low levels if the loading on the motor increases during future operation. This occurs because the required reactive power increases for the higher loading condition, and the capacitor will fall short of the needed reactive power, causing the PF to decline. If the corrected value is designed higher than 0.98, the PF may rise to unity, or perhaps become leading if the loading on the motor decreases during future operation (see Appendix D for a look-up table of k coefficients, indexed for PF_1 and PF_2).

Frequently, induction motors experience time-dependent loading. The variation from high and low-loading operation can be large, and correspondingly, PF values swing. In Equation 2.1, the value of P declines when loading is low, but k rises. While the influence of P is linear, k varies trigonometrically. Therefore, a motor requires less reactive power to correct to near unity PF while lightly loaded than it does when fully loaded. For this reason, the capacitor should be sized for the low load operational condition. If the sizing was calculated for the high-load state it would generate too much reactive power during the low-load condition, resulting in leading PF, and possibly over-correcting and subjecting the motor to over-voltage conditions.

2.2.2 Harmonic Considerations and Filtering

Harmonics currents are perhaps the biggest obstacle to industrial PF correction with distributed motor capacitors. As the frequency of a waveform rises, the inductive reactance increases while the capacitive reactance decreases. The frequency where the two are equal is called the parallel resonance point (see Equation 2.2).

$$h_R = \sqrt{\frac{S_{tx}}{Q_{cap} \cdot Z_{tx}}} \qquad 2.2$$

Where h_R is the parallel resonance point frequency, S_{tx} is the apparent power rating of the upstream transformer, Q_{cap} is the reactive power output of the capacitors on the bus, and Z_{tx} is the impedance of the transformer (in %). If harmonic current exists in the distribution system near the parallel resonance point, current flow in the capacitor can exceed fuse and conductor ratings, damaging the capacitor. Therefore, for a facility with harmonic generating equipment, capacitors require filtering protection. This is accomplished by de-tuning the capacitor, which shifts the resonant frequency of the distribution system away from the harmonic current components.

Motor drives are a common source of harmonics in industrial facilities. The harmonics follow Equation 2.3.

$$h = np \pm 1 \qquad 2.3$$

Where h is the harmonic number, n are positive integers, and p is the number of pulses in the drive. The most common drives are 6-pulse, so the dominant harmonic components are the 5th, 7th, 11th, and 13th harmonics. To avoid these operating harmonic points, capacitor filters are tuned to have a resonance point below the 5th harmonic.

The total harmonic current distortion (THD) provides a practical method for gauging the need for de-tuning. If the THD is greater than 15%, detuning is suggested. This prevents excessive current from damaging the capacitor (see Equation 2.4).

$$THD = \frac{\sqrt{\left(\sum_{i=2..n}^{n} I_i^2\right)^2}}{I_1} \qquad 2.4$$

2.2.3 System Voltage and De-Rating Capacitors

Capacitors for PF correction are manufactured in low and medium voltage tolerances. The most common voltage that distributed motor capacitors encounter is 480 volts, but larger motors sometimes operate at 2300 volts and 4160 volts.

Once the correct voltage is selected, the capacitor must be de-rated to account for deviation in the measured system voltage. The actual reactive power output is reduced if the line voltage sags below rated value (see Equation 2.5).

$$Q_M = Q_R \frac{{V_M}^2}{{V_R}^2} \qquad 2.5$$

Where Q_M is the actual reactive output of the capacitor, Q_R is the rated output, V_R is the rated voltage, and V_M is the measured voltage.

2.3 Project Engineering Drivers

In addition to the presence of induction motor loads, a range of additional conditions determine if a distributed motor capacitor project is sensible.

2.3.1 Motor Loading

For a motor that continuously operates at low loading, a greater amount of PF correction is achievable, and a larger segment of the total current supplying the motor can be provided by the capacitor locally (and thereby eliminated from the distribution system). This translates to a greater percentage of ohmic loss reduction in the distribution system branch for that motor.

This capability is absent in entrance capacitor bank designs because the capacitor is terminated upstream of the facility distribution system, and does not influence the magnitude of the current flowing in the facility itself. Low motor loading is a positive condition for distributed motor capacitor designs.

2.3.2 Condition of the Distribution System

While motor loading determines the proportion of current flowing to the motor which can be removed from the upstream branch, the condition of the distribution system itself determines if ohmic losses are significant. If a facility is old or maintenance is poor, the contact resistance may be large, and therefore the branch resistance for each induction motor may be high. Thus, ohmic losses are greater, and PF correction by motor capacitors will yield larger real power reduction for the plant.

2.3.3 Line Lengths

In section 1.5.2, the behavior of line resistance was discussed. Table 2 showed that for a given electrical cable, the line resistance increases linearly with increases to the length. For loads supplied by long line lengths the resistance is higher, which results in larger ohmic loss that can be addressed by distributed capacitors. So the presence of long line lengths is a favorable condition for a distributed motor capacitor project.

2.3.4 Number of Protection Devices

As noted above, the majority of the resistance in a branch can accumulate at the connection points along the pathway, because of high contact resistance that results from fretting corrosion. For a load protected by a greater number of protective devices, the resistance may be larger. Higher resistance translates to higher ohmic losses, which favors a distributed motor capacitor design.

2.4 The Electric Bill

Now we will focus on the economics of a distributed motor capacitor project. This includes a study of the electric bill, which is compiled after a meter reading is acquired at the customer's facility. The utility meter is normally located near the entrance transformer. Billing determinants are applied to the electrical numbers gathered during the reading, fees are assessed, and then the rate structure is applied to determine the monthly charge. The typical billing determinants are demand, energy usage, and fuel charges. For smaller customers the demand is normally not a determinant. Additionally, there are often specialized charges such as rate multipliers, adjustments, etc.

2.4.1 Demand Charge

The demand portion of the bill (in KW) is defined as the highest average, continuous real power draw for a given time increment (usually 15 or 30 minutes), during the period for that billing cycle. The demand establishes the highest amount of real power that was demanded by the customer for the given period.

2.4.2 Energy Charge

The energy portion of the bill (in KWH) is the sum of the instantaneous power, integrated over time, and factored over the entire period of the billing cycle. The energy charge defines the total amount of energy consumed by the facility for the billing cycle.

2.4.3 Fuel Charge

The fuel charge compensates the electric utility for the fuel used to produce the power delivered to the customer. The charge is normally the weighted-average fuel mix for the energy used during the period, including natural gas, coal, nuclear, and also the power purchased from other companies.

2.4.4 Power Factor Tariff

As the United States embraces deregulation in the electric utility industry, rate structures have begun to change in regions of the country. Some customers who never suffered economic consequences for a low PF have begun to face penalties. For many rate structures a surcharge is accessed for power drawn at a PF below a certain threshold, though the implementation of the penalty can take many forms. Some electric utilities bill on a KW basis, with a penalty for PF values below 0.95. Other utilities bill on a KVA basis, which implies a PF threshold of 1.00. In any case, a PF improvement project can eliminate this penalty.

2.5 Financial Barometers

Several indicators can be employed to characterize the effectiveness of an engineering project. We will examinee payback, net present value, and the internal rate of return. These figures assume that a measurable savings stream is produced by the project, such as a reduction in the energy or PF tariff portion of the utility bill. These indicators are used to index the financial effectiveness of the project.

2.5.1 Payback

The payback (PB) of a project is the time period needed to recover the funds invested in a project. The total cost of the project including equipment, installation, and design fees, divided by the savings generated per unit time, yields the payback. Typically, a PB of 24 months or less is considered an attractive project by many companies. (see Equation 2.6).

$$PB = \frac{I}{CF} \qquad 2.6$$

Where I (in dollars) is the initial investment in the project and CF (in dollars / month) is the cash flow that is produced per unit time, frequently given in months. A low project payback is desirable.

2.5.2 Net Present Value

The net present value (NPV) is a criterion that allows a customer to evaluate the benefits of a project to the investment cost, over a span of time. It incorporates the time-value of money. The NPV can be found by discounting future cash flows to the present (see Equation 2.7).

$$NPV = -I + \sum_{i}^{n} \frac{CF_i}{(1+r)^i} \qquad 2.7$$

where I (in dollars) is the initial investment, n (in years) is the period of the project in which financial savings are derived, CF_i (in dollars / month) is the cash flow in year i, and r (in %) is the discount rate, which is the rate of return that could be had on the funds if allocated to another investment.

For most industrial companies, the r value is the weighted average cost of capital for the company considering the project investment. The value n is the evaluated life of the project equipment. Values of r =5-8% and n = 10 years are typical, as this correlates to forecast equipment life spans allowed by federal tax codes. The NPV illustrates the current value of the future cash flow provided by the project, less the initial cost. If NPV is negative, the costs of the project will outweigh the benefits, and the project would not be advised from a financial standpoint. NPV is given in currency, and a higher value indicates a more worthy project.

2.5.3 Internal Rate of Return

The internal rate of return (IRR) is the discount rate that matches the cash flow benefits over time to the initial investment, thus producing a NPV of $0. For a project with PB = 12 or 24 months, the IRR = 100% and 50%, respectively. This method allows easy comparisons between many investment opportunities, and facilitates prioritizing investments when company funds are limited. The IRR is given in percentage form, and takes into account the time-value of money. A high IRR implies a worthwhile project.

2.6 Project Economic Drivers

To justify a distributed motor capacitor project, financial savings usually must be generated, unless it is undertaken solely for engineering benefit (to liberate capacity in the transformer(s) or to free up capacity in the lines within a facility, elevate the voltage, guard against transients, etc). These savings may take the form of reductions to the energy and/or PF tariff portions of the bill. In addition, several additional conditions determine if a distributed motor capacitor project is sensible.

2.6.1 Capacitor Unit Cost

The magnitude of ohmic losses reduced by a capacitor is proportional to the size of the capacitor. However, the capacitor unit price falls exponentially as capacitor size increases (see Figure 13).[10] Smaller motors require smaller capacitors, so the payback for those motors will be longer when treated by distributed motor capacitors.

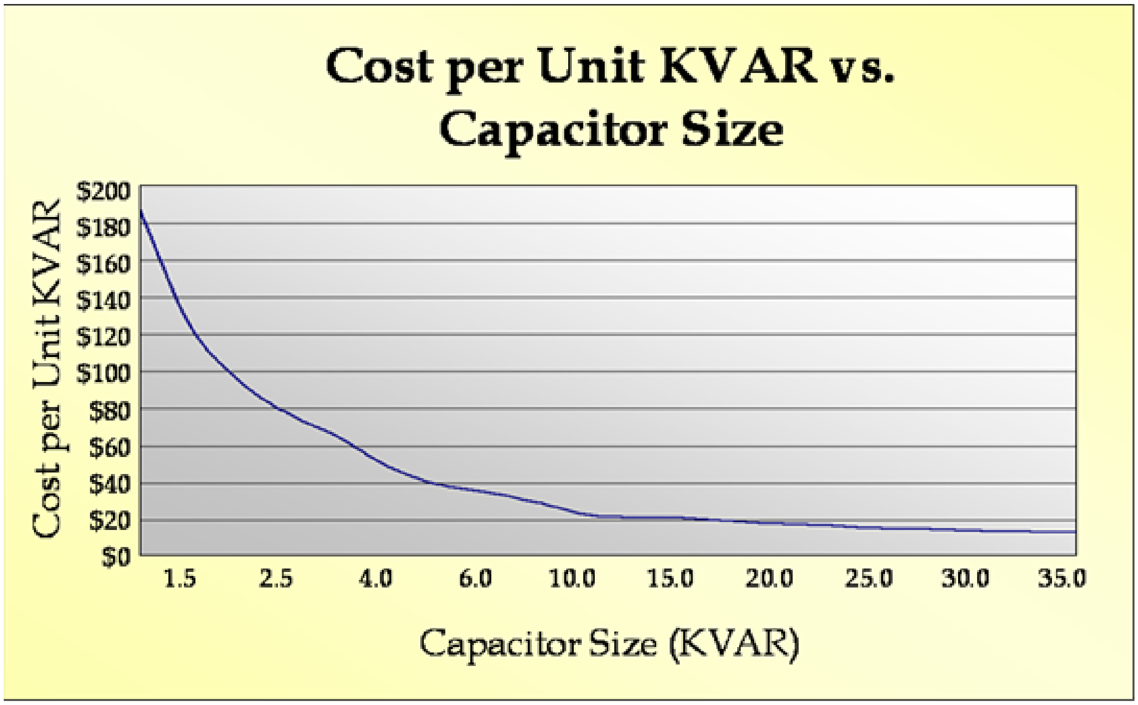

Fig. 13. Per unit cost as capacitor size increases

2.6.2 Ohmic Loss Reduction

The reduction of ohmic losses that is achieved by the capacitor cannot be forecast exactly, due to the random nature of contact resistance. In Figure 14 we illustrate the payback for individual capacitors based upon the capacitor size and the percentage of real power reduction (ohmic losses as a proportion of the total real power flowing to the motor). Predictably, the capacitor which produces the greatest reduction to ohmic losses displays the lowest payback for each size.

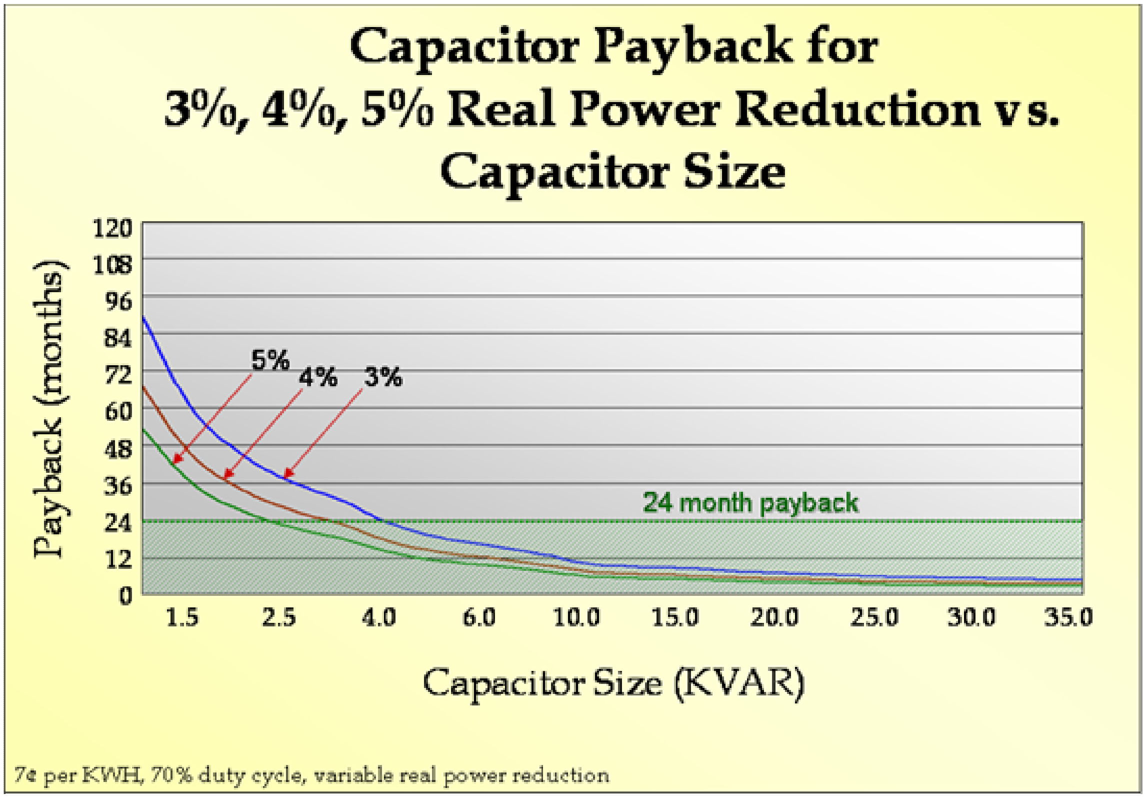

Fig. 14. Payback as a function of capacitor size and real power reduction

2.6.3 Motor Duty Cycle

At every moment the capacitor functions, the real power flow to the motor is reduced. The longer the motor operates, the more energy is saved. Only those motors that run for an appreciable time are good candidates for distributed motor capacitor treatment. In Figure 15 we illustrate the payback for individual motor capacitors based upon the capacitor size and the duty cycle. Unsurprisingly, the capacitor paired with the motor which operates the most displays the lowest payback for each capacitor size.

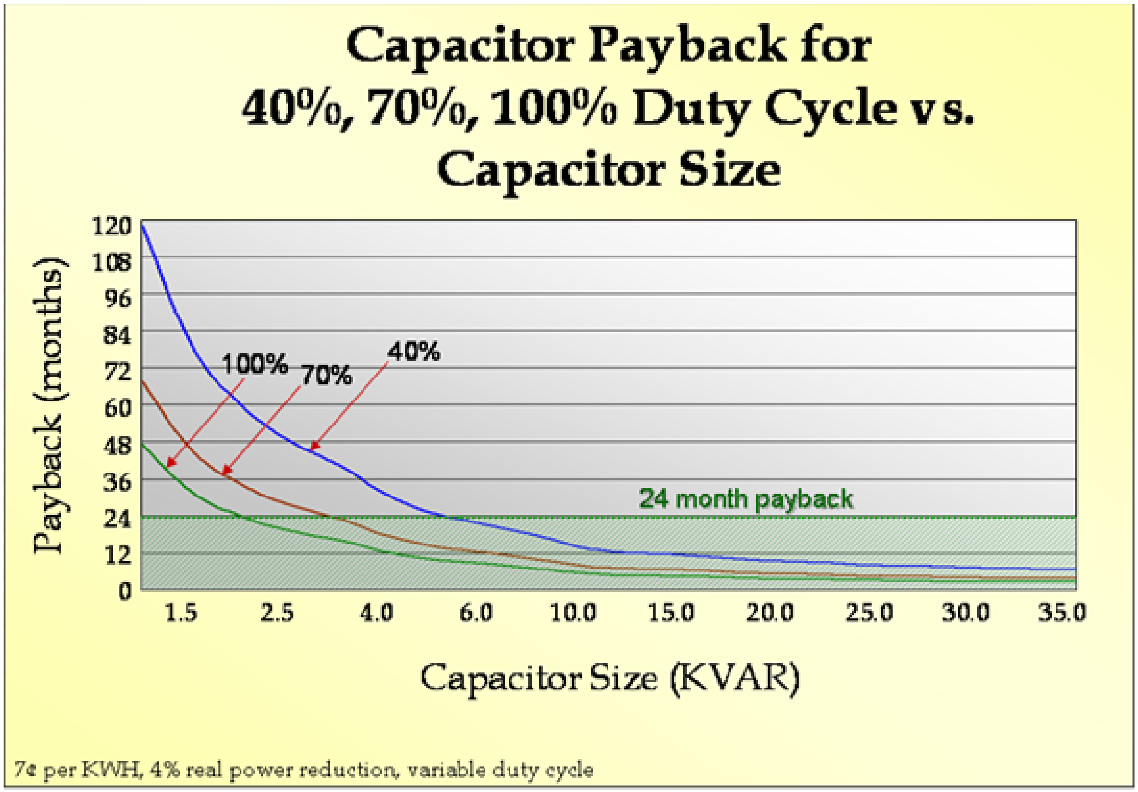

Fig. 15. Payback as a function of capacitor size and duty cycle

2.6.4 Cost of Electricity

As the cost of electricity increases, the financial gain from a distributed motor capacitor grows. In Figure 16 we illustrate the payback for individual motor capacitors based upon the capacitor size and the cost of electricity. As expected, the facility with the most costly electricity displays the lowest payback for each capacitor size.

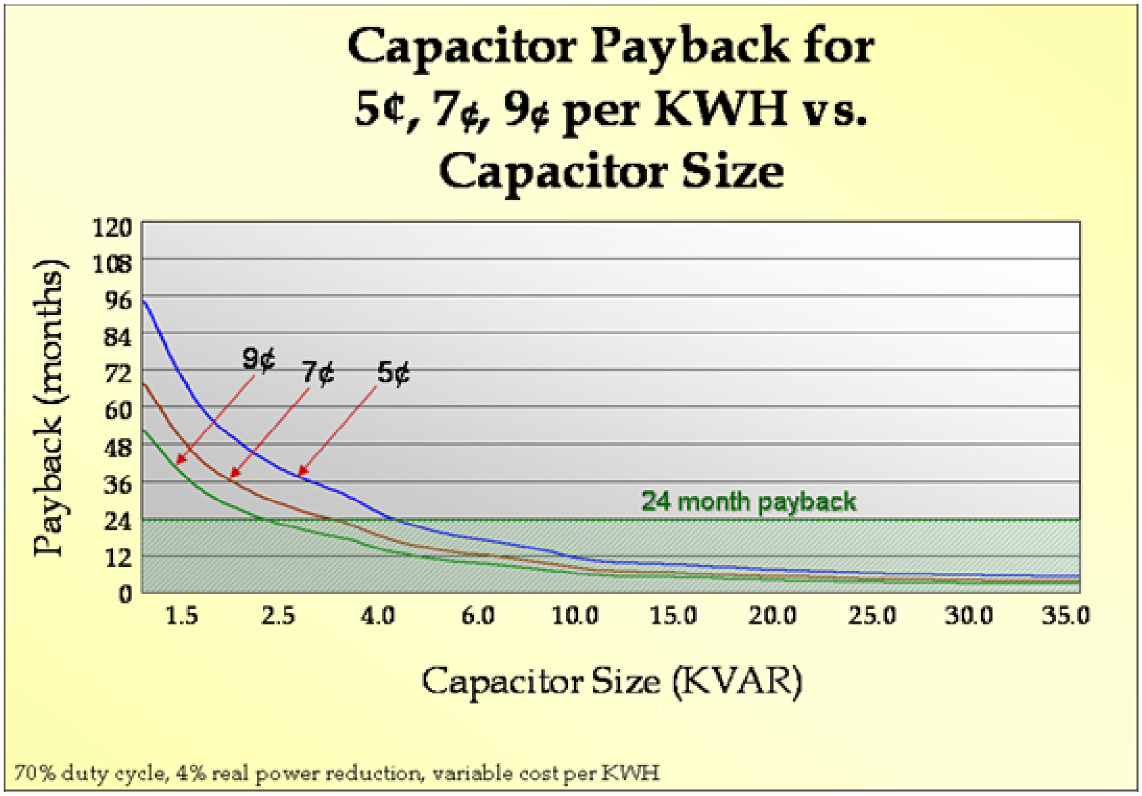

Fig. 16. Payback as a function of capacitor size and cost per KWH

2.6.5 Presence of Harmonics

If significant harmonic currents are present in a facility, such as from adjustable speed drives, electronic lighting, or office equipment using switch-mode power supplies, then PF correction capacitors (either entrance banks or distributed motor capacitors at individual loads) must be filtered. This can dramatically increase the cost of the capacitors, making the project economics unattractive. The impact is substantially more costly for distributed capacitors, however. Filtered entrance banks may experience a 50-100% increase in price, but smaller distributed capacitor prices may increase by as much as 1000%.

CHAPTER III
METHODOLOGY OF A DISTRIBUTED MOTOR CAPACITOR PROJECT

In this chapter we will present the methods used to survey, design, implement, and measure the outcome for a distributed motor capacitor project. This will include a description of the equipment used to carry out measurements, and an example which illustrates the methods.

3.1 Electrical Survey

The first stage of every motor capacitor project is to survey the facility. The electric utility rate structure is studied, and a billing history is gathered. One-line diagrams are acquired, and detailed electrical information is obtained for each candidate induction motor.

3.1.1 Meters

Appropriate equipment must be used to gather the motor operating parameters. Two good meters include the *Fluke 43 Power Quality Analyzer*, and the *Dranetz 4300 Three-Phase Power Platform* (see Appendix C for meter specifications). The Fluke is a single-phase, compact meter that is useful for snapshot readings. The Dranetz is more bulky, but is effective at detailed capture of trending data.

3.1.2 Billing Information

In addition to the engineering detail that must be gathered to physically characterize the facility, economic information must also be collected. This includes the billing rate structure that is imposed by the electric utility provider. The presence or absence of a PF tariff will greatly affect payback and other financial indicators. The billing record for a year or more provides a benchmark for later comparisons to validate savings (assuming similar production patterns from one year to the next).

3.1.3 One-Line Diagrams

A one-line diagram illustrates the physical layout and operation of a facility. It illustrates the service entrance that delivers power to the facility, load centers, large individual loads, and the line segments and protective devices that transmit the power. One-line diagrams contain technical detail about each line segment and the protective devices that safeguard the loads. Many industrial customers maintain up-to-date diagrams and can furnish them during the survey. This allows better modeling during the design.

Figure 4 shows a sample one-line diagram. The diagram shows motor loads, along with motor starters and fuses for each, a breaker, disconnect switches, and finally the service entrance transformer. The one-line diagram may also list the size and length of each line in the branch of the distribution system.

3.1.4 Motor Parameters

A motor can be characterized by 6 quantities: voltage, current, real power, reactive power, apparent power, and PF. A total of 18 measurements should be taken for each three-phase motor. The measured real power of the motor is compared to the rated real power to determine motor loading. Also, the duty cycle of the motor should be obtained from personnel on site. This suite of parameters is called a motor data set.

A PF correction capacitor can be characterized by 3 quantities: voltage, current, and reactive power. A total of 9 measurements should be taken for each three-phase capacitor. Equation 2.5 is used to determine de-rating, then the measured reactive power of the capacitor is compared to the rated reactive power to determine deviation from rated reactive power. This suite of parameters is called a capacitor data set.

3.1.5 Irregular Loading

When comparing the motor data sets obtained before and after the capacitor is installed, it is important to take the reading at the same position on the loading curve, should the load be non-constant. If this practice is not observed measurements will not be meaningful. In Figure 17 Panel A, the load is constant. After a capacitor is installed, the real power flow is decreased as shown in Panel B, and the measurement reveals $P_2<P_1$ demonstrating the reduction. In Panel C the load is irregular. After the capacitor is installed, the real power draw of the motor is decreased as shown in Panel D, but the measurement shows $P_2>P_1$, falsely indicating a rise in the real power flow to the motor. This occurs because the measurement points for t_1 and t_2 occur at different positions on the loading curve.

It is often the case that the load curve is irregular. For this situation, it is only possible to obtain a valid reading for the motor with long-term trending measurements. The Dranetz 4300 meter is a good instrument for this type of detailed measurement. A typical reading of one half to a full hour of trending data would be collected for the motor with the capacitor in service, then with capacitor out of service for comparison and analysis.

3.2 Project Design

Once the motor parameters have been collected, each motor data set is used to size the capacitor. The values for PF_1 and P are determined during the survey, then Equation 2.1 is used with $PF_2 = 0.97$.

Once the motor capacitors have been sized, the payback can be predicted for each capacitor. This is accomplished by computing the reduction in real power flow to each motor (based on an approximated demand reduction), and hence energy savings that is provided by each capacitor. Energy savings translates to savings in operating cost, which recoups the investment in the capacitor. The process is repeated for every surveyed motor. The capacitors with good payback numbers (typically less than 24 months) are recommended, and those with longer paybacks are not. The total project payback is calculated, as well as net present value and internal rate of return. The cost of equipment installation may also be embedded in the figures, and a proposal is created.

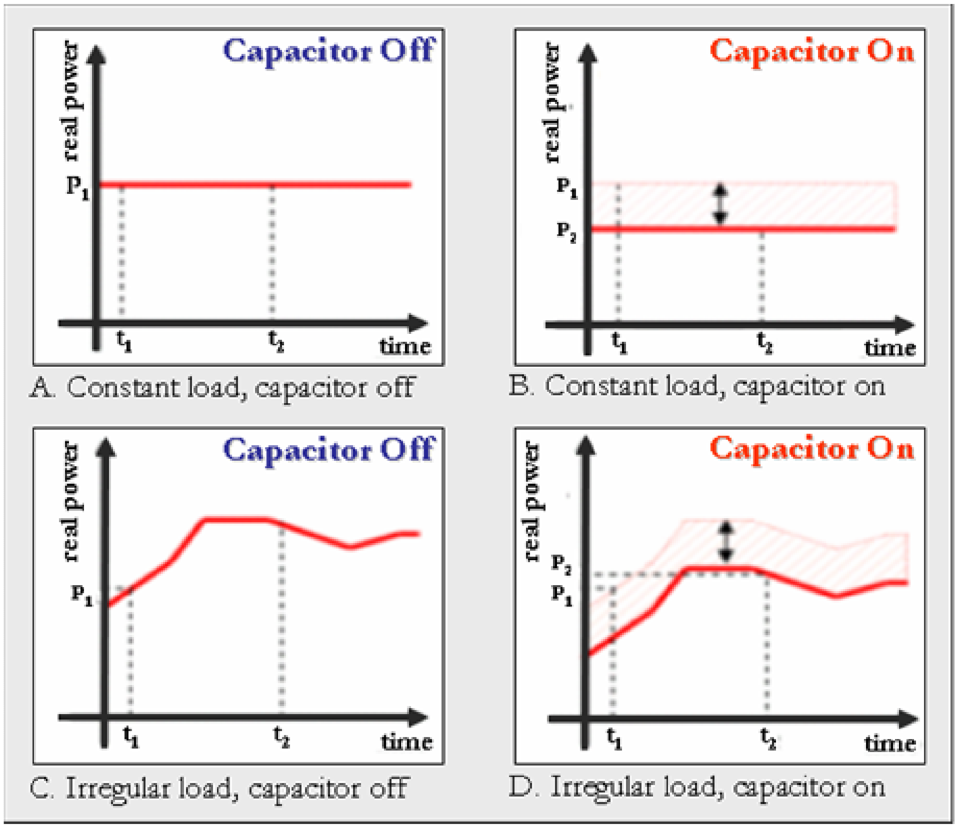

Fig. 17. Constant vs. irregular loading conditions

3.3 Implementation of the Design

Once the design has been planned and the proposal accepted by the facility customer, an order for the equipment is placed. A qualified electrical team is contracted, and the date for installation is arranged. The capacitors are installed, and measurements are performed to evaluate the results.

3.4 Measuring the Outcome

Once the capacitors are installed, a motor data set is obtained again for each motor where a capacitor has been installed. The measurement position for this reading is shown in Figure 18. It is the most upstream point along the branch where current flows for only one motor. Upstream of this point other loads join the branch, which would obscure the parameters for the motor in question. The reading is compared to the first motor data set from the survey, and the outcome of the project is quantified.

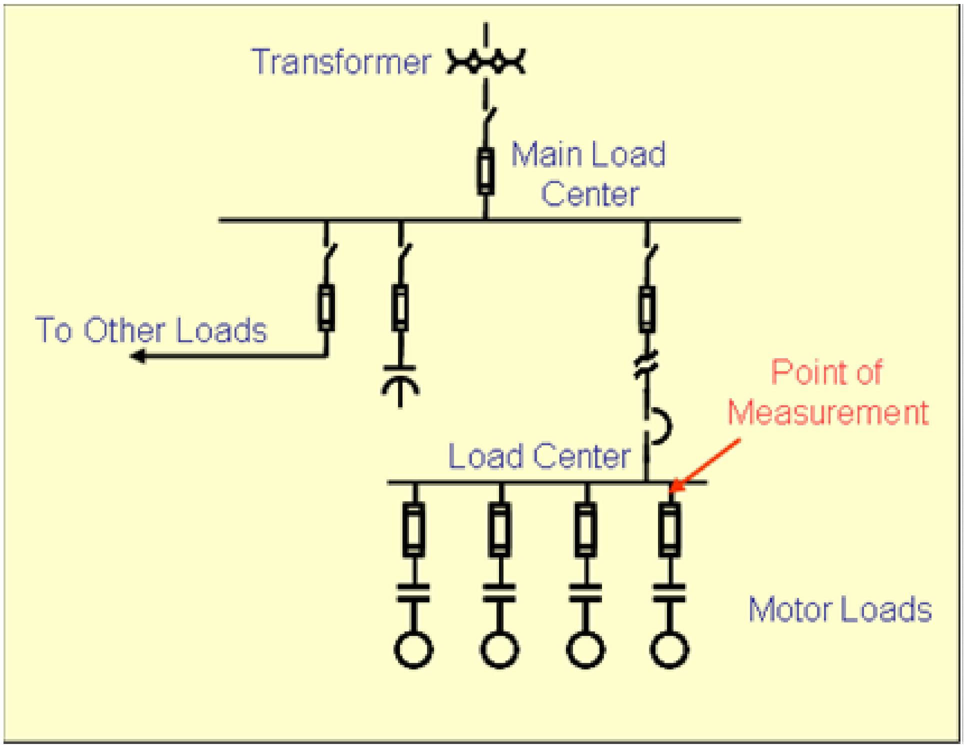

Fig. 18. Measurement point, where only load supplied

The process of survey, design, and implementation is illustrated in Figure 19.

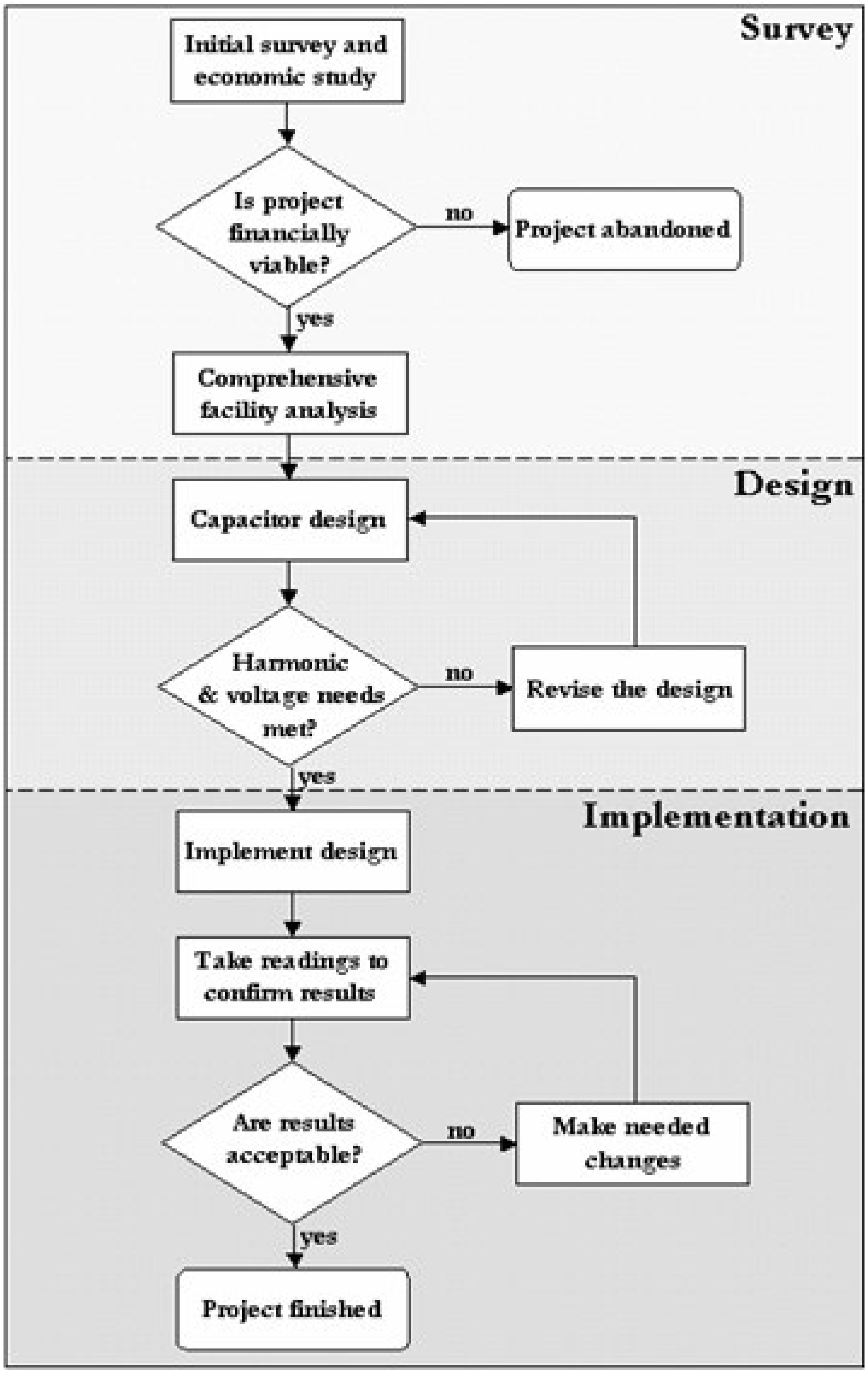

Fig. 19. Project survey, design, and implementation process

3.5 Design Example

To demonstrate the method for planning, measuring, sizing, and implementing a distributed motor capacitor project, we will examine an air conditioner system from a light industrial facility (see Chapter IV for an analysis of the entire facility). Figure 20 shows air conditioner Unit 1. Eleven motors in the system are eligible for power factor correction with motor capacitors.

3.5.1 Initial Survey

The following information is gathered:

- Duty cycle of motors
- Cost of electricity per KWH
- PF tariff information
- One-line diagram

To warrant individual PF correction, the motors should meet the following characteristics.

- Three-phase
- Large enough size (typically 10 HP or larger preferred)
- Low loading preferred
- Low PF preferred

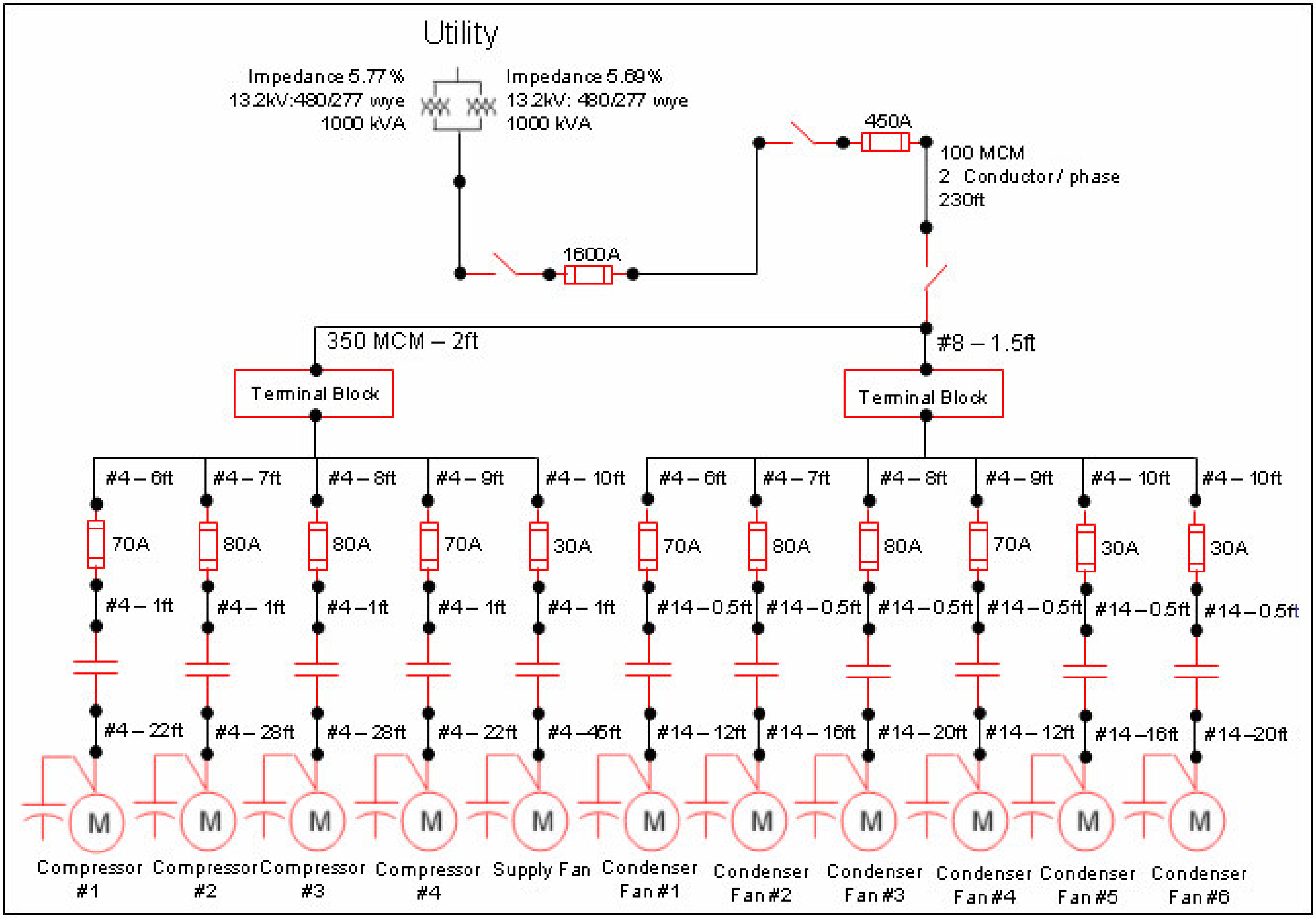

Fig. 20. One-line diagram: air conditioner unit 1

3.5.2 Measuring Harmonic Currents

A measurement should be performed to characterize the presence of facility harmonics. If harmonic currents are large enough to require filtering at each capacitor, the economic impact is severe, as the cost per capacitor can increase by over 10 times. Equation 2.2 determines if detuning is necessary to avoid high voltage resonance (i.e. harmonics near the 5th). Equation 2.4 is used by a measuring instrument to determine total harmonic current distortion. A total THD of over 15% would necessitate filtering.

The harmonics present at the air conditioner system displayed in Figure 20 were found to be insignificant, and filtering was not required (see Table 4).

Table 4 – Total harmonic current distortion for facility transformers

TRANSFORMER CURRENT THD				
Transformer	Ph. 1	Ph. 2	Ph. 3	Total
West - 1	3.66%	3.17%	2.64%	3.16%
West - 2	4.94%	4.60%	4.00%	4.51%
East - 1	5.23%	4.58%	2.96%	4.26%
East - 2	3.94%	4.31%	3.26%	3.84%

3.5.3 Gathering Motor Operational Data

Once candidate motors for individual PF correction have been identified, operational data must be gathered to properly size the capacitors. A motor data set is collected for each candidate.

The air conditioner in this example is an active load, so measurements could only be taken when the motors were operating normally. Compressor 4 and Condenser Fan 6 were not running, and no operational data was collected for them. In addition, the Supply Fan capacitor was not installed at the time of the measurement. Parameters were collected for the motors that were measured (see Table 5). The motor parameters were used to determine loading (see Table 6).

3.5.4 Sizing the Capacitor

Once the measured real power and PF were known, Equation 2.1 was used to size the capacitors. Condenser Fan 4, for example, was found to operate at a PF of 0.75 with a demand of 2.46 KW. If the target PF is 0.97, then the required capacitor size would be:

$$Q = (2.46KW)\cdot\left[\tan\left(a\cos(0.75)\right) - \tan\left(a\cos(0.97)\right)\right] = 1.38KVAR$$

Capacitors are manufactured in established common values. The nearest available value from General Electric (the vendor chosen for this project) is 1.5 KVAR. This size would elevate the PF to 0.965, which is an acceptable value. The next larger capacitor size of 2.0 KVAR would raise the PF to 0.9977, however, which is too large. In Table 7 we list capacitor sizes that would elevate each motor to 0.95 and to 1.00 PF, and also the value that was selected.

Table 5 – Motor data sets for air conditioner Unit 1 – capacitor off

MOTOR DATA SET - CAPACITORS OFF														
Condenser Fan 1					Condenser Fan 2					Condenser Fan 3				
	Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total
volt	265.0	266.0	266.0	265.7	volt	264.0	267.0	267.0	266.0	volt	265.0	267.0	267.0	266.5
amp	3.97	3.99	4.08	4.01	amp	3.87	3.94	4.01	3.94	amp	4.03	3.97	4.05	4.02
kw	0.72	0.70	0.75	2.17	kw	0.75	0.75	0.73	2.23	kw	0.81	0.81	0.78	2.40
kva	1.04	1.01	1.08	3.13	kva	1.02	1.05	1.05	3.12	kva	1.07	1.06	1.08	3.21
kvar	0.77	0.73	0.78	2.28	kvar	0.70	0.75	0.79	2.24	kvar	0.71	0.70	0.76	2.17
pf	0.68	0.68	0.67	0.68	pf	0.71	0.70	0.67	0.69	pf	0.73	0.74	0.71	0.73
Condenser Fan 4					Condenser Fan 5					Compressor 1				
	Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total
volt	266.0	268.0	267.0	266.8	volt	266.0	268.0	267.0	266.6	volt	265.0	267.0	267.0	266.3
amp	3.97	4.00	4.10	4.02	amp	3.81	3.78	4.07	3.89	amp	46.33	47.35	47.96	47.21
kw	0.81	0.84	0.81	2.46	kw	0.73	0.74	0.77	2.24	kw	9.54	10.10	9.98	29.62
kva	1.05	1.08	1.08	3.21	kva	1.01	1.00	1.08	3.09	kva	12.20	12.50	12.80	37.50
kvar	0.70	0.70	0.74	2.14	kvar	0.71	0.68	0.75	2.14	kvar	7.74	7.44	7.96	23.14
pf	0.74	0.76	0.74	0.75	pf	0.70	0.73	0.71	0.71	pf	0.77	0.79	0.77	0.78
Compressor 2					Compressor 3									
	Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total
volt	265.0	267.0	266.0	266.0	volt	265.0	267.0	267.0	266.0	volt				
amp	35.90	37.08	38.90	37.29	amp	34.35	35.40	37.63	35.79	amp				
kw	6.71	7.45	7.35	21.51	kw	6.60	7.20	7.22	21.02	kw				
kva	9.43	9.80	10.20	29.43	kva	9.10	9.45	9.96	28.51	kva				
kvar	6.65	6.40	7.20	20.25	kvar	6.40	6.25	7.03	19.68	kvar				
pf	0.70	0.74	0.70	0.71	pf	0.70	0.75	0.71	0.72	pf				

Table 6 – Motor loading calculations for air conditioner Unit 1

MOTOR LOADING			
Motor	KW (rated)	KW (meas)	Loading
Condenser Fan #1	3.73	2.17	58.2%
Condenser Fan #2	3.73	2.23	59.8%
Condenser Fan #3	3.73	2.40	64.3%
Condenser Fan #4	3.73	2.46	66.0%
Condenser Fan #5	3.73	2.24	60.1%
Compressor #1	44.76	29.62	66.2%
Compressor #2	44.76	21.51	48.1%
Compressor #3	44.76	21.02	47.0%
Total	19.12	10.46	54.7%

3.5.5 Capacitor Performance

Once installed, the capacitors themselves were measured for performance. The voltage, current, and reactive power output for each phase was obtained. In Table 8, we observe that all of the capacitors were supplied with a voltage below the nominal 277 volts (phase-to-neutral). The capacitors were de-rated according to Equation 2.5.

Table 7 – Capacitor sizes for power factor correction

CAPACITOR DESIGN					
Motor	KW (meas)	PF$_1$	Capacitor PF$_2$ = 0.95	Capacitor PF$_2$ = 1.00	Capacitor Selected
Cond Fan #1	2.17	0.68	1.65	2.36	1.5
Cond Fan #2	2.23	0.69	1.59	2.32	1.5
Cond Fan #3	2.40	0.73	1.48	2.26	1.5
Cond Fan #4	2.46	0.75	1.38	2.19	1.5
Cond Fan #5	2.24	0.71	1.47	2.20	1.5
Comp #1	29.62	0.78	14.26	23.96	15.0
Comp #2	21.51	0.71	14.08	21.12	15.0
Comp #3	21.02	0.72	13.35	20.23	15.0
Total	10.46	0.72	6.16	9.58	6.56

Table 8 – Capacitor data set for air conditioner Unit 1

CAPACITOR DATA SET														
Condenser Fan 1					Condenser Fan 2					Condenser Fan 3				
	Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total
volt	266.2	268.4	268.4	267.7	volt	266.6	268.4	267.9	267.6	volt	265.9	267.6	267.6	267.0
amp	2.04	2.07	2.11	2.07	amp	2.05	2.07	2.12	2.08	amp	2.11	2.14	2.08	2.11
kvar	0.54	0.55	0.56	1.65	kvar	0.54	0.55	0.57	1.66	kvar	0.56	0.56	0.55	1.67
			Dev	-17.5%				Dev	-17.0%				Dev	-16.5%
Condenser Fan 4					Condenser Fan 5					Compressor 1				
	Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total
volt	266.7	268.8	268.6	268.0	volt	266.8	268.5	268.7	268.0	volt	265.0	266.8	266.6	266.1
amp	2.14	2.02	2.12	2.09	amp	2.05	2.08	2.10	2.08	amp	17.09	16.69	16.85	16.88
kvar	0.57	0.54	0.56	1.67	kvar	0.54	0.55	0.56	1.65	kvar	4.48	4.40	4.38	13.26
			Dev	-16.5%				Dev	-17.5%				Dev	-11.6%
Compressor 2					Compressor 3									
	Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total
volt	264.8	266.3	267.2	266.1	volt	265.6	267.3	267.0	266.6	volt				
amp	16.62	16.52	17.31	16.82	amp	16.78	16.97	16.79	16.85	amp				
kvar	4.36	4.38	4.57	13.31	kvar	4.47	4.51	4.50	13.48	kvar				
			Dev	-11.3%				Dev	-10.1%					

As an example, the capacitor on Condenser Fan 4 was -16.5% below the rated value of 2.0 KVAR. It was de-rated by -6.6%, but even accounting for the low voltage it almost exceeded the standard capacitor tolerance of ±10%.

3.5.6 Improvements to Motor Performance

A motor data set was collected for each of the motors (see Table 9). The numbers were compared to the first motor data sets from the survey, and analysis was performed (see Table 10).

Table 9 – Motor data sets for air conditioner Unit 1 – capacitor on

MOTOR DATA SET - CAPACITORS ON														
Condenser Fan 1					Condenser Fan 2					Condenser Fan 3				
	Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total
volt	264.0	267.0	266.0	265.5	volt	266.0	269.0	268.0	267.7	volt	266.0	268.0	269.0	267.8
amp	2.60	2.65	2.60	2.62	amp	2.66	2.71	2.66	2.68	amp	2.88	2.88	2.82	2.86
kw	0.66	0.68	0.66	2.00	kw	0.69	0.69	0.68	2.06	kw	0.75	0.76	0.73	2.24
kva	0.68	0.70	0.67	2.05	kva	0.70	0.71	0.71	2.12	kva	0.76	0.77	0.75	2.28
kvar	0.18	0.16	0.15	0.49	kvar	0.15	0.17	0.18	0.50	kvar	0.15	0.11	0.17	0.43
pf	0.96	0.97	0.96	0.96	pf	0.97	0.96	0.96	0.96	pf	0.98	0.98	0.97	0.98
Condenser Fan 4					Condenser Fan 5					Compressor 1				
	Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total
volt	267.0	268.0	268.0	267.7	volt	266.0	268.0	268.0	267.5	volt	264.0	267.0	265.0	265.2
amp	2.80	2.96	2.90	2.89	amp	2.57	2.60	2.76	2.64	amp	38.03	39.35	39.76	39.05
kw	0.73	0.78	0.76	2.27	kw	0.66	0.68	0.70	2.04	kw	9.47	9.93	9.83	29.23
kva	0.74	0.78	0.78	2.30	kva	0.68	0.67	0.72	2.07	kva	9.95	10.40	10.50	30.85
kvar	0.13	0.11	0.16	0.40	kvar	0.14	0.12	0.17	0.43	kvar	3.01	3.01	3.40	9.42
pf	0.98	0.99	0.98	0.98	pf	0.98	0.98	0.96	0.97	pf	0.95	0.95	0.94	0.95
Compressor 2					Compressor 3									
	Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total		Ph. 1	Ph. 2	Ph. 3	Total
volt	262.0	265.0	265.0	263.9	volt	266.0	268.0	268.0	267.3	volt				
amp	29.89	32.63	31.50	31.34	amp	25.55	28.00	28.68	27.41	amp				
kw	7.37	8.49	7.93	23.79	kw	6.35	7.03	7.16	20.54	kw				
kva	7.65	8.70	8.42	24.77	kva	6.70	7.30	7.70	21.70	kva				
kvar	2.04	1.91	2.84	6.79	kvar	2.10	1.90	2.51	6.51	kvar				
pf	0.95	0.97	0.94	0.95	pf	0.94	0.96	0.93	0.94	pf				

Table 10 – Motor gains for air conditioner Unit 1

ENGINEERING GAINS				
Name	Voltage Elevation	PF Elevation	% RMS Current Reduction	% Real Power Reduction
Condenser Fan 1	-0.05%	0.29	34.8%	7.8%
Condenser Fan 2	0.66%	0.27	32.1%	7.6%
Condenser Fan 3	0.49%	0.25	28.8%	6.7%
Condenser Fan 4	0.34%	0.24	28.3%	7.7%
Condenser Fan 5	0.33%	0.26	32.0%	8.9%
Compressor 1	-0.44%	0.17	17.3%	1.3%
Compressor 2	-0.79%	0.24	16.0%	-10.6%
Compressor 3	0.50%	0.22	23.4%	2.3%
Total	0.13%	0.24	26.6%	4.0%

Note - The real power reduction for Compressor 2 showed a negative result. This was due to irregular loading of the motor. The initial and final measurements for the compressor motor were taken at different periods of the loading curve, so the results for this motor must be discarded, as discussed in Section 3.1.5. Additionally, several motors in Table 10 displayed a drop in voltage after the capacitor was installed. This was due to swinging in the general facility voltage. Slight voltage fluctuations were observed throughout the day due to variations in the incoming utility voltage, independent of the presence or absence of capacitors.

3.5.7 Economic Outcome

Once the engineering analysis was concluded, the results were characterized economically. When reduction to real power demand was known, we used the duty cycle and cost per KWH to find the amount of monthly energy savings achieved by that motor capacitor. In addition, the amount of PF elevation that was provided to the overall facility could be found for each capacitor, and the fraction of the PF tariff that was eliminated by this elevation could be calculated. The installed cost of the capacitor was divided by the dollar savings to produce a payback for each motor capacitor.

Condenser Fan 4, for example, was treated with a 2.0 KVAR capacitor at an installed price of \$291. The capacitor achieved a reduction of 0.17 KW in the real power flow to its motor. The savings was calculated from the assumption of 84 hours per week operation (50% duty cycle), and a cost of \$0.0734 per KWH.

$$\Delta KWH = (0.17KW)\cdot(84 hours/week)\cdot\left(\frac{52 weeks}{12 months}\right)\rightarrow 62KWH$$

$$EnergySavings = \left(\frac{62KWH}{month}\right)\cdot\left(\frac{\$0.0734}{KWH}\right)\rightarrow \$4.54/month$$

We solved Equation 2.1 for PF_2 to find the corrected facility PF due to the single capacitor (see Equation 3.1).

$$PF_2 = \cos(a\tan([\tan(a\cos(PF_1)) - \frac{Q_{cap}}{P_{facility}}])) \qquad 3.1$$

We assumed a facility peak demand $P_{facility}$ of 1,750 KW, uncorrected PF_1 of 0.8560, and measured reactive power output of the capacitor of 1.65 KVAR. Once the corrected value for PF_2 was known, we determined the PF tariff savings. We applied the PF tariff determinant to find the decrease to the tariff from the elevated PF, assuming a demand charge of $5.81 per KW.

$$PF_2 = \cos(a\tan([\tan(a\cos(0.856)) - \frac{1.65KVAR}{1750KW}])) \rightarrow$$

$$PF_2 = 0.8564$$

$$\mathit{Original\ PF\ Tariff} = (1750) \cdot (\$5.81) \cdot \left(\frac{0.9500}{0.8560} - 1 \right) \rightarrow \$1116.52$$

$$\mathit{New\ PF\ Tariff} = (1750) \cdot (\$5.81) \cdot \left(\frac{0.9500}{0.8564} - 1 \right) \rightarrow \$1111.82$$

PF Tariff Savings = $1116.52 – $1111.82 → $4.70/month

So the total savings = energy savings + PF tariff savings →

$*4.54 + $4.70 = $9.24*

Finally, we calculated the payback:

$$Payback = \left(\frac{\$291}{\$9.24 / month} \right) \rightarrow 31.5 months$$

The payback of over 31 months was longer than the industry favored 24 months. However, motors with marginal payback can be included if larger motors with better payback values are available to bring down the overall average below 24 months. This is a strategy for capturing additional monthly savings. Table 11 shows a payback for each of the example motors.

Table 11 – Savings and payback for air conditioner Unit 1

ECONOMICS GAINS						
Name	KW Reduction	KWH Reduction	Energy Savings	PF Tariff Savings	Installed Price	Payback
Condenser Fan 1	0.17	62	$4.54	$4.70	$291	31.5
Condenser Fan 2	0.17	62	$4.54	$4.73	$291	31.4
Condenser Fan 3	0.16	58	$4.27	$4.76	$291	32.2
Condenser Fan 4	0.19	69	$5.08	$4.76	$291	29.6
Condenser Fan 5	0.20	73	$5.34	$4.70	$291	29.0
Compressor 1	0.39	142	$10.42	$37.66	$421	8.8
Compressor 2	-2.28	-830	-$60.92	$37.80	$421	-18.2
Compressor 3	0.48	175	$12.82	$38.28	$421	8.2
Total *	1.76	641	$47.02	$99.58	$2,297	15.7

* Totals do not include data for Compressor 2, which displayed a negative KW reduction, and accordingly a negative KWH reduction, monthly dollar savings, and payback. This was due to irregular loading which skewed the motor data set.

CHAPTER IV
DATA

In this chapter we will present and analyze the data collected from the motor capacitor project referenced in Chapter III. The project was implemented at a light industrial facility (2.9 MW peak load) in August 2004. It was initiated due to a change in the customer's billing structure that included a PF penalty tariff. The customer's average PF for the previous year of billing was 0.856. The tariff threshold was triggered for power drawn below 0.950 PF, which corresponded to an 11% increase in the demand portion of the utility bill. To elevate the facility power factor to 0.95, a total of 800 KVAR of capacitance was required.

4.1 Overview and Survey

Taylor Publishing is a 300,000 ft^2 printing facility located in Dallas, Texas. A survey of the facility was conducted in December 2003 (see Figure 21).

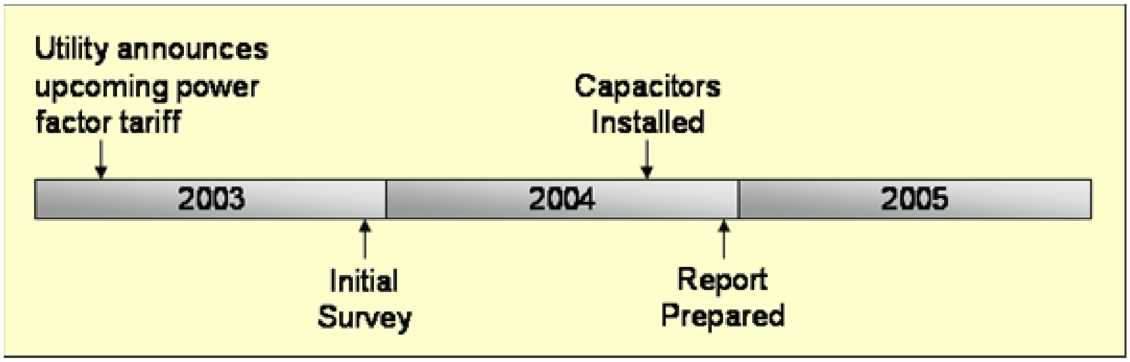

Fig. 21. Timeline of project events

The facility is supplied by four 1,000 KVA transformers. A pair of transformers is located on the east side, and a pair on the west side of the facility. A main load center is supplied by each transformer pair, and many small loads associated with printing processes are positioned throughout the facility. Additionally, there are 10 air conditioning systems on the roof and 2 large air compressors in the basement. Each air conditioner system consists of 4 to 11 motors, divided into 3 classes: compressors, condenser fans, and supply fans. They are all three-phase, 480 volt induction motors (see Appendix A for complete one-line diagrams).

After the survey was conducted and economic models applied, 70 air conditioner and 2 air compressor motors were selected for distributed motor capacitor treatment (see Table 12). The billing history for the previous 12 months was collected. The average monthly demand was 2.5 MW, the average energy consumption was 1,100,000 KWH, the average cost per KWH was $0.0734, and the average monthly electric bill was $67,236.

After the survey, a capacitor design was prepared, taking into account the data collected for each motor. The electric bills were analyzed. Engineering and economic evaluations were integrated into a project proposal. The capacitors were shipped by the manufacturer (General Electric) in July 2004, and were installed August-September 2004.

4.2 Design

Motor data sets were obtained for 69 of the 72 motor candidates. Three motors were unavailable due to mechanical problems. In addition, the compressor motor loads were irregular, so the comparison of motor data sets before and after capacitor installation produced irrelevant results (see Section 3.1.5). For this reason the results for the compressor motors were discarded. This left 30 motor samples for analysis. A motor data set is presented for each (see Table 13).

Equation 2.1 was used to size each capacitor. It was carried out for PF_2=0.97 and PF_2=1.00, for every motor. This provided an envelope from which an available capacitor could be chosen (see Table 14).[10]

Table 12 – Motors chosen for individual power factor correction

MOTOR CAPACITOR CANDIDATES					
Motor	Unit	Name	Motor	Unit	Name
1	1	Compressor 1	37	5	Compressor 3
2	1	Compressor 2	38	5	Compressor 4
3	1	Compressor 3	39	5	Condenser Fan 1
4	1	Compressor 4	40	5	Condenser Fan 2
5	1	Condenser Fan 1	41	5	Supply Fan
6	1	Condenser Fan 2	42	6	Compressor 1
7	1	Condenser Fan 3	43	6	Compressor 2
8	1	Condenser Fan 4	44	6	Compressor 3
9	1	Condenser Fan 5	45	6	Compressor 4
10	1	Condenser Fan 6	46	6	Condenser Fan 1
11	1	Supply Fan	47	6	Condenser Fan 2
12	2	Compressor 1	48	6	Supply Fan
13	2	Compressor 2	49	7	Compressor 1
14	2	Compressor 3	50	7	Compressor 2
15	2	Compressor 4	51	7	Compressor 3
16	2	Condenser Fan 1	52	7	Compressor 4
17	2	Condenser Fan 2	53	7	Condenser Fan 1
18	2	Condenser Fan 3	54	7	Condenser Fan 2
19	2	Supply Fan 1	55	7	Supply Fan
20	2	Supply Fan 2	56	8	Compressor 1
21	3	Compressor 1	57	8	Compressor 2
22	3	Compressor 2	58	8	Compressor 3
23	3	Compressor 3	59	8	Compressor 4
24	3	Compressor 4	60	8	Condenser Fan 1
25	3	Condenser Fan 1	61	8	Condenser Fan 2
26	3	Condenser Fan 2	62	8	Supply Fan
27	3	Supply Fan	63	9	Compressor 1
28	4	Compressor 1	64	9	Compressor 2
29	4	Compressor 2	65	9	Condenser Fan 1
30	4	Compressor 3	66	9	Supply Fan
31	4	Compressor 4	67	10	Compressor 1
32	4	Condenser Fan 1	68	10	Compressor 2
33	4	Condenser Fan 2	69	10	Condenser Fan 1
34	4	Supply Fan	70	10	Supply Fan
35	5	Compressor 1	71	Dock	Air Compressor 1
36	5	Compressor 2	72	Dock	Air Compressor 2

Table 13 – Motor data sets prior to capacitor installation

MOTOR DATA SET - CAPACITOR OFF								
Motor	Unit	Name	Volts	Amps	KW	KVA	KVAR	PF
1	1	Condenser Fan 1	265.7	4.01	2.17	3.13	2.28	0.68
2	1	Condenser Fan 2	266.0	3.94	2.23	3.12	2.24	0.69
3	1	Condenser Fan 3	266.5	4.02	2.40	3.21	2.17	0.73
4	1	Condenser Fan 4	266.8	4.02	2.46	3.21	2.14	0.75
5	1	Condenser Fan 5	266.6	3.89	2.24	3.09	2.14	0.71
6	2	Condenser Fan 1	268.2	4.83	3.13	3.86	2.26	0.80
7	2	Condenser Fan 2	268.0	4.82	3.12	3.85	2.26	0.80
8	2	Condenser Fan 3	268.6	4.75	3.10	3.83	2.25	0.80
9	2	Supply Fan	268.4	14.55	9.72	11.64	6.50	0.82
10	3	Condenser Fan 1	264.2	10.20	5.66	8.11	5.80	0.67
11	3	Condenser Fan 2	265.0	11.33	6.19	8.95	6.46	0.68
12	3	Supply Fan	265.1	33.23	22.23	26.57	14.50	0.83
13	4	Condenser Fan 1	262.7	15.35	10.17	11.96	6.27	0.84
14	4	Condenser Fan 2	262.6	9.46	6.14	7.48	4.29	0.81
15	4	Supply Fan	253.9	22.21	13.90	16.84	9.47	0.82
16	5	Condenser Fan 1	266.5	14.11	8.94	11.24	6.81	0.78
17	5	Condenser Fan 2	266.5	8.84	3.98	7.09	5.84	0.55
18	5	Supply Fan	265.2	20.27	12.85	16.11	9.71	0.79
19	6	Condenser Fan 1	261.4	5.56	4.01	4.35	1.75	0.91
20	6	Supply Fan	261.1	22.87	15.91	17.85	8.36	0.88
21	7	Condenser Fan 1	260.9	8.43	4.47	6.56	4.77	0.67
22	7	Condenser Fan 2	260.9	7.29	4.11	5.68	3.96	0.71
23	7	Supply Fan	260.4	16.77	11.15	12.95	6.60	0.85
24	8	Condenser Fan 1	259.8	5.56	3.58	4.34	2.43	0.81
25	8	Supply Fan	267.9	14.62	9.64	11.58	6.75	0.81
26	9	Condenser Fan 1	259.3	6.81	3.98	5.27	3.53	0.74
27	9	Supply Fan	260.8	9.40	4.95	7.42	5.50	0.61
28	10	Condenser Fan 1	258.2	6.85	3.97	5.36	3.71	0.71
29	10	Supply Fan	264.0	9.77	5.51	7.75	5.53	0.69
30	Dock	Air Compressor 2	261.6	108.03	74.90	84.50	40.70	0.87
Total	-	-	263.8	415.79	266.81	326.90	186.98	0.76

Table 14 – Project capacitor sizes for power factor correction

CAPACITOR DESIGN							
Motor	Unit	Name	KW (meas)	PF_1	Capacitor PF_2=0.97	Capacitor PF_2=1.00	Capacitor Selected
1	1	Condenser Fan 1	2.00	0.68	1.7	4.1	2.0
2	1	Condenser Fan 2	2.06	0.69	1.6	3.9	2.0
3	1	Condenser Fan 3	2.24	0.73	1.6	3.5	2.0
4	1	Condenser Fan 4	2.27	0.75	1.5	3.3	2.0
5	1	Condenser Fan 5	2.04	0.71	1.5	3.7	2.0
6	2	Condenser Fan 1	2.95	0.80	1.5	2.8	2.0
7	2	Condenser Fan 2	2.95	0.80	1.5	2.8	2.0
8	2	Condenser Fan 3	2.86	0.80	1.5	2.8	2.0
9	2	Supply Fan	9.33	0.82	4.2	7.8	5.0
10	3	Condenser Fan 1	5.31	0.67	4.5	12.3	5.0
11	3	Condenser Fan 2	5.84	0.68	4.8	8.0	4.0
12	3	Supply Fan	21.55	0.83	8.9	19.8	10.0
13	4	Condenser Fan 1	9.68	0.84	3.8	7.2	4.0
14	4	Condenser Fan 2	5.64	0.81	2.6	8.0	5.0
15	4	Supply Fan	13.14	0.82	5.9	15.6	15.0
16	5	Condenser Fan 1	8.16	0.78	4.4	8.9	5.0
17	5	Condenser Fan 2	3.76	0.55	4.8	17.0	5.0
18	5	Supply Fan	12.41	0.79	6.5	17.4	10.0
19	6	Condenser Fan 1	3.81	0.91	0.8	2.5	3.0
20	6	Supply Fan	15.40	0.88	4.5	8.0	7.5
21	7	Condenser Fan 1	4.26	0.67	3.7	6.2	3.0
22	7	Condenser Fan 2	3.86	0.71	2.9	5.6	3.0
23	7	Supply Fan	10.58	0.85	3.8	9.1	7.5
24	8	Condenser Fan 1	3.36	0.81	1.6	4.1	3.0
25	8	Supply Fan	9.13	0.81	4.4	10.9	7.5
26	9	Condenser Fan 1	3.80	0.74	2.5	5.1	3.0
27	9	Supply Fan	4.56	0.61	4.7	19.2	5.0
28	10	Condenser Fan 1	3.75	0.71	2.8	5.6	3.0
29	10	Supply Fan	5.20	0.69	4.2	11.7	5.0
30	Dock	Air Compressor 2	71.80	0.87	22.1	41.6	25.0
Total	-	-	253.7	0.76	120.6	278.7	159.5

After installation, it was discovered that the data for motors 12 and 15 (Unit 3 and Unit 4 supply fans) were mistakenly switched during the design phase. Fortunately, each motor experienced a good response to the capacitors that were installed and no further action was required (Motor 12: corrected PF_2=0.95, Motor 15: corrected PF_2=0.97).

4.3 Data

Once the capacitors were installed, a motor data set was obtained for each motor. The motor data sets were each acquired at the highest point along the branch from which only that motor was supplied. This allowed the current reduction provided by the capacitor (and hence real power reduction due to lessening of ohmic losses) to be most fully observed. Unfortunately, this introduced a limitation in measuring the complete real power reduction afforded by the capacitor. The entire pathway from the motor to the service entrance transformer could not be isolated due to other loads being active on the distribution system. Therefore, the values shown in Tables 13, 15, 16 are for the minimum expected gains, since additional reactive current reduction occurs along the upstream portions of the branch that could not be measured. Table 16 summarizes the gains achieved by the capacitors (See Appendix B for a complete collection of motor data sets and analysis).

Table 15 - Motor data sets after capacitor installation

MOTOR DATA SET - CAPACITOR ON								
Motor	Unit	Name	Volts	Amps	KW	KVA	KVAR	PF
1	1	Condenser Fan 1	265.5	2.62	2.00	2.05	0.49	0.96
2	1	Condenser Fan 2	267.7	2.68	2.06	2.12	0.50	0.96
3	1	Condenser Fan 3	267.8	2.86	2.24	2.28	0.43	0.98
4	1	Condenser Fan 4	267.7	2.89	2.27	2.30	0.40	0.98
5	1	Condenser Fan 5	267.5	2.64	2.04	2.07	0.43	0.97
6	2	Condenser Fan 1	269.3	3.77	2.95	3.02	0.54	0.98
7	2	Condenser Fan 2	269.3	3.74	2.95	3.00	0.54	0.98
8	2	Condenser Fan 3	269.4	3.64	2.86	2.91	0.47	0.98
9	2	Supply Fan	269.3	12.18	9.33	9.70	2.11	0.97
10	3	Condenser Fan 1	265.6	7.16	5.31	5.57	1.62	0.95
11	3	Condenser Fan 2	267.0	8.28	5.84	6.61	3.06	0.88
12	3	Supply Fan	268.4	28.46	21.55	22.39	5.89	0.95
13	4	Condenser Fan 1	257.6	12.83	9.68	9.90	2.02	0.98
14	4	Condenser Fan 2	261.5	7.57	5.64	5.72	0.94	0.98
15	4	Supply Fan	259.4	17.78	13.14	13.40	2.67	0.98
16	5	Condenser Fan 1	269.9	11.19	8.16	9.07	3.75	0.87
17	5	Condenser Fan 2	269.9	5.31	3.76	4.12	1.73	0.90
18	5	Supply Fan	266.9	15.64	12.41	12.44	1.18	0.99
19	6	Condenser Fan 1	266.0	4.89	3.81	3.88	0.69	0.98
20	6	Supply Fan	268.0	19.46	15.40	15.49	1.65	0.99
21	7	Condenser Fan 1	259.6	6.25	4.26	4.86	2.24	0.88
22	7	Condenser Fan 2	259.5	5.37	3.86	4.14	1.45	0.93
23	7	Supply Fan	267.7	13.07	10.58	10.70	0.47	1.00
24	8	Condenser Fan 1	260.6	4.38	3.36	3.36	0.07	0.99
25	8	Supply Fan	268.0	11.70	9.13	9.17	0.13	1.00
26	9	Condenser Fan 1	260.1	5.19	3.80	4.01	1.18	0.94
27	9	Supply Fan	268.3	6.37	4.56	5.10	2.04	0.90
28	10	Condenser Fan 1	267.3	5.09	3.75	4.04	1.31	0.94
29	10	Supply Fan	268.2	6.75	5.20	5.37	1.34	0.96
30	Dock	Air Compressor 2	265.6	93.20	71.80	74.30	17.70	0.97
Total	-	-	266.0	332.95	253.70	263.09	59.04	0.96

Table 16 – Motor gains produced by capacitors

ENGINEERING GAINS									
Motor	Unit	Name	Loading	Volts	Amps	KW	KVA	KVAR	PF
1	1	Condenser Fan 1	58.2%	-0.1%	-34.8%	-7.8%	-34.5%	-78.5%	0.29
2	1	Condenser Fan 2	59.8%	0.7%	-32.1%	-7.6%	-32.1%	-77.7%	0.27
3	1	Condenser Fan 3	64.4%	0.5%	-28.8%	-6.7%	-29.0%	-80.2%	0.25
4	1	Condenser Fan 4	66.0%	0.3%	-28.3%	-7.7%	-28.3%	-81.3%	0.24
5	1	Condenser Fan 5	60.1%	0.3%	-32.0%	-8.9%	-33.0%	-79.9%	0.26
6	2	Condenser Fan 1	84.0%	0.4%	-22.0%	-5.8%	-21.8%	-76.1%	0.18
7	2	Condenser Fan 2	83.7%	0.5%	-22.5%	-5.4%	-22.1%	-76.1%	0.18
8	2	Condenser Fan 3	83.1%	0.3%	-23.4%	-7.7%	-24.0%	-79.1%	0.18
9	2	Supply Fan	86.9%	0.3%	-16.3%	-4.0%	-16.7%	-67.5%	0.15
10	3	Condenser Fan 1	50.6%	0.5%	-29.8%	-6.2%	-31.3%	-72.1%	0.28
11	3	Condenser Fan 2	83.0%	0.8%	-26.9%	-5.7%	-26.1%	-52.6%	0.20
12	3	Supply Fan	74.5%	1.3%	-14.4%	-3.1%	-15.7%	-59.4%	0.12
13	4	Condenser Fan 1	90.9%	-1.9%	-16.4%	-4.8%	-17.2%	-67.8%	0.14
14	4	Condenser Fan 2	54.9%	-0.4%	-20.0%	-8.1%	-23.5%	-78.1%	0.17
15	4	Supply Fan	62.1%	2.2%	-19.9%	-5.5%	-20.4%	-71.8%	0.16
16	5	Condenser Fan 1	79.9%	1.3%	-20.7%	-8.7%	-19.3%	-44.9%	0.09
17	5	Condenser Fan 2	35.6%	1.3%	-40.0%	-5.5%	-41.9%	-70.4%	0.35
18	5	Supply Fan	57.4%	0.7%	-22.8%	-3.4%	-22.8%	-87.8%	0.20
19	6	Condenser Fan 1	71.7%	1.8%	-12.1%	-5.0%	-10.8%	-60.6%	0.07
20	6	Supply Fan	106.7%	2.7%	-14.9%	-3.2%	-13.2%	-80.3%	0.11
21	7	Condenser Fan 1	79.9%	-0.5%	-25.8%	-4.7%	-25.9%	-53.0%	0.21
22	7	Condenser Fan 2	73.5%	-0.5%	-26.3%	-6.1%	-27.1%	-63.4%	0.22
23	7	Supply Fan	74.8%	2.8%	-22.1%	-5.1%	-17.4%	-92.9%	0.15
24	8	Condenser Fan 1	64.0%	0.3%	-21.2%	-6.1%	-22.6%	-97.1%	0.18
25	8	Supply Fan	64.6%	0.0%	-19.9%	-5.3%	-20.8%	-98.1%	0.19
26	9	Condenser Fan 1	71.2%	0.3%	-23.8%	-4.5%	-23.9%	-66.6%	0.20
27	9	Supply Fan	44.3%	2.9%	-32.2%	-7.9%	-31.3%	-62.9%	0.28
28	10	Condenser Fan 1	71.0%	3.5%	-25.7%	-5.5%	-24.6%	-64.7%	0.23
29	10	Supply Fan	49.3%	1.6%	-30.9%	-5.6%	-30.7%	-75.8%	0.27
30	Dock	Air Compressor 2	100.4%	1.5%	-13.7%	-4.1%	-12.1%	-56.5%	0.09
Total *	-	-	70.2%	0.8%	-24.0%	-5.9%	-24.0%	-72.4%	0.20

* These values are the averages for each column. The weighted averages – which describe the project s a whole – are slightly different. The weighted average results were: RMS Current reduction: -19.9% , Real Power reduction: -4.9%, Apparent Power reduction: -19.5%, and Reactive Power reduction: -68.5%.

In section 1.6.3 we discussed the effect of contact resistance on the branch supplying each motor. The magnitude of the resistance plays an important role, because the ohmic losses in the branch are directly proportional to the resistance, as described by Equation 1.22. If the losses are insignificant due to low branch resistance, then reduction of the losses is inconsequential. The reduction in branch current – and associated decrease in real power flow – that was achieved by each capacitor allowed us to calculate the branch resistances (up to the point of measurement, but not to the transformer itself) for each motor. Using Equation 1.26, the branch resistance was determined for each motor. The resistances averaged almost 4 ohms (see Table 17). These values were larger than expected, if line resistance alone were considered. The contribution of the contact resistance increased each branch resistance, and reduction of ohmic losses by the capacitors was significantly large.

Table 17 – Calculated branch resistance values and associated ohmic losses

BRANCH RESISTANCE AND OHMIC LOSSES

Motor	Unit	Name	Branch Resistance	I_1	I_2	ΔP	P_{loss1} (KW)	P_{loss2} (KW)	$\%\Delta P_{loss}$
1	1	Condenser Fan 1	6.12	4.01	2.62	0.17	0.10	0.04	57.5%
2	1	Condenser Fan 2	6.78	3.94	2.68	0.17	0.11	0.05	53.8%
3	1	Condenser Fan 3	6.71	4.02	2.86	0.16	0.11	0.05	49.3%
4	1	Condenser Fan 4	8.06	4.02	2.89	0.19	0.13	0.07	48.5%
5	1	Condenser Fan 5	8.21	3.89	2.64	0.20	0.12	0.06	53.7%
6	2	Condenser Fan 1	6.59	4.83	3.77	0.18	0.15	0.09	39.1%
7	2	Condenser Fan 2	6.09	4.82	3.74	0.17	0.14	0.09	40.0%
8	2	Condenser Fan 3	8.56	4.75	3.64	0.24	0.19	0.11	41.4%
9	2	Supply Fan	2.06	14.55	12.18	0.39	0.44	0.31	29.9%
10	3	Condenser Fan 1	2.21	10.20	7.16	0.35	0.23	0.11	50.8%
11	3	Condenser Fan 2	1.95	11.33	8.28	0.35	0.25	0.13	46.6%
12	3	Supply Fan	0.77	33.23	28.46	0.68	0.85	0.62	26.7%
13	4	Condenser Fan 1	2.30	15.35	12.83	0.49	0.54	0.38	30.2%
14	4	Condenser Fan 2	5.18	9.46	7.57	0.50	0.46	0.30	36.0%
15	4	Supply Fan	1.43	22.21	17.78	0.76	0.71	0.45	35.9%
16	5	Condenser Fan 1	3.52	14.11	11.19	0.78	0.70	0.44	37.1%
17	5	Condenser Fan 2	1.47	8.84	5.31	0.22	0.11	0.04	64.0%
18	5	Supply Fan	0.88	20.27	15.64	0.44	0.36	0.22	40.4%
19	6	Condenser Fan 1	9.52	5.56	4.89	0.20	0.29	0.23	22.6%
20	6	Supply Fan	1.18	22.87	19.46	0.51	0.62	0.45	27.6%
21	7	Condenser Fan 1	2.19	8.43	6.25	0.21	0.16	0.09	44.9%
22	7	Condenser Fan 2	3.43	7.29	5.37	0.25	0.18	0.10	45.8%
23	7	Supply Fan	1.72	16.77	13.07	0.57	0.48	0.29	39.3%
24	8	Condenser Fan 1	6.26	5.56	4.38	0.22	0.19	0.12	38.0%
25	8	Supply Fan	2.22	14.62	11.70	0.51	0.47	0.30	35.9%
26	9	Condenser Fan 1	3.09	6.81	5.19	0.18	0.14	0.08	41.9%
27	9	Supply Fan	2.72	9.40	6.37	0.39	0.24	0.11	54.1%
28	10	Condenser Fan 1	3.49	6.85	5.09	0.22	0.16	0.09	44.8%
29	10	Supply Fan	2.07	9.77	6.75	0.31	0.20	0.09	52.3%
30	Dock	Air Compressor 2	0.35	108.03	93.20	3.10	4.08	3.04	25.6%
Total	-	-	3.90	415.79	332.95	13.11	12.94	8.56	41.8%

After installation, the capacitors themselves were measured to determine performance. It was found that all the capacitors generated reactive power below rated levels (with the exception of motor 13, whose capacitor was mistakenly switched for the capacitor on motor 14 during installation). The average deviation from rated reactive power output was -15.3% (see Table 18).

Table 18 – Measured capacitors parameters

CAPACITOR DATA SET							
Motor	Unit	Name	Volts	Amps	KVAR (rated)	KVAR (meas)	Deviation
1	1	Condenser Fan 1	267.7	2.07	2.00	1.65	-17.50%
2	1	Condenser Fan 2	267.6	2.08	2.00	1.66	-17.00%
3	1	Condenser Fan 3	267.0	2.11	2.00	1.67	-16.50%
4	1	Condenser Fan 4	268.0	2.09	2.00	1.67	-16.50%
5	1	Condenser Fan 5	268.0	2.08	2.00	1.65	-17.50%
6	2	Condenser Fan 1	268.9	2.08	2.00	1.66	-17.00%
7	2	Condenser Fan 2	268.8	2.08	2.00	1.67	-16.50%
8	2	Condenser Fan 3	269.1	2.15	2.00	1.73	-13.50%
9	2	Supply Fan	268.9	5.34	5.00	4.27	-14.60%
10	3	Condenser Fan 1	268.1	15.55	5.00	4.13	-17.40%
11	3	Condenser Fan 2	268.5	12.49	4.00	3.33	-16.75%
12	3	Supply Fan	267.6	32.52	10.00	8.63	-13.70%
13	4	Condenser Fan 1	264.5	16.14	4.00	4.20	5.00%
14	4	Condenser Fan 2	265.5	12.71	5.00	3.32	-33.60%
15	4	Supply Fan	266.5	49.80	15.00	13.09	-12.73%
16	5	Condenser Fan 1	266.8	16.25	5.00	4.30	-14.00%
17	5	Condenser Fan 2	265.6	15.89	5.00	4.18	-16.40%
18	5	Supply Fan	266.4	32.36	10.00	8.51	-14.90%
19	6	Condenser Fan 1	267.0	9.51	3.00	2.51	-16.33%
20	6	Supply Fan	267.0	24.31	7.50	6.45	-14.00%
21	7	Condenser Fan 1	258.9	9.31	3.00	2.35	-21.67%
22	7	Condenser Fan 2	259.6	9.27	3.00	2.36	-21.33%
23	7	Supply Fan	267.2	24.29	7.50	6.43	-14.27%
24	8	Condenser Fan 1	262.1	9.51	3.00	2.46	-18.00%
25	8	Supply Fan	268.9	24.08	7.50	6.43	-14.27%
26	9	Condenser Fan 1	259.5	2.97	3.00	2.30	-23.33%
27	9	Supply Fan	267.3	5.51	5.00	4.34	-13.20%
28	10	Condenser Fan 1	265.4	3.17	3.00	2.49	-17.00%
29	10	Supply Fan	263.2	5.43	5.00	4.19	-16.20%
30	Dock	Air Compressor 2	264.9	27.38	25.00	21.51	-13.96%
Total	-	-	266.1	380.54	159.5	135.14	-15.27%

The deviation can be justified in part due to the low line voltage that was observed for the facility.

4.4 Analysis

After the project was installed and empirical data was gathered, the engineering and economic results were determined.

4.4.1 Engineering Gains

The voltage and PF were elevated at each motor. This lowered the reactive power flowing across the distribution system to each motor. The total current flow was reduced, and resulting losses were diminished. Lower ohmic losses manifested as a reduction in the total real power flow. The following average gains were observed: Motor Loading: 70.2%, Voltage Elevation: 0.8%, Power Factor Gain: 0.20, RMS Current: -24.0%, Reactive Power: -72.4%, Real Power: -5.9%, Apparent Power: -24.0%.

Motor Loading and Power Factor Gain

As shown in Table 16, the motors were nearly all under-loaded. This means that most were operating at below rated PF. As the motor loading increased, the PF also increased. Therefore, the heavily loaded motors offered a smaller sum of PF to elevate with motor capacitors (see Figure 22). In the figure, we have ordered the sample by motor loading. The left Y-axis shows the motor loading percentage, and the right Y-axis shows the PF gain that was achieved by installing the capacitor. One can see from the figure that as motor loading increased, the amount of PF gain decreased.

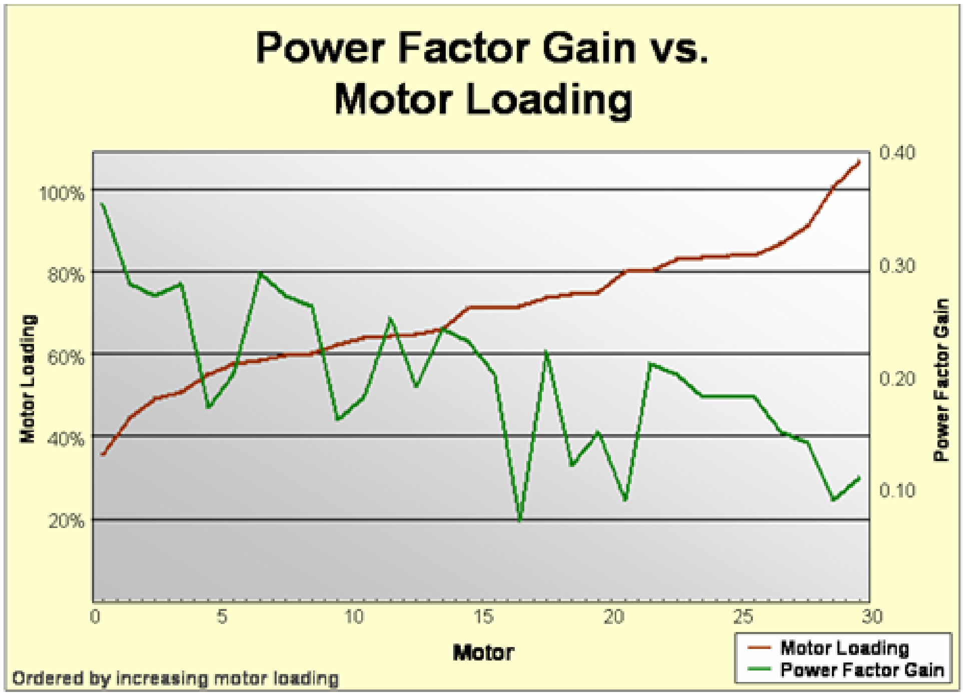

Fig. 22. Decreasing power factor gain as motor load increases

Power Factor Gain and RMS Current Reduction

For the motor capacitors that produced a low PF gain, relatively little RMS current reduction was achieved. As the PF gain increased, the RMS current reduction also increased. Therefore, the motor capacitors that achieved a large PF gain reduced the RMS current by the greatest margin (see Figure 23). In the figure, we have ordered the sample by PF gain. The left Y-axis shows the PF gain, and the right Y-axis shows the RMS current reduction percentage that was achieved by installing the capacitor. One can see from the figure that as PF gain increased, the amount of RMS current reduction increased.

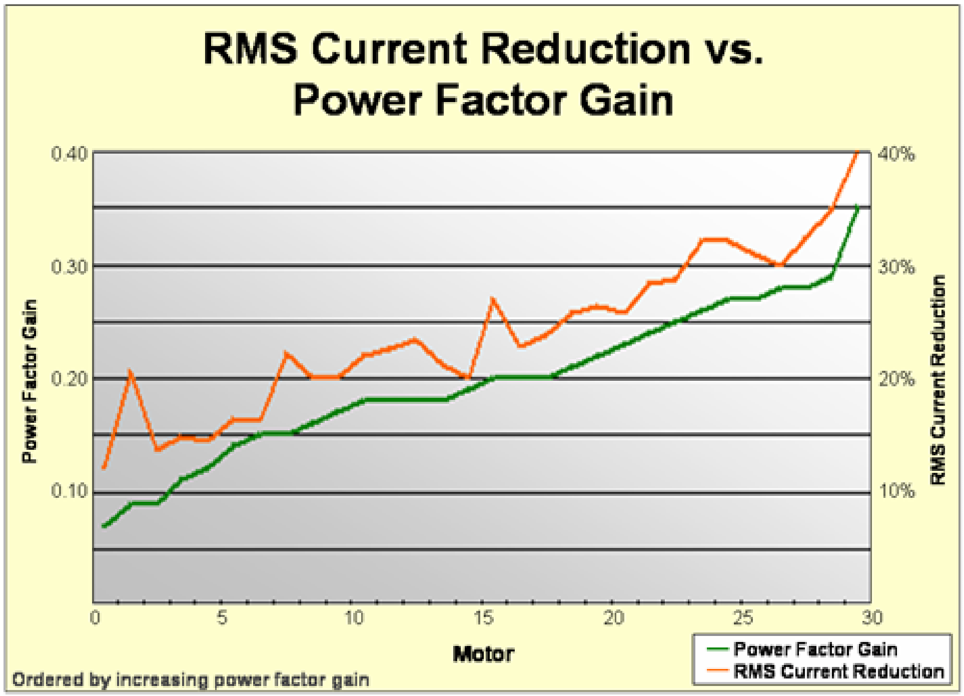

Fig. 23. Increasing RMS current reduction as power factor gain increases

RMS Current Reduction and Real Power Reduction

For the motor capacitors that produced a small RMS current reduction, a smaller real power reduction was achieved. As the RMS current reduction increased, the real power reduction also increased. Therefore, the motor capacitors that achieved a large real power reduction lowered the real power by the largest margin (see Figure 24). In the figure, we have ordered the sample by RMS current reduction. The left Y-axis shows the RMS current reduction percentage, and the right Y-axis shows the real power reduction percentage that was achieved by installing the capacitor. One can see from the figure that as RMS current reduction increased, the amount of real power reduction increased. The erratic behavior of the real power reduction curve occurred in part due to the random nature of contact resistance.

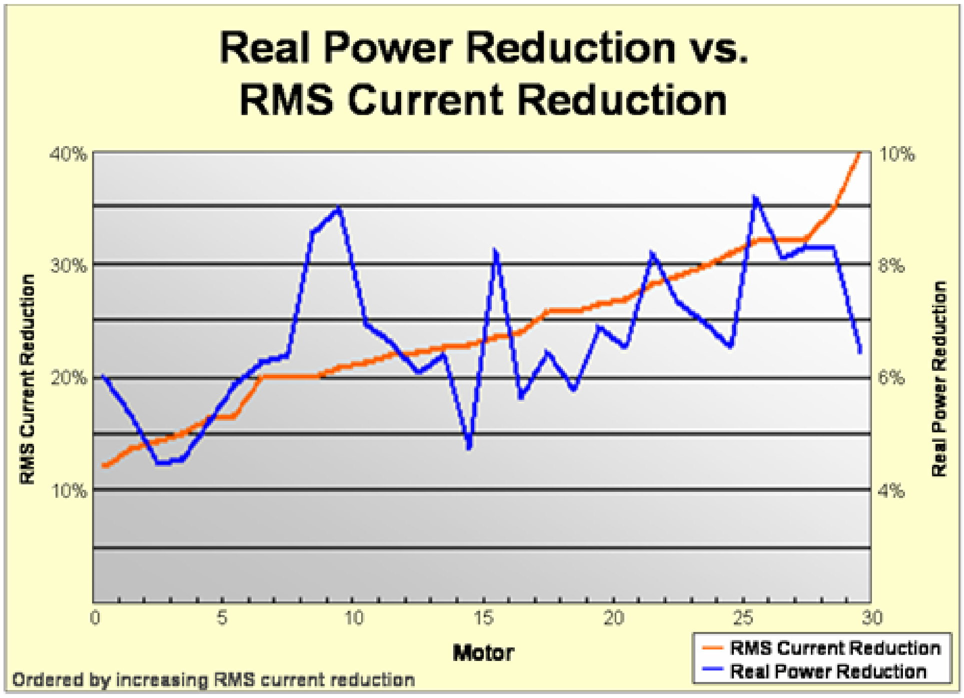

Fig. 24. Increasing real power reduction as RMS current reduction increases

Figures 22–24 suggest the following trends:

- Underloaded motors draw a larger ratio of reactive to apparent power
- Distributed motor capacitors individually raise the PF of each motor, supplying reactive power locally to the motor
- Total upstream RMS current is reduced by distributed motor capacitors
- Associated ohmic (I^2R) losses are reduced by distributed motor capacitors
- Instantaneous real power demand is reduced by distributed motor capacitors *
- When integrated over time, the total energy for a billing cycle is reduced

See Figure 25 for a picture of installed, distributed capacitors.

Fig. 25. Installed capacitors

* In addition, total peak demand is reduced when the facility motors are treated with capacitors. This can affect the customer's monthly utility bill, but due to ratchets and other billing systems, the impact may be smaller than for energy reduction.

4.4.2 Economics Gains

After analyzing the completed motor data sets in Table 13 and Table 15, the amount of monthly savings was calculated for each motor. The reduction to KWH assumed 50% duty cycle (84 hours per week operation). The associated energy savings were based on a cost of $0.0734 per KWH.

A total reduction of 13.11 KW, and hence 4772 KWH was observed. This generated an Energy Savings of $350 per month. The capacitors in the sample combined to provide 135 KVAR (measured) of reactive power to the facility. This elevated the overall facility PF to 0.885 (from the uncorrected value of 0.856). The PF tariff was reduced by $384 because of the 30 motors (see Table 19).

The following numbers were tabulated:

- Installed Project Cost: $9,327
- Total Monthly Savings: $734
- Total Payback 13.1 months
- Net Present Value: $49,828
- Internal Rate of Return: 94.4%

Table 19 – Project savings and payback

ECONOMIC SAVINGS								
Motor	Unit	Name	KW Reduction	KWH Reduction	Energy Savings	PF Tariff Savings	Installed Price	Payback
1	1	Condenser Fan 1	0.17	62	$4.54	$4.70	$291.00	31.5
2	1	Condenser Fan 2	0.17	62	$4.54	$4.73	$291.00	31.4
3	1	Condenser Fan 3	0.16	58	$4.27	$4.76	$291.00	32.2
4	1	Condenser Fan 4	0.19	69	$5.08	$4.76	$291.00	29.6
5	1	Condenser Fan 5	0.20	73	$5.34	$4.70	$291.00	29.0
6	2	Condenser Fan 1	0.18	66	$4.81	$4.73	$291.00	30.5
7	2	Condenser Fan 2	0.17	62	$4.54	$4.76	$291.00	31.3
8	2	Condenser Fan 3	0.24	87	$6.41	$4.93	$291.00	25.7
9	2	Supply Fan	0.39	142	$10.42	$12.16	$298.00	13.2
10	3	Condenser Fan 1	0.35	127	$9.35	$11.76	$298.00	14.1
11	3	Condenser Fan 2	0.35	127	$9.35	$9.49	$297.00	15.8
12	3	Supply Fan	0.68	248	$18.17	$24.55	$331.00	7.7
13	4	Condenser Fan 1	0.49	178	$13.09	$11.96	$297.00	11.9
14	4	Condenser Fan 2	0.50	182	$13.36	$9.46	$298.00	13.1
15	4	Supply Fan	0.76	277	$20.31	$37.18	$421.00	7.3
16	5	Condenser Fan 1	0.78	284	$20.84	$12.25	$298.00	9.0
17	5	Condenser Fan 2	0.22	80	$5.88	$11.91	$298.00	16.8
18	5	Supply Fan	0.44	160	$11.76	$24.21	$331.00	9.2
19	6	Condenser Fan 1	0.20	73	$5.34	$7.15	$295.00	23.6
20	6	Supply Fan	0.51	186	$13.63	$18.36	$324.00	10.1
21	7	Condenser Fan 1	0.21	76	$5.61	$6.70	$295.00	24.0
22	7	Condenser Fan 2	0.25	91	$6.68	$6.72	$295.00	22.0
23	7	Supply Fan	0.57	207	$15.23	$18.30	$324.00	9.7
24	8	Condenser Fan 1	0.22	80	$5.88	$7.01	$295.00	22.9
25	8	Supply Fan	0.51	186	$13.63	$18.30	$324.00	10.1
26	9	Condenser Fan 1	0.18	66	$4.81	$6.55	$295.00	26.0
27	9	Supply Fan	0.39	142	$10.42	$12.36	$298.00	13.1
28	10	Condenser Fan 1	0.22	80	$5.88	$7.09	$295.00	22.7
29	10	Supply Fan	0.31	113	$8.28	$11.93	$298.00	14.7
30	Dock	Air Compressor 2	3.10	1128	$82.82	$60.91	$494.00	3.4
Total	-	-	13.11	4,772	$350.27	$366.92	$9,327.00	13.1

CHAPTER V
CONCLUSION

In this chapter we will consider the results of the distributed motor capacitor study that was conducted, and surmise significant trends. We will discuss the conditions that are favorable to a motor capacitor project, and then present areas where the work could be expanded.

5.1 Distributed Motor Capacitor Projects Are Viable

In the previous chapter we analyzed the results of a motor capacitor project that was implemented at a light industrial facility. We found that the engineering and economic indicators were both satisfactory, and that measured results were good. We established the following benefits of implementing a motor capacitor project, rather than a service entrance capacitor bank:*

- Elimination of PF tariff (partially due to the motor capacitors)
- Reduction of real power flow through the facility, and hence lower energy consumption
- It should be noted that the total reactive power provided by the motor capacitor set sample outlined in Chapter IV was less than the amount required for the total facility (for PF correction to over 0.95). For the total 72 distributed motor capacitors, sufficient reactive power was generated to achieve 0.95 PF during summer months, but not during the winter, so entrance capacitor banks were also needed to provide the balance of reactive power for peak operation periods during the winter when most of the load is not air conditioning.

5.2 Favorable Conditions

The following engineering and economic factors were found to encourage distributed motor capacitor projects:

Engineering Conditions

- Older or poorly maintained distribution system (increased branch resistance)
- Abundance of motors with low loading
- Large number of protective devices
- Long line segments

Economic Conditions

- Power factor tariff imposed
- High cost of electricity
- Large motors (low capacitor cost / unit size)
- High motor duty cycle (hours of operation)
- Insignificant nearby harmonic loads

5.3 Further Considerations

As with any study, this work could be expanded in a number of areas. More samples could be gathered to provide a larger motor population for statistical analysis. Also, the measurements used to produce each sample could be more detailed, and captured over longer intervals to account for irregular loading. This includes the simultaneous three-phase capture of all motor data set numbers, reducing human error in the reading.

The format for distributed motor capacitors presented in this paper relied on passive devices that were individually sized. Even when optimally sized, however, the total reactive power required by the motor could not be satisfied entirely. The capacitors are also susceptible to damage from harmonic currents. Perhaps an active device could be developed with a high input impedance, which continuously provides all the reactive power needed by the motor despite changes in loading. The device would completely eliminate the upstream reactive current flow for each motor, reducing ohmic loss even further. The high input impedance would protect the device from nearby harmonics. Such a device could reduce the time spent during the design phase, optimize reactive current savings, and prevent damage to capacitors in a harmonic environment.

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APPENDIX A

ONE-LINE DIAGRAMS

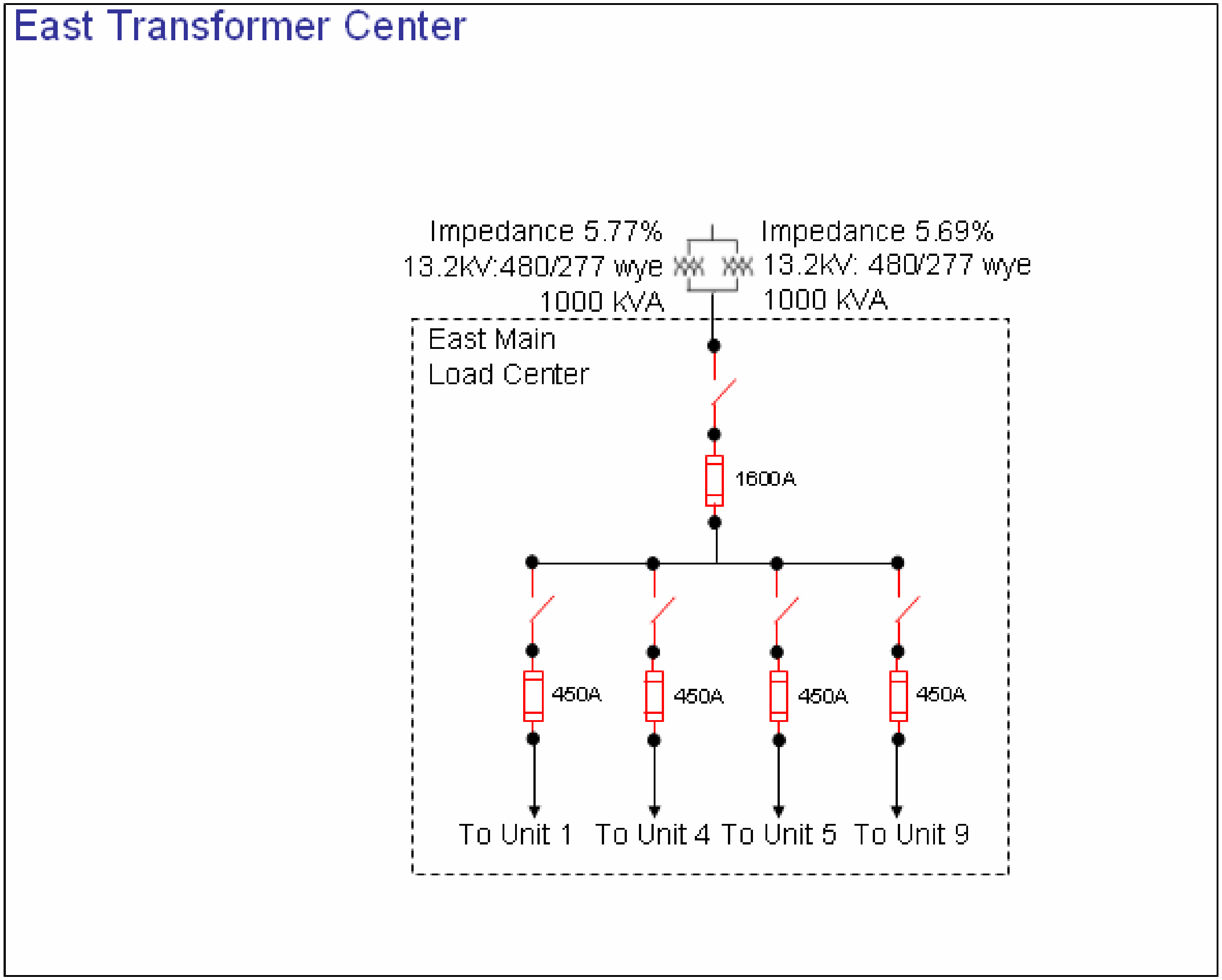


Fig. 26. East transformer load center

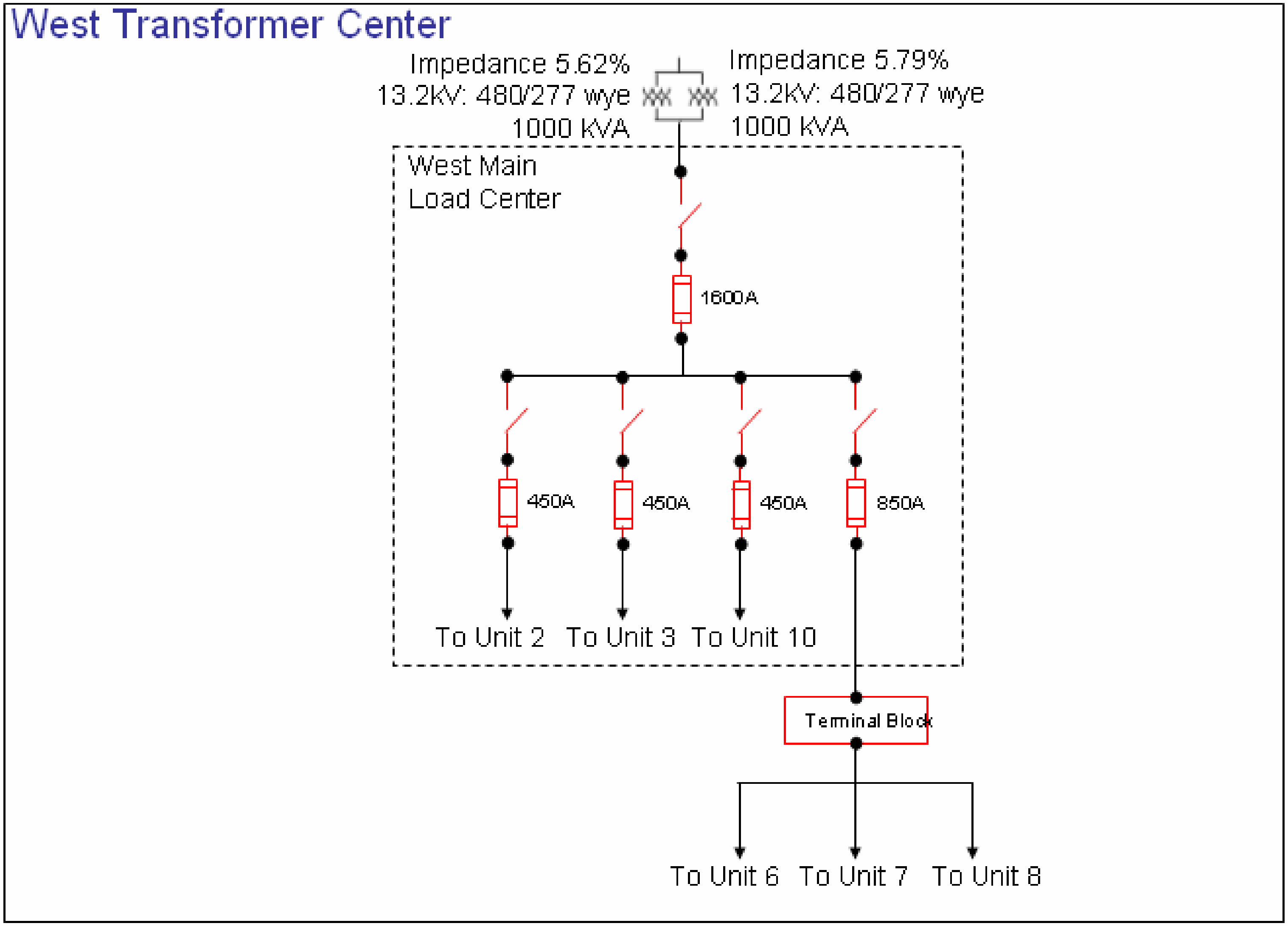


Fig. 27. West transformer load center

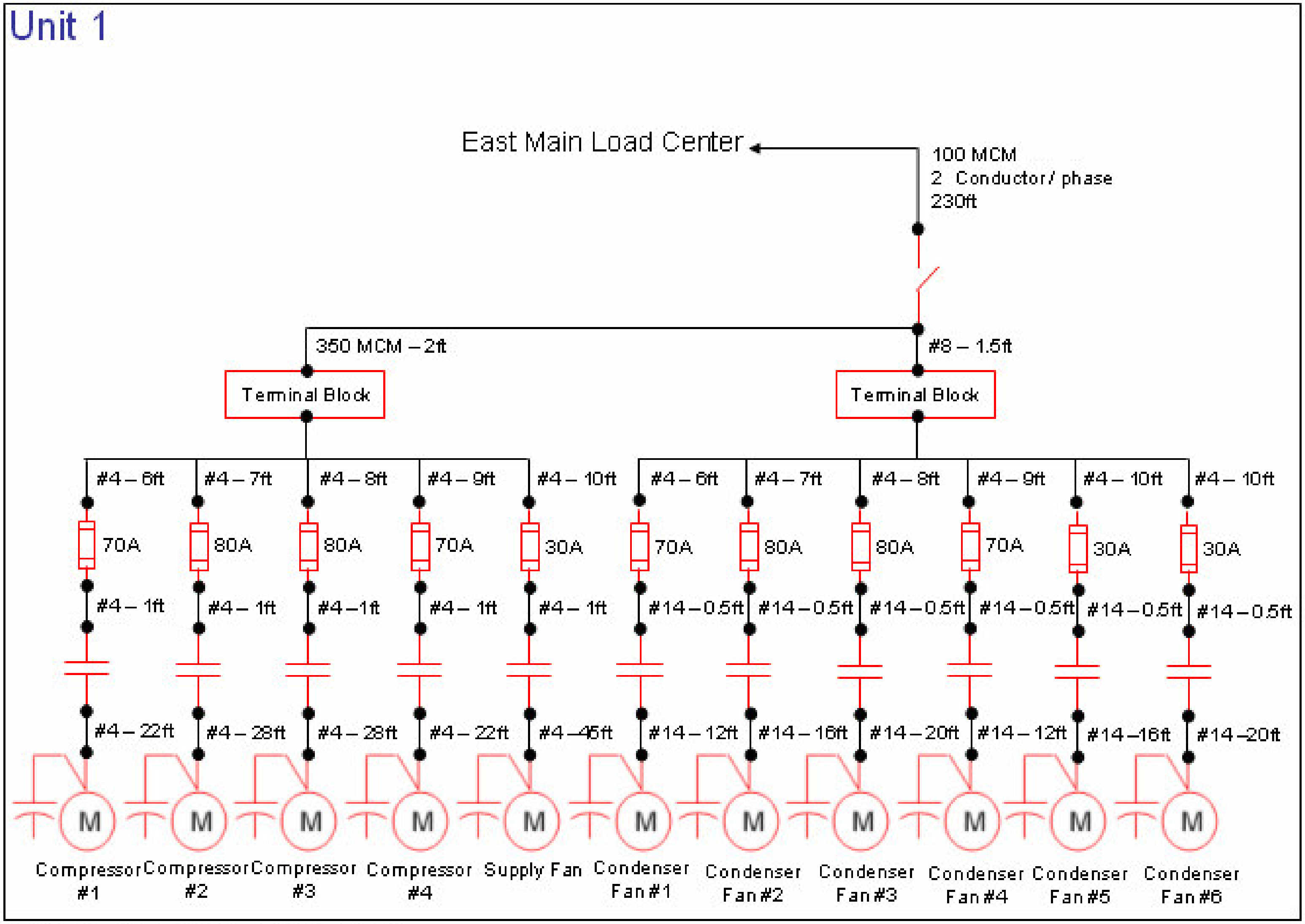


Fig. 28. Air conditioner unit 1

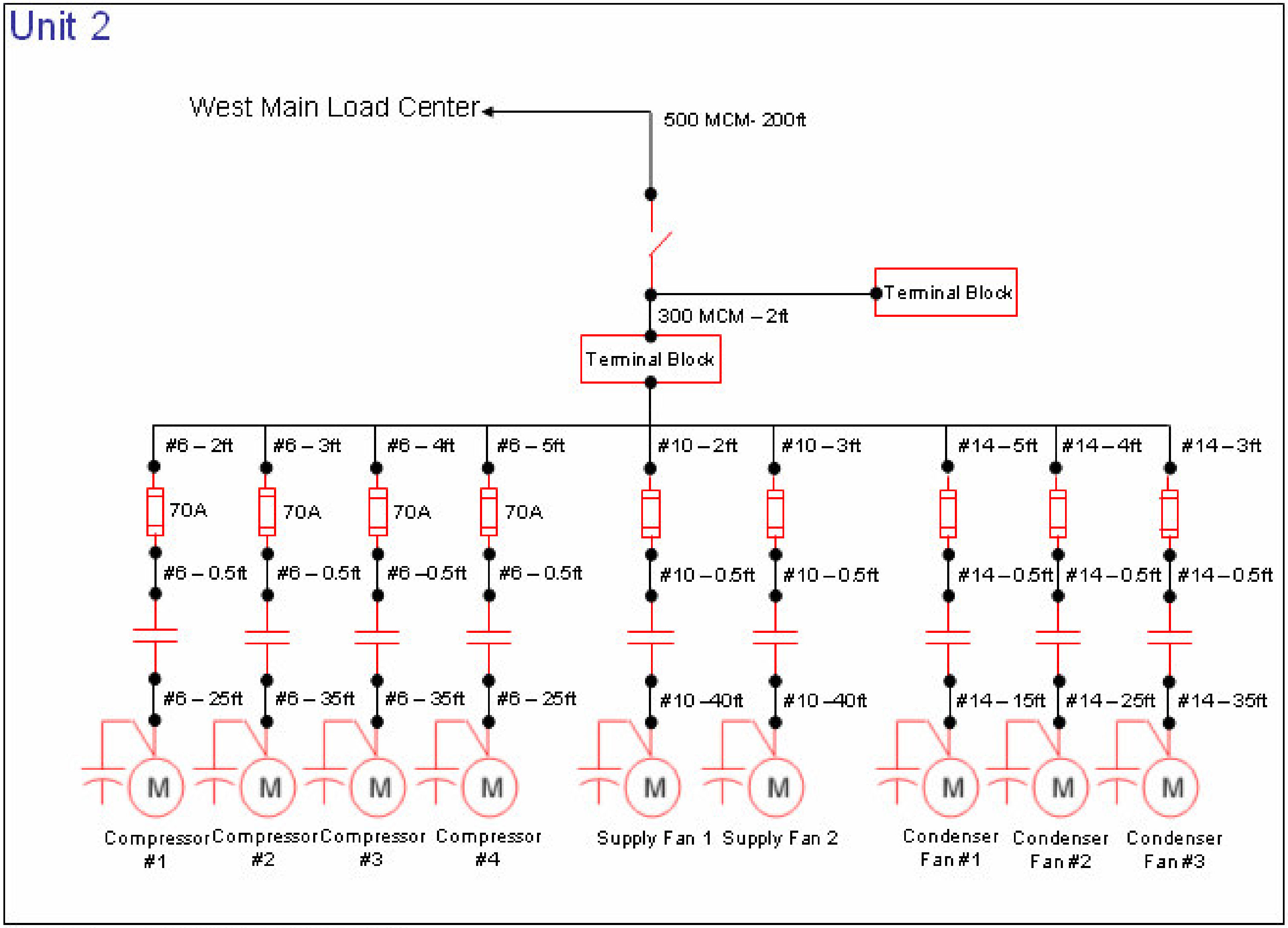


Fig. 29. Air conditioner unit 2

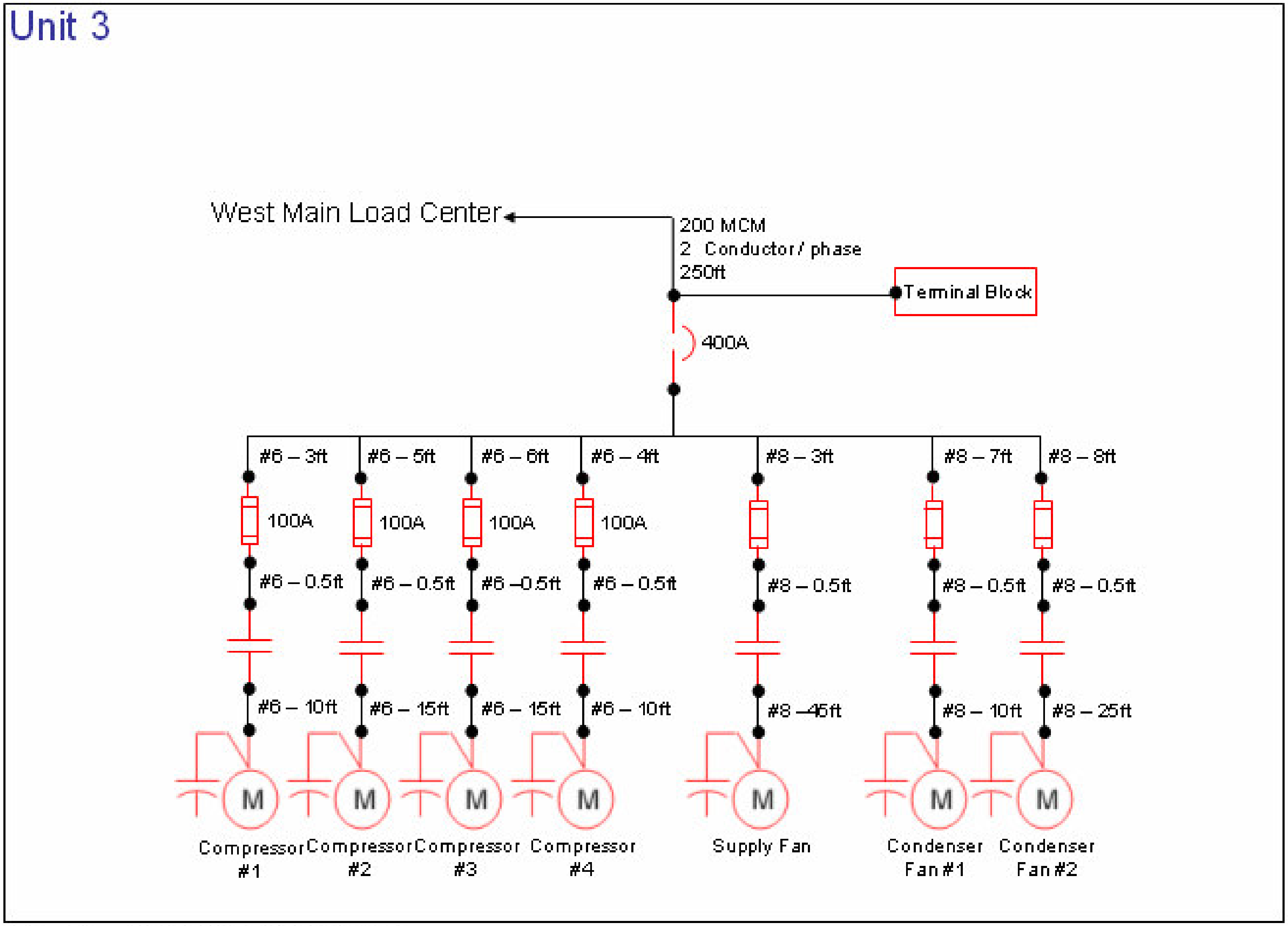


Fig. 30. Air conditioner unit 3

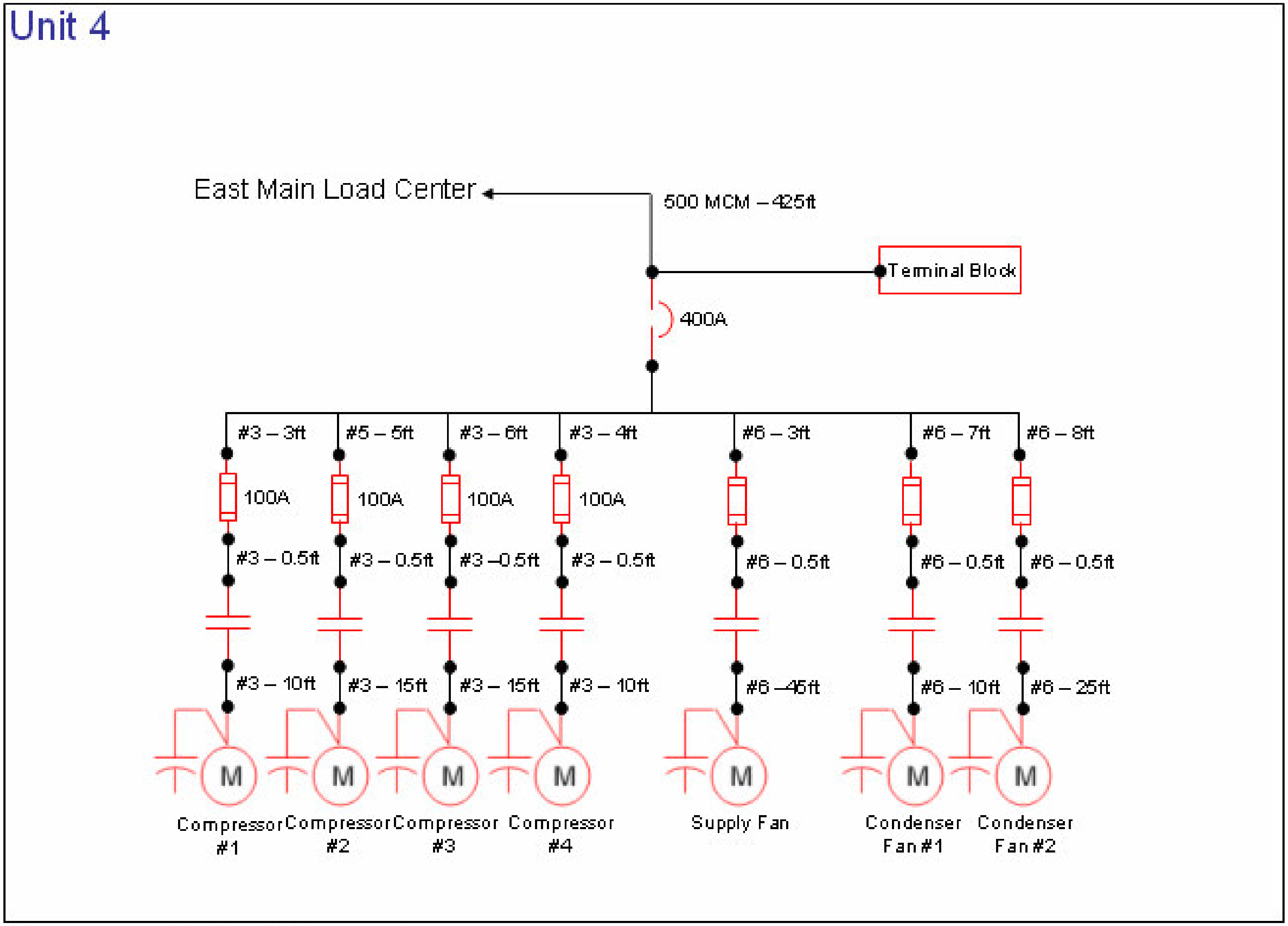


Fig. 31. Air conditioner unit 4

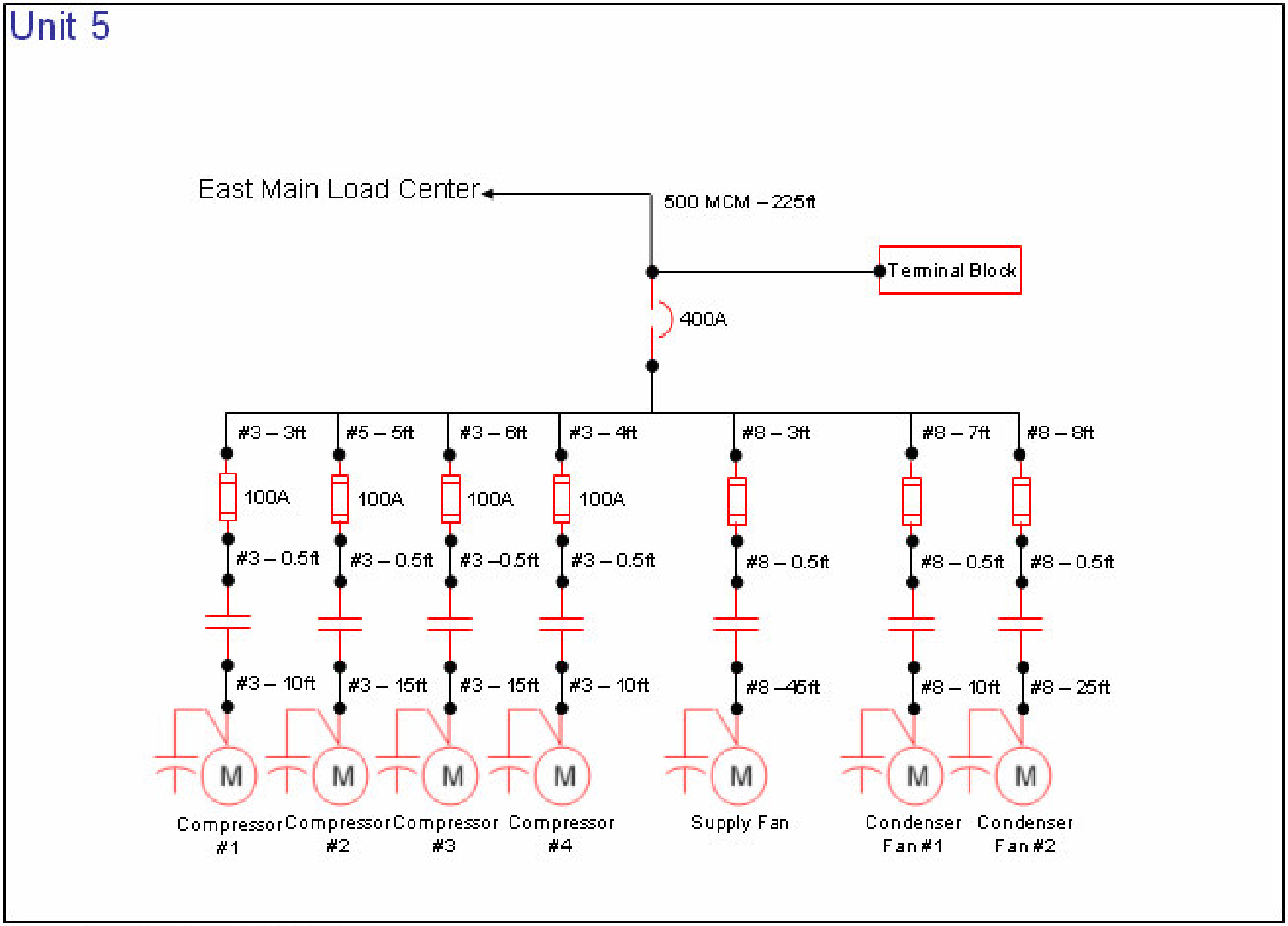


Fig. 32. Air conditioner unit 5

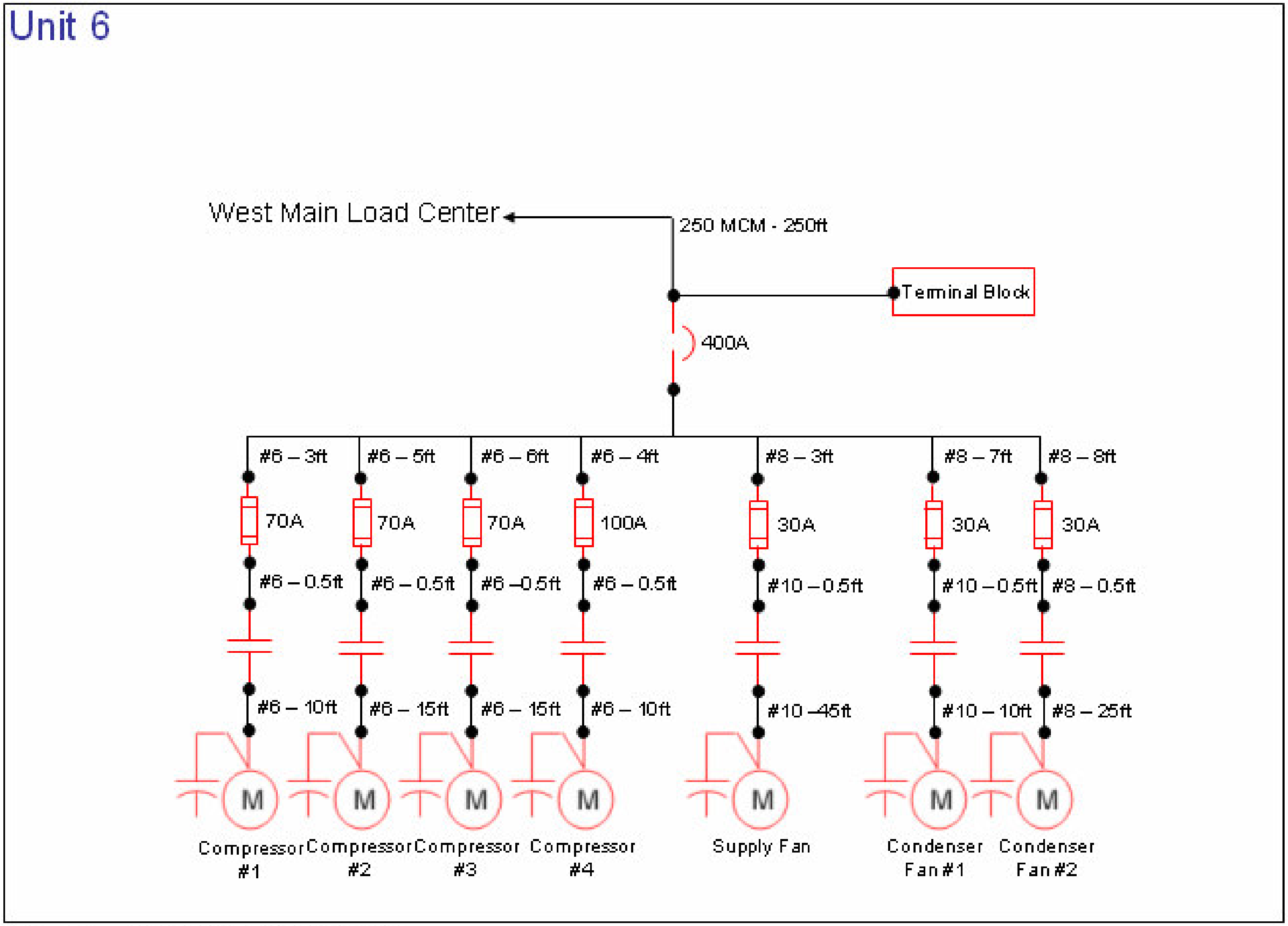


Fig. 33. Air conditioner unit 6

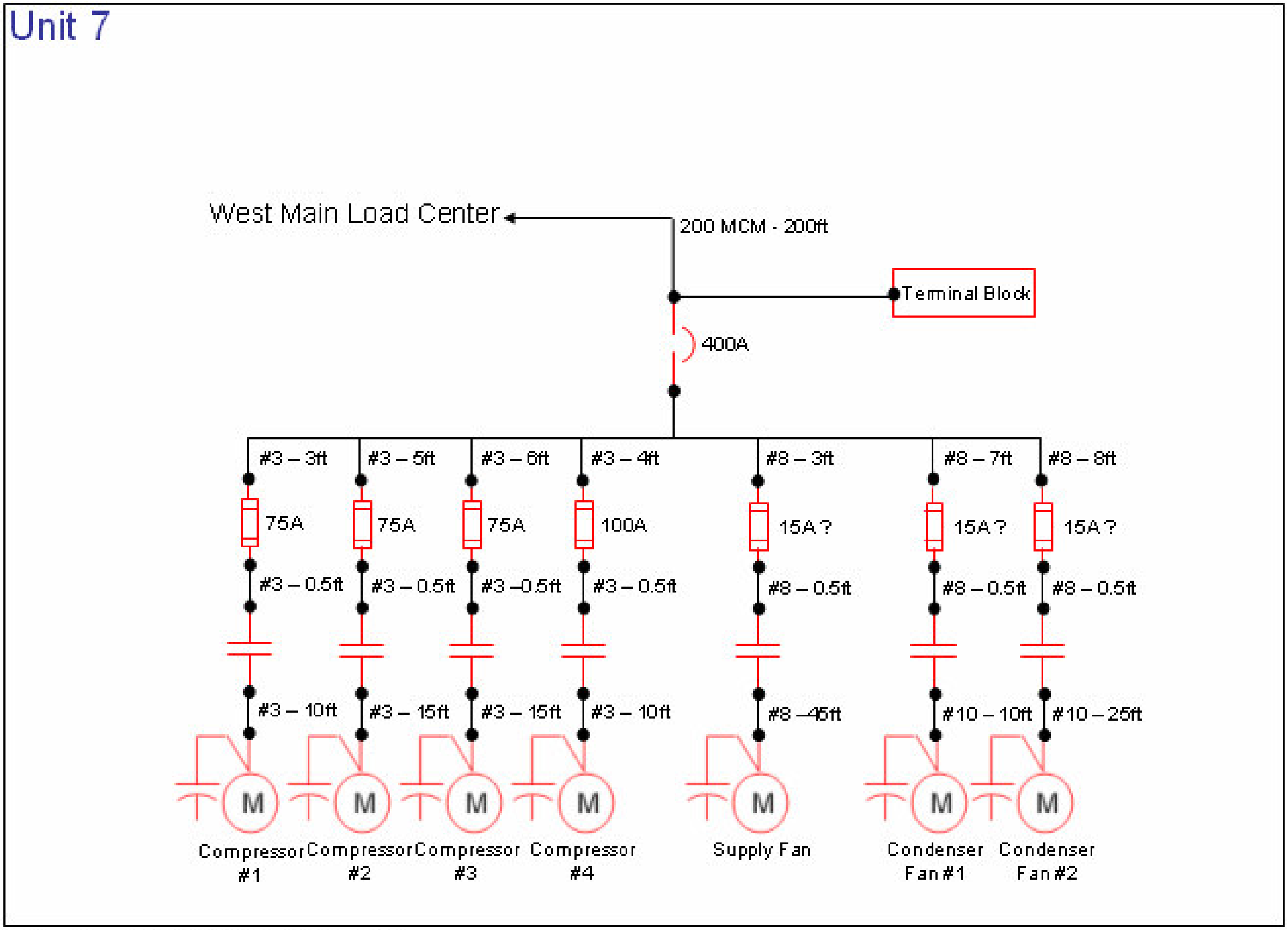


Fig. 34. Air conditioner unit 7

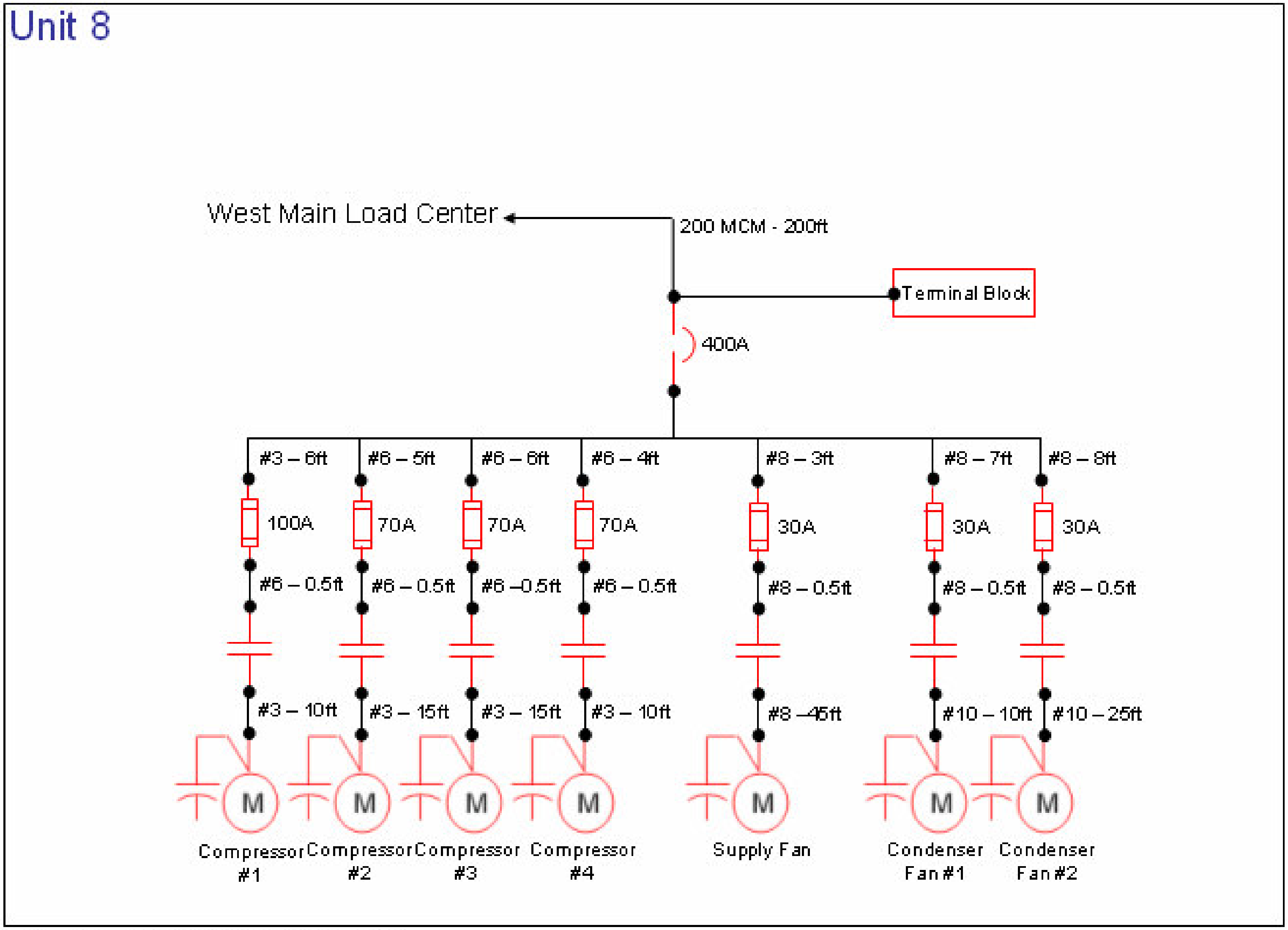


Fig. 35. Air conditioner unit 8

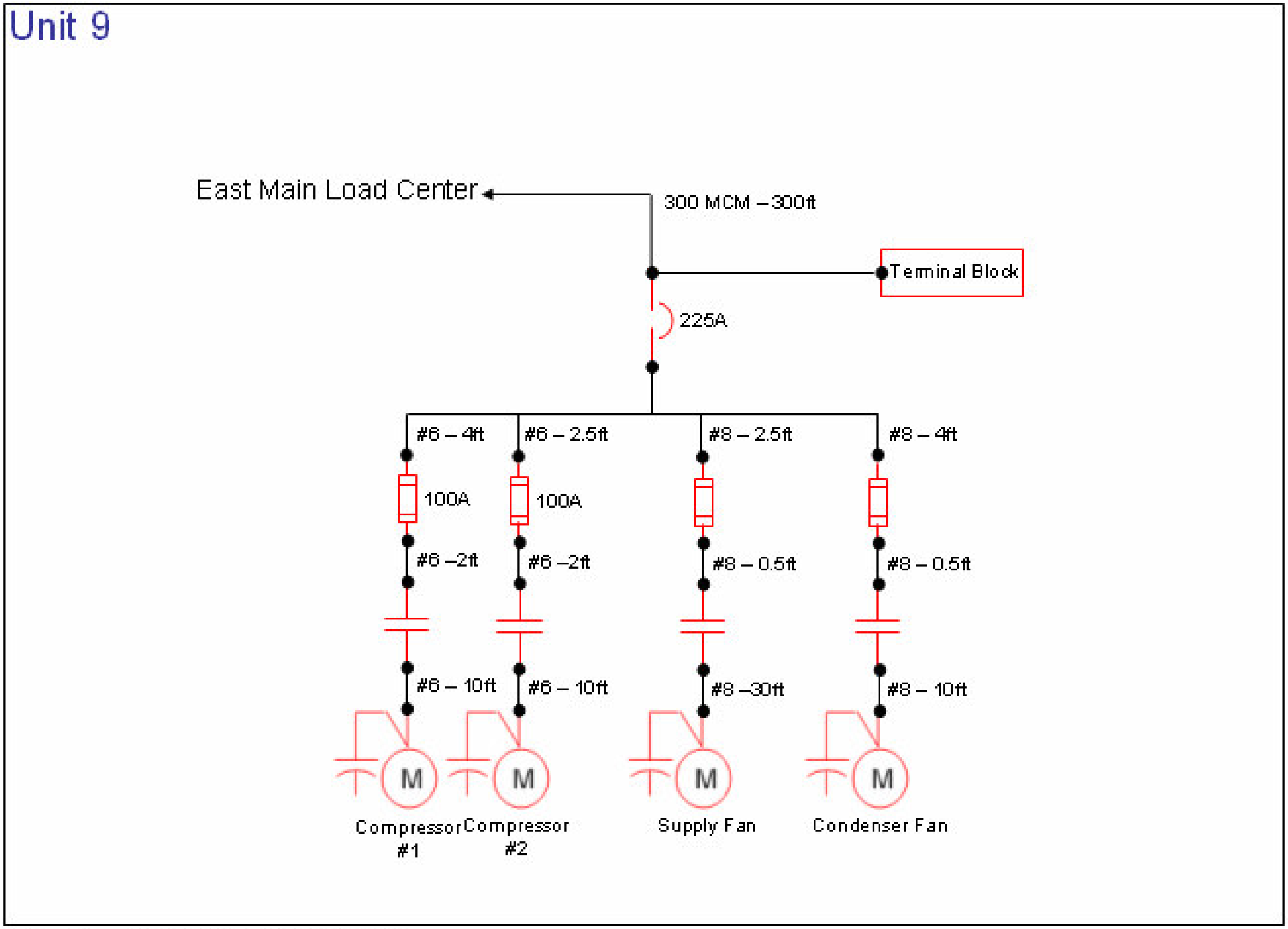


Fig. 36. Air conditioner unit 9

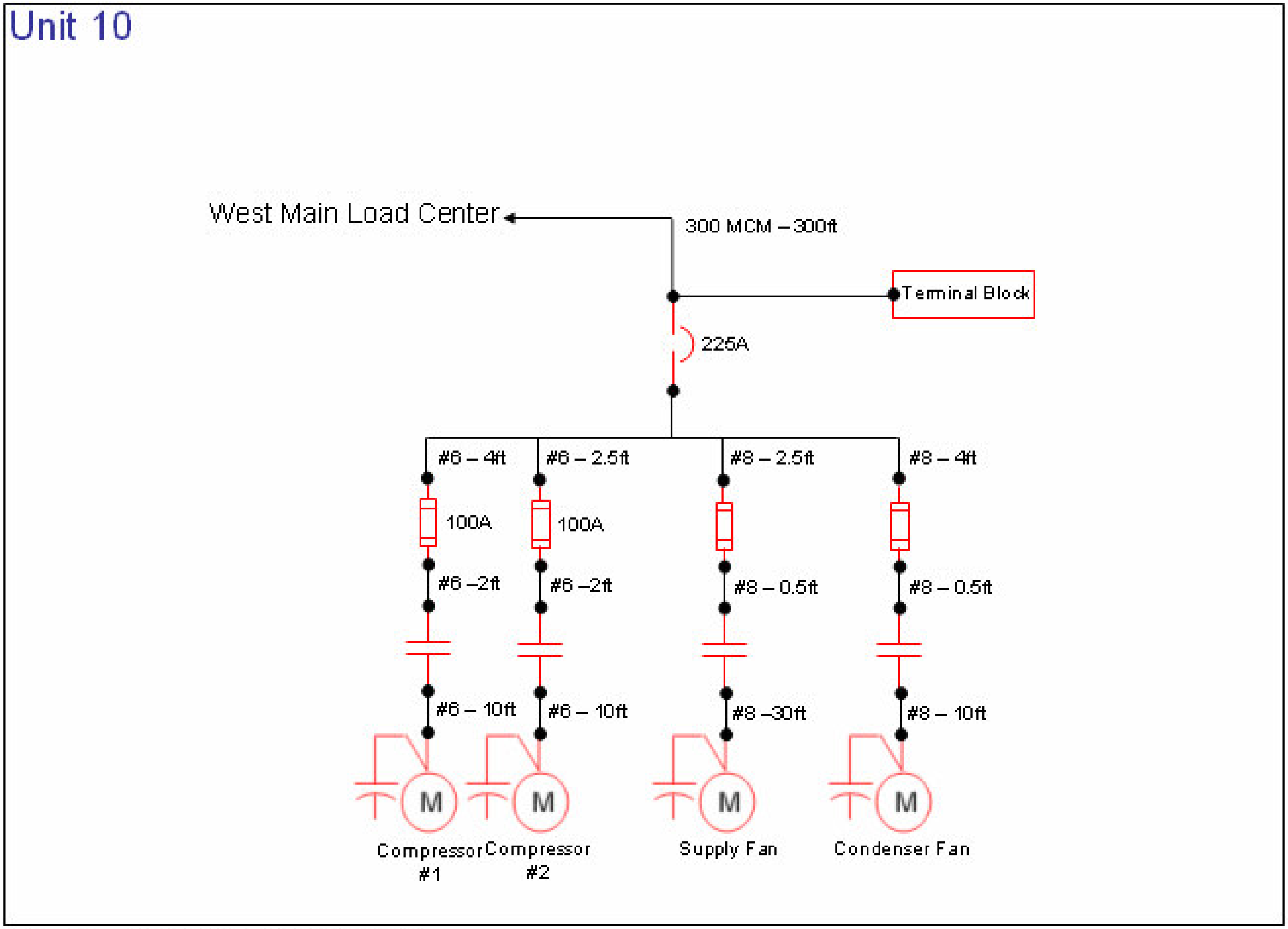


Fig. 37. Air conditioner unit 10

APPENDIX B

DETAILED PROJECT MOTOR DATA SETS

Table 20 – Motor data set and gains for motor 1

MOTOR 1

Description	
Air Conditioner Unit	1
Motor Name	Condenser Fan 1
Rated Real Power (kw)	3.73
% of Rated Loading	58.2%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.2	268.4	268.4	267.7
amp	2.04	2.07	2.11	2.07
kvar	0.54	0.55	0.56	1.65
Rated Reactive Power (kvar)				2.0
Reactive Power Deviation				-11.6%

Analysis	
Branch Resistance (ohms)	6.12
Ohmic Loss Reduction	57.5%
Voltage Elevation	-0.05%
Power Factor Elevation	0.29
RMS Current Reduction (amps)	1.40
Percent RMS Current Reduction	34.8%
Real Power Reduction (kw)	0.17
Percent Real Power Reduction	7.8%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	264.6	266.3	266.1	265.7
amp	3.97	3.99	4.08	4.01
kw	0.72	0.70	0.75	2.17
kva	1.04	1.01	1.08	3.13
kvar	0.77	0.73	0.78	2.28
pf	0.68	0.68	0.67	0.68

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	264.0	266.6	266.0	265.5
amp	2.60	2.65	2.60	2.62
kw	0.66	0.68	0.66	2.00
kva	0.68	0.70	0.67	2.05
kvar	0.18	0.16	0.15	0.49
pf	0.96	0.97	0.96	0.96

Table 21 – Motor data set and gains for motor 2

MOTOR 2

Description	
Air Conditioner Unit	1
Motor Name	Condenser Fan 2
Rated Real Power (kw)	3.73
% of Rated Loading	59.8%

Analysis	
Branch Resistance (ohms)	6.78
Ohmic Loss Reduction	53.8%
Voltage Elevation	0.66%
Power Factor Elevation	0.27
RMS Current Reduction (amps)	1.26
Percent RMS Current Reduction	32.1%
Real Power Reduction (kw)	0.17
Percent Real Power Reduction	7.6%

Capacitor Data Set

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.6	268.4	267.9	267.6
amp	2.05	2.07	2.12	2.08
kvar	0.54	0.55	0.57	1.66
Rated Reactive Power (kvar)				2.0
Reactive Power Deviation				-11.0%

Motor Data Set - Capacitor Off

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	264.4	267.0	266.5	266.0
amp	3.87	3.94	4.01	3.94
kw	0.75	0.75	0.73	2.23
kva	1.02	1.05	1.05	3.12
kvar	0.70	0.75	0.79	2.24
pf	0.71	0.70	0.67	0.69

Motor Data Set - Capacitor On

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.2	268.7	268.3	267.7
amp	2.66	2.71	2.66	2.68
kw	0.69	0.69	0.68	2.06
kva	0.70	0.71	0.71	2.12
kvar	0.15	0.17	0.18	0.50
pf	0.97	0.96	0.96	0.96

Table 22 – Motor data set and gains for motor 3

MOTOR 3

Description	
Air Conditioner Unit	1
Motor Name	Condenser Fan 3
Rated Real Power (kw)	3.73
% of Rated Loading	64.3%

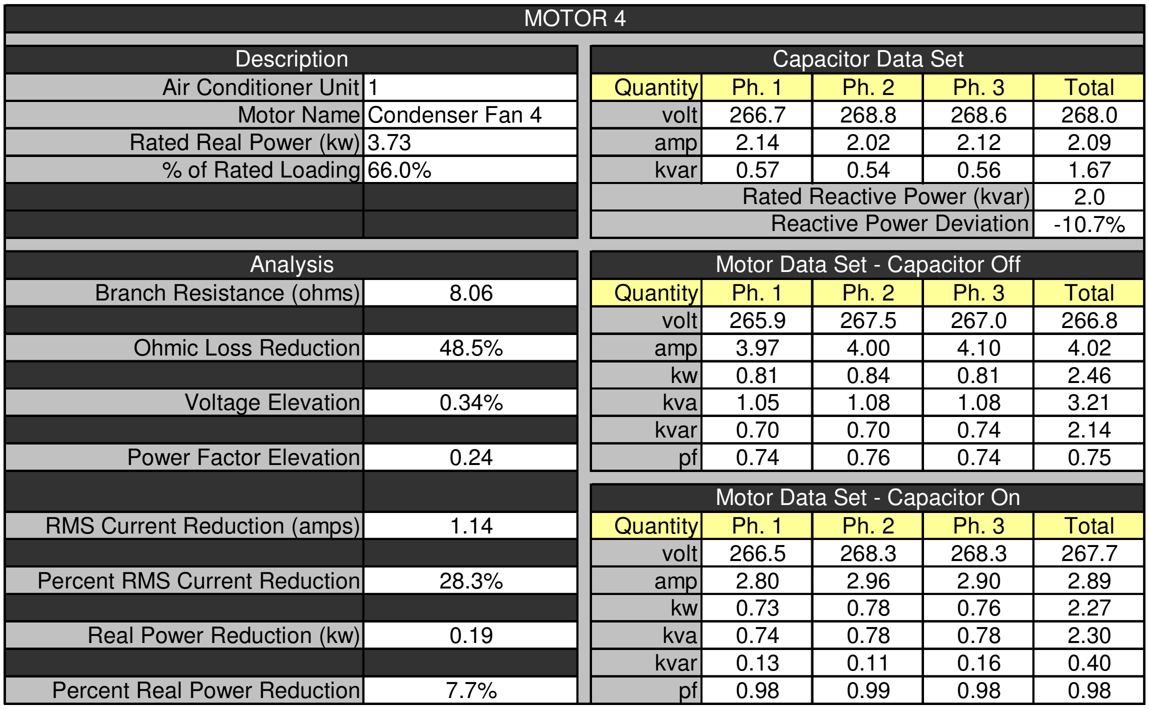
Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.9	267.6	267.6	267.0
amp	2.11	2.14	2.08	2.11
kvar	0.56	0.56	0.55	1.67
Rated Reactive Power (kvar)				2.0
Reactive Power Deviation				-10.1%

Analysis	
Branch Resistance (ohms)	6.71
Ohmic Loss Reduction	49.3%
Voltage Elevation	0.49%
Power Factor Elevation	0.25
RMS Current Reduction (amps)	1.16
Percent RMS Current Reduction	28.8%
Real Power Reduction (kw)	0.16
Percent Real Power Reduction	6.7%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.1	267.3	267.0	266.5
amp	4.03	3.97	4.05	4.02
kw	0.81	0.81	0.78	2.40
kva	1.07	1.06	1.08	3.21
kvar	0.71	0.70	0.76	2.17
pf	0.73	0.74	0.71	0.73

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.3	268.4	268.6	267.8
amp	2.88	2.88	2.82	2.86
kw	0.75	0.76	0.73	2.24
kva	0.76	0.77	0.75	2.28
kvar	0.15	0.11	0.17	0.43
pf	0.98	0.98	0.97	0.98

Table 23 – Motor data set and gains for motor 4



MOTOR 4

Description	
Air Conditioner Unit	1
Motor Name	Condenser Fan 4
Rated Real Power (kw)	3.73
% of Rated Loading	66.0%

Capacitor Data Set

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.7	268.8	268.6	268.0
amp	2.14	2.02	2.12	2.09
kvar	0.57	0.54	0.56	1.67
Rated Reactive Power (kvar)				2.0
Reactive Power Deviation				-10.7%

Analysis	
Branch Resistance (ohms)	8.06
Ohmic Loss Reduction	48.5%
Voltage Elevation	0.34%
Power Factor Elevation	0.24
RMS Current Reduction (amps)	1.14
Percent RMS Current Reduction	28.3%
Real Power Reduction (kw)	0.19
Percent Real Power Reduction	7.7%

Motor Data Set - Capacitor Off

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.9	267.5	267.0	266.8
amp	3.97	4.00	4.10	4.02
kw	0.81	0.84	0.81	2.46
kva	1.05	1.08	1.08	3.21
kvar	0.70	0.70	0.74	2.14
pf	0.74	0.76	0.74	0.75

Motor Data Set - Capacitor On

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.5	268.3	268.3	267.7
amp	2.80	2.96	2.90	2.89
kw	0.73	0.78	0.76	2.27
kva	0.74	0.78	0.78	2.30
kvar	0.13	0.11	0.16	0.40
pf	0.98	0.99	0.98	0.98

Table 24 – Motor data set and gains for motor 5

MOTOR 5

Description	
Air Conditioner Unit	1
Motor Name	Condenser Fan 5
Rated Real Power (kw)	3.73
% of Rated Loading	60.1%

Analysis	
Branch Resistance (ohms)	8.21
Ohmic Loss Reduction	53.7%
Voltage Elevation	0.33%
Power Factor Elevation	0.26
RMS Current Reduction (amps)	1.24
Percent RMS Current Reduction	32.0%
Real Power Reduction (kw)	0.20
Percent Real Power Reduction	8.9%

Capacitor Data Set

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.8	268.5	268.7	268.0
amp	2.05	2.08	2.10	2.08
kvar	0.54	0.55	0.56	1.65
Rated Reactive Power (kvar)				2.0
Reactive Power Deviation				-11.8%

Motor Data Set - Capacitor Off

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.5	267.5	266.8	266.6
amp	3.81	3.78	4.07	3.89
kw	0.73	0.74	0.77	2.24
kva	1.01	1.00	1.08	3.09
kvar	0.71	0.68	0.75	2.14
pf	0.70	0.73	0.71	0.71

Motor Data Set - Capacitor On

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.0	268.3	268.1	267.5
amp	2.57	2.60	2.76	2.64
kw	0.66	0.68	0.70	2.04
kva	0.68	0.67	0.72	2.07
kvar	0.14	0.12	0.17	0.43
pf	0.98	0.98	0.96	0.97

Table 25 – Motor data set and gains for motor 6

MOTOR 6

Description	
Air Conditioner Unit	2
Motor Name	Condenser Fan 1
Rated Real Power (kw)	3.73
% of Rated Loading	83.9%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	268.0	269.5	269.1	268.9
amp	2.06	2.09	2.08	2.08
kvar	0.55	0.56	0.55	1.66
Rated Reactive Power (kvar)				2.0
Reactive Power Deviation				-11.8%

Analysis	
Branch Resistance (ohms)	6.59
Ohmic Loss Reduction	39.1%
Voltage Elevation	0.44%
Power Factor Elevation	0.18
RMS Current Reduction (amps)	1.06
Percent RMS Current Reduction	22.0%
Real Power Reduction (kw)	0.18
Percent Real Power Reduction	5.8%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.3	268.6	268.6	268.2
amp	4.50	4.88	5.10	4.83
kw	0.97	1.06	1.10	3.13
kva	1.20	1.29	1.37	3.86
kvar	0.72	0.72	0.82	2.26
pf	0.78	0.82	0.79	0.80

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	268.3	269.5	270.2	269.3
amp	3.42	3.90	3.98	3.77
kw	0.88	1.03	1.04	2.95
kva	0.91	1.04	1.07	3.02
kvar	0.15	0.14	0.25	0.54
pf	0.98	0.99	0.97	0.98

Table 26 – Motor data set and gains for motor 7

MOTOR 7

Description	
Air Conditioner Unit	2
Motor Name	Condenser Fan 2
Rated Real Power (kw)	3.73
% of Rated Loading	83.6%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.6	269.6	269.1	268.8
amp	2.07	2.09	2.08	2.08
kvar	0.55	0.56	0.56	1.67
Rated Reactive Power (kvar)				2.0
Reactive Power Deviation				-11.2%

Analysis	
Branch Resistance (ohms)	6.09
Ohmic Loss Reduction	40.0%
Voltage Elevation	0.47%
Power Factor Elevation	0.18
RMS Current Reduction (amps)	1.09
Percent RMS Current Reduction	22.5%
Real Power Reduction (kw)	0.17
Percent Real Power Reduction	5.4%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.1	268.3	268.6	268.0
amp	4.61	4.86	5.00	4.82
kw	0.98	1.07	1.07	3.12
kva	1.22	1.29	1.34	3.85
kvar	0.73	0.73	0.80	2.26
pf	0.79	0.81	0.79	0.80

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	268.2	269.4	270.2	269.3
amp	3.51	3.84	3.86	3.74
kw	0.91	1.02	1.02	2.95
kva	0.93	1.03	1.04	3.00
kvar	0.17	0.14	0.23	0.54
pf	0.98	0.99	0.97	0.98

Table 27 – Motor data set and gains for motor 8

MOTOR 8

Description	
Air Conditioner Unit	2
Motor Name	Condenser Fan 3
Rated Real Power (kw)	3.73
% of Rated Loading	83.1%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	268.0	269.8	269.4	269.1
amp	2.11	2.21	2.14	2.15
kvar	0.56	0.59	0.58	1.73
Rated Reactive Power (kvar)				2.0
Reactive Power Deviation				-8.2%

Analysis	
Branch Resistance (ohms)	8.56
Ohmic Loss Reduction	41.4%
Voltage Elevation	0.29%
Power Factor Elevation	0.18
RMS Current Reduction (amps)	1.11
Percent RMS Current Reduction	23.4%
Real Power Reduction (kw)	0.24
Percent Real Power Reduction	7.7%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.7	269.0	269.2	268.6
amp	4.54	4.82	4.90	4.75
kw	0.98	1.08	1.04	3.10
kva	1.22	1.30	1.31	3.83
kvar	0.72	0.72	0.81	2.25
pf	0.79	0.82	0.78	0.80

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	268.5	269.5	270.2	269.4
amp	3.41	3.81	3.70	3.64
kw	0.89	1.00	0.97	2.86
kva	0.91	1.01	0.99	2.91
kvar	0.15	0.11	0.21	0.47
pf	0.98	0.99	0.97	0.98

Table 28 – Motor data set and gains for motor 9

MOTOR 9

Description	
Air Conditioner Unit	2
Motor Name	Supply Fan
Rated Real Power (kw)	11.19
% of Rated Loading	86.9%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	269.2	267.7	269.7	268.9
amp	5.40	5.25	5.37	5.34
kvar	1.44	1.40	1.43	4.27
Rated Reactive Power (kvar)				5.0
Reactive Power Deviation				-9.3%

Analysis	
Branch Resistance (ohms)	2.06
Ohmic Loss Reduction	29.9%
Voltage Elevation	0.32%
Power Factor Elevation	0.15
RMS Current Reduction (amps)	2.37
Percent RMS Current Reduction	16.3%
Real Power Reduction (kw)	0.39
Percent Real Power Reduction	4.0%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.6	268.7	268.9	268.4
amp	14.80	14.40	14.44	14.55
kw	3.25	3.17	3.30	9.72
kva	3.90	3.86	3.88	11.64
kvar	2.20	2.26	2.04	6.50
pf	0.82	0.80	0.84	0.82

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	268.0	269.8	270.0	269.3
amp	12.30	11.84	12.40	12.18
kw	3.10	3.05	3.18	9.33
kva	3.24	3.16	3.30	9.70
kvar	0.76	0.74	0.61	2.11
pf	0.97	0.97	0.98	0.97

Table 29 – Motor data set and gains for motor 10

MOTOR 10

Description	
Air Conditioner Unit	3
Motor Name	Condenser Fan 1
Rated Real Power (kw)	11.19
% of Rated Loading	50.6%

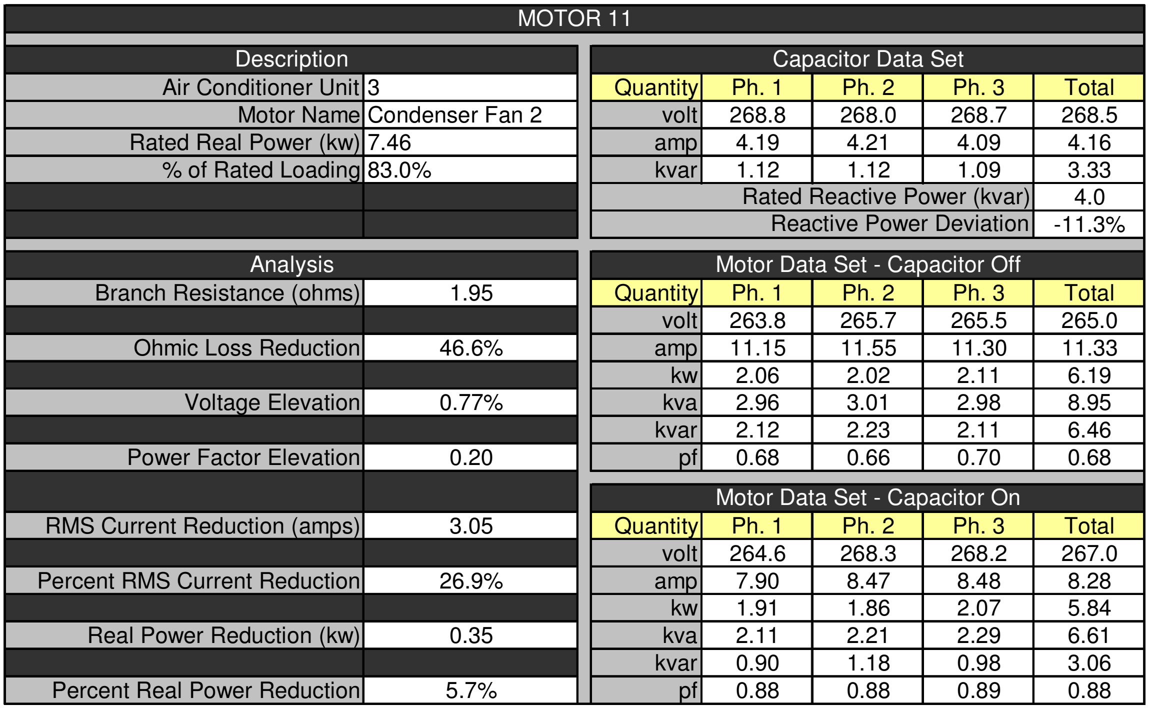
Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	268.3	268.6	267.5	268.1
amp	5.20	5.16	5.19	5.18
kvar	1.39	1.37	1.37	4.13
Rated Reactive Power (kvar)				5.0
Reactive Power Deviation				-11.8%

Analysis	
Branch Resistance (ohms)	2.21
Ohmic Loss Reduction	50.8%
Voltage Elevation	0.52%
Power Factor Elevation	0.28
RMS Current Reduction (amps)	3.04
Percent RMS Current Reduction	29.8%
Real Power Reduction (kw)	0.35
Percent Real Power Reduction	6.2%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	263.8	264.5	264.4	264.2
amp	9.58	10.72	10.31	10.20
kw	1.74	1.92	2.00	5.66
kva	2.52	2.85	2.74	8.11
kvar	1.83	2.11	1.86	5.80
pf	0.67	0.65	0.70	0.67

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.7	267.8	263.3	265.6
amp	6.26	7.36	7.86	7.16
kw	1.58	1.81	1.92	5.31
kva	1.62	1.96	1.99	5.57
kvar	0.36	0.75	0.51	1.62
pf	0.97	0.92	0.97	0.95

Table 30 – Motor data set and gains for motor 11



MOTOR 11

Description	
Air Conditioner Unit	3
Motor Name	Condenser Fan 2
Rated Real Power (kw)	7.46
% of Rated Loading	83.0%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	268.8	268.0	268.7	268.5
amp	4.19	4.21	4.09	4.16
kvar	1.12	1.12	1.09	3.33
			Rated Reactive Power (kvar)	4.0
			Reactive Power Deviation	-11.3%

Analysis	
Branch Resistance (ohms)	1.95
Ohmic Loss Reduction	46.6%
Voltage Elevation	0.77%
Power Factor Elevation	0.20
RMS Current Reduction (amps)	3.05
Percent RMS Current Reduction	26.9%
Real Power Reduction (kw)	0.35
Percent Real Power Reduction	5.7%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	263.8	265.7	265.5	265.0
amp	11.15	11.55	11.30	11.33
kw	2.06	2.02	2.11	6.19
kva	2.96	3.01	2.98	8.95
kvar	2.12	2.23	2.11	6.46
pf	0.68	0.66	0.70	0.68

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	264.6	268.3	268.2	267.0
amp	7.90	8.47	8.48	8.28
kw	1.91	1.86	2.07	5.84
kva	2.11	2.21	2.29	6.61
kvar	0.90	1.18	0.98	3.06
pf	0.88	0.88	0.89	0.88

Table 31 – Motor data set and gains for motor 12

MOTOR 12

Description	
Air Conditioner Unit	3
Motor Name	Condenser Fan 3
Rated Real Power (kw)	29.84
% of Rated Loading	74.5%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.2	268.4	267.3	267.6
amp	10.86	10.85	10.81	10.84
kvar	2.89	2.89	2.85	8.63
Rated Reactive Power (kvar)				10.0
Reactive Power Deviation				-7.5%

Analysis	
Branch Resistance (ohms)	0.77
Ohmic Loss Reduction	26.7%
Voltage Elevation	1.26%
Power Factor Elevation	0.12
RMS Current Reduction (amps)	4.77
Percent RMS Current Reduction	14.4%
Real Power Reduction (kw)	0.68
Percent Real Power Reduction	3.1%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.2	265.8	264.3	265.1
amp	33.89	33.11	32.70	33.23
kw	7.58	7.27	7.38	22.23
kva	8.91	8.98	8.68	26.57
kvar	4.68	5.26	4.56	14.50
pf	0.84	0.81	0.85	0.83

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	268.0	268.9	268.4	268.4
amp	29.44	28.72	27.22	28.46
kw	7.35	7.12	7.08	21.55
kva	7.60	7.51	7.28	22.39
kvar	1.94	2.27	1.68	5.89
pf	0.96	0.95	0.95	0.95

Table 32 – Motor data set and gains for motor 13

MOTOR 13

Description	
Air Conditioner Unit	4
Motor Name	Condenser Fan 1
Rated Real Power (kw)	11.19
% of Rated Loading	90.9%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	264.9	264.3	264.4	264.5
amp	5.38	5.36	5.40	5.38
kvar	1.39	1.41	1.40	4.20
Rated Reactive Power (kvar)				4.0
Reactive Power Deviation				15.2%

Analysis	
Branch Resistance (ohms)	2.30
Ohmic Loss Reduction	30.2%
Voltage Elevation	-1.93%
Power Factor Elevation	0.14
RMS Current Reduction (amps)	2.52
Percent RMS Current Reduction	16.4%
Real Power Reduction (kw)	0.49
Percent Real Power Reduction	4.8%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	262.4	263.3	262.4	262.7
amp	15.12	15.74	15.20	15.35
kw	3.16	3.48	3.53	10.17
kva	3.74	4.10	4.12	11.96
kvar	2.00	2.15	2.12	6.27
pf	0.84	0.83	0.85	0.84

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	256.5	256.1	260.3	257.6
amp	12.24	12.88	13.37	12.83
kw	3.09	3.23	3.36	9.68
kva	3.15	3.32	3.43	9.90
kvar	0.58	0.73	0.71	2.02
pf	0.98	0.98	0.97	0.98

Table 33 – Motor data set and gains for motor 14

MOTOR 14

Description	
Air Conditioner Unit	4
Motor Name	Condenser Fan 2
Rated Real Power (kw)	11.19
% of Rated Loading	54.9%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.3	265.3	265.8	265.5
amp	4.22	4.26	4.23	4.24
kvar	1.10	1.11	1.11	3.32
Rated Reactive Power (kvar)				5.0
Reactive Power Deviation				-27.6%

Analysis	
Branch Resistance (ohms)	5.18
Ohmic Loss Reduction	36.0%
Voltage Elevation	-0.41%
Power Factor Elevation	0.17
RMS Current Reduction (amps)	1.89
Percent RMS Current Reduction	20.0%
Real Power Reduction (kw)	0.50
Percent Real Power Reduction	8.1%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	261.8	263.0	263.0	262.6
amp	8.87	9.85	9.66	9.46
kw	1.96	2.06	2.12	6.14
kva	2.38	2.56	2.54	7.48
kvar	1.35	1.53	1.41	4.29
pf	0.82	0.80	0.82	0.81

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	259.8	264.4	260.4	261.5
amp	7.48	7.58	7.65	7.57
kw	1.78	1.87	1.99	5.64
kva	1.79	1.92	2.01	5.72
kvar	0.24	0.40	0.30	0.94
pf	0.98	0.98	0.98	0.98

Table 34 – Motor data set and gains for motor 15

MOTOR 15

Description	
Air Conditioner Unit	4
Motor Name	Supply Fan
Rated Real Power (kw)	22.38
% of Rated Loading	62.1%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.7	266.5	266.3	266.5
amp	16.72	16.54	16.54	16.60
kvar	4.40	4.34	4.35	13.09
Rated Reactive Power (kvar)				15.0
Reactive Power Deviation				-5.6%

Analysis	
Branch Resistance (ohms)	1.43
Ohmic Loss Reduction	35.9%
Voltage Elevation	2.15%
Power Factor Elevation	0.16
RMS Current Reduction (amps)	4.43
Percent RMS Current Reduction	19.9%
Real Power Reduction (kw)	0.76
Percent Real Power Reduction	5.5%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	250.9	255.8	255.1	253.9
amp	21.30	22.65	22.67	22.21
kw	4.38	4.67	4.85	13.90
kva	5.31	5.77	5.76	16.84
kvar	3.01	3.38	3.08	9.47
pf	0.82	0.81	0.83	0.82

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	256.8	262.8	258.6	259.4
amp	17.68	17.60	18.05	17.78
kw	4.34	4.34	4.46	13.14
kva	4.44	4.41	4.55	13.40
kvar	0.97	0.81	0.89	2.67
pf	0.97	0.98	0.98	0.98

Table 35 – Motor data set and gains for motor 16

MOTOR 16

Description	
Air Conditioner Unit	5
Motor Name	Condenser Fan 1
Rated Real Power (kw)	11.19
% of Rated Loading	79.9%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.8	266.2	267.3	266.8
amp	5.44	5.38	5.43	5.42
kvar	1.43	1.43	1.44	4.30
Rated Reactive Power (kvar)				5.0
Reactive Power Deviation				-7.2%

Analysis	
Branch Resistance (ohms)	3.52
Ohmic Loss Reduction	37.1%
Voltage Elevation	1.28%
Power Factor Elevation	0.09
RMS Current Reduction (amps)	2.92
Percent RMS Current Reduction	20.7%
Real Power Reduction (kw)	0.78
Percent Real Power Reduction	8.7%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.4	267.1	266.9	266.5
amp	13.90	14.52	13.92	14.11
kw	2.87	3.01	3.06	8.94
kva	3.68	3.85	3.71	11.24
kvar	2.30	2.41	2.10	6.81
pf	0.77	0.77	0.81	0.78

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	270.7	269.0	269.9	269.9
amp	12.93	9.95	10.70	11.19
kw	2.96	2.32	2.88	8.16
kva	3.38	2.74	2.95	9.07
kvar	1.63	1.47	0.65	3.75
pf	0.88	0.82	0.91	0.87

Table 36 – Motor data set and gains for motor 17

MOTOR 17

Description	
Air Conditioner Unit	5
Motor Name	Condenser Fan 2
Rated Real Power (kw)	11.19
% of Rated Loading	35.6%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.1	266.0	264.7	265.6
amp	5.36	5.27	5.26	5.30
kvar	1.41	1.39	1.38	4.18
Rated Reactive Power (kvar)				5.0
Reactive Power Deviation				-9.0%

Analysis	
Branch Resistance (ohms)	1.47
Ohmic Loss Reduction	64.0%
Voltage Elevation	1.30%
Power Factor Elevation	0.35
RMS Current Reduction (amps)	3.54
Percent RMS Current Reduction	40.0%
Real Power Reduction (kw)	0.22
Percent Real Power Reduction	5.5%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.7	267.2	266.5	266.5
amp	8.41	9.18	8.94	8.84
kw	1.21	1.32	1.45	3.98
kva	2.23	2.46	2.40	7.09
kvar	1.84	2.08	1.92	5.84
pf	0.53	0.54	0.58	0.55

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	269.5	270.1	270.2	269.9
amp	4.83	5.37	5.72	5.31
kw	1.16	1.27	1.33	3.76
kva	1.26	1.43	1.43	4.12
kvar	0.52	0.66	0.55	1.73
pf	0.91	0.88	0.92	0.90

Table 37 – Motor data set and gains for motor 18

MOTOR 18

Description	
Air Conditioner Unit	5
Motor Name	Supply Fan
Rated Real Power (kw)	22.38
% of Rated Loading	57.4%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.7	266.8	266.6	266.4
amp	10.81	10.83	10.72	10.79
kvar	2.84	2.84	2.83	8.51
Rated Reactive Power (kvar)				10.0
Reactive Power Deviation				-7.9%

Analysis	
Branch Resistance (ohms)	0.88
Ohmic Loss Reduction	40.4%
Voltage Elevation	0.67%
Power Factor Elevation	0.20
RMS Current Reduction (amps)	4.62
Percent RMS Current Reduction	22.8%
Real Power Reduction (kw)	0.44
Percent Real Power Reduction	3.4%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	263.7	266.1	265.7	265.2
amp	19.37	20.72	20.71	20.27
kw	4.09	4.28	4.48	12.85
kva	5.10	5.48	5.53	16.11
kvar	3.04	3.43	3.24	9.71
pf	0.79	0.77	0.81	0.79

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.3	267.7	266.8	266.9
amp	15.22	15.83	15.88	15.64
kw	4.03	4.17	4.21	12.41
kva	4.03	4.21	4.20	12.44
kvar	0.25	0.57	0.36	1.18
pf	0.99	0.99	0.99	0.99

Table 38 – Motor data set and gains for motor 19

MOTOR 19	
Description	
Air Conditioner Unit	6
Motor Name	Condenser Fan 1
Rated Real Power (kw)	5.60
% of Rated Loading	71.7%
Analysis	
Branch Resistance (ohms)	9.52
Ohmic Loss Reduction	22.6%
Voltage Elevation	1.77%
Power Factor Elevation	0.07
RMS Current Reduction (amps)	0.67
Percent RMS Current Reduction	12.1%
Real Power Reduction (kw)	0.20
Percent Real Power Reduction	5.0%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	266.7	267.5	266.7	267.0
amp	3.22	3.20	3.09	3.17
kvar	0.85	0.85	0.81	2.51
Rated Reactive Power (kvar)				3.0
Reactive Power Deviation				-9.8%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	260.7	261.4	262.1	261.4
amp	5.50	5.48	5.70	5.56
kw	1.35	1.32	1.34	4.01
kva	1.44	1.43	1.48	4.35
kvar	0.50	0.58	0.67	1.75
pf	0.92	0.91	0.90	0.91

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.0	268.1	265.0	266.0
amp	4.87	4.77	5.03	4.89
kw	1.26	1.25	1.30	3.81
kva	1.27	1.28	1.33	3.88
kvar	0.20	0.28	0.21	0.69
pf	0.98	0.98	0.99	0.98

Table 39 – Motor data set and gains for motor 20

MOTOR 20

Description	
Air Conditioner Unit	6
Motor Name	Supply Fan
Rated Real Power (kw)	14.92
% of Rated Loading	106.6%

Capacitor Data Set

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.4	267.3	266.4	267.0
amp	8.16	8.09	8.06	8.10
kvar	2.17	2.15	2.13	6.45
Rated Reactive Power (kvar)				7.5
Reactive Power Deviation				-7.4%

Analysis	
Branch Resistance (ohms)	1.18
Ohmic Loss Reduction	27.6%
Voltage Elevation	2.66%
Power Factor Elevation	0.11
RMS Current Reduction (amps)	3.41
Percent RMS Current Reduction	14.9%
Real Power Reduction (kw)	0.51
Percent Real Power Reduction	3.2%

Motor Data Set - Capacitor Off

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	261.0	261.3	261.0	261.1
amp	22.60	22.50	23.50	22.87
kw	5.26	5.20	5.45	15.91
kva	5.89	5.86	6.10	17.85
kvar	2.74	2.70	2.92	8.36
pf	0.88	0.88	0.88	0.88

Motor Data Set - Capacitor On

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.5	268.2	268.4	268.0
amp	19.29	19.17	19.92	19.46
kw	5.07	5.10	5.23	15.40
kva	5.09	5.13	5.27	15.49
kvar	0.50	0.57	0.58	1.65
pf	0.99	0.99	0.99	0.99

Table 40 – Motor data set and gains for motor 21

MOTOR 21

Description	
Air Conditioner Unit	7
Motor Name	Condenser Fan 1
Rated Real Power (kw)	5.60
% of Rated Loading	79.9%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	258.3	259.0	259.3	258.9
amp	3.14	3.08	3.09	3.10
kvar	0.79	0.77	0.79	2.35
Rated Reactive Power (kvar)				3.0
Reactive Power Deviation				-10.2%

Analysis	
Branch Resistance (ohms)	2.19
Ohmic Loss Reduction	44.9%
Voltage Elevation	-0.50%
Power Factor Elevation	0.21
RMS Current Reduction (amps)	2.17
Percent RMS Current Reduction	25.8%
Real Power Reduction (kw)	0.21
Percent Real Power Reduction	4.7%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	259.9	261.2	261.7	260.9
amp	8.20	8.55	8.53	8.43
kw	1.41	1.50	1.56	4.47
kva	2.11	2.22	2.23	6.56
kvar	1.50	1.66	1.61	4.77
pf	0.68	0.65	0.68	0.67

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	258.5	260.2	260.2	259.6
amp	6.04	6.33	6.39	6.25
kw	1.34	1.43	1.49	4.26
kva	1.55	1.64	1.67	4.86
kvar	0.70	0.79	0.75	2.24
pf	0.88	0.87	0.89	0.88

Table 41 – Motor data set and gains for motor 22

MOTOR 22

Description	
Air Conditioner Unit	7
Motor Name	Condenser Fan 2
Rated Real Power (kw)	5.60
% of Rated Loading	73.5%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	260.2	258.7	259.8	259.6
amp	3.08	3.09	3.10	3.09
kvar	0.79	0.78	0.79	2.36
Rated Reactive Power (kvar)				3.0
Reactive Power Deviation				-10.3%

Analysis	
Branch Resistance (ohms)	3.43
Ohmic Loss Reduction	45.8%
Voltage Elevation	-0.55%
Power Factor Elevation	0.22
RMS Current Reduction (amps)	1.92
Percent RMS Current Reduction	26.3%
Real Power Reduction (kw)	0.25
Percent Real Power Reduction	6.1%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	260.2	261.4	261.1	260.9
amp	6.85	7.36	7.65	7.29
kw	1.34	1.32	1.45	4.11
kva	1.80	1.91	1.97	5.68
kvar	1.24	1.37	1.35	3.96
pf	0.72	0.68	0.72	0.71

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	259.1	260.1	259.2	259.5
amp	5.15	5.41	5.54	5.37
kw	1.25	1.26	1.35	3.86
kva	1.32	1.38	1.44	4.14
kvar	0.43	0.53	0.49	1.45
pf	0.94	0.91	0.93	0.93

Table 42 – Motor data set and gains for motor 23

MOTOR 23

Description	
Air Conditioner Unit	7
Motor Name	Supply Fan
Rated Real Power (kw)	14.92
% of Rated Loading	74.7%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.0	267.8	266.8	267.2
amp	7.98	8.02	8.29	8.10
kvar	2.11	2.13	2.19	6.43
Rated Reactive Power (kvar)				7.5
Reactive Power Deviation				-7.8%

Analysis	
Branch Resistance (ohms)	1.72
Ohmic Loss Reduction	39.3%
Voltage Elevation	2.82%
Power Factor Elevation	0.15
RMS Current Reduction (amps)	3.71
Percent RMS Current Reduction	22.1%
Real Power Reduction (kw)	0.57
Percent Real Power Reduction	5.1%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	259.1	261.0	261.1	260.4
amp	16.32	16.90	17.10	16.77
kw	3.65	3.70	3.80	11.15
kva	4.20	4.35	4.40	12.95
kvar	2.07	2.26	2.27	6.60
pf	0.87	0.84	0.85	0.85

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.4	267.1	268.7	267.7
amp	12.30	13.50	13.40	13.07
kw	3.35	3.58	3.65	10.58
kva	3.40	3.67	3.63	10.70
kvar	0.08	0.21	0.18	0.47
pf	1.00	1.00	1.00	1.00

Table 43 – Motor data set and gains for motor 24

MOTOR 24

Description	
Air Conditioner Unit	8
Motor Name	Condenser Fan 1
Rated Real Power (kw)	5.60
% of Rated Loading	64.0%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	261.1	261.9	263.2	262.1
amp	3.16	3.20	3.15	3.17
kvar	0.82	0.83	0.81	2.46
			Rated Reactive Power (kvar)	3.0
			Reactive Power Deviation	-8.3%

Analysis	
Branch Resistance (ohms)	6.26
Ohmic Loss Reduction	38.0%
Voltage Elevation	0.33%
Power Factor Elevation	0.18
RMS Current Reduction (amps)	1.18
Percent RMS Current Reduction	21.2%
Real Power Reduction (kw)	0.22
Percent Real Power Reduction	6.1%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	259.3	259.4	260.6	259.8
amp	5.31	5.64	5.72	5.56
kw	1.18	1.10	1.30	3.58
kva	1.40	1.48	1.46	4.34
kvar	0.81	0.78	0.84	2.43
pf	0.80	0.81	0.81	0.81

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	259.8	260.7	261.4	260.6
amp	4.08	4.34	4.71	4.38
kw	1.04	1.12	1.20	3.36
kva	1.04	1.12	1.20	3.36
kvar	0.03	0.03	0.01	0.07
pf	0.98	0.99	0.99	0.99

Table 44 – Motor data set and gains for motor 25

MOTOR 25

Description	
Air Conditioner Unit	8
Motor Name	Supply Fan
Rated Real Power (kw)	14.92
% of Rated Loading	64.6%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	269.4	268.1	269.3	268.9
amp	8.06	8.00	8.02	8.03
kvar	2.15	2.13	2.15	6.43
Rated Reactive Power (kvar)				7.5
Reactive Power Deviation				-9.0%

Analysis	
Branch Resistance (ohms)	2.22
Ohmic Loss Reduction	35.9%
Voltage Elevation	0.05%
Power Factor Elevation	0.19
RMS Current Reduction (amps)	2.91
Percent RMS Current Reduction	19.9%
Real Power Reduction (kw)	0.51
Percent Real Power Reduction	5.3%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.4	268.7	267.6	267.9
amp	14.50	14.35	15.00	14.62
kw	3.21	3.18	3.25	9.64
kva	3.81	3.82	3.95	11.58
kvar	2.16	2.29	2.30	6.75
pf	0.82	0.80	0.80	0.81

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	268.3	269.6	266.2	268.0
amp	11.41	11.20	12.50	11.70
kw	3.01	3.00	3.12	9.13
kva	3.01	3.04	3.12	9.17
kvar	0.01	0.08	0.04	0.13
pf	1.00	1.00	1.00	1.00

Table 45 – Motor data set and gains for motor 26

MOTOR 26

Description	
Air Conditioner Unit	9
Motor Name	Condenser Fan 1
Rated Real Power (kw)	5.60
% of Rated Loading	71.1%

Capacitor Data Set

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	258.4	260.5	259.7	259.5
amp	2.96	2.97	2.98	2.97
kvar	0.76	0.77	0.77	2.30
Rated Reactive Power (kvar)				3.0
Reactive Power Deviation				-12.6%

Analysis	
Branch Resistance (ohms)	3.09
Ohmic Loss Reduction	41.9%
Voltage Elevation	0.33%
Power Factor Elevation	0.20
RMS Current Reduction (amps)	1.62
Percent RMS Current Reduction	23.8%
Real Power Reduction (kw)	0.18
Percent Real Power Reduction	4.5%

Motor Data Set - Capacitor Off

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	259.3	257.5	261.0	259.3
amp	6.62	6.87	6.93	6.81
kw	1.27	1.36	1.35	3.98
kva	1.72	1.75	1.80	5.27
kvar	1.19	1.14	1.20	3.53
pf	0.72	0.76	0.74	0.74

Motor Data Set - Capacitor On

Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	260.0	259.7	260.7	260.1
amp	5.29	5.00	5.27	5.19
kw	1.27	1.23	1.30	3.80
kva	1.35	1.30	1.36	4.01
kvar	0.36	0.42	0.40	1.18
pf	0.94	0.93	0.94	0.94

Table 46 – Motor data set and gains for motor 27

MOTOR 27

Description	
Air Conditioner Unit	9
Motor Name	Supply Fan
Rated Real Power (kw)	11.19
% of Rated Loading	44.2%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.4	265.8	268.7	267.3
amp	5.52	5.51	5.50	5.51
kvar	1.44	1.44	1.46	4.34
Rated Reactive Power (kvar)				5.0
Reactive Power Deviation				-6.7%

Analysis	
Branch Resistance (ohms)	2.72
Ohmic Loss Reduction	54.1%
Voltage Elevation	2.88%
Power Factor Elevation	0.28
RMS Current Reduction (amps)	3.03
Percent RMS Current Reduction	32.2%
Real Power Reduction (kw)	0.39
Percent Real Power Reduction	7.9%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	259.7	261.1	261.7	260.8
amp	9.00	9.64	9.55	9.40
kw	1.67	1.67	1.61	4.95
kva	2.38	2.53	2.51	7.42
kvar	1.70	1.90	1.90	5.50
pf	0.63	0.61	0.60	0.61

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.4	267.9	269.7	268.3
amp	5.50	6.00	7.60	6.37
kw	1.37	1.39	1.80	4.56
kva	1.40	1.70	2.00	5.10
kvar	0.55	0.84	0.65	2.04
pf	0.91	0.85	0.93	0.90

Table 47 – Motor data set and gains for motor 28

MOTOR 28

Description	
Air Conditioner Unit	10
Motor Name	Condenser Fan 1
Rated Real Power (kw)	5.60
% of Rated Loading	71.0%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.6	264.9	265.8	265.4
amp	3.16	3.13	3.23	3.17
kvar	0.82	0.82	0.85	2.49
Rated Reactive Power (kvar)				3.0
Reactive Power Deviation				-9.5%

Analysis	
Branch Resistance (ohms)	3.49
Ohmic Loss Reduction	44.8%
Voltage Elevation	3.51%
Power Factor Elevation	0.23
RMS Current Reduction (amps)	1.76
Percent RMS Current Reduction	25.7%
Real Power Reduction (kw)	0.22
Percent Real Power Reduction	5.5%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	259.7	260.8	254.1	258.2
amp	6.73	6.90	6.93	6.85
kw	1.33	1.30	1.34	3.97
kva	1.77	1.78	1.81	5.36
kvar	1.25	1.23	1.23	3.71
pf	0.70	0.71	0.71	0.71

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	264.2	268.9	268.7	267.3
amp	4.96	5.16	5.16	5.09
kw	1.22	1.24	1.29	3.75
kva	1.30	1.36	1.38	4.04
kvar	0.38	0.48	0.45	1.31
pf	0.95	0.93	0.94	0.94

Table 48 – Motor data set and gains for motor 29

MOTOR 29

Description	
Air Conditioner Unit	10
Motor Name	Supply Fan
Rated Real Power (kw)	11.19
% of Rated Loading	49.2%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	263.6	262.5	263.4	263.2
amp	5.53	5.32	5.44	5.43
kvar	1.43	1.36	1.40	4.19
Rated Reactive Power (kvar)				5.0
Reactive Power Deviation				-7.1%

Analysis	
Branch Resistance (ohms)	2.07
Ohmic Loss Reduction	52.3%
Voltage Elevation	1.60%
Power Factor Elevation	0.27
RMS Current Reduction (amps)	3.02
Percent RMS Current Reduction	30.9%
Real Power Reduction (kw)	0.31
Percent Real Power Reduction	5.6%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	263.6	264.2	264.1	264.0
amp	9.66	9.76	9.90	9.77
kw	1.81	1.81	1.89	5.51
kva	2.55	2.59	2.61	7.75
kvar	1.80	1.87	1.86	5.53
pf	0.69	0.68	0.70	0.69

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	267.9	267.9	268.8	268.2
amp	6.43	6.72	7.11	6.75
kw	1.66	1.70	1.84	5.20
kva	1.71	1.77	1.89	5.37
kvar	0.37	0.53	0.44	1.34
pf	0.97	0.95	0.96	0.96

Table 49 – Motor data set and gains for motor 30

MOTOR 30

Description	
Air Conditioner Unit	Air Compressor
Motor Name	Qunicy 2
Rated Real Power (kw)	74.60
% of Rated Loading	100.4%

Capacitor Data Set				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	265.4	265.9	263.3	264.9
amp	27.44	27.68	27.02	27.38
kvar	7.24	7.30	6.97	21.51
Rated Reactive Power (kvar)				25.0
Reactive Power Deviation				-5.8%

Analysis	
Branch Resistance (ohms)	0.35
Ohmic Loss Reduction	25.6%
Voltage Elevation	1.52%
Power Factor Elevation	0.09
RMS Current Reduction (amps)	14.83
Percent RMS Current Reduction	13.7%
Real Power Reduction (kw)	3.10
Percent Real Power Reduction	4.1%

Motor Data Set - Capacitor Off				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	260.5	262.0	262.4	261.6
amp	107.90	108.30	107.90	108.03
kw	24.60	25.20	25.10	74.90
kva	28.00	28.30	28.20	84.50
kvar	13.50	13.60	13.60	40.70
pf	0.87	0.88	0.87	0.87

Motor Data Set - Capacitor On				
Quantity	Ph. 1	Ph. 2	Ph. 3	Total
volt	264.5	266.3	266.0	265.6
amp	92.00	94.80	92.80	93.20
kw	23.30	24.50	24.00	71.80
kva	24.40	25.20	24.70	74.30
kvar	6.20	5.80	5.70	17.70
pf	0.96	0.97	0.97	0.97

APPENDIX C

POWER QUALITY METER SPECIFICATIONS

FLUKE 43 POWER QUALITY ANALYZER

Fig. 38. Fluke 43 Power Quality Analyzer

General Specifications

• Power	Line voltage adapter/battery charger included Installed battery: Rechargeable Ni-Cd pack Operating time: 4 hours Charging time: 4 hours
• Environmental	Temperature: 0°C to 50°C (32°F to 122°F) Environmental: MIL 28800E, Type 3, Class III, Style B, Enclosure: IP51 (dust, drip water proof)
• Mechanical Data 2 inches)	Size: (H x W x D) 232 x 115 x 50 mm (9.1 x 4.5 x Weight: 1.1 kg (2.5 lbs)
• Safety installations,	For measurements on 600V rms Category III Pollution Degree 2, per: ANSI/ISA S82.01-1994 EN61010-1 (1993) (IEC1010-1) CAN/CSA-C22.2 No. 1010.1-92 UL3111-1 (approval pending) Surge Protection: 6 kV on input A and B Floating measurements: 600V rms from any

terminal to ground
Warranty: 3 years parts and labor on Fluke 43, 1 year on accessories

Technical Data

• Input Characteristics	Input Impedance: 1MΩ, 20pF Voltage Rating: 600V rms, CAT III
• Volt/Amps/Hertz Display	True-RMS voltage (ac + dc) Ranges: 5.000V, 50.00V, 500.0V, 1250V Accuracy: ±(1% +10 counts) True-rms current (ac + dc) Ranges: 50.00A, 500.0A, 5.000 kA, 50.00 kA Accuracy: ±(1% +10 counts) Mains frequency Ranges: 40.0 to 70.0 Hz Accuracy: ±(0.5% +2 counts)
• Power Display	Watts, VA, VAR Ranges: 250 W, 2.50 kW, 25.0 kW, 250 kW, 2.50 MW, 250 MW Accuracy: ±(4% +4 counts) Power Factor, PF Displacement Power Factor, DPF Range: 0.00 to 0.25 Accuracy: Not specified Range: 0.25 to 1.0 Accuracy: ±0.04
• Harmonics Display	Voltage Ranges: 1st to 51st harmonic Accuracy: ±(3% +2 counts) to ±(15% +5 counts) Current Ranges: 1st to 51st harmonic Accuracy: ±(3% +8 counts) to ±(5% +8 counts) Power Ranges: 1st to 51st harmonic Accuracy: ±(5% +2 counts) to ±(30% +5 counts) Line Frequency Ranges: 40 Hz to 70 Hz fundamental Accuracy: ±0.25 Hz Phase Ranges: 2nd to 51st harmonic Accuracy: ±3° to ±15° k-factor Ranges: 1.0 to 30.0 Accuracy: ±10%

DRANETZ 4300 THREE-PHASE POWER PLATFORM

Fig. 39. Dranetz 4300 Three-Phase Power Platform

• Voltage measurements	4 fully differential channels 10-600Vrms; user selected 0.5-20Vrms on one channel Accuracy: ±1% reading, ±0.05% full scale
• Voltage transients channel	50-1000Vpk; user selected 1-30Vpk on one 1 microsecond minimum duration Accuracy: ±10% reading, ±1% full scale NOTE: Requires TASKCard PQLite H-T, PQLite H-T-M or H-T-E-M
• Current measurements	4 fully independent current channels 10-200% of full-scale current probe rating Accuracy: ±1% reading, ±0.05% full scale (at fundamental, plus current probe accuracy)
• Current transients full scale	10-300% CT full scale except Chan D 2-200% CT 1 microsecond minimum duration Accuracy: ±10% reading, ±1% full scale plus probe

	NOTE: Requires TASKCard PQLite H-T, PQLite H-T-M or H-T-E-M
• Frequency	Fundamental range 16-450 Hz NOTE: for frequencies outside the 50-60Hz range. Accuracy: ±0.2% of reading
• Update rates	All parameters updated once per second (harmonic-based parameters updated every 5 seconds)
• Environment	Temperature: +5°C to +45°C (41°F to 113°F) Humidity: 10% - 90% non-condensing
• Battery	2 hours operation 3 hours full recharge (continuous operation from battery eliminator)
• PC Software Package	DRANVIEW
• Latest released version	PQLite V3.5, Task808 V1.2

APPENDIX D

CAPACITOR SIZING LOOKUP TABLE

Table 50 – Look up table for power factor correction

Old PF	**Corrected PF**										
	0.90	**0.91**	**0.92**	**0.93**	**0.94**	**0.95**	**0.96**	**0.97**	**0.98**	**0.99**	**1.00**
0.60	0.849	0.878	0.907	0.938	0.970	1.005	1.042	1.083	1.130	1.191	1.333
0.61	0.815	0.843	0.873	0.904	0.936	0.970	1.007	1.048	1.096	1.157	1.299
0.62	0.781	0.810	0.839	0.870	0.903	0.937	0.974	1.015	1.062	1.123	1.265
0.63	0.748	0.777	0.807	0.837	0.870	0.904	0.941	0.982	1.030	1.090	1.233
0.64	0.716	0.745	0.775	0.805	0.838	0.872	0.909	0.950	0.998	1.058	1.201
0.65	0.685	0.714	0.743	0.774	0.806	0.840	0.877	0.919	0.966	1.027	1.169
0.66	0.654	0.683	0.712	0.743	0.775	0.810	0.847	0.888	0.935	0.996	1.138
0.67	0.624	0.652	0.682	0.713	0.745	0.779	0.816	0.857	0.905	0.966	1.108
0.68	0.594	0.623	0.652	0.683	0.715	0.750	0.787	0.828	0.875	0.936	1.078
0.69	0.565	0.593	0.623	0.654	0.686	0.720	0.757	0.798	0.846	0.907	1.049
0.70	0.536	0.565	0.594	0.625	0.657	0.692	0.729	0.770	0.817	0.878	1.020
0.71	0.508	0.536	0.566	0.597	0.629	0.663	0.700	0.741	0.789	0.849	0.992
0.72	0.480	0.508	0.538	0.569	0.601	0.635	0.672	0.713	0.761	0.821	0.964
0.73	0.452	0.481	0.510	0.541	0.573	0.608	0.645	0.686	0.733	0.794	0.936
0.74	0.425	0.453	0.483	0.514	0.546	0.580	0.617	0.658	0.706	0.766	0.909
0.75	0.398	0.426	0.456	0.487	0.519	0.553	0.590	0.631	0.679	0.739	0.882
0.76	0.371	0.400	0.429	0.460	0.492	0.526	0.563	0.605	0.652	0.713	0.855
0.77	0.344	0.373	0.403	0.433	0.466	0.500	0.537	0.578	0.626	0.686	0.829
0.78	0.318	0.347	0.376	0.407	0.439	0.474	0.511	0.552	0.599	0.660	0.802
0.79	0.292	0.320	0.350	0.381	0.413	0.447	0.484	0.525	0.573	0.634	0.776
0.80	0.266	0.294	0.324	0.355	0.387	0.421	0.458	0.499	0.547	0.608	0.750
0.81	0.240	0.268	0.298	0.329	0.361	0.395	0.432	0.473	0.521	0.581	0.724
0.82	0.214	0.242	0.272	0.303	0.335	0.369	0.406	0.447	0.495	0.556	0.698
0.83	0.188	0.216	0.246	0.277	0.309	0.343	0.380	0.421	0.469	0.530	0.672
0.84	0.162	0.190	0.220	0.251	0.283	0.317	0.354	0.395	0.443	0.503	0.646
0.85	0.135	0.164	0.194	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
0.86	0.109	0.138	0.167	0.198	0.230	0.265	0.302	0.343	0.390	0.451	0.593
0.87	0.082	0.111	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
0.88	0.055	0.084	0.114	0.145	0.177	0.211	0.248	0.289	0.337	0.397	0.540
0.89	0.028	0.057	0.086	0.117	0.149	0.184	0.221	0.262	0.309	0.370	0.512
0.90		0.029	0.058	0.089	0.121	0.156	0.193	0.234	0.281	0.342	0.484
0.91			0.030	0.060	0.093	0.127	0.164	0.205	0.253	0.313	0.456
0.92				0.031	0.063	0.097	0.134	0.175	0.223	0.284	0.426
0.93					0.032	0.067	0.104	0.145	0.192	0.253	0.395
0.94						0.034	0.071	0.112	0.160	0.220	0.363
0.95							0.037	0.078	0.126	0.186	0.329
0.96								0.041	0.089	0.149	0.292
0.97									0.048	0.108	0.251
0.98										0.061	0.203
0.99											0.142

APPENDIX E
NOMENCLATURE

ϕ	Displacement Phase Angle
Ω	Ohm (unit of resistance)
AC	Alternating Current
Hz	Hertz (cycles per second)
I, i	Current
IEEE	Institute of Electrical and Electronics Engineers
IRR	Internal Rate of Return
KVA	Kilovolt-Ampere
KVAR	Kilovolt-Ampere-Reactive
KW	Kilowatt
KWH	Kilowatt-Hour
NEC	National Electrical Code
NEMA	National Electrical Manufacturers Association
NPV	Net Present Value
P	Real Power
PB	Payback
PF	Power Factor
R	Resistance
RMS	Root Mean Square
rpm	Revolutions per Minute
Q	Reactive Power
S	Apparent Power
V, v	Voltage
X	Reactance
Z	Impedance

VITA

William Jeffrey Hillhouse obtained his Bachelor of Science in Physics from Texas A&M University in May of 1999. Being a third-generation alumni, he remained at Texas A&M and entered graduate studies in the Department of Electrical Engineering. He received his Master of Science in August of 2005. His professional interests include industrial facility power distribution systems and power quality issues such as voltage sags and surges, single-phasing, harmonics, and PF correction. He collaborated with the firm *Hillhouse Power Solutions* to acquire the data presented in this thesis.

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