# Solving Power Quality Issues from Large Motor Starts using Fast-Acting Capacitor Bank Assistance

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***Abstract* – Starting a large motor, even with modern soft-start equipment, is frequently problematic. With ever increasing focus on power quality, an electric utility can experience voltage sag problems when an industrial customer installs a large motor (400 - 2500 HP). Other customers can be adversely affected as well as the company with the motor(s). Of course, the utility is generally blamed by both.**

**Solving these problems is not trivial. Capacitor assistance can be a viable and relatively inexpensive solution but it must be done correctly. This paper discusses the benefits (both for customers and for the utility), techniques, problems, relative costs and savings, alternatives, and analysis of capacitor assisted motor starting. Examples of actual installations and case studies will be shown.**

***Index Terms* – Motor start, capacitor assistance, soft start, voltage sag, voltage fluctuation, voltage surge, power quality, zero voltage closing.**

## I. Nomenclature

**Large motor –** For the purposes of this paper a large motor is any induction ac machine which causes a drop in voltage at its point of delivery of more than 6% during startup.
**Motor startup** – The time, usually between 10 and 40 seconds, required to bring the motor from 0 to full speed.
**Soft-Starter** – A device that reduces and in some cases varies voltage applied to the motor during startup.
**VFD (Variable Frequency Drive) –** A device for controlling a running motor's speed.
**PLC (Programmable Logic Controller)** – A user programmable control device with a variety of inputs, outputs and timers. It is usually programmed using Ladder Logic.
**IED (Intelligent Electronic Device)** – Sometimes called a Relay, it is a user programmable control device with relatively specific functionality. Like the PLC, it has inputs, outputs and timers. It is usually programmed by adding and modifying logic equations. For the purposes of clarity and brevity this paper will refer to it as a PLC. When PLC is used, it generally will mean that a PLC or an IED or some other logic device may be used.
**ZVC (Zero Voltage Closing)** – A technique employed in some capacitor controllers that causes the capacitor switches to close precisely as the voltage waveform on each phase is passing through the zero voltage point.

## II. Introduction

The need to start large motors is a fact of life. Their operation enriches our lives in countless ways. In order for them to operate, of course, they have to start. But starting a large motor is frequently problematic. This is because, all too often, the distribution system is sized adequately for running the large motors but not for starting them. Problem severity can range from minor irritations to complete disruption of normal operation.

This paper will examine the problems and their causes. It will look at some of the viable solutions with their relative costs, advantages and disadvantages. It will also show techniques for analyzing and applying capacitor assistance to motor starts and give some case studies to illustrate these techniques.

## III. Problems

Large motors frequently cause problems at startup for the owner, for other electric utility customers, and for the electric utility itself. Most of these are a direct result of the high current draw of the starting motor but a few are secondary in nature.

### A. *Problems for the Motor Owner/Operator*

Many times the first indications of startup problems are noticed by the organization that has the motor. They can include:

- Perceptible annoying, voltage sags that occur when current is sufficient to cause significant voltage drop between the source and the load.
- Interference with other equipment such as VFDs, electronic controls, etc. that can happen with devices that are sensitive to supply voltage.
- Long startups, repeated startups, and inability to achieve start. These are all due to excessive voltage sag. They are indications that the line is not sized properly for starting the installed motor.
- Motor overheating – usually the result of repeated attempts to achieve start.

- Lost production – naturally occurring when motor start is delayed or not achievable.

### B. Problems for other Utility Customers

Third party customers, unlike the utility and the motor owner have no vested interest in whether the motor runs or not. They just want good power quality. These problems are complaint generators.

- Perceptible voltage sags – very annoying, particularly to residential customers. This is by far the most common complaint.
- Resetting of devices with clocks – can occur if the sag and or dv/dt is sufficient to interfere with sensitive equipment.
- Damage to electronic appliances – can occur if starting assistance capacitors remain energized after motor comes up to speed because of the resulting voltage surge.

### C. Problems for the Electric Utility

Most of the utility's problems are political and financial in nature.

- Having to deal with customer's complaints – by definition a problem.
- A large motor owner/operator that is difficult to work with – one of the most difficult issues.
- Loss of revenue that occurs if the motor cannot be started.
- Potential loss of customers.

## IV. CAUSES

Before addressing these issues and finding solutions, the causes need to be quantified and understood. The high current draw from the motor start is due to the nature of the load placed on the line as the motor begins to turn and comes up to speed. They can be placed into three major categories: Annoyance phenomena, difficulty starting the primary machine(s), and electrical interference with other equipment.

### A. Annoyance Phenomena

According to numerous studies [1] voltage sags or blinks which exceed 6% are objectionable to people. Fluctuations that happen less than once per hour and less than 6% are reasonably acceptable. At a rate of less than one per hour and 3% or less, they are virtually unnoticeable.

Large motors are almost never started more than once per hour unless they require multiple tries to achieve start. However, they can cause considerably more than a 6% dip in voltage. Clearly, this sag is a cause of customer irritation and thus complaints.

The cause of the sag is the current drawn by the motor as it starts. Full voltage starting current is between 6 and 7 times full load current. Even with a soft starter, peak current during start is at least 3 times full load current. This current draw does not diminish significantly until the motor reaches around 90% full speed. The effect on the distribution line is worse when the motor load is far from the substation because of the increased conductor impedance. Since a large contributor to the line impedance is reactive, increasing conductor size is not usually a solution.

### B. Difficulty Starting the Primary Machine

Long starting times or downright inability to start the motor is a direct result of the voltage being too low. There is always a voltage below which the motor will not start (usually around 60% of full voltage). If a soft-starter is already reducing voltage, the combination with the distribution line drop can make for difficulty starting.

Motor acceleration is proportional to the difference in torque applied by current in the windings and the load torque. This is complicated by the fact that a completely unloaded motor still needs significant current (usually around 33% of full load amps) [2]. Torque at any given speed is proportional to voltage squared. Fig. 1 shows a typical set of torque curves for an induction machine.

For each voltage curve in Fig. 1 the accelerating torque is the difference between the solid line and the load torque (dashed) line. Note that for 50% voltage, while the motor will start turning initially, at around 45% of synchronous, acceleration goes to zero. It can never reach full speed. At 35% voltage, the motor will not start at all.

### C. Electrical Interference with other Equipment

Many types of industrial electronic controllers, particularly VFDs, are very sensitive to voltage excursions outside their normal operating power tolerance. This type of small to medium size motor control equipment is frequently observed to experience self-imposed shutdowns when a nearby large motor is starting.

The main reason that current is so high and torque is so low during startup is that the locked rotor power factor is very low, usually around 10%. This means that only a small fraction of the current is actually producing real kW, i.e. torque. The rest is kVAr and only produces energy in the distribution lines as $I^2R$ loss.

## V. SOLUTIONS

It usually (although not always) falls to the electric utility to find solutions to motor start problems. Solutions must be tailored to the particular combination of utility construction and customer equipment. Most solutions involve the reduction of current required from the source.

They are almost always unique and usually require engineering analysis to produce good results. The use of plain old common sense cannot be overstressed.

There are typically several alternatives when it comes to solutions. Those listed below assume that the motor owner is cooperative and is willing to do everything possible to mitigate the problems. This includes using a soft-starter, employing engineering services, complying with recommendations, etc.

### *A. Using Higher Voltage*

This solution involves an increase in distribution voltage level such as going from 12.5 kV to 25 kV, not just stepping the voltage regulators up a little. It is very effective because it cuts the current in half and usually involves new line. However, it can be very expensive, usually in the hundreds of thousands of dollars. Normally the customer is also required to make expensive changes. It is not often a viable option unless the higher voltage is already part of a planned project.

### *B. Rebuilding the Line with Larger Conductor*

Larger conductor is less effective than raising the voltage because, with any distance, the inductance of the line contributes a large part of the impedance. This means that it will not have as much effect on voltage drop as reducing current will. This is rarely a viable option.

### *C. Building a new Substation Nearby*

This can be a very effective solution but is usually prohibitive from a cost standpoint unless it was already part of a pre-existing plan. Substation cost is generally in the millions of dollars.

### *D. Using Fast-acting Capacitor Assistance*

Because properly sized, localized capacitors compensate the poor power factor of the starting motor, the current draw from the substation can be drastically reduced during startup. The reduction can be up to 85% of uncompensated current. These solutions need to be designed and analyzed before implementation. Very often small changes are required at commissioning.

This is by far the least expensive option for improving motor start performance. With costs in the tens of thousands of dollars, savings over other methods are easily an order of magnitude or more.

## VI. Fast-acting Capacitor Control Basics

Fast-acting capacitor assistance involves the installation of a switched capacitor bank or banks that can be energized and de-energized in a timely manner. These are usually distribution voltage banks. The switching functions need to be fast-acting for three reasons:

1. At the beginning of startup the capacitors must be energized before the voltage has sagged too much.
2. If multiple switched banks are used the banks must be staged precisely according to pre-determined conditions.
3. The capacitors must be de-energized at the end of startup such that the voltage does not increase beyond tolerable limits.

The fast switching actions require a logic device or controller with inputs, outputs, and timing capability such as a small PLC or an IED. An algorithm must be developed for the controller. There is no universal algorithm because the equipment and solution needs are always different.

The PLC's algorithm acts upon received inputs and internal timers for its functions and decisions. These inputs include:

- Signals from the motor starting equipment
- Load current
- Line Voltage
- Some combination of the above

Signals from the motor starting equipment can be sent via wires, fiber optics, or radio. Load current and line voltage may be measured directly from PTs, CTs and Line Post Sensors if it has that capability or it can receive digital threshold crossing outputs from a current and voltage pre-processor.

Control of the capacitor bank(s) is accomplished by operating mechanical relays or, in some cases, sending signals to a ZVC capacitor control. A ZVC control is recommended when capacitor switching might cause voltage transients that would interfere with the operation of other sensitive electronic equipment. It is also recommended when multiple closely spaced capacitor banks are used in the motor start solution. This is because it eliminates high current discharges between capacitors on the same phase when energizing consecutive banks. High current discharges between capacitors can damage capacitors as well as the switches and they can blow capacitor fuses.

## VII. Capacitor Assistance System Design

The complexity of a fast-acting capacitor assistance system design varies with the nature and severity of the problems being experienced or anticipated. Design of the system generally requires four major efforts:

- Analysis of the subsystem affected by the motor startups
- Engineering a solution
- Implementing the solution

- Modifying the implementation as necessary for satisfactory results

*A. Analysis of the subsystem affected by the motor startups*

It is very important to quantify the electrical parameters of the substation and the feeder that serve the customer with the motor(s). The gathering of accurate data is crucial to engineering a solution. A step by step suggested process is presented:

1. If possible, take substation feeder current and voltage readings immediately before taking motor start readings.
2. Using a portable power analyzer, take motor start readings with the following conditions:
   - Start the motor in normal configuration.
   - Measurement point at a location to get the motor current with no other significant load present.
   - Include current and voltage for each phase with resolution of one cycle.
   - Start the recording before the motor starts and end after the motor is up to speed
3. Obtain accurate information about the applicable subsystem. A suggested list follows:
   - Transmission line primary voltage
   - Substation
     - Transformer size
     - Transformer secondary voltage
     - Total loading
     - Capacitors
     - Regulators / Tap changer
   - Feeder
     - Conductor size and type
     - Sectional variations
     - Overall length
     - Distance to the motor(s)
     - Load distribution
     - Downline capacitors and regulators
   - Motor load
     - Transformer size and secondary voltage
     - Soft-start equipment
     - Motor size, # poles, brand and model number
     - Efficiency and starting power factor
     - Locked rotor amps and full load amps
     - Other pertinent information as available

*B. Engineering a Solution*

Once all the information detailed in sub-section A has been collected, the design process can begin. Start by creating a model using the following suggested steps:

1. Use Power*Tools by SKM Systems Analysis, Inc. or Windmill by Milsoft Utility Solutions to create the model.
2. Model at a minimum the following components:
   - Transmission line
   - Substation transformer
   - Line sections
   - Distributed loads
   - Downline capacitor banks and regulators
   - Motor transformer
   - Soft-starter with bypass contactor
   - Motor(s)
   - Nodes for measurement data placed as needed

   Auto-transformers can be used in place of regulators and soft-starters if they are not available.
3. Run the model
   - Work with the components until the data produced with a model run closely approximates the voltage and current readings taken in sub-section A.
   - The closer the model matches the actual readings, the better the design will be.
   - If the model is not within 2% of the readings, something is wrong. Check for errors. Make adjustments. Use common sense.

Once an accurate model has been created, start to modify it as the first step toward engineering the fast-acting assistance system. There is no set way to engineer this solution. Remember that these steps are only suggestions.

4. Add capacitor banks to the model.
   - A good starting rule of thumb for 12470 volt feeders is:

     C = 0.2 * M * d

     Where:

     C = Total kVAr of the bank(s)
     M = Motor HP
     d = distance from the substation in km
   - Start with a single bank of that size. With the bank energized, run the model with the motor in start mode. Then run it with the motor in run mode. Observe how much voltages vary. Use common sense to determine if multiple banks would be helpful.
   - Try various combinations of two banks energized at various times during the start process.
   - Try a fixed bank at least 1.5 km upline.

When the model seems to produce good results in all modes of motor start and run, and given that timely energizing and de-energizing of the capacitors can be achieved, it is time to begin determination of the PLC algorithm parameters.

If the issues with motor startup are at the motor location, focus should be on voltages there. If, instead, the problems are mainly 3rd party annoyance related, work should be concentrated to optimize power quality along the feeder. Using a spreadsheet will help with calculations:

5. Put the model data into a spreadsheet
   - Run the model using soft-start voltages to produce ramping motor currents as they appeared in the power analyzer readings.
   - Bring on capacitor banks(s) at various points in the current ramp so as to find the best capacitor switching times.
   - If a pre-start signal will be available from the motor start equipment, it is possible that energizing capacitors before the motor starts may be beneficial.
   - Observe model voltages at various points along the feeder.
   - Record all this information in the spreadsheet.
   - Include as many model settings for reference as possible. This will allow reproduction of the data later and can be very helpful when acting on an alternate idea or trying something different.
   - Use the data to make a graph of the modeled feeder voltages during the startup.
   - Use the model to generate graphs for high, normal, and lightly loaded feeder conditions.
   - Work with the capacitor bank sizes and operation times to optimize the design.

### *C. Implementing the Solution*

Once the solution has been engineered it is time to build the equipment that will implement the solution.

The capacitor racks are fairly straight forward and will not be discussed, other than to recommend the use of solenoid operated switches. This is important for timely energization unless capacitors will be energized prior to motor start and for de-energization unless over voltage has been determined not to be a problem after the motor is up to speed.

The PLC needs to be programmed to embody the algorithm created in the solution. It is assumed that the designer has the resources to program the PLC or to have it done.

The fast-acting control will consist of multiple components. Recommendations based on the author's experience with these systems are listed:

- Signals from motor start equipment
  - Freewave FGRIO radio pair
  - Multimode glass fibers
  - Wires not recommended because of vulnerability to lightning.
- Voltage and Current data measurements
  - SEL relay such as a 735 or 2411
  - Various other
- PLC
  - Omron ZEN series controller
  - SEL relay
- Control Devices
  - Mechanical relays
  - ZVC control operated by radio or fiber. These can be found on the internet.

### *D. Modifying the implementation as necessary for satisfactory results*

With the new design in place, once again take readings with the same power analyzer. If the solution is satisfactory, the work is done.

Most of the time, however, there will need to be some improvements. The vast majority of these can simply be done on-site at commissioning time by modifying the algorithm slightly, moving some of the thresholds, or changing some timings.

## VIII. CASE STUDIES

### *A. Case Study #1*

Grayson-Collin Electric Cooperative, Texas May, 2008
6 km of 4/0 AWG from the substation
12470 Volts
Three 500 HP Compressor Motors

This case study shows how easy it is, in some cases, to bring about a successful solution to a large motor startup problem. From start to finish the solution only required about one week. It specifically deals with a situation involving inability to achieve motor start. The method of utilizing signals from starting equipment is introduced.

An Oil & Gas company has a small plant that uses three 500 HP compressors. There are never more than two running at once and rarely more than one. The plant attempted to go on line in May of 2008 but found that it could not start the motors using the constructed line. The cooperative decided to use switched capacitor banks to solve the problem. They wanted to incorporate power factor correction as well as provide starting assistance.

For the assistance capacitor size they used the simple rule of thumb mentioned in Section V, Sub-section 4

kVAr = 0.2 * 500 * 6 = 600 kVAr

For power factor they assumed about 80% in normal running conditions. 500 HP is approximately 373 kW. With a little math it can be seen that the associated reactive load would be about 280 kVAr. They decided to use two 300 kVAr banks to provide the stating assistance and drop one off after the motor was running. If two motors are running they keep both banks on for the power factor correction.

A small PLC was installed with mechanical relays to control the two banks with motor operated oil switches.

The banks were constructed on the same pole. The oil and gas company provided six signals in the form of dry contacts to the PLC consisting of a Start and a Run contact for each compressor. The Start contacts close just prior to motor startup. The Run contacts stay closed as long as the motor is running.

With the capacitor assistance, the oil and gas company never has a problem starting motors and feeder power factor is maintained near unity.

*B. Case Study #2*

DCP Midstream, New Mexico August, 2010
5.5 km of 477 from the substation
12470 Volts
Two 1250 HP Compressor Motors

This case study points out that many times the initial design must be modified in the field. It specifically deals with motor starts causing disruptions in operation of other equipment. The use of radios to pass signals from starting equipment to capacitor controller is also shown.

DCP Midstream needed to install two 1250 HP compressors in a plant in New Mexico. They knew that they would have starting problems with the large motors so they contracted an engineering company to determine how to achieve startup. The engineering company designed a system using two Benshaw soft-starters, and a 1200 kVAr switched capacitor bank with a Zero Voltage Closing control. The reason for including ZVC was that the bank was relatively large and ZVC would help to keep switching transients from affecting existing sensitive electronic equipment.

As designed, the capacitor bank controller employs a small PLC which receives signals from the soft-starters via a pair of Freewave FGRIO radios. These radios pass signals back and forth as if the system is connected with wires. Signals are sent to the PLC which indicate that the soft-starter is in startup mode.

The control scheme was initially designed such that the bank would be energized for the duration of the start of either compressor and would be de-energized when running mode was achieved. This was entirely possible by just employing timing techniques because the Benshaw programming allowed for very precise timing of the voltage and speed ramp.

At commissioning it was discovered that when the capacitors were energized, several running VFD controls that were operating separately stopped their operation for an over-voltage condition. VFDs are known for being very sensitive to voltage fluctuations.

A programming change was made such that the capacitor control PLC would delay energizing capacitors for 2.5 seconds. This allowed the soft-starter to reach sufficient current (with associated voltage drop) so that when the capacitors were energized the voltage would not affect the VFDs.

The change solved the problem and the system is still in operation to this day.

*C. Case Study #3*

Cimarron Electric Cooperative, Oklahoma August 2014
16 km of 1/0 from the substation
12470 Volts
One 400 HP Rock Crusher Motor

This case study is more complex. It details the process of gathering data, modeling the system, and creating a solution. It specifically addresses techniques for avoiding customer dissatisfaction with power quality during motor startups.

In May of 2014 Cimarron Electric had a customer at a gypsum plant that used a 400 HP motor with a solid state soft-starter to drive a rock crushing machine. The plant was served by a very old 17 km transmission line that had been converted for distribution use. There was a problem in that the old line was in a serious state of disrepair and was getting worse. As they saw it they had two options:

1. They could rebuild the existing line for about \$400,000.
2. They could switch the load over to an existing 16 km distribution line with many residential customers.

The first option was unattractive because of the high cost. The problem with the second was that they knew the motor starts were going to cause a lot of grief with the existing customers due to voltage sags. To top it off, the customer closest to the rock crusher was a member of the cooperative's board.

An engineer at one of their equipment distributors suggested the possibility of using fast-acting capacitor assistance to mitigate the voltage issues. Discussions with an engineer who had experience solving large motor start problems, led to the effort to provide a capacitor assistance solution. The engineers took the following design steps:

1. Cycle by cycle measurements of voltage and current were taken during a motor startup.
2. The 16 km feeder with the addition of the gypsum plant was modeled using SKM software.
3. Accuracy of the model was verified by comparison to the measured data.
4. A multi-bank capacitor system was engineered to correct the voltage fluctuations.
5. The design was massaged by modifying bank sizes and placements while re-running the SKM model to achieve the desired results.

Voltage and current measurements showed that the soft-starter ramped voltage from about 10% to 100% voltage over a 10 second period. The bypass contactor came in and the motor took another 8 seconds to come up to speed. During that time the voltage dropped some 12–

14%. This verified that the sag experienced by other customers would not be acceptable. The SKM model also backed this up.

The final design included a fixed bank of 450 kVAr about 3 km up line, and two 600 kVAr switched banks at the plant. Because the switched banks would be only one span apart, the second one incorporated ZVC control to prevent high current discharges between capacitors on the same phase during energization.

Knowing that adding capacitors would raise the voltage, the idea was to bring the capacitors on separately during the voltage ramp so as to saw-tooth the line voltage in such a way that customers would never experience more than the magical 6% variation. By playing with the timing a scheme was worked out that accomplished this.

- If both banks are off and current > 27 amps then energize bank 1
- If one bank is on and current > 55 amps then energize bank 2
- If both banks are on and (current < 50 amps or voltage > 120) then de-energize bank 2
- If one bank is on and (current < 22 amps or voltage > 120) de-energize bank 1

This system was built by the equipment distributor and commissioned. It worked properly from the very start. No modifications to the algorithm were necessary. Since the installation, no customer complaints have been received that can be related to the gypsum plant motor startup.

A spokesperson at Cimarron Electric said that the system had paid for itself 10 times over when compared with the cost of rebuilding the old line.

Fig. 2 and Fig. 3 show the 'before' and 'after' solution data readings. The saw-tooth effect is quite visible during the soft-start ramp. Note that before the solution was implemented, fluctuations exceeded 12%. Afterward they were significantly less than 5%. Bear in mind that voltage fluctuations up line are even less pronounced.

## IX. Conclusion

The startups of large motors frequently cause voltage sag issues due to the heavy currents required. These range from minor 3rd party annoyances to severe problems that can shut down an operation. There are usually several solutions to choose from which vary in complexity, effectiveness, difficulty, and cost. In most cases, fast-acting capacitor assistance provides the quickest and least expensive solution.

While engineering a capacitor assistance solution may seem a daunting task, by understanding the steps outlined above and employing a little ingenuity it can definitely be accomplished.

## Appendix

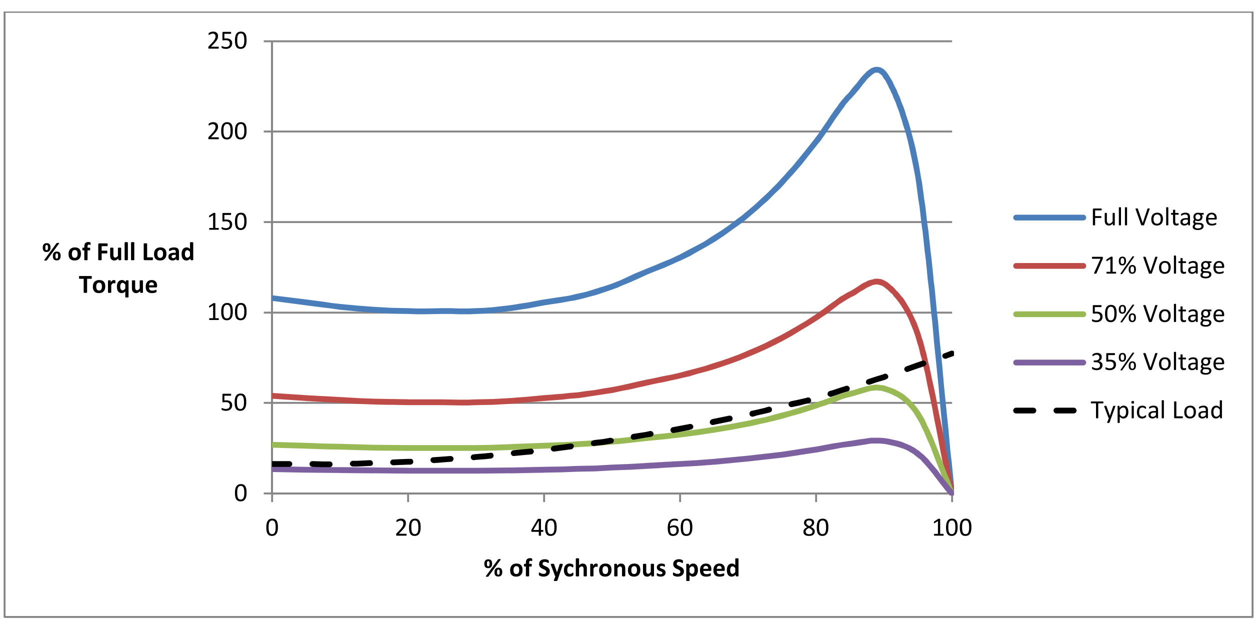


Fig 1. Voltage related torque as a function of motor speed

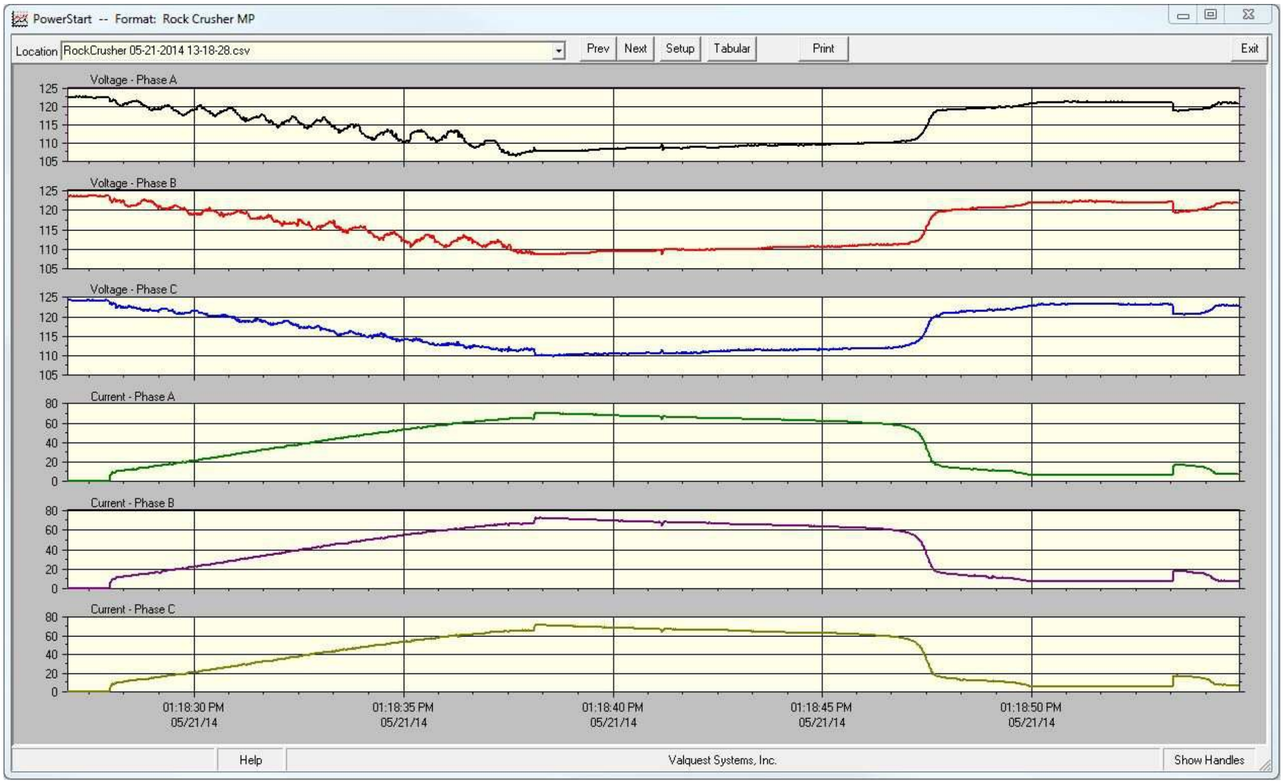


Fig. 2 Voltage and current readings from Case Study #3 before solution

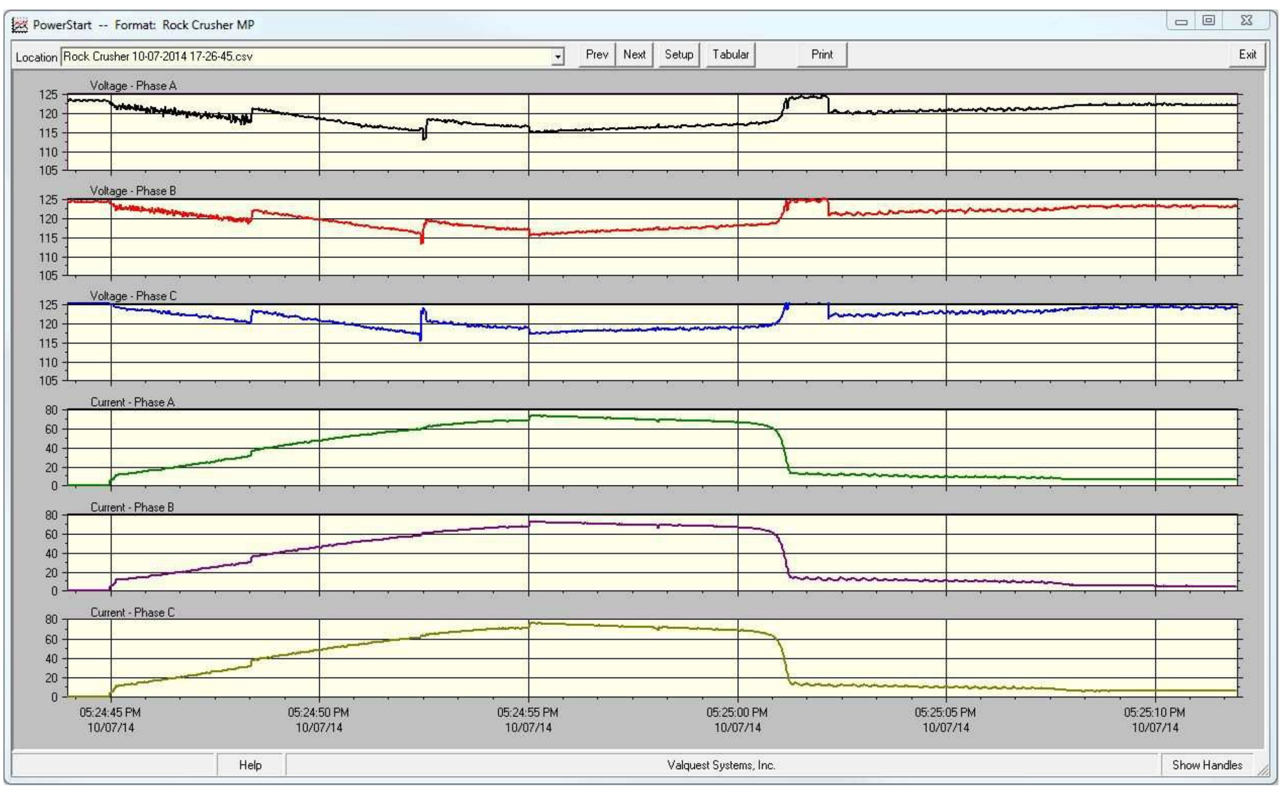


Fig 3. Voltage and current readings from Case Study #3 after solution

## Acknowledgements

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# Large Motor Starts

## Presentation:

- Problems
- Causes
- Solutions
- Capacitor Assistance
- Case Studies

# Large Motor Starts

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## Problems

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# Motor Start Problems

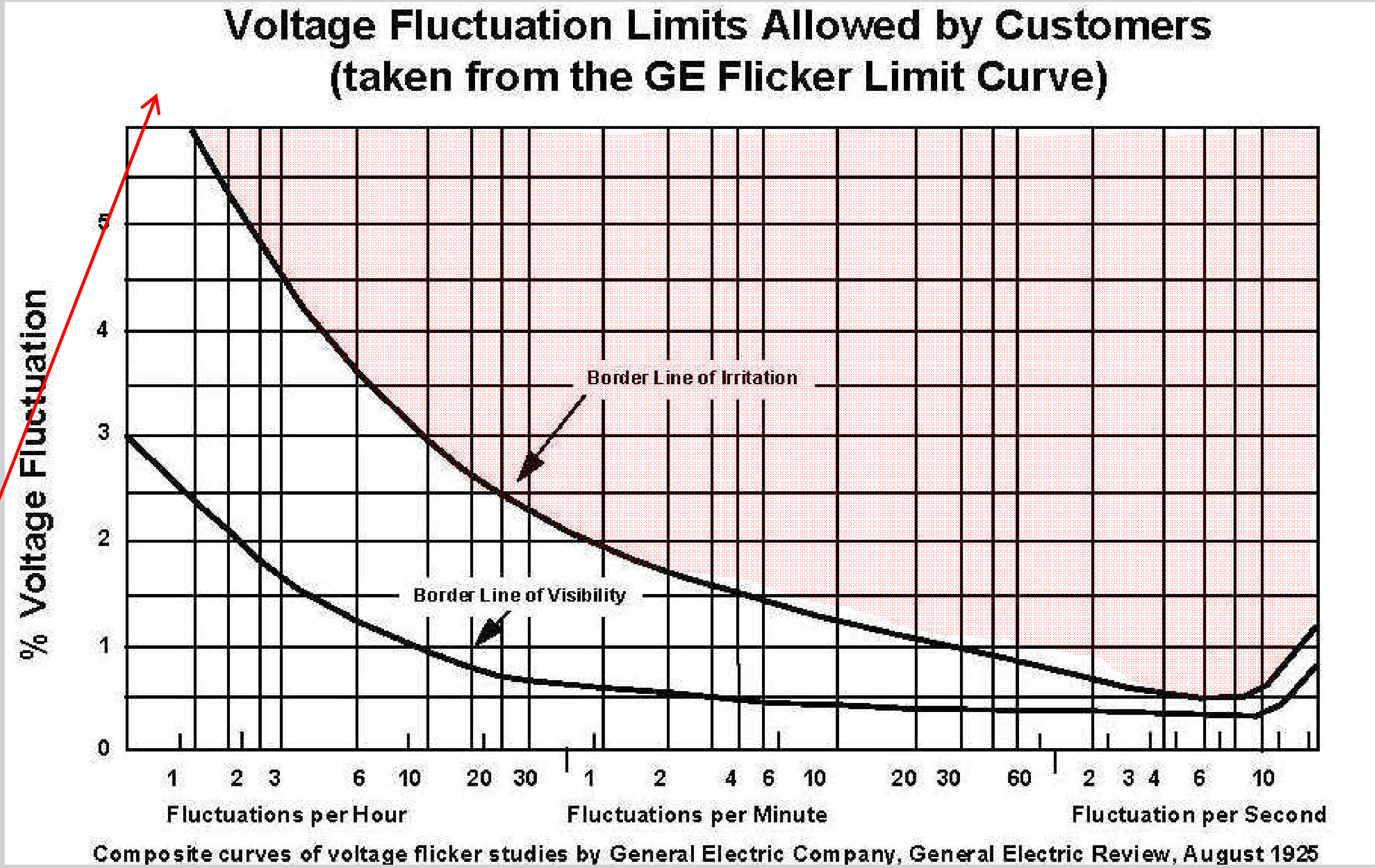
| Problem | Motor Owner | Other Customers | Electric Utility |
|---|---|---|---|
| Annoying Voltage Sags | ✕ | ✕ | |
| Inability to achieve Start | ✕ | | |
| Interference with Equipment | ✕ | ✕ | |
| Long Startups | ✕ | | |
| Motor Overheating | ✕ | | |
| Lost Revenue | ✕ | ✕ | ✕ |
| Damage to Electronic Devices | ✕ | ✕ | |
| Perceived Damage to Devices | | ✕ | |
| Having to deal with Complaints | | | ✕ |
| Legal Issues from Customers | | | ✕ |
| Customers that are Difficult | | | ✕ |
| Loss of Customers | | | ✕ |

# Problems

## Flicker Annoyance

# Motor Start Problems

## Annoyance Phenomena



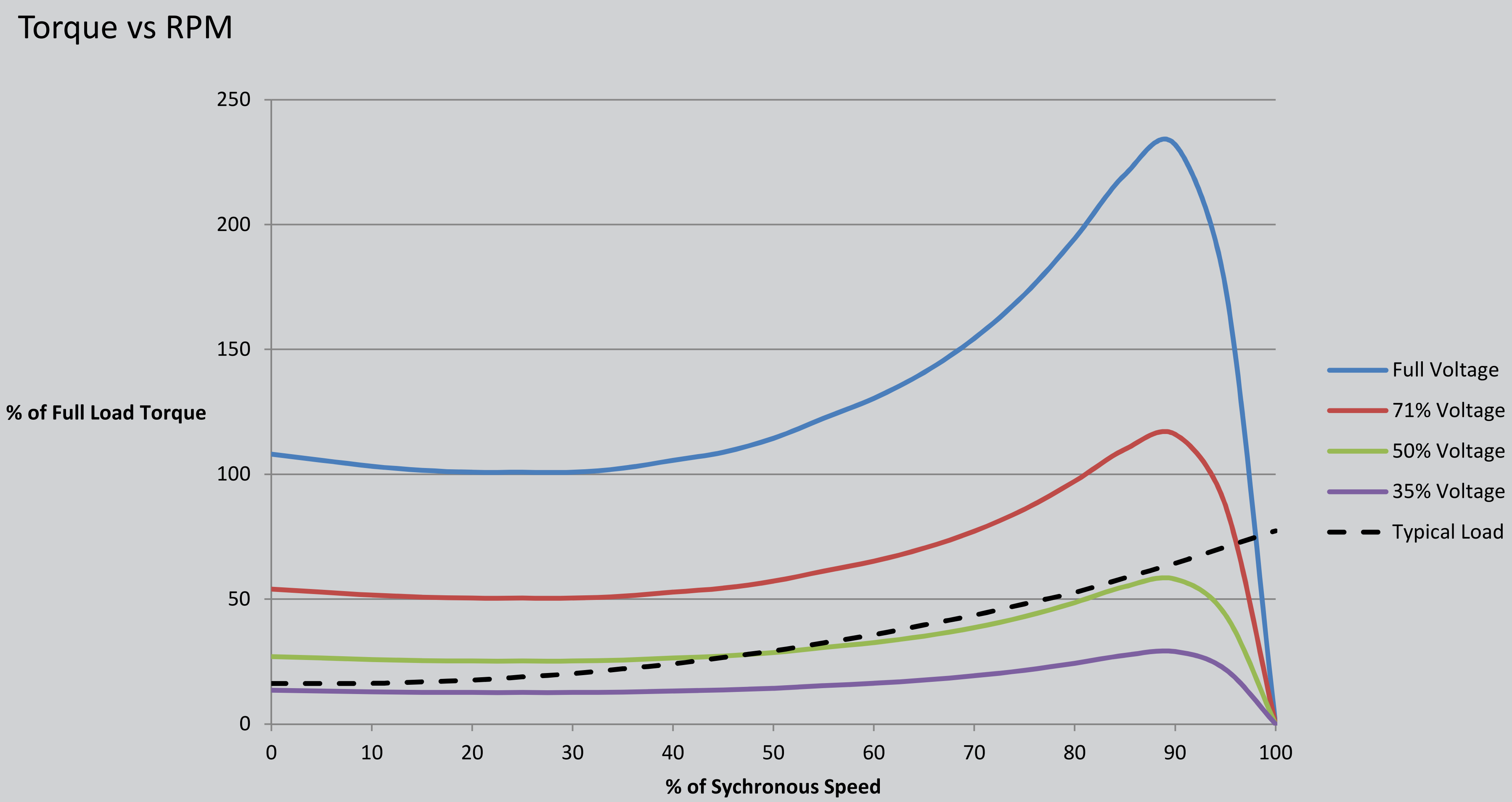

If we can keep the voltage sags < 6% and < once per hour – we're OK.

# Problems

## Starting the Motor

# Motor Start Problems

## Difficulty Starting

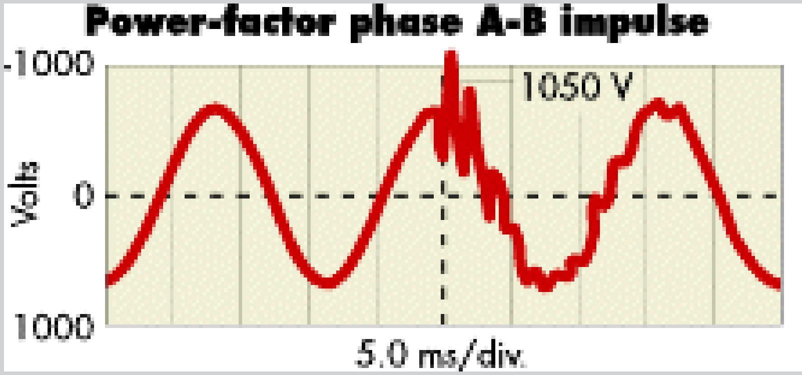


# Problems

## Other Equipment

# Motor Start Problems
## Interference with other Equipment

- **Motor controllers are sensitive to voltage excursions outside their normal tolerance.**




- **Running VFDs can shut down when starting assistance capacitors kick in.**

# Large Motor Starts

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# Causes

# Problem Causality



- Most problems associated with large motor starts come down to voltage sag.

- This sag is a direct result of
  - High current draw

    acting on
  - Distribution line impedance

- In other words: IZ drop *not* IR drop

# Problem Causality

## Line Impedance

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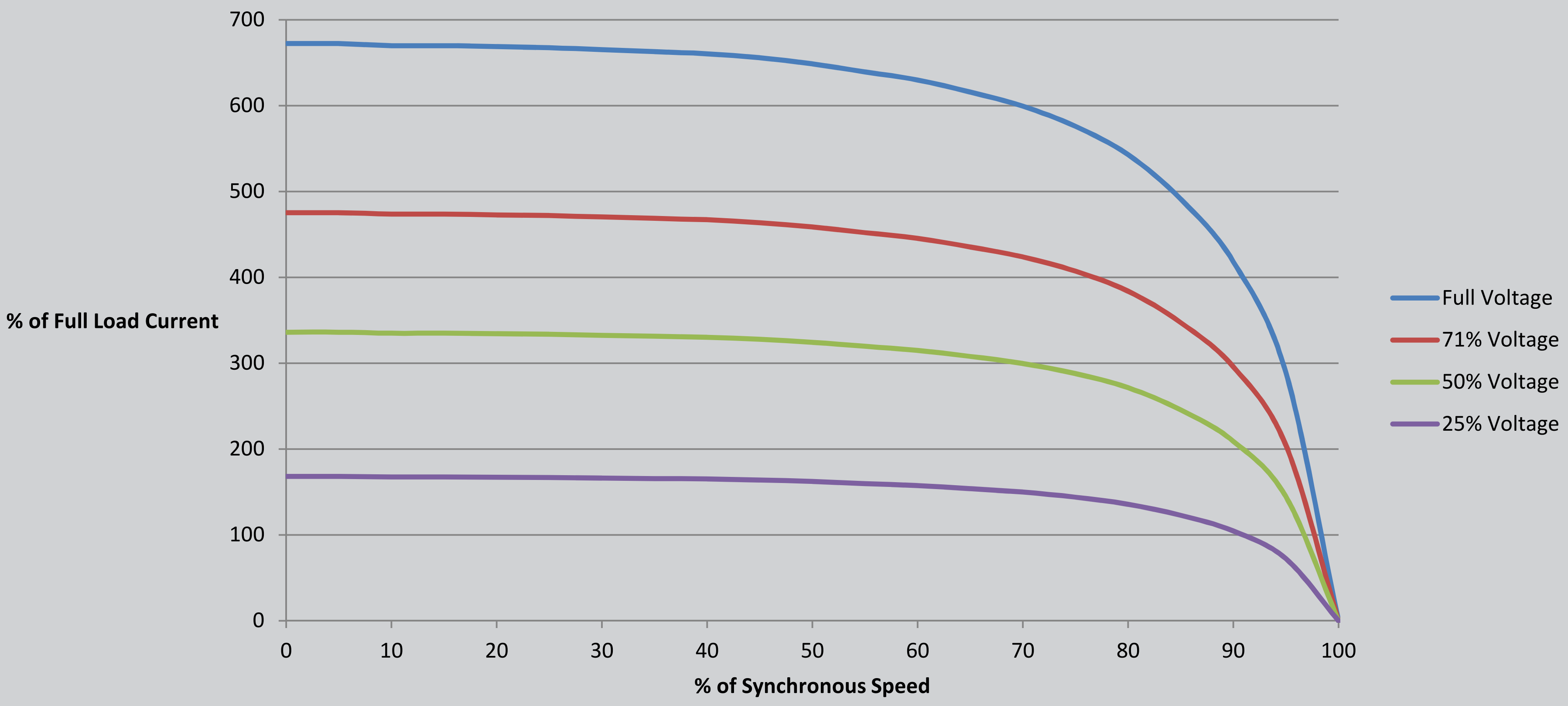
| Conductor ACSR | Resistance R: Ω/mi | Reactance X: Ω/mi | Impedance Z: Ω/mi |
|---|---|---|---|
| #4 | 2.13 | 0.71 | 2.24 |
| 1/0 | 0.84 | 0.66 | 1.07 |
| 2/0 | 0.67 | 0.64 | 0.93 |
| 4/0 | 0.42 | 0.61 | 0.74 |
| 477 | 0.19 | 0.57 | 0.60 |

Above 2/0 : Reactance dominates Impedance

# Problem Causality

## Starting Current

Current vs RPM



# Problem Causality
## Starting Current

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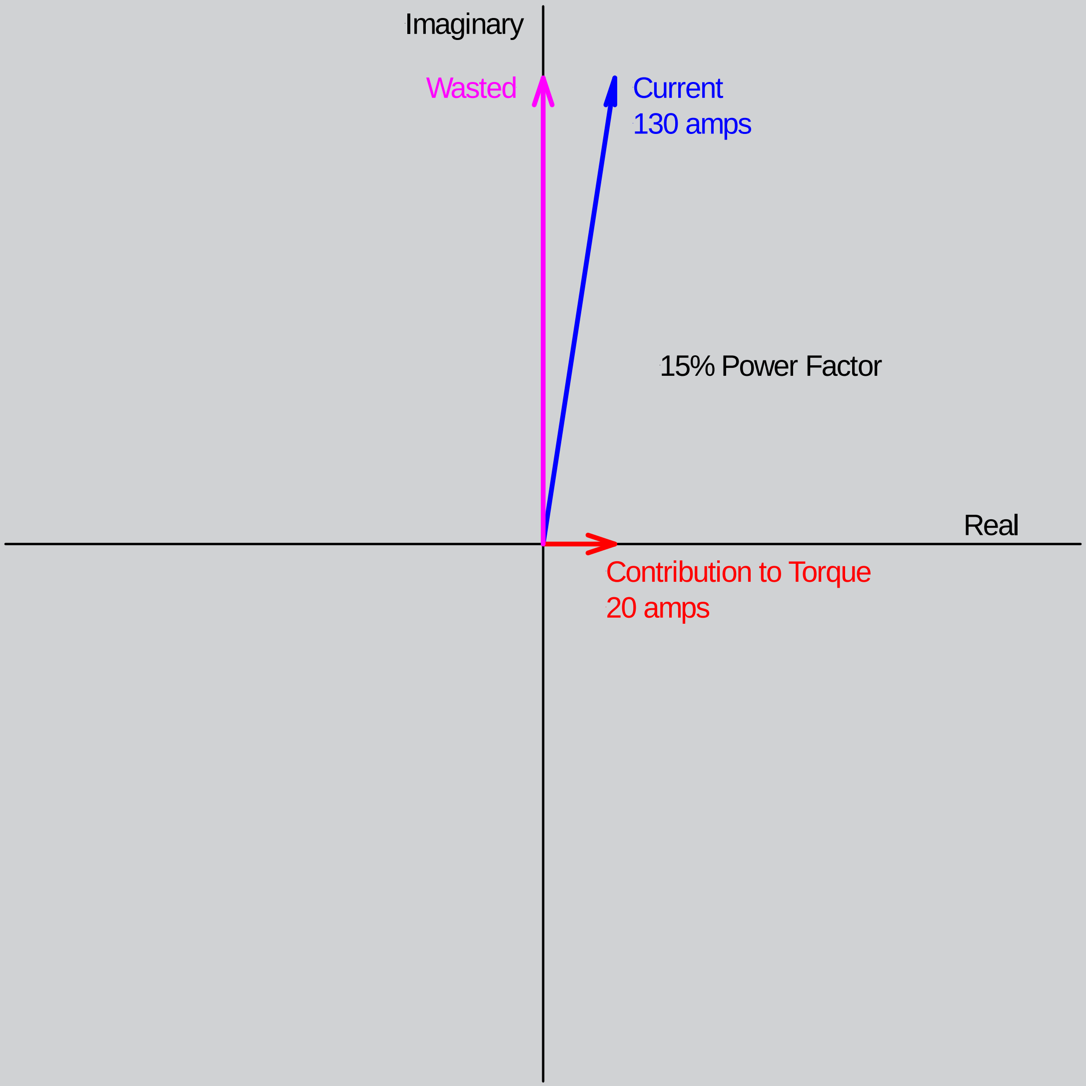
**Why is the current so high at start?**

**(Even at only 50% torque)**

Power Factor

**Power factor of a starting motor is 10%-20%.**

# Problem Causality
## Starting Current



## Large Motor Starts

# Solutions

# Solutions



**It usually falls to the electric utility to find solutions for motor start problems.**

**Most solutions are completely unique.**

# Solutions

**We need to get**

**creative**

**The use of plain old**

**common sense**

**cannot be overstressed**

# Solution Types

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## There are at least four types of solutions

| Type | Effectiveness | Cost |
|---|---|---|
| Larger Conductor | | $$$$$$$$$$ |
| Higher Voltage | | $$$$$$$$$$$$$$ |
| New Substation | | $$$$$$$$$$$$$$$$$$$$$$$$$ |
| Capacitor Assistance | | $ |

# So why would we use capacitors

# ?

# Source Current Reduction

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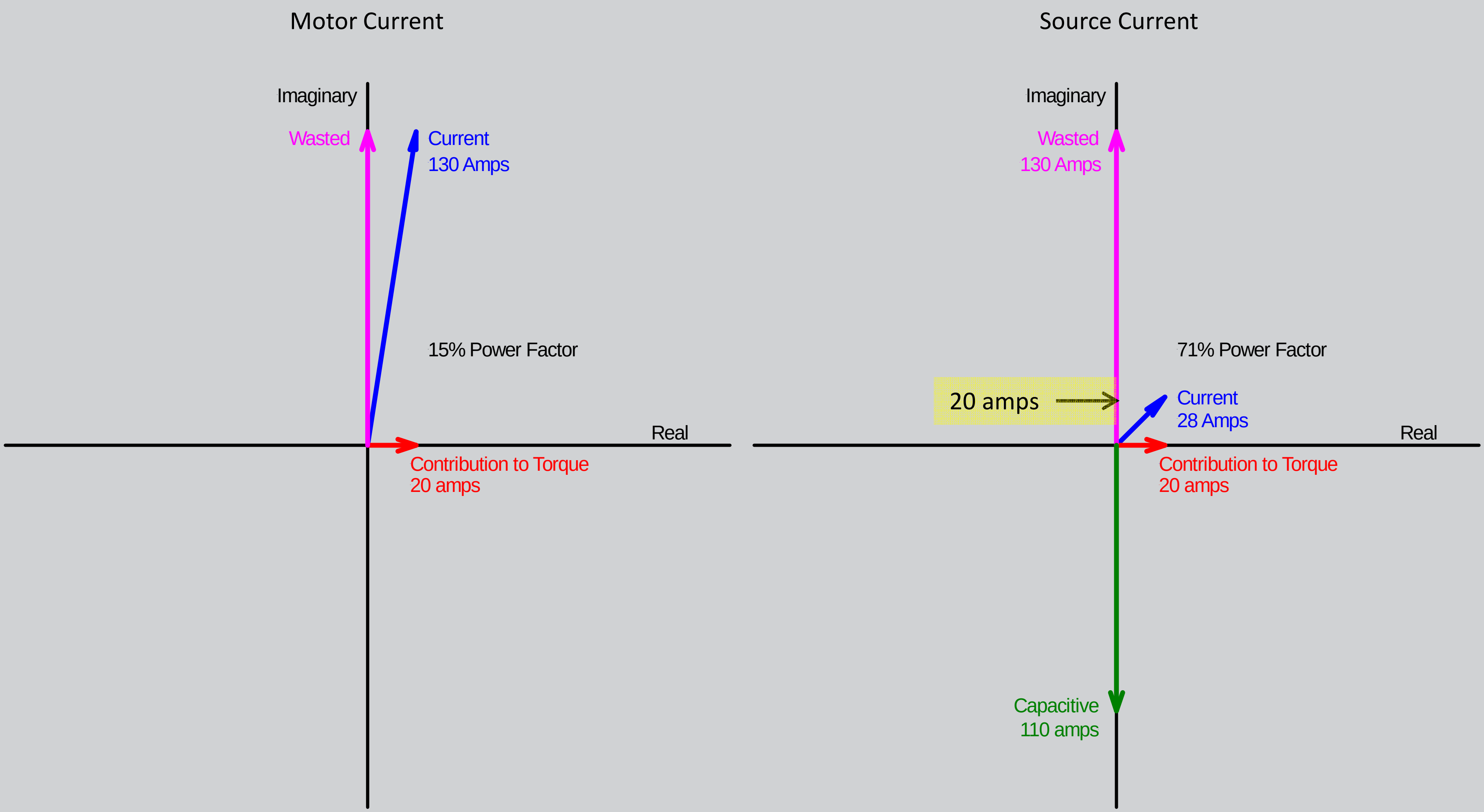
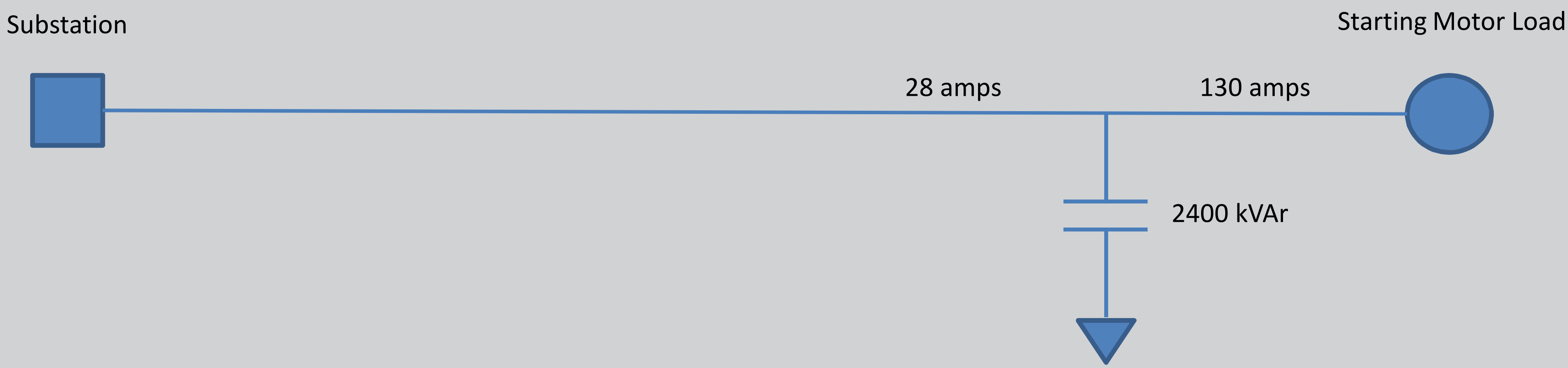


# Source Current Reduction

REPC 2018 MEMPHIS

Another way of looking at it



## Large Motor Starts



# Capacitor Assistance

# Fast-Acting Cap Control Basics

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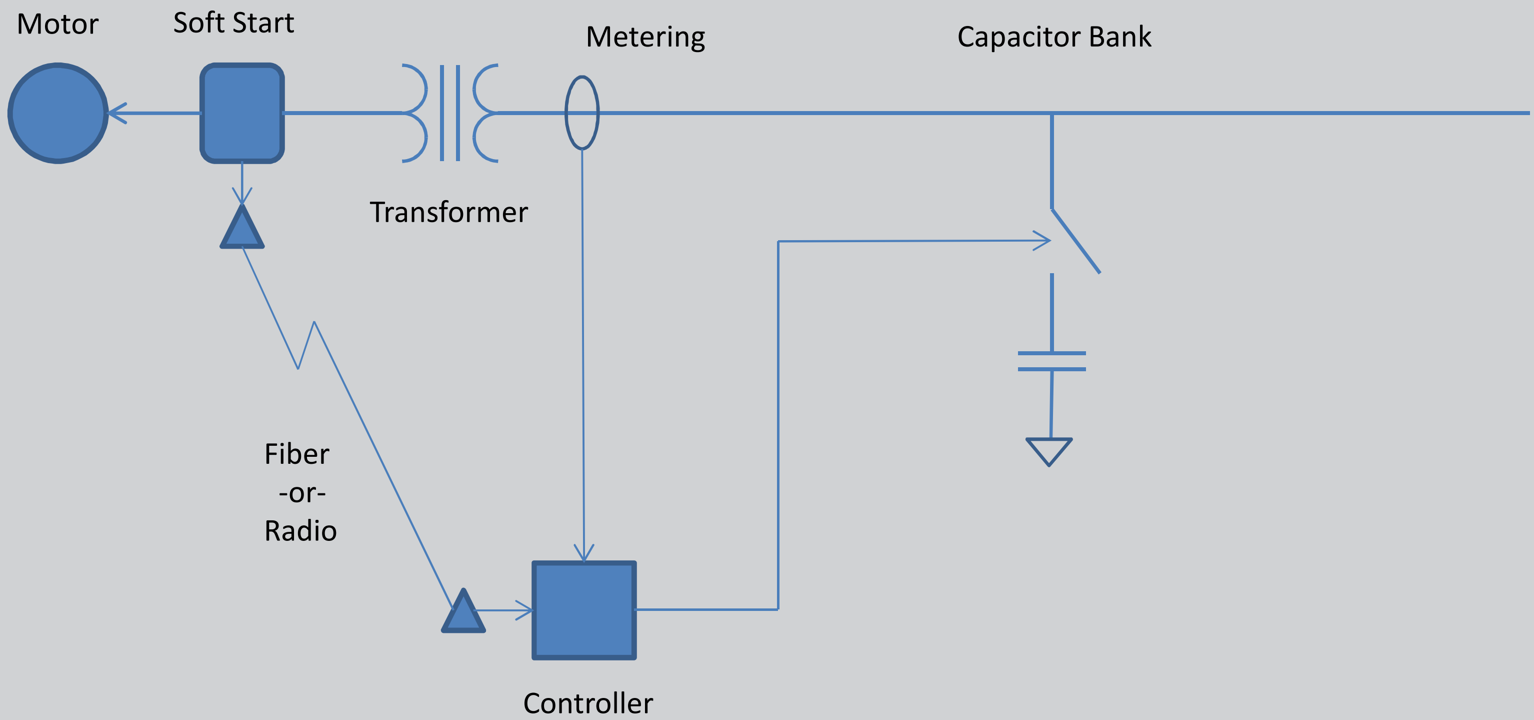
Typical Single Bank Configuration



# Fast-Acting Cap Control Basics

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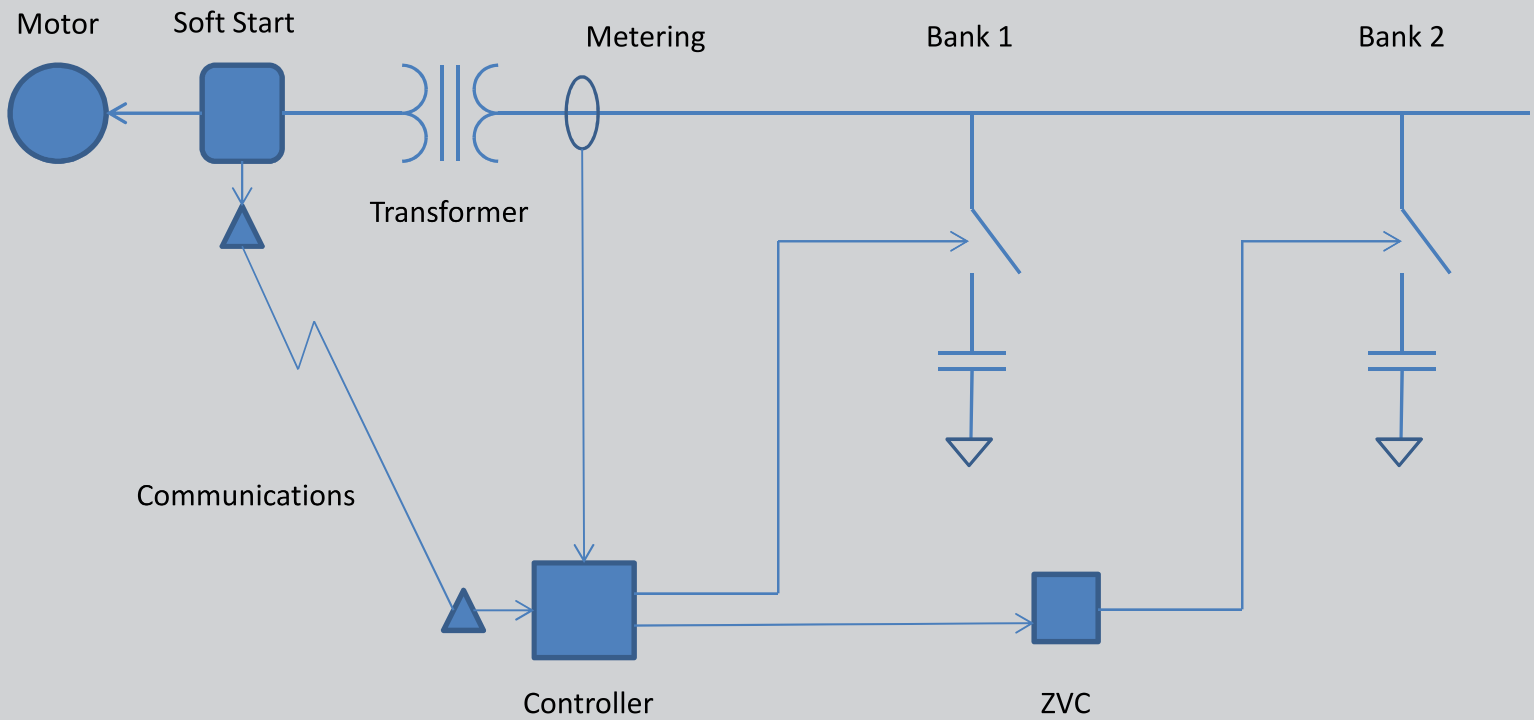
Typical Multiple Bank Configuration



# Capacitor Assistance System Design



## System Design in Four Basic Steps:

A. Analysis

B. Model

C. Build

D. Tweak

# Capacitor Assistance

## A. Analysis

# A. Analysis of the Subsystems Affected by the Motor Startups

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## Feeder Current and Voltage Readings

Voltage: 125.4

Current: 17 amps


At the substation or from SCADA

# A. Analysis of the Subsystems Affected by the Motor Startups

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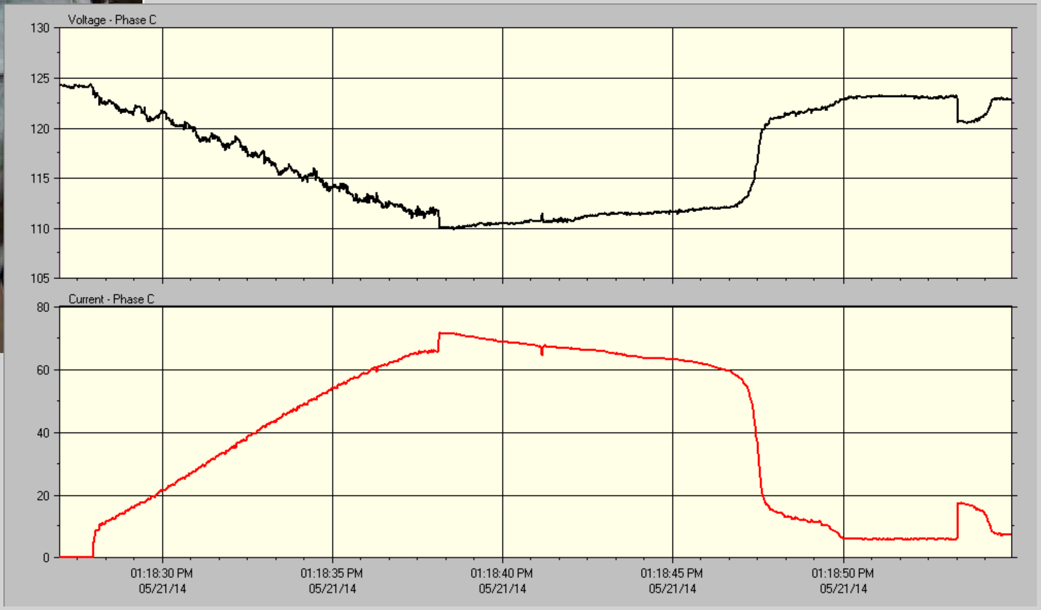
## Motor Start Readings

All 3 phases

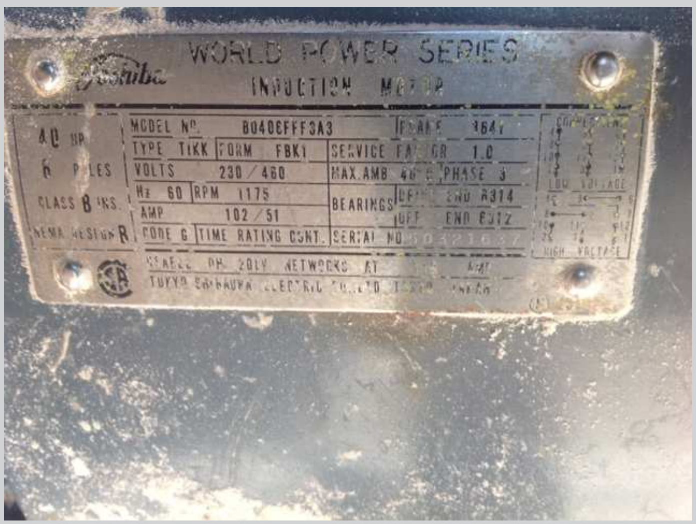


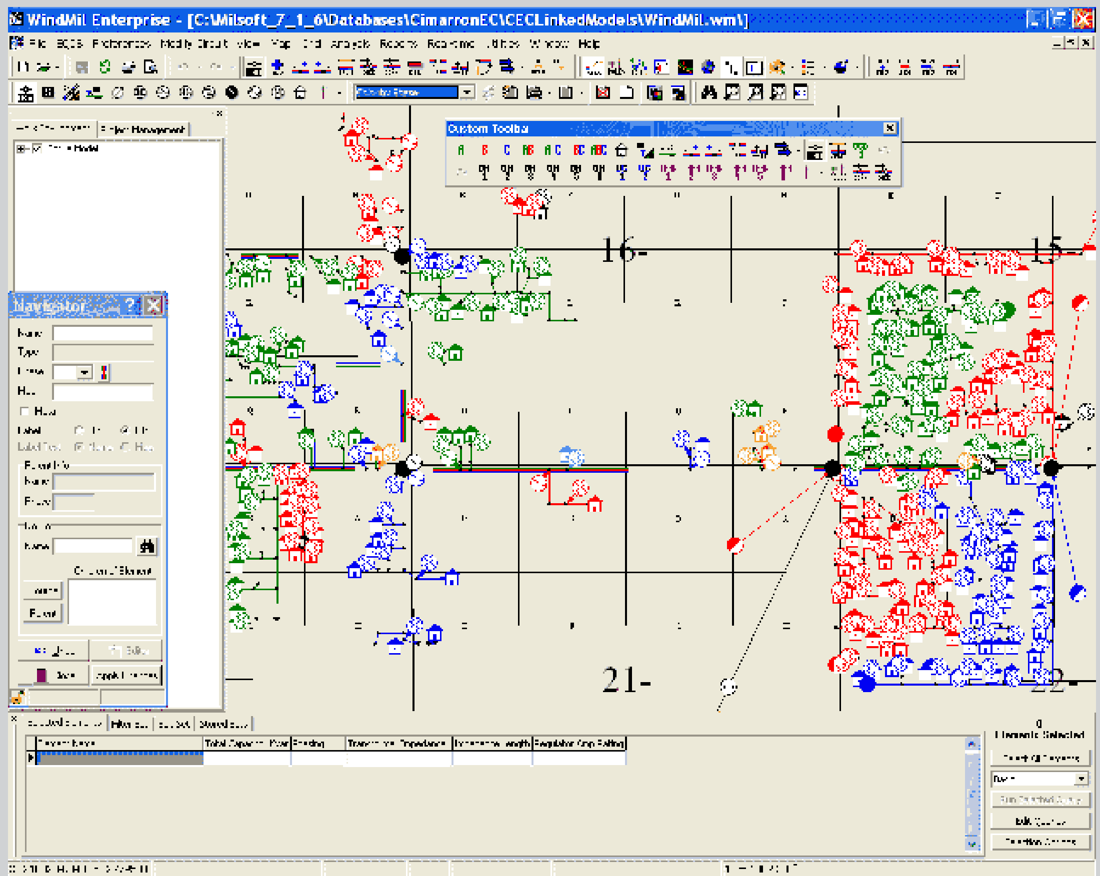

Work Safe!

# A. Analysis of the Subsystems Affected by the Motor Startups



## Information about the Motor Subsystem




Nameplates Maps Models

# Information about the Applicable Subsystem

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- **Substation**
  - Transformer
  - Loading
  - Capacitors
  - Regulators / Tap changer
- **Feeder**
  - Conductor size
  - Sectional variations
  - Overall length
  - Distance to motor(s)
  - Downline Capacitors/Regulators
- **Motor Equipment**
  - Transformer
    - Size
    - Secondary voltage
  - Soft start equipment
  - Motor
    - Size
    - Number of poles
    - Model number
    - Efficiency
    - Starting power factor
    - Locked rotor amps
    - Full load amps
  - Any other pertinent Info

# Capacitor Assistance

## B. Model

# B. Engineering a Solution

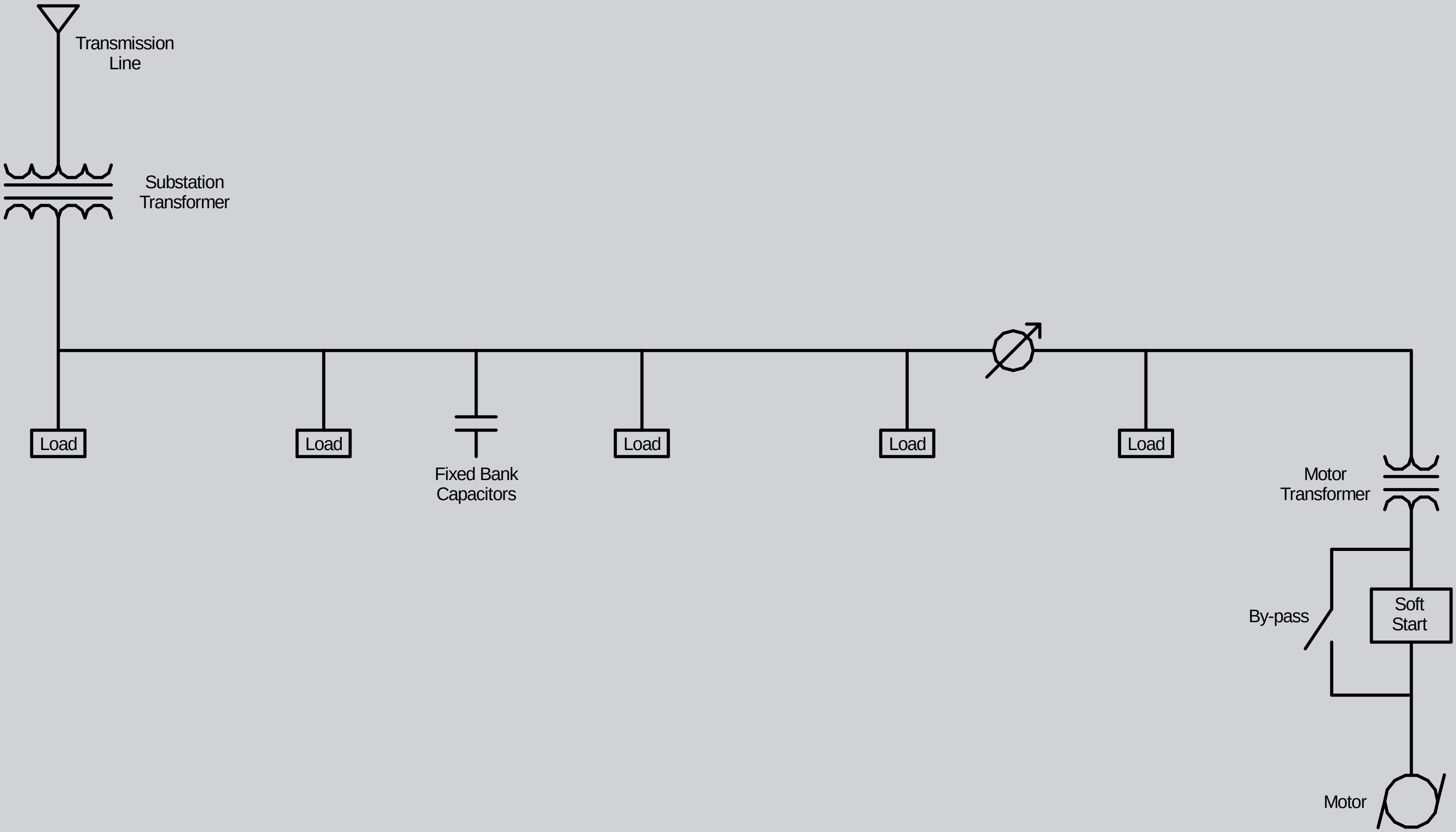


1. **Start by creating a model of the applicable subsystem**
   - **Power Tools** **by SKM Systems Analysis**
   - **WindMil** **by Milsoft Utility Solutions**

# B. Engineering a Solution

IEEE
REPC 2018 MEMPHIS

Typical Model



# B. Engineering a Solution

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2. **Populate the model ← Step A**

- Feeder voltage
- Line sections
- Distributed loads
- Motor Equipment

- Nodes for measurement data

# B. Engineering a Solution

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## 3. Run the model

- Work with the components until the data produced approximates the voltage and current readings in Step A.2
- Model accuracy should be < 2%.
- Do not proceed until the base model accurately matches the real world.

# B. Engineering a Solution



## 4. Put the model data into a spreadsheet

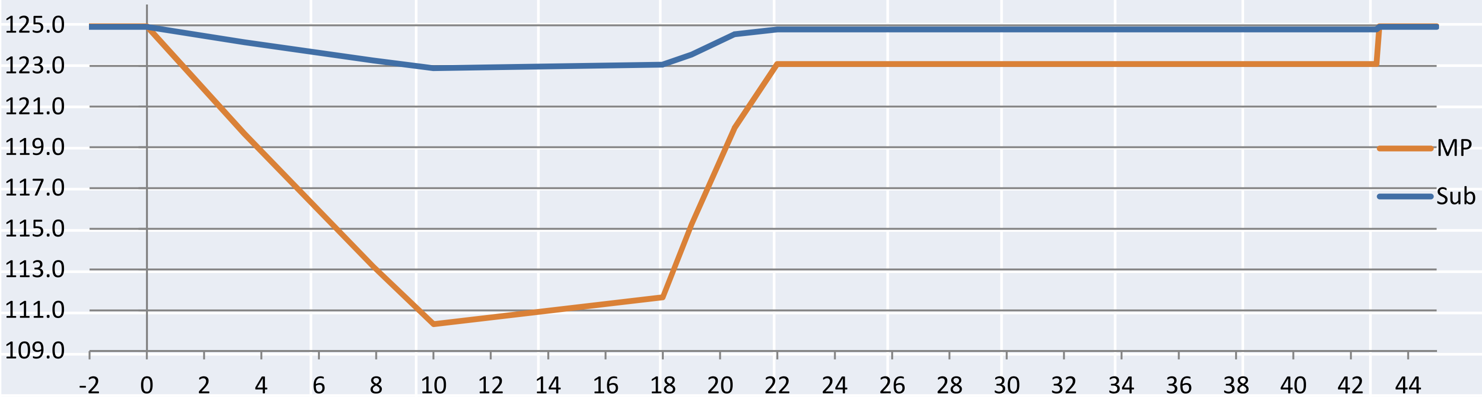
- **Run the model repeatedly to time-model the motor start.**
  - **Vary the soft-start to produce voltage ramping.**
  - **Make the ramp match the power analyzer readings from Step A.**

- **Record voltages and currents in the spreadsheet.**

- **Generate spreadsheet graphs of the model's voltages.**

# B. Engineering a Solution

| Event | Time Secs | Volts Sub | Volts MP | dV Sub | dV MP | Motor HP | Motor State | Primary Sub | Primary MP | Current MP |
|---|---|---|---|---|---|---|---|---|---|---|
| About to Start | -2 | 124.9 | 124.9 | | | | Off | 12981 | 12984 | 0.0 |
| 400 HP Start | 0 | 124.9 | 124.9 | | | | Off | 12981 | 12984 | 0.0 |
| Ramp at 26 A | 3.4 | 124.2 | 119.7 | -0.8 | -5.3 | 92.6 | Start | 12903 | 12435 | 26.0 |
| Ramp at 57 A | 7.9 | 123.3 | 113.1 | -0.9 | -6.5 | 215.1 | Start | 12809 | 11758 | 57.0 |
| Contactor In | 10 | 122.9 | 110.3 | -0.4 | -2.8 | 270 | Start | 12771 | 11465 | 70.0 |
| Entering Linear Region | 18 | 123.1 | 111.6 | -0.2 | 1.3 | 230 | Start | 12788 | 11601 | 64.0 |
| Nearly to speed | 19 | 123.5 | 115.2 | 0.5 | 3.6 | 175 | Start | 12839 | 11974 | 47.2 |
| Motor Running | 20.5 | 124.6 | 119.9 | 1.0 | 4.7 | 435 | Run | 12944 | 12464 | 19.2 |
| Motor Coasting | 22 | 124.8 | 123.1 | 1.2 | 3.2 | 165 | Run | 12968 | 12792 | 7.1 |
| | 42.9 | 124.8 | 123.1 | | | 165 | Run | 12968 | 12792 | 7.1 |
| Motors Off | 43 | 124.9 | 124.9 | | | | Off | 12981 | 12984 | 0.0 |
| | 45 | 124.9 | 124.9 | | | | Off | 12981 | 12984 | 0.0 |



# B. Engineering a Solution

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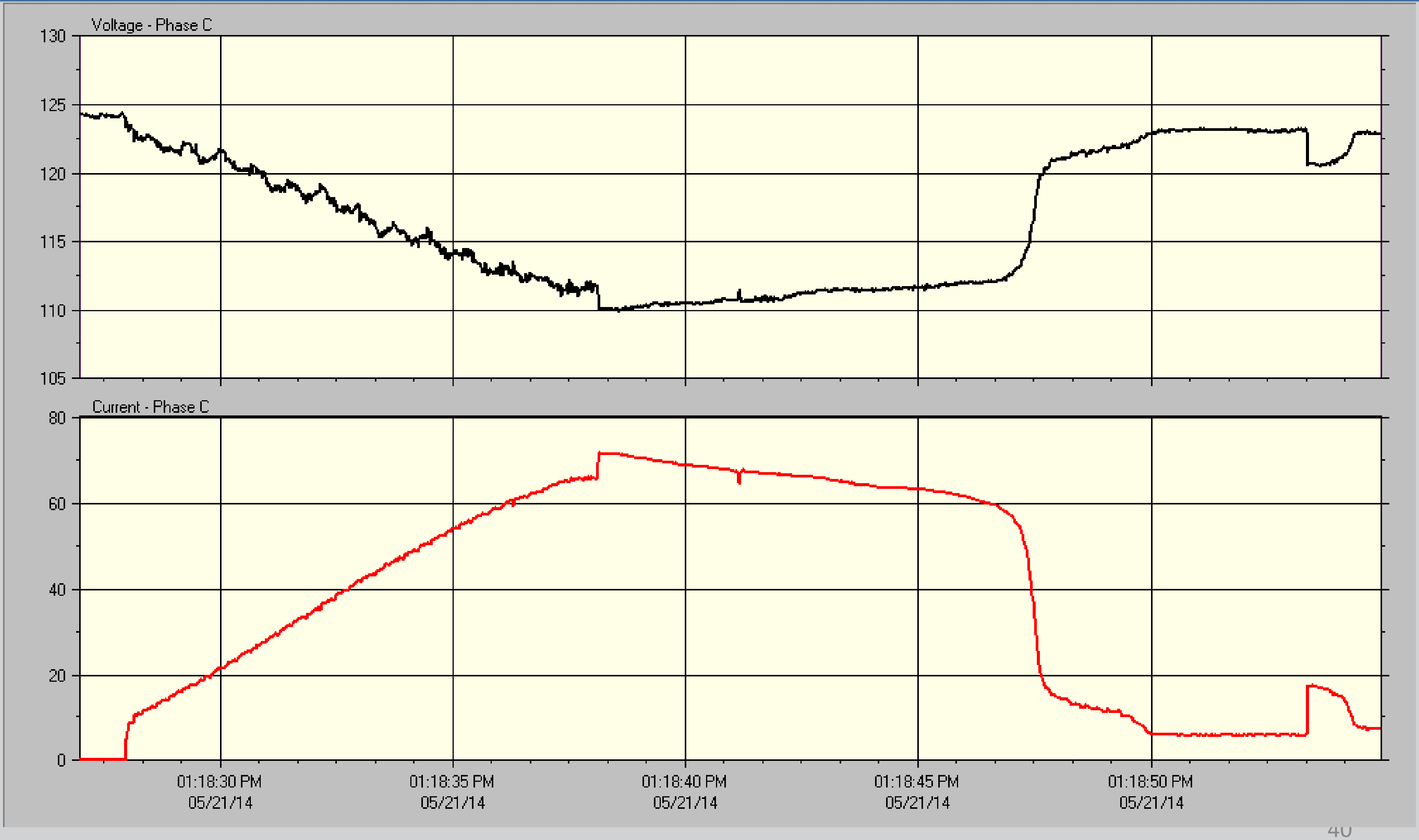


Motor Start Readings

# B. Engineering a Solution

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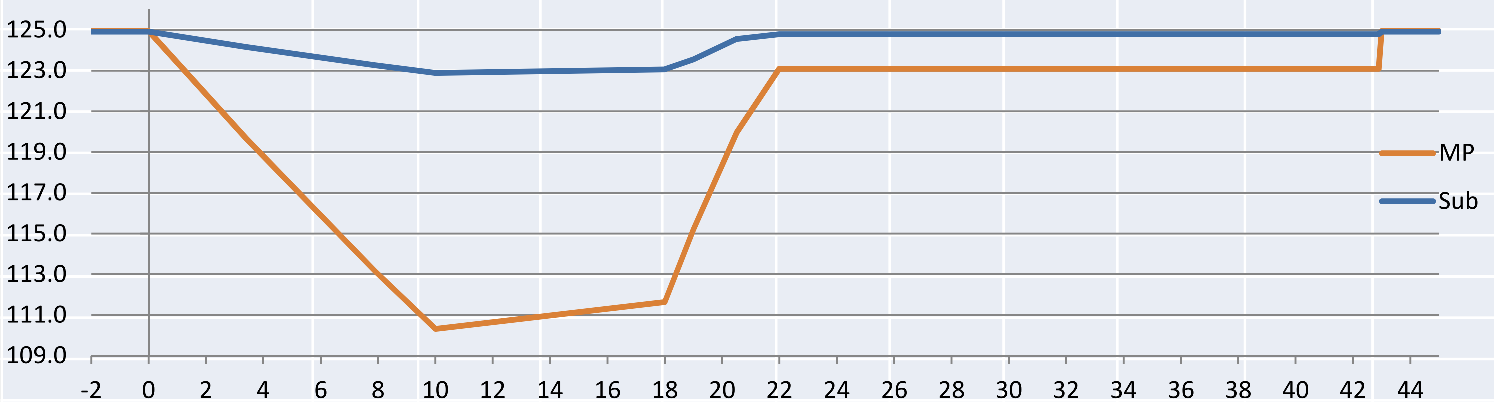
| Event | Time Secs | Volts Sub | Volts MP | dV Sub | dV MP | Motor HP | Motor State | Primary Sub | Primary MP | Current MP |
|---|---|---|---|---|---|---|---|---|---|---|
| About to Start | -2 | 124.9 | 124.9 | | | | Off | 12981 | 12984 | 0.0 |
| 400 HP Start | 0 | 124.9 | 124.9 | | | | Off | 12981 | 12984 | 0.0 |
| Ramp at 26 A | 3.4 | 124.2 | 119.7 | -0.8 | -5.3 | 92.6 | Start | 12903 | 12435 | 26.0 |
| Ramp at 57 A | 7.9 | 123.3 | 113.1 | -0.9 | -6.5 | 215.1 | Start | 12809 | 11758 | 57.0 |
| Contactor In | 10 | 122.9 | 110.3 | -0.4 | -2.8 | 270 | Start | 12771 | 11465 | 70.0 |
| Entering Linear Region | 18 | 123.1 | 111.6 | -0.2 | 1.3 | 230 | Start | 12788 | 11601 | 64.0 |
| Nearly to speed | 19 | 123.5 | 115.2 | 0.5 | 3.6 | 175 | Start | 12839 | 11974 | 47.2 |
| Motor Running | 20.5 | 124.6 | 119.9 | 1.0 | 4.7 | 435 | Run | 12944 | 12464 | 19.2 |
| Motor Coasting | 22 | 124.8 | 123.1 | 1.2 | 3.2 | 165 | Run | 12968 | 12792 | 7.1 |
| | 42.9 | 124.8 | 123.1 | | | 165 | Run | 12968 | 12792 | 7.1 |
| Motors Off | 43 | 124.9 | 124.9 | | | | Off | 12981 | 12984 | 0.0 |
| | 45 | 124.9 | 124.9 | | | | Off | 12981 | 12984 | 0.0 |



# B. Engineering a Solution



## 6. Add capacitor bank(s) to the model

- **A good starting rule of thumb for a 12470 feeder is:**

  **kVAr = 0.2 * HP * km**

- **Start with a single bank of that size.**
- **Modify model components until a good solution is found.**
- **The IEEE paper gives more details about this process.**

# Capacitor Assistance

**C. Build**

# C. Implementing the Solution

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## Build the System

- New line construction (if any)
- Capacitor rack or racks
- The control system
- Inputs to the controller

# Capacitor Assistance

**D. Tweak**

# D. Modifying the implementation as necessary for satisfactory results

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- **Take readings with the same power analyzer as before**
  - **If the results are satisfactory – the work is done.**

- **Usually improvements will be desirable or necessary**

- **Occasionally some redesign must be done to handle unforeseen circumstances.**

# Case Study #1

REPC 2018 MEMPHIS

| | |
|---|---|
| **Utility:** | **Grayson-Collin Electric Cooperative, Texas** |
| **Consultant:** | **Scarborough Engineering** |
| **Date:** | **May, 2008** |
| **Voltage:** | **12470 volts phase-phase** |
| **Line:** | **6 km of 4/0 AWG from substation to load** |
| **Load:** | **Three 500 HP compressor motors (2 + 1 spare)** |
| **Soft-start:** | **Unknown** |
| **Capacitors:** | **Two 300 kVAr switched banks** |
| **Switches:** | **Cooper Type NR motor operated oil switches** |
| **PLC:** | **Omron 20C1AR-A-V2** |
| **Signals:** | **Dry contacts from each motor start controller** |

- **Connections** — **Copper wire**
- **Start contact** — **Closes just prior to motor start**
- **Run contact** — **Stay closed while the motor is running**

# Case Study #1

IEEE REPC 2018 MEMPHIS

| | |
|---|---|
| Utility: | Grayson-Collin Electric Cooperative, Texas |
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| Signals: | Dry contacts from each motor start controller |

- Connections — Copper wire
- Start contact — Closes just prior to motor start
- Run contact — Stay closed while the motor is running

# Case Study #1
## Problem

### The Problem

- Motors could not be started

### The Bonus

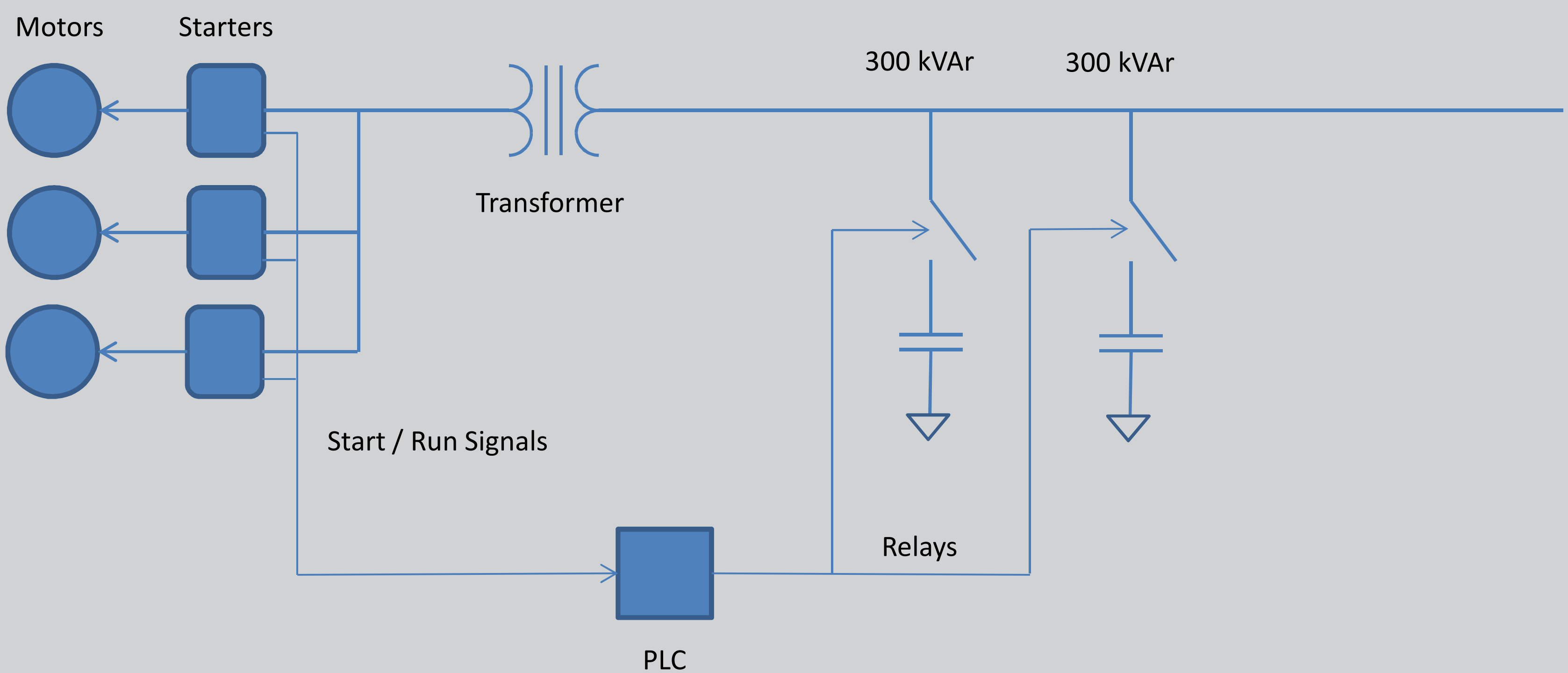
- Feeder could use power factor correction

# The Solution

- **Starting capacitor sizing rule of thumb for 12.5 kV**
  - kVAr = 0.2 * HP * km
  - 0.2 * 500 * 6 = 600 kVAr
- **Power Factor Correction**
  - 500 HP = 373 kW
  - ~ 80% PF : ~ 280 kVAr
- **The Algorithm Design**
  - Use two 300 kVAr banks to start
  - Leave one 300 kVAr bank in for each running motor
  - Use Start and Run auxiliary contacts

# Case Study #1
## Solution

Grayson-Collin EC Capacitor Assistance



# Case Study #1

## Capacitor Banks

# Case Study #1
## Control



# Case Study #2

REPC 2018 MEMPHIS

| | |
|---|---|
| Company: | DCP Midstream, New Mexico |
| Consultant: | Meers Engineering |
| Date: | August, 2010 |
| Voltage: | 12470 volts phase-phase |
| Line: | 5.5 km of 477 kcmil from substation to load |
| Load: | Two 1250 HP compressor motors |
| Soft-start: | Benshaw |
| Capacitors: | One 1200 kVAr ZVC switched bank |
| Switches: | Maysteel Ultra-Sync solenoid operated vacuum switches |
| PLC: | Omron 20C1DR-D-V2 |
| Signals: | Dry contacts from each Benshaw |

- Connections — Freewave radio pair
- Start contacts — Close at motor start

# Case Study #2

IEEE REPC 2018 MEMPHIS

| | |
|---|---|
| Company: | DCP Midstream, New Mexico |
| Consultant: | Meers Engineering |
| Date: | August, 2010 |
| Voltage: | 12470 volts phase-phase |
| Line: | 5.5 km of 477 kcmil from substation to load |
| Load: | Two 1250 HP compressor motors |
| Soft-start: | Benshaw |
| Capacitors: | One 1200 kVAr ZVC switched bank |
| Switches: | Maysteel Ultra-Sync solenoid operated vacuum switches |
| PLC: | Omron 20C1DR-D-V2 |
| Signals: | Dry contacts from each Benshaw |

- Connections — Freewave radio pair
- Start contacts — Close at motor start

## Case Study #2
### Main Problem

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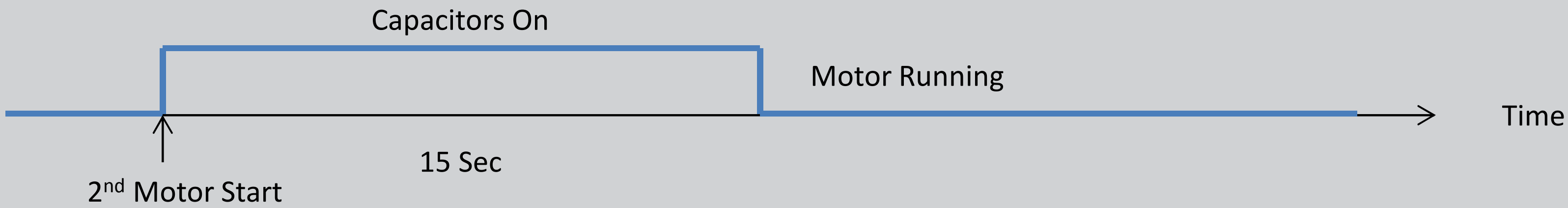
# The Main Problem

2nd motor could not be started when the 1st was already running and loaded.

# The Main Solution

- **Starting capacitor sizing rule of thumb for 12.5 kV**
  - **0.2 * 1250 * 5.5 = 1375 kVAr**
  - **They used 1200 kVAr**

- **Initial Algorithm Design**



# Case Study #2

## Secondary Problem



**The Secondary Problem**

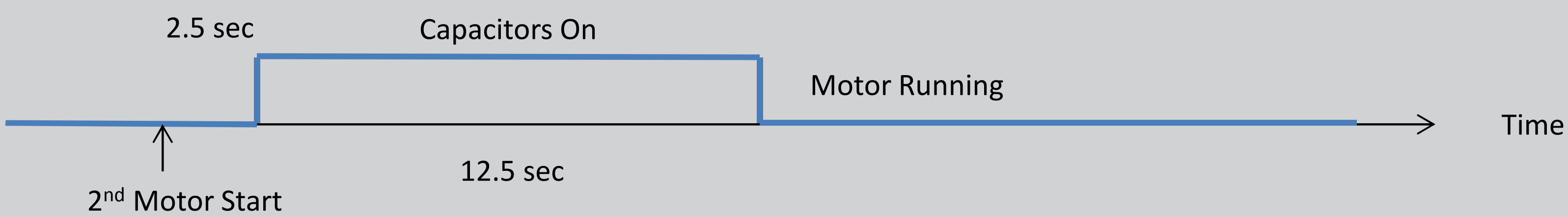
– Caused by the solution to the first problem.

VFD controllers were shutting down due to high voltage when assistance capacitors were energized.

# Case Study #2
## Final Solution

# The Final Solution

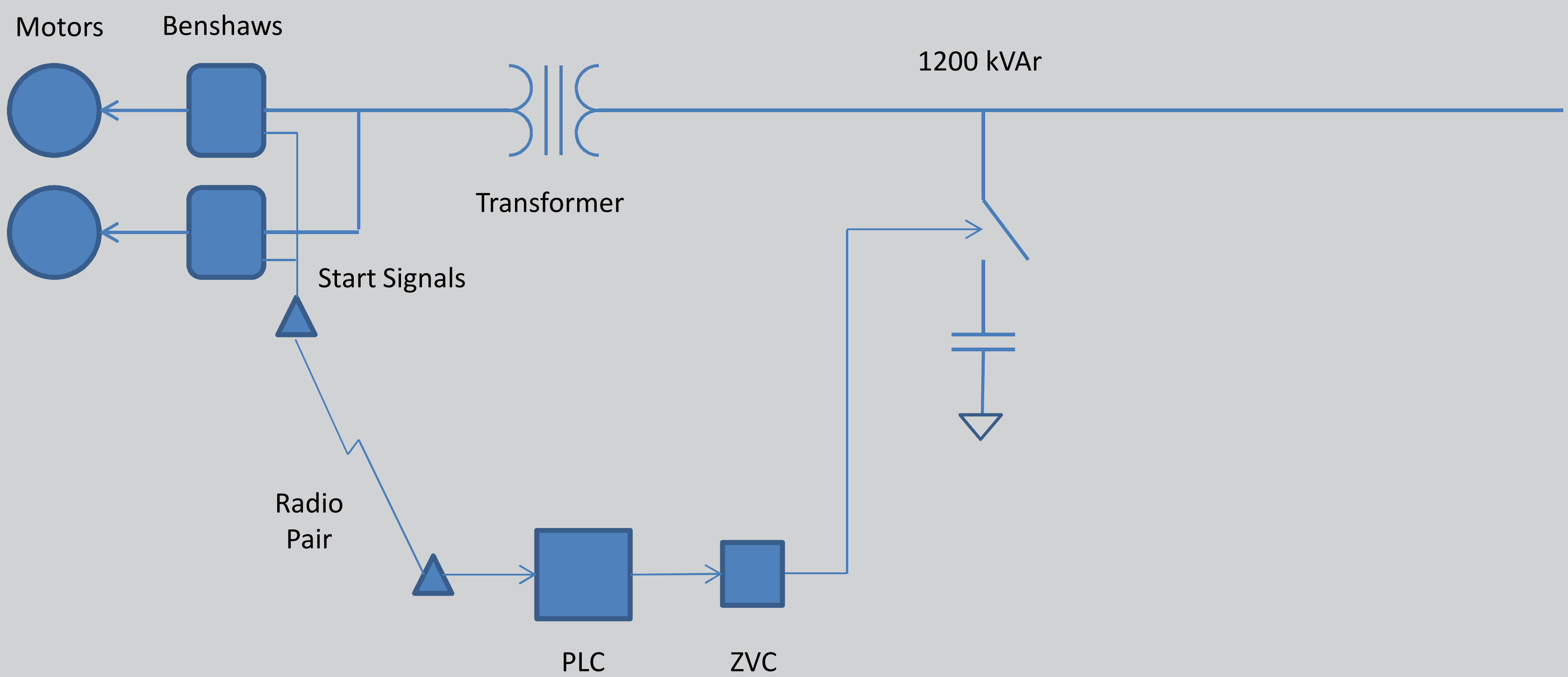
- **Final Algorithm Design (after two trials)**
  - **Allow voltage to sag for 2.5 seconds**



# Case Study #2

## Main Solution

DCP Midstream Capacitor Assistance



# Case Study #2
## Control

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# Case Study #2

## Control

# Case Study #3

REPC 2018 MEMPHIS

| | |
|---|---|
| Utility: | Cimarron Electric Cooperative, Oklahoma |
| Consultant: | Valquest Systems |
| Date: | August, 2014 |
| Voltage: | 12470 volts phase-phase |
| Line: | 16 km of 1/0 AWG from substation to load |
| Load: | One 400 HP rock crusher drive motor |
| | One 100 HP conveyer belt motor |
| Soft-start: | Toshiba (on the 400 HP motor) |
| Capacitors: | One 600 kVAr switched bank |
| | One 600 kVAr ZVC switched bank |
| | One 450 kVAr fixed bank |
| Switches: | Joslyn VSV solenoid operated vacuum switches |
| PLC: | Omron 10C1DR-D-V2 |
| Signals: | Voltage and current analog signals from the metering point |
| | Fiber signals from the main control to the ZVC slave control |

# Case Study #3

| | |
|---|---|
| Utility: | Cimarron Electric Cooperative, Oklahoma |
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| Voltage: | 12470 volts phase-phase |
| Line: | 16 km of 1/0 AWG from substation to load |
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| | One 100 HP conveyer belt motor |
| Soft-start: | Toshiba (on the 400 HP motor) |
| Capacitors: | One 600 kVAr switched bank |
| | One 600 kVAr ZVC switched bank |
| | One 450 kVAr fixed bank |
| Switches: | Joslyn VSV solenoid operated vacuum switches |
| PLC: | Omron 10C1DR-D-V2 |
| Signals: | Voltage and current analog signals from the metering point |
| | Fiber signals from the main control to the ZVC slave control |

# Case Study #3
## Problem

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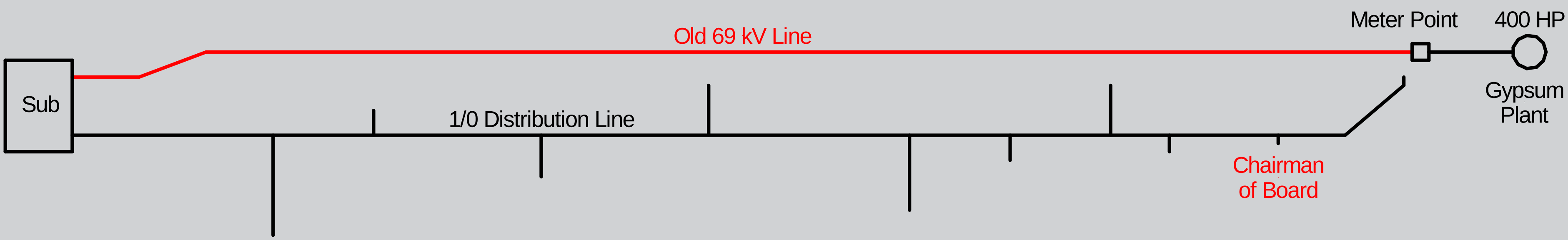
## The Problem



# Case Study #3
## Options

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### The Options

1. **Spend a lot of money**
   Rebuild  the 69 kV line
2. **Create annoyance issues**
   Re-feed from the new line
3. **Use Capacitor Assistance**
   1/10  the cost of  #1

**No-brainer!**

# Case Study #3
## Analysis

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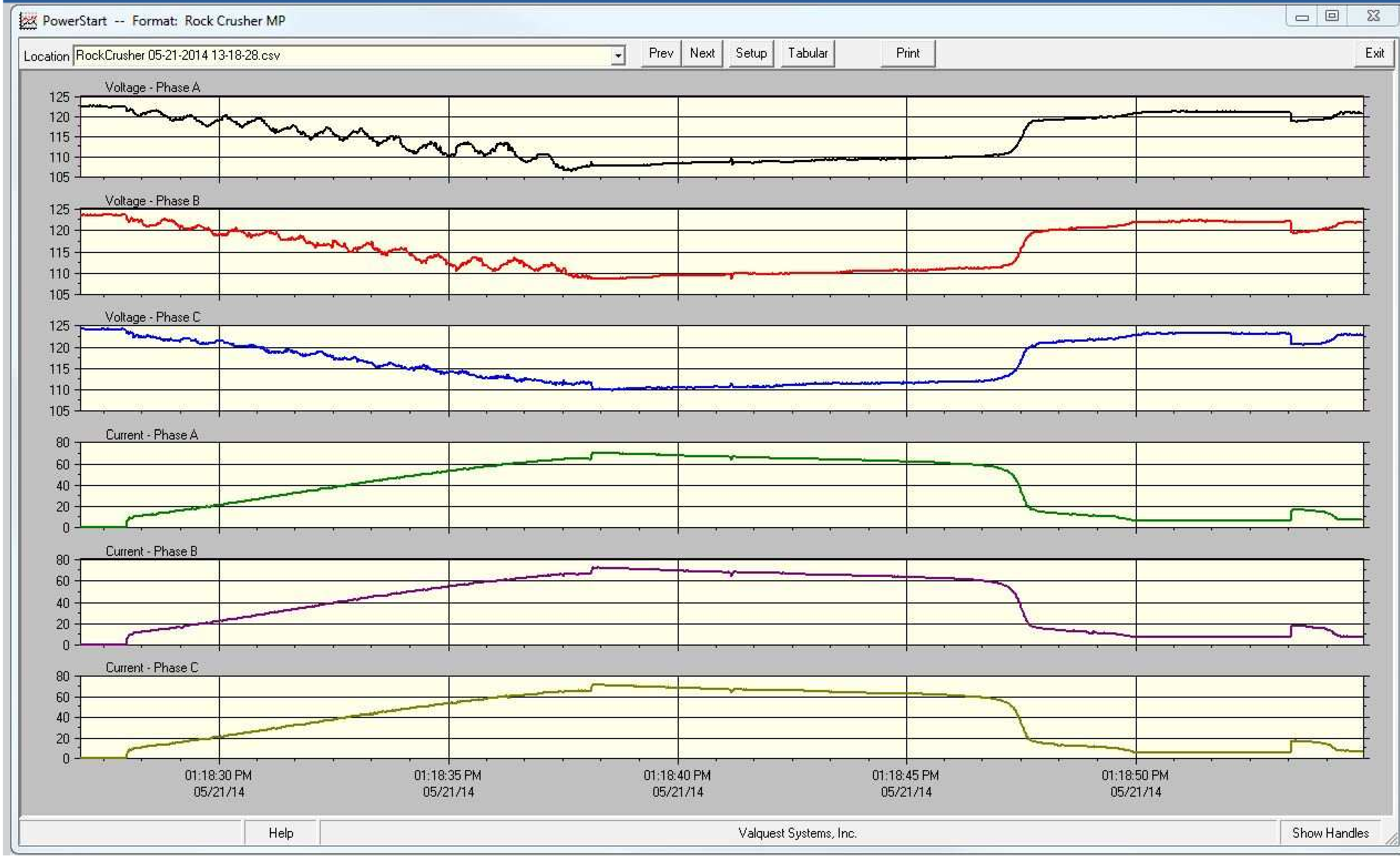
## The Analysis

1. **Motor startup was recorded.**
2. **The system was modeled using SKM.**
3. **Accuracy of the model was verified.**

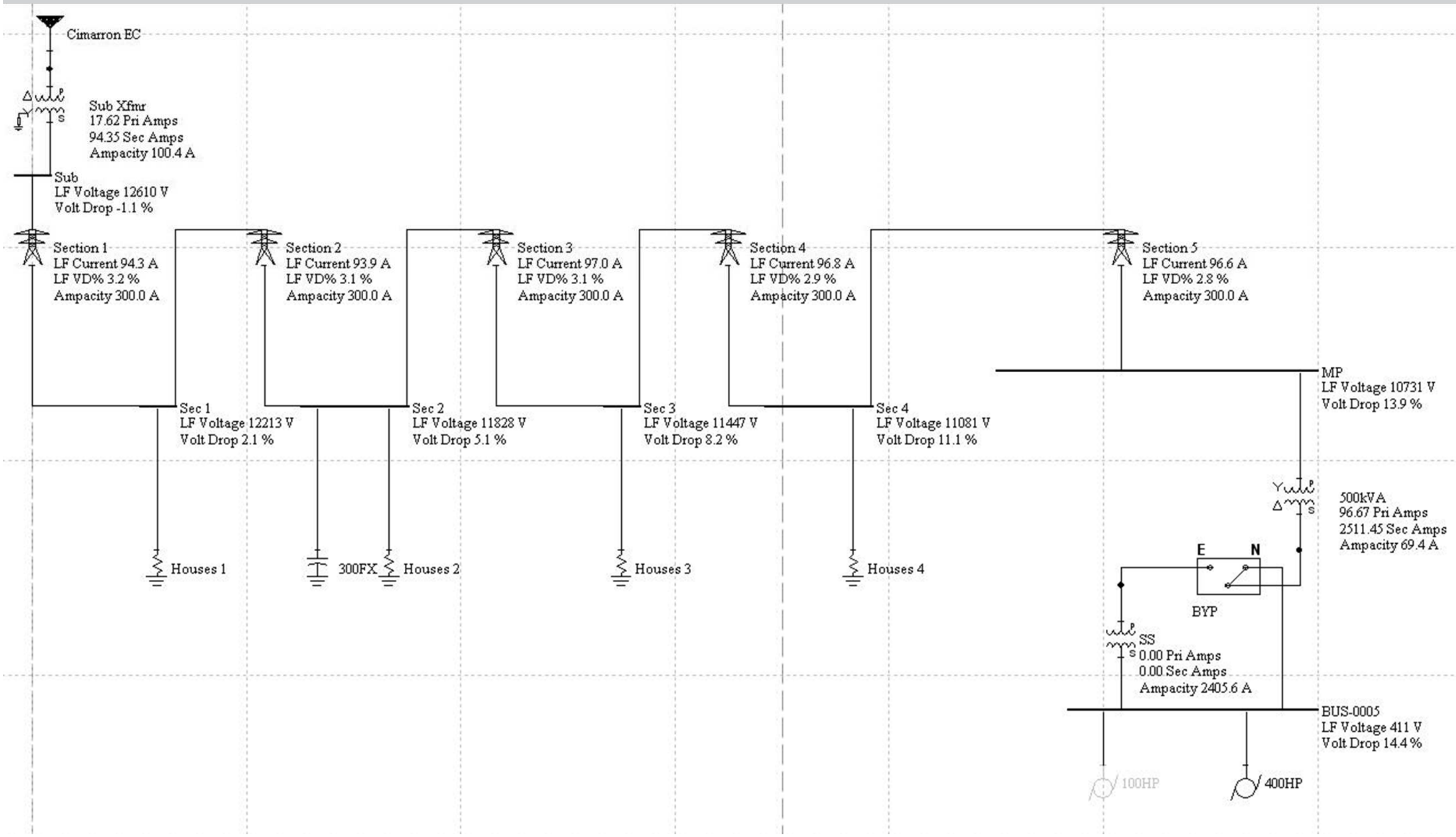
# Case Study #3

## Power Analyzer Data



# Case Study #3
## Initial Model

Starting Model - SKM



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## The Design

- Capacitors were added to the model.
  - 0.2 * 16 * 400 = 1280
- A multi-bank system was chosen.
  - 2 x 600 kVAr
- Focus was on minimizing fluctuations.
- The design was optimized in a spreadsheet.

# Case Study #3

## Final Model

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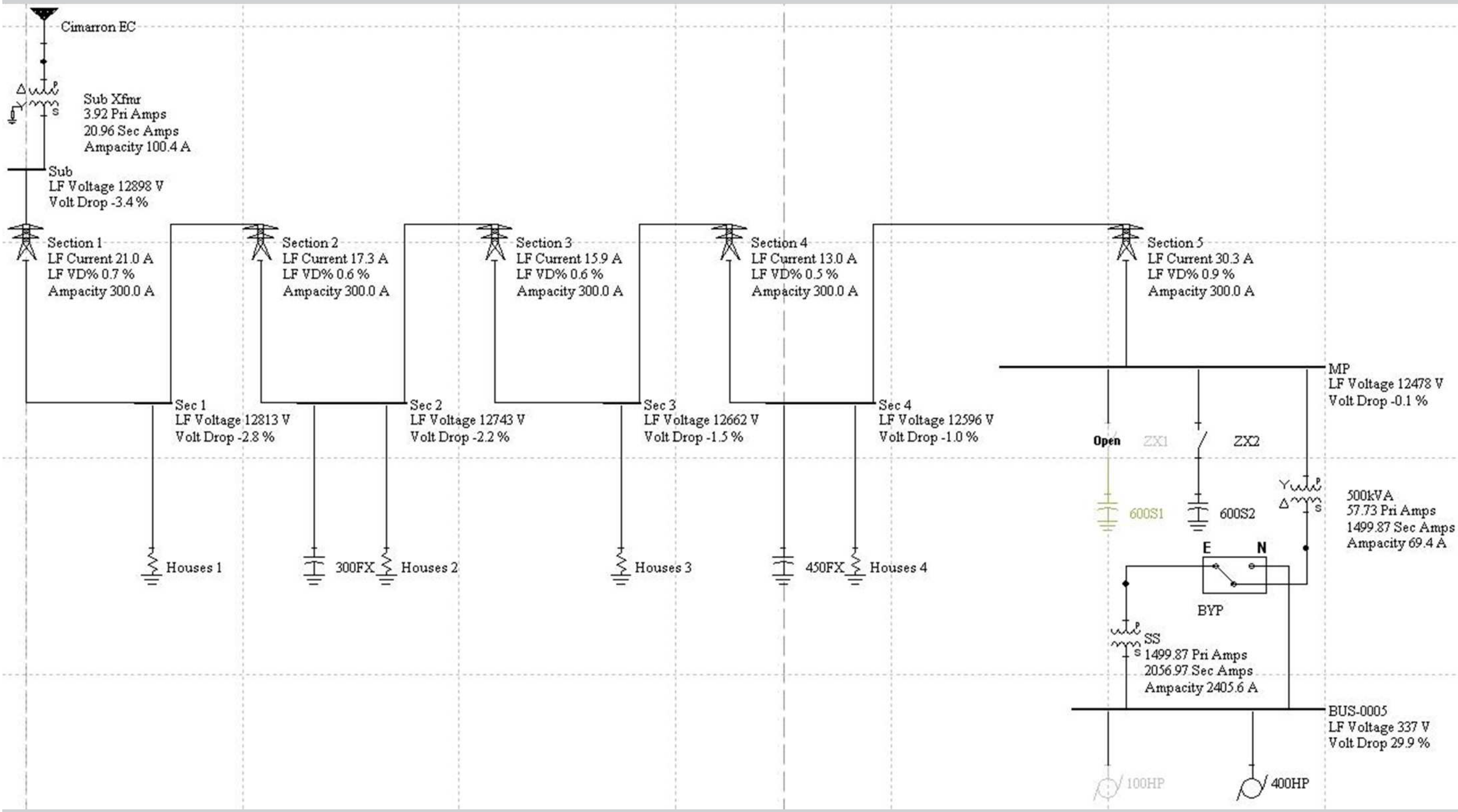
Model with Capacitors Added



# Case Study #3
## Spreadsheet

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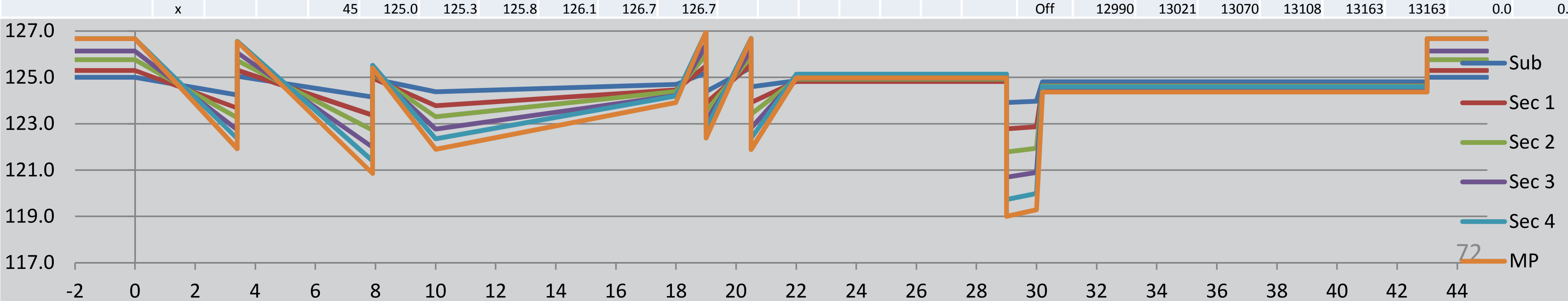
| | |
|---|---|
| Cimarron Electric | Diamond Gypsum Meter Point |
| 9 Mile Line | Four 2 mi sections & One 1 mi section) |
| 300 kVAr Fixed | 4 Mi from Sub (existing) |
| 450 kVAr Fixed | 8 mi from Sub |
| 2 600 kVAr Switched | at Meter Point |
| Loaded 330 kW | Distributed between Sections |

| Event | Cap Fix | Cap 1 | Cap 2 | Time | Volts | Volts | Volts | Volts | Volts | Volts | dV | dV | dV | dV | dV | dV | Motor | Motor | Primary | Primary | Primary | Primary | Primary | Primary | Current | Curremt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 450kVAr | 600kVAr | 600kVAr | Secs | Sub | Sec 1 | Sec 2 | Sec 3 | Sec 4 | MP | Sub | Sec 1 | Sec | Sec 3 | Sec 4 | MP | HP | State | Sub | Sec 1 | Sec | Sec 3 | Sec 4 | MP | MP | Sub |
| About to Start | x | | | -2 | 125.0 | 125.3 | 125.8 | 126.1 | 126.7 | 126.7 | | | | | | | | Off | 12990 | 13021 | 13070 | 13108 | 13163 | 13163 | 0.0 | 0.4 |
| 400 HP Start | x | | | 0 | 125.0 | 125.3 | 125.8 | 126.1 | 126.7 | 126.7 | | | | | | | | Off | 12990 | 13021 | 13070 | 13108 | 13163 | 13163 | 0.0 | 0.4 |
| Ramp at 26 A | x | Close | | 3.4 | 124.2 | 123.7 | 123.3 | 122.7 | 122.4 | 121.9 | -0.8 | -1.6 | -2.5 | -3.4 | -4.3 | -4.8 | 91 | Start | 12911 | 12853 | 12809 | 12756 | 12716 | 12670 | 26.0 | 25.8 |
| Cap Bank 1 On | x | x | | 3.4 | 125.0 | 125.3 | 125.7 | 126.1 | 126.6 | 126.5 | 0.8 | 1.6 | 2.5 | 3.3 | 4.2 | 4.6 | 91 | Start | 12995 | 13022 | 13066 | 13101 | 13152 | 13151 | 27.0 | 3.4 |
| Ramp at 57 A | x | x | Close | 7.9 | 124.1 | 123.4 | 122.7 | 122.0 | 121.4 | 120.8 | -0.1 | -0.3 | -0.5 | -0.8 | -1.0 | -5.7 | 201.5 | Start | 12901 | 12820 | 12753 | 12677 | 12616 | 12559 | 57.0 | 29.7 |
| Cap Bank 2 On | x | x | x | 7.9 | 124.9 | 125.0 | 125.2 | 125.3 | 125.5 | 125.4 | -0.1 | -0.3 | -0.6 | -0.8 | -1.0 | 4.5 | 201.5 | Start | 12984 | 12986 | 13006 | 13017 | 13045 | 13031 | 59.2 | 6.3 |
| Contactor In | x | x | x | 10 | 124.4 | 123.8 | 123.3 | 122.8 | 122.3 | 121.9 | -0.7 | -1.5 | -2.4 | -3.3 | -4.2 | -3.5 | 270 | Start | 12925 | 12863 | 12814 | 12758 | 12714 | 12667 | 77.0 | 22.7 |
| Entering Linear Region | x | x | x | 18 | 124.7 | 124.5 | 124.4 | 124.2 | 124.2 | 123.9 | 0.6 | 1.1 | 1.7 | 2.2 | 2.8 | 2.0 | 230 | Start | 12959 | 12934 | 12926 | 12909 | 12906 | 12878 | 66.7 | 12.2 |
| Nearly to speed [127 V] | x | x | Trip | 19 | 125.2 | 125.5 | 126.0 | 126.4 | 127.0 | 127.0 | 0.1 | 0.2 | 0.3 | 0.3 | 0.4 | 3.1 | 171 | Start | 13010 | 13042 | 13092 | 13136 | 13195 | 13197 | 50.9 | 8.8 |
| Cap Bank 2 Off | x | x | | 19 | 124.4 | 123.9 | 123.5 | 123.1 | 122.8 | 122.4 | -0.8 | -1.6 | -2.4 | -3.3 | -4.2 | -4.6 | 171 | Start | 12926 | 12875 | 12838 | 12793 | 12761 | 12718 | 49.0 | 21.4 |
| Motor Running [19 A] | x | Trip | | 20.5 | 125.4 | 125.6 | 125.9 | 126.2 | 126.7 | 126.7 | 1.0 | 1.7 | 2.4 | 3.1 | 3.9 | 4.3 | 455 | Run | 13034 | 13049 | 13084 | 13115 | 13165 | 13163 | 19.0 | 25.0 |
| Cap Bank 1 Off | x | | | 20.5 | 124.6 | 123.9 | 123.4 | 122.8 | 122.4 | 121.9 | -0.8 | -1.6 | -2.5 | -3.4 | -4.3 | -4.8 | 455 | Run | 12948 | 12878 | 12824 | 12763 | 12716 | 12666 | 19.7 | 20.4 |
| Motor Coasting | x | | | 22 | 124.9 | 124.8 | 124.9 | 125.0 | 125.1 | 125.0 | -0.3 | -0.7 | -1.1 | -1.4 | -1.8 | 2.6 | 165 | Run | 12975 | 12971 | 12983 | 12986 | 13005 | 12988 | 7.0 | 6.9 |
| | x | | | 29 | 124.9 | 124.8 | 124.9 | 125.0 | 125.1 | 125.0 | | | | | | | 165 | Run | 12975 | 12971 | 12983 | 12986 | 13005 | 12988 | 7.0 | 6.9 |
| 100 HP Start | x | | | 29 | 123.9 | 122.8 | 121.8 | 120.7 | 119.7 | 119.0 | -0.9 | -2.0 | -3.1 | -4.3 | -5.4 | -6.0 | 165 | Run | 12878 | 12759 | 12656 | 12542 | 12443 | 12366 | 37.1 | 37.0 |
| | x | | | 30 | 124.0 | 122.9 | 121.9 | 120.9 | 120.0 | 119.3 | | | | | | | 165 | Run | 12883 | 12769 | 12672 | 12564 | 12470 | 12396 | 35.6 | 35.5 |
| Both Motors Running | x | | | 30.2 | 124.8 | 124.6 | 124.6 | 124.5 | 124.6 | 124.4 | 0.8 | 1.8 | 2.7 | 3.6 | 4.6 | 5.4 | 165 | Run | 12970 | 12953 | 12951 | 12943 | 12948 | 12924 | 9.5 | 9.4 |
| | x | | | 43 | 124.8 | 124.6 | 124.6 | 124.5 | 124.6 | 124.4 | | | | | | | 165 | Run | 12970 | 12953 | 12951 | 12943 | 12948 | 12924 | 9.5 | 9.4 |
| Motors Off | x | | | 43 | 125.0 | 125.3 | 125.8 | 126.1 | 126.7 | 126.7 | 0.2 | 0.7 | 1.1 | 1.6 | 2.1 | 2.3 | | Off | 12990 | 13021 | 13070 | 13108 | 13163 | 13163 | 0.0 | 0.0 |
| | x | | | 45 | 125.0 | 125.3 | 125.8 | 126.1 | 126.7 | 126.7 | | | | | | | | Off | 12990 | 13021 | 13070 | 13108 | 13163 | 13163 | 0.0 | 0.0 |



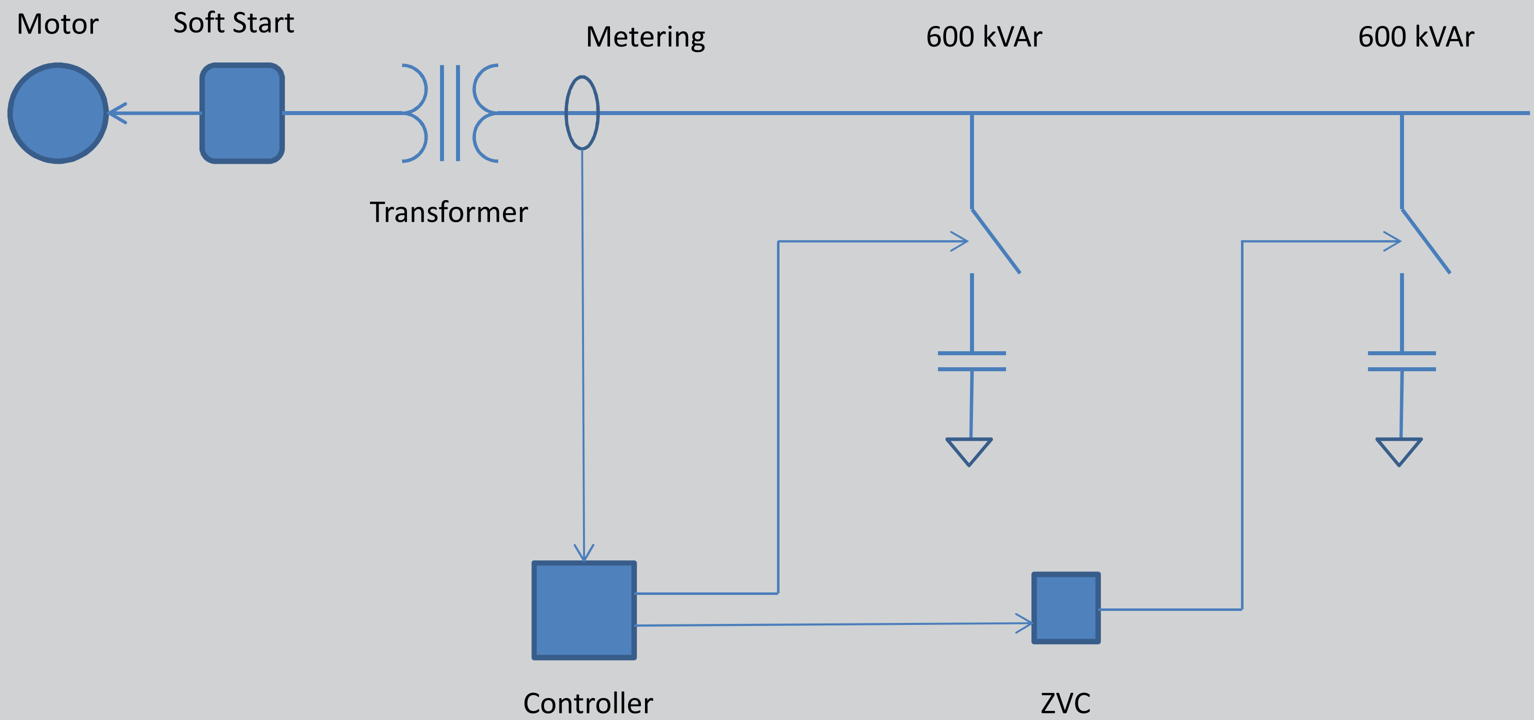
# The Solution

- Two cap banks were energized in stages based on current.
- The banks opened when the motor was up to speed.
- Voltage override was also implemented.

# Case Study #3
## Solution



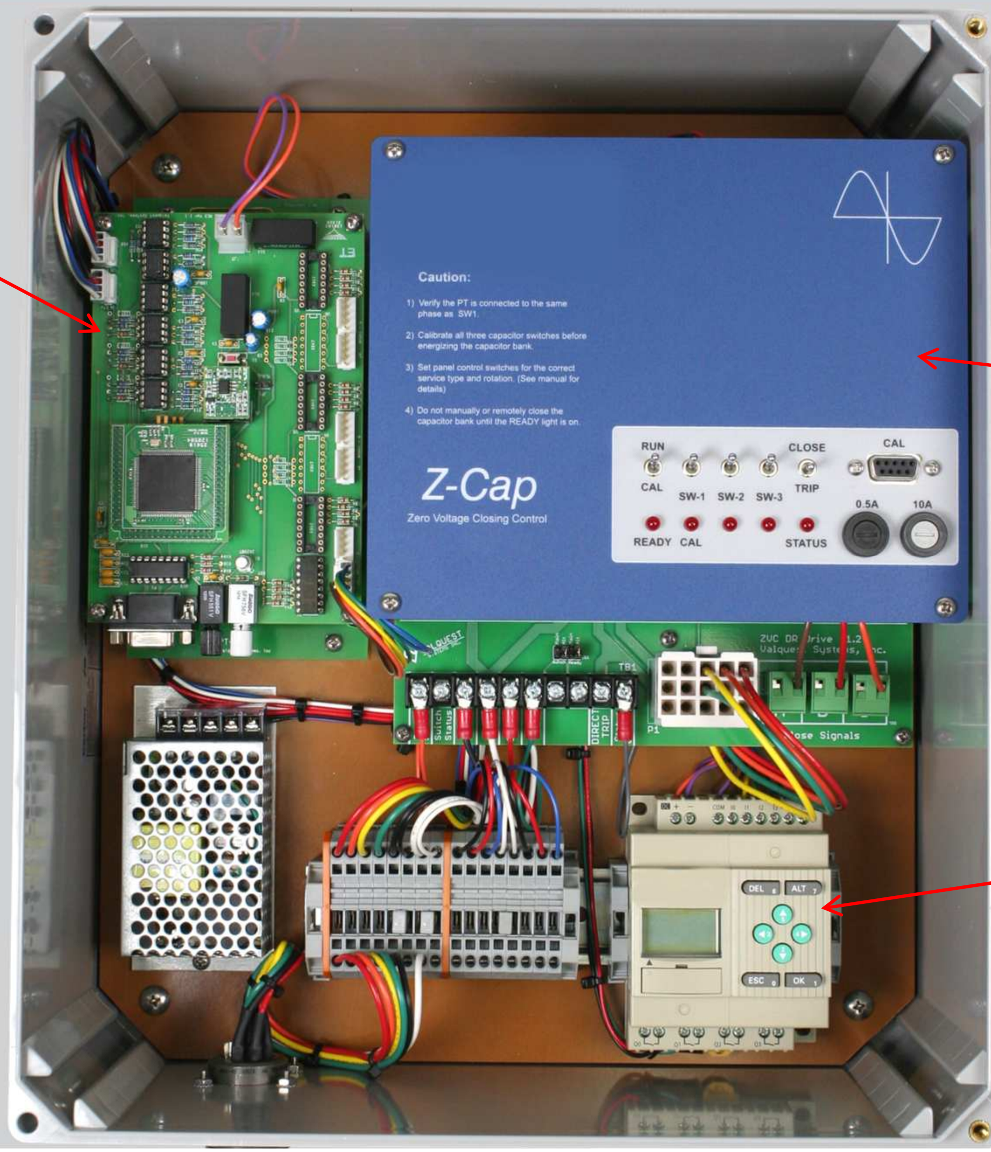
Cimarron Electric – Gypsum Plant



# Case Study #3
## Construction

# Case Study #3
## Control

Voltage & Current Detection



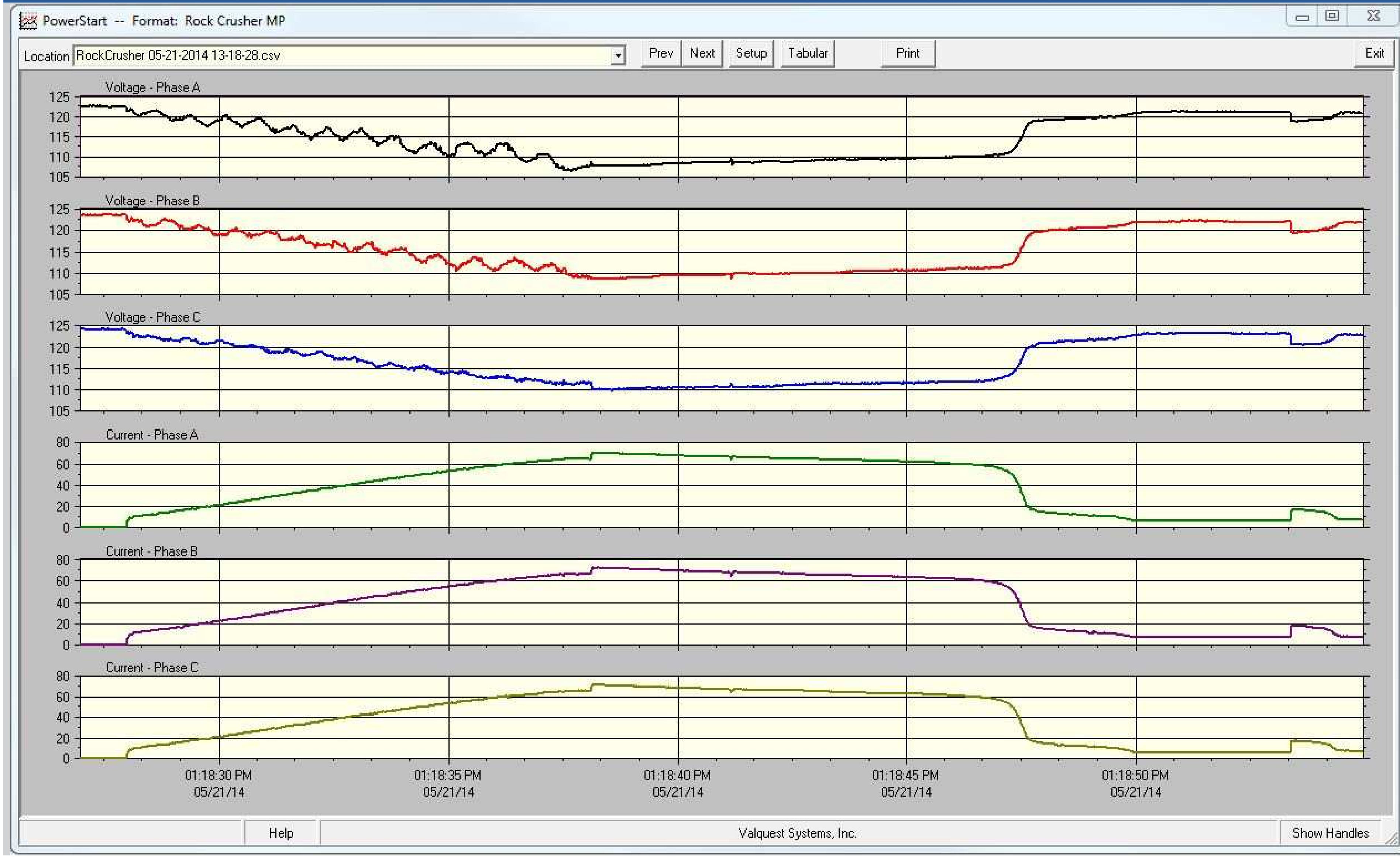

ZVC Control

PLC

Cimarron EC Main Control

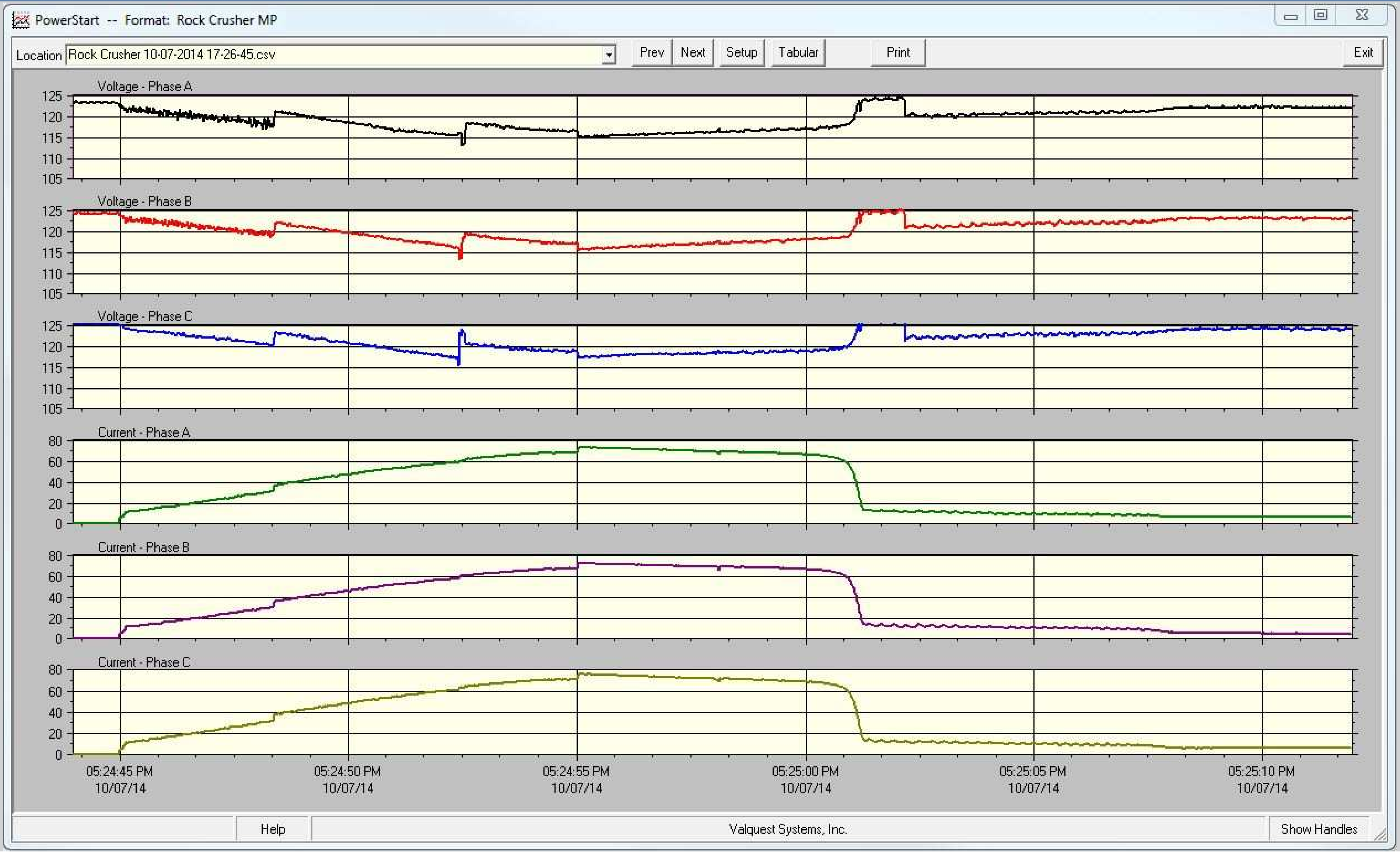
# Case Study #3

## Before



# Case Study #3

## After



REPC 2018 MEMPHIS

Solving Power Quality Issues from Large Motor Starts using Fast-Acting Capacitor Assistance

Toby Landes, P.E.

# Questions