

Module D1-c

Introduction to Distribution Systems (Continued)

General comments

1. Please perform ISU course evaluation. You should have received email on how to do this.
2. Topics today:
 - Final exam
 - Power factor correction
 - Taking EIT/PE exams.
 - Induction motors
 - Power electronics

Comments on Final Exam

1. Exam logistics:
 1. Monday May 6, 2019, 12:00-2:00pm
 2. Open book, open notes (must be hardcopies)
 3. No computer.
 4. No device that communicates.
 5. Expect to be in the room for 2 hours.
2. What is on the exam:
 - a. Between 4-7 problems to work.
 - b. Additionally (possibly) short-answer or true false.
 - c. Expect problems that integrate several topics.
 - d. Points during semester when I said “This would be good final exam question.”
3. Exam coverage: Comprehensive over coverage of entire semester.
 - a. Energy system overview;
 - b. Three-phase and per-unit analysis;
 - c. Component model, operation, analysis for transformers, lines, synch gens
 - d. Systems analysis: power flow problem.
 - e. Systems analysis: economic dispatch
 - f. Distribution systems and two-ports
 - g. Power factor correction
 - h. Induction machines
 - i. Power electronics(?)

Power Factor Correction

Recall: $P = 3 |V| |I| \cos \theta$

$$P_{Loss} = 3 |I|^2 R$$

Assume $|V|$ is constant.

Given that we desire to supply a load that consumes a specified power P , do we want:

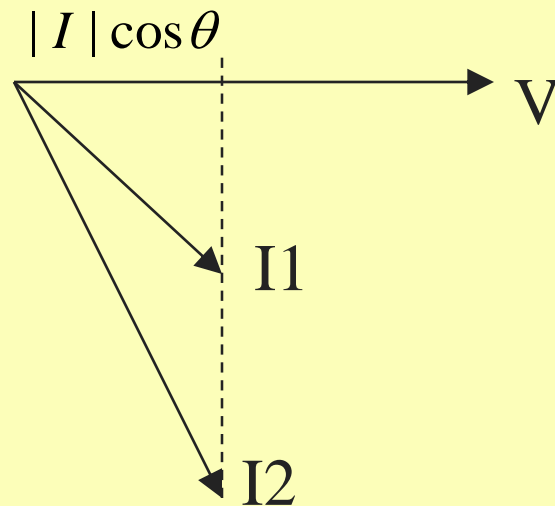
- pf close to 1 (θ close to 0) ?
- pf close to 0 (θ close to 90) ?

Why?

Answer:

We want pf close to 1.0 because then I is minimum for the given P . Observe:

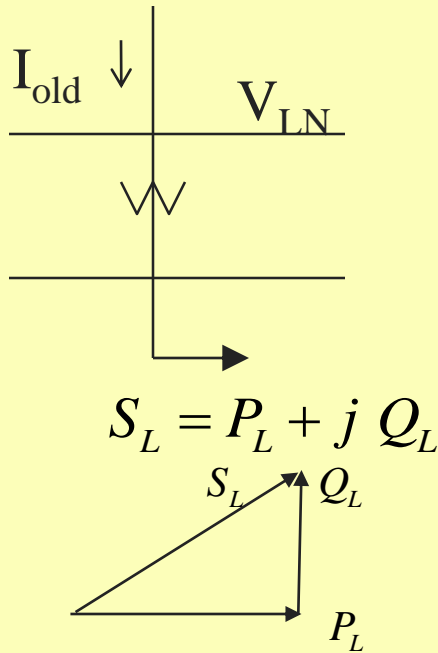
$$P = 3 |V| |I| \cos \theta$$



So both currents I_1 and I_2 provide the same real power, but

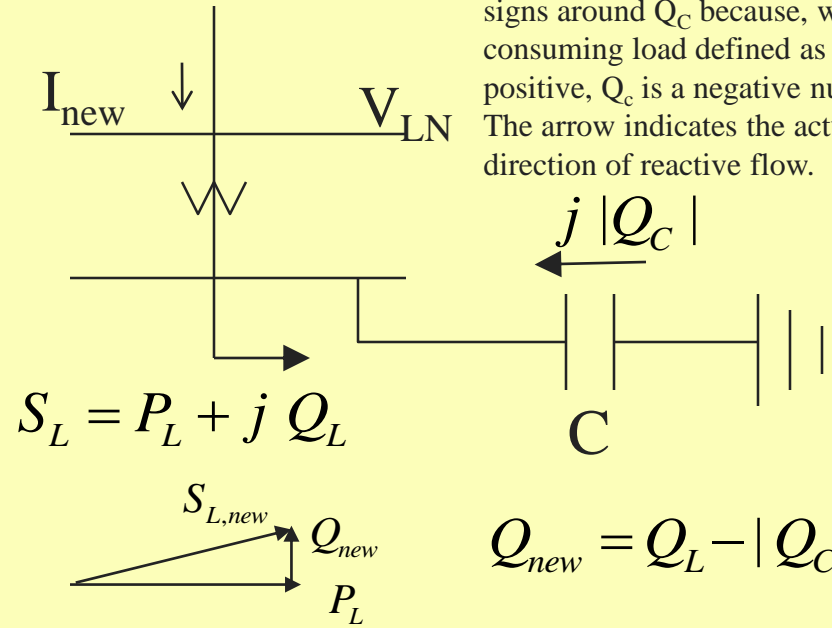
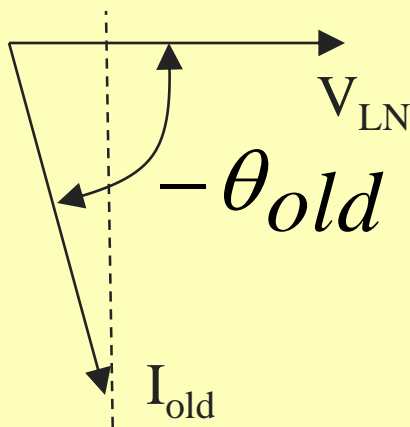
$$|I_1|^2 R < |I_2|^2 R$$

Power Factor Correction: Basic Idea



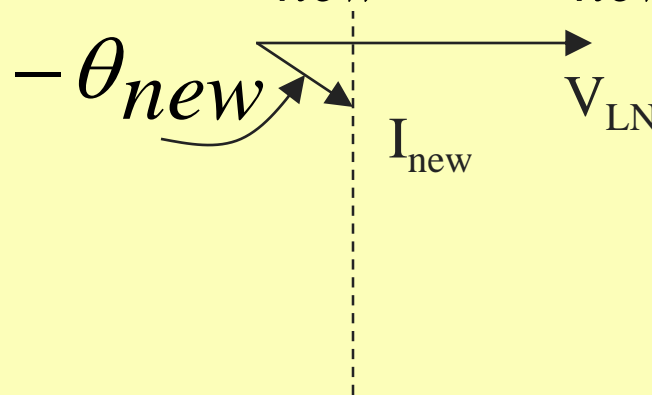
$$\theta_{old} = \text{atan}(Q_L / P_L)$$

$$pf_{old} = \cos \theta_{old}$$



$$\theta_{new} = \text{atan}(Q_{new} / P_L)$$

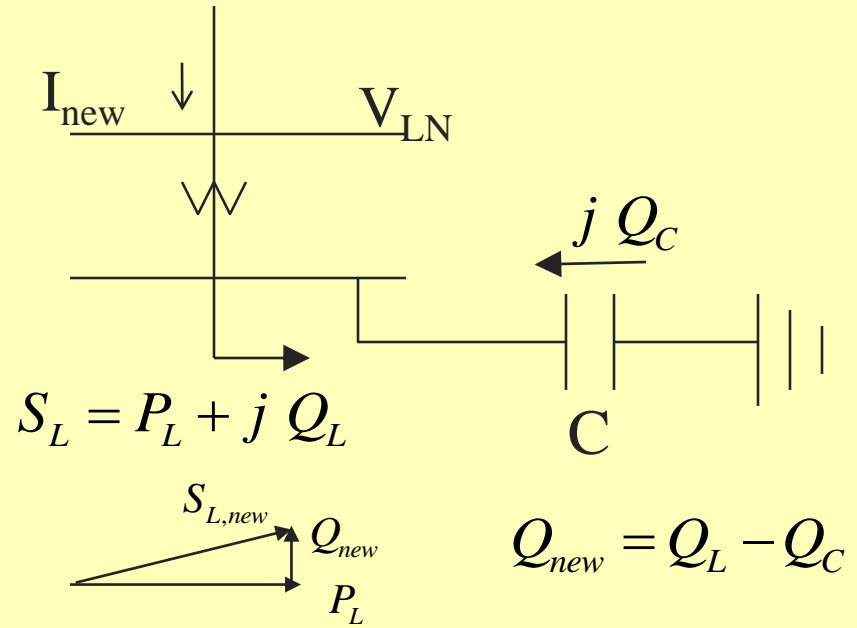
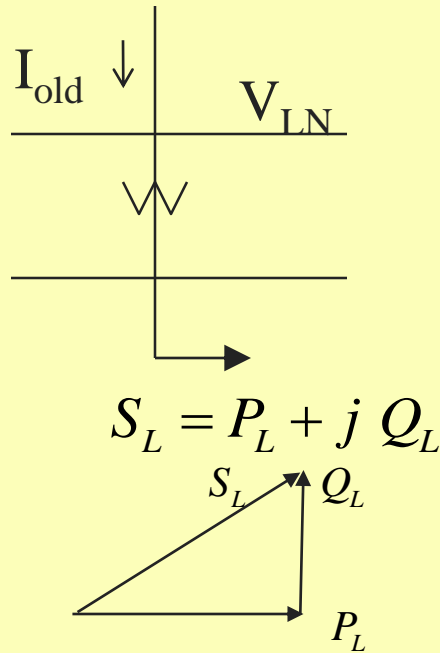
$$pf_{new} = \cos \theta_{new}$$



Note: We use absolute value signs around Q_C because, with a consuming load defined as positive, Q_C is a negative number. The arrow indicates the actual direction of reactive flow.

$$Q_{new} = Q_L - |Q_C|$$

Power Factor Correction: Approach



Known (given or can be obtained): P_L , pf_{old} , pf_{new}

Compute:

1. $\theta_{old} = \arccos(pf_{old})$, $\theta_{new} = \arccos(pf_{new})$
2. $Q_L = P_L \tan \theta_{old}$, $Q_{new} = P_L \tan \theta_{new}$,
3. $Q_C = Q_{new} - Q_L$
4. $X_{C,Y} = (V_{LN})^2 / Q_{C,1\phi} = (V_{LL})^2 / Q_C \rightarrow X_{C,\Delta} = 3X_{C,Y}$.
5. Use the appropriate X_C to compute: $B_C = 1/X_C$, $C = 1/\omega X_C$

SHOULD YOU TRY TO OBTAIN YOUR PROFESSIONAL ENGINEERING LICENSE?

www.nspe.org/resources/licensure/what-pe

The screenshot shows a web browser window displaying the NSPE website. The browser tabs include 'EE.PSE.D1.pdf', 'All Users - E_E 303 (Spring 2', and 'What is a PE?'. The address bar shows 'nspe.org/resources/licensure/what-pe'. The page layout includes a left sidebar with navigation links, a main content area with a blue header, and a right sidebar with member information and a hotline.

Member Benefits
Types of Membership
About NSPE
Who We Are & What We Do

RESOURCES
Licensure
What is a PE
Why Get Licensed
How to Get Licensed
Maintaining a License
NSPE Protects Your PE
License
Licensing Boards
Resources
Continuing Education
Ethics
Issues and Advocacy
Career Center
Interest Groups
Professional Liability
Partners and State Societies
News & Publications
Blogs
Shop NSPE

What is a PE?

Home » Licensure » What is a PE?

To a client, it means you've got the credentials to earn their trust. To an employer, it signals your ability to take on a higher level of responsibility. Among your colleagues, it demands respect. To yourself, it's a symbol of pride and measure of your own hard-won achievement.

To become licensed, engineers must complete a four-year college degree, work under a Professional Engineer for at least four years, pass two intensive competency exams and earn a license from their [state's licensure board](#). Then, to retain their licenses, PEs must continually maintain and improve their skills throughout their careers.

Yet the results are well worth the effort. By combining their specialized skills with their high standards for ethics and quality assurance, PEs help make us healthier, keep us safer and allow all of us to live better lives than ever before.

A century ago, anyone could work as an engineer without proof of competency. In order to protect the public health, safety, and welfare, the [first engineering licensure law](#) was enacted in 1907 in Wyoming. Now every state regulates the practice of engineering to ensure public safety by granting only Professional Engineers (PEs) the authority to sign and seal engineering plans and offer their services to the public.

To use the PE seal, engineers must complete several steps to ensure their

Sr. Mechanical Engineer
Harriman, Auburn, ME, US

Electrical Safety Engineer
Jet Propulsion Laboratory, Pasadena, CA, US

General Manager
Flex-N-Gate Oklahoma, LLC, OK, US

Hotline for Members

Licensure and Ethics Hotline
Are you an NSPE member with a question about engineering licensure, ethics, or law? If so, call [888-384-4295](tel:888-384-4295) or e-mail legal@nspe.org.

Sign Up

Not a member?
Sign up to stay informed of key industry news and

Windows taskbar: Ask me anything, 12:23 PM 4/19/2017

SHOULD YOU TRY TO OBTAIN YOUR PROFESSIONAL ENGINEERING LICENSE?

www.nspe.org/resources/licensure/what-pe

The screenshot shows a web browser window with the URL www.nspe.org/resources/licensure/what-pe. The page content includes a green 'CALENDAR OF EVENTS' button, a list of social media icons (Facebook, Twitter, LinkedIn, Email, Print), and a main article titled 'What makes a PE different from an engineer?'. The article text states that PEs must continuously demonstrate competency and improve skills through continuing education. It lists several key responsibilities and requirements for PEs, such as preparing and sealing engineering plans, holding high ethical standards, and being licensed for government positions and teaching. On the right side of the page, there are three promotional banners: 'PE Outfitters' with a 'WELCOME TO PE OUTFITTERS' graphic, 'C-990 Construction-Related Documents Set' endorsed by NLUCA, and 'D-990 Design/Build Document Set'. At the bottom right, there is a blue banner for the 'NATIONAL SOCIETY OF PROFESSIONAL ENGINEERS' with the slogan 'Protect Your Priorities'.

CALENDAR OF EVENTS

What makes a PE different from an engineer?

PEs must also continuously demonstrate their competency and maintain and improve their skills by fulfilling continuing education requirements depending on the state in which they are licensed.

- Only a licensed engineer may prepare, sign and seal, and submit engineering plans and drawings to a public authority for approval, or seal engineering work for public and private clients.
- PEs shoulder the responsibility for not only their work, but also for the lives affected by that work and must hold themselves to high ethical standards of practice.
- Licensure for a consulting engineer or a private practitioner is not something that is merely desirable; it is a legal requirement for those who are in responsible charge of work, be they principals or employees.
- Licensure for engineers in government has become increasingly significant. In many federal, state, and municipal agencies, certain governmental engineering positions, particularly those considered higher level and responsible positions, must be filled by licensed professional engineers.
- Many states require that individuals teaching engineering must also be licensed. Exemptions to state laws are under attack, and in the future, those in education, as well as industry and government, may need to be licensed to practice. Also, licensure helps educators prepare students for their future in engineering.

PE Outfitters
WELCOME TO PE OUTFITTERS

C-990 Construction-Related Documents Set
EJCDC Construction Documents Endorsed by NLUCA

D-990 Design/Build Document Set

NSPE™ NATIONAL SOCIETY OF PROFESSIONAL ENGINEERS
Protect Your Priorities

Windows taskbar: Ask me anything, 12:27 PM, 4/19/2017

SHOULD YOU TRY TO OBTAIN YOUR PROFESSIONAL ENGINEERING LICENSE?

www.nspe.org/resources/licensure/what-pe

To use the PE seal, engineers must complete several steps to ensure their competency.

- Earn a four-year degree in engineering from an **accredited engineering program**
- Pass the Fundamentals of Engineering (FE) exam
- Complete four years of progressive engineering experience under a PE
- Pass the Principles and Practice of Engineering (PE) exam

SHOULD YOU TRY TO OBTAIN YOUR PROFESSIONAL ENGINEERING LICENSE?

www.nspe.org/resources/licensure/what-pe

Answer is “yes” if you want to practice engineering.

The next problem was taken from a PE exam.

This problem is a good practical problem of what you will see in the industry.

I expect, for the final exam, that you can *begin* to “put things together” from the course, think, and solve problems like this.

SITUATION

A paper mill is supplied by a 13.8 kV, 3 ϕ , 60 Hz system with appropriate transformers. The total load is as follows:

Induction motors: 600 hp
Eff = 85%
pf = .8 lag

Heating and lighting: 100 kW
pf = unity

Synchronous motors: 200 hp
Eff = 90%

- The synchronous motors are being operated at rated kVA and are over excited to correct the plant power factor to .95 lagging (so the synchronous motors are operating leading).
- It is desired to increase the mill output by 20%
- A plant survey indicated that the installed induction motor capacity could provide 20% more power than it is presently providing, but the synchronous machines are at rated kVA and cannot provide any more horsepower output.

It is suggested that it might be possible to increase the HP output of the synchronous motors by correcting the power factor of the synchronous motors to unity with a static bank of capacitors.

The idea is to relieve the motors of their electrical reactive output in order to increase their real mechanical output.

REQUIREMENT

- (a) Determine if it is *possible* to increase the output of the synchronous motors by 20% by reducing their excitation without exceeding the kVA ratings.

- (b) Determine the reactive power required, to correct the power factor to .95 lagging.

Define:

- **operating condition 1**: as described (600 hp ind. mot., 200 hp sync. mot, 100 kW lighting, plant power factor at 0.95, with high vars supplied by synchronous motors.
- **operating condition 2**: 20% more mechanical output from motors, plant power factor at 0.95 using power factor correction capacitors.

a) Synchronous motor presently consumes P_1 , Q_1 , where

$$P_1^2 + Q_1^2 = S_{rated}^2$$

The question is, if we force reactive power to zero so that $P_2 = S_{rated}$, will

$$\frac{P_2 - P_1}{P_1} \geq 0.2 \quad ?$$

$$S_{rated}^2 = P_1^2 + Q_1^2$$

So we need to obtain S_{rated} , since $P_2=S_{rated}$, and we can do this if we get P_1 and Q_1 via analysis of operating condition 1.

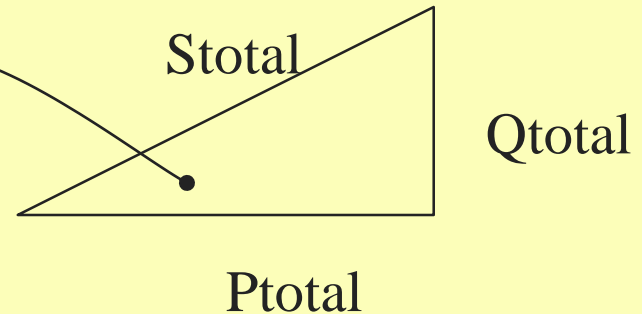
P_1 is easy:

$$P_1 = \frac{200hp \bullet 746w / hp}{.90} = 165,778w$$

To get Q_1 , we begin from knowing that under operating condition 1, the synchronous motor supplies enough Q to correct plant pf to 0.95. This means the power triangle for the entire plant appears as

$$\tan \theta = \frac{Q}{P}$$

$$\theta = \cos^{-1} 0.95$$



$$P_{total} = P_{other} + P_1$$

$$Q_{total} = Q_{other} + Q_1$$

Other:

induction motor
& lighting loads.

Values are positive for load consuming power.

$$\tan^{-1} \left[\frac{Q_{total}}{P_{total}} \right] = \cos^{-1} (.95)$$

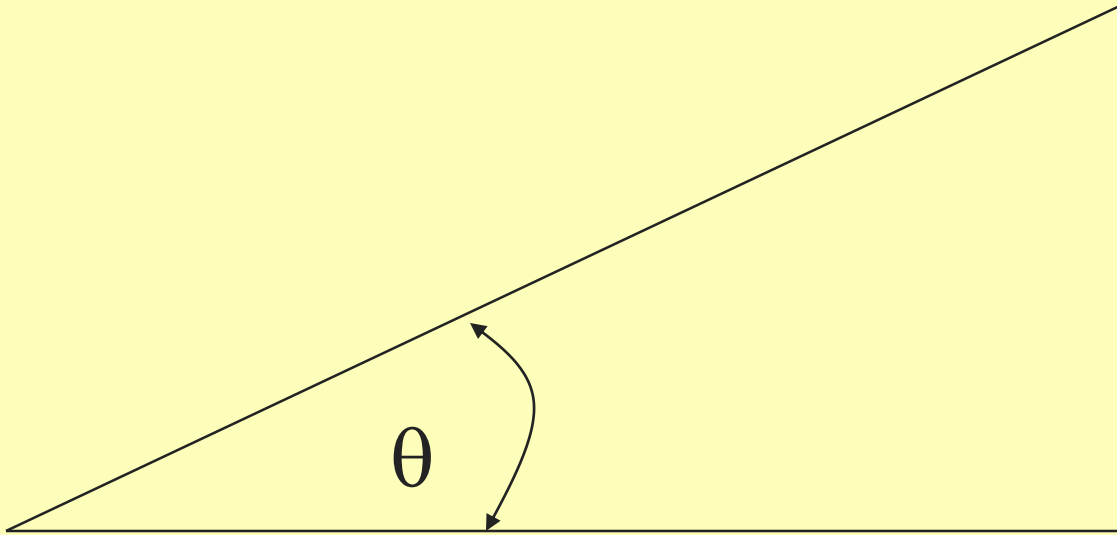
$$\tan^{-1} \left[\frac{Q_{other} + Q_1}{P_{other} + P_1} \right] = \cos^{-1} (.95)$$

$$= 18.19^\circ$$

$$\Rightarrow \frac{Q_{other} + Q_1}{P_{other} + P_1} = \tan(18.19) = 0.329$$

$$\Rightarrow Q_1 = [P_{other} + P_1][.329] - Q_{other}$$

Use a power triangle to show the relationship between all terms in the above equation.



$$\begin{aligned} Q_{\text{total}} &= Q_{\text{other}} + Q_1 \\ &= Q_{\text{IM}} + Q_1 \end{aligned}$$

$$\begin{aligned} P_{\text{total}} &= P_{\text{other}} + P_1 \\ &= P_{\text{H\&L}} + P_{\text{IM}} + P_1 \end{aligned}$$

So our job is to find P_{other} and Q_{other} , which are the total real and reactive powers, respectively, consumed by all other components in the plant:

- induction motor load**
- heating and lighting load**

Induction Motor

$$P_{IM} = \frac{600 \cdot 746}{0.85} = 526,588 \text{ w}$$

$$Q_{IM} = (526,588) \tan \left(\cos^{-1} 0.8 \right)$$
$$= 394,941 \text{ var}$$

Heating and Lightning Load

$$P_{HL} = 100,000 \text{ w}$$

$$Q_{HL} = 0$$

$$\begin{aligned}\Rightarrow P_{other} &= P_{IM} + P_{HL} \\ &= 526588 + 100000 = 626588 \quad \text{w}\end{aligned}$$

$$\begin{aligned}\Rightarrow Q_{other} &= Q_{IM} + Q_{HL} \\ &= 394941 + 0 = 394941 \quad \text{var}\end{aligned}$$

So from boxed equation,

$$Q_1 = [P_{other} + P_1][.329] - Q_{other}$$

$$\begin{aligned} Q_1 &= \\ &[626588 + 165778][.329] - 394941 \\ &= -134253 \text{ var} \end{aligned}$$

Negative value indicates motors are supplying power.

$$P_2 = S_{rated} = \sqrt{P_1^2 + Q_1^2}$$

$$= \sqrt{165,778^2 + 134,252^2}$$

$$= 213,321 \text{watts}$$

So the % increase in power which is possible is:

$$\frac{P_2 - P_1}{P_1} = \frac{213,321 - 165,778}{165,778}$$

$$= 28.7\%$$

So we can increase beyond 20%.

Now at this point, we have only shown that we can increase mechanical output of synchronous motors by up to 28.7 % if we reduce its reactive demand.

Now we want to compute exactly what reactive supply is needed from the capacitors at the 13.8 kV bus in order to maintain the plant 0.95 pf (lagging) and also provide for the 20% increase in plant output.

Assumption

Synchronous motor increases output by 20% and is maintained at rated kVA. Note that since we are not increasing to the full 28.7%, there will still be some capability to supply reactive power.

We do want to get as much reactive support from the synchronous motors as possible since it will reduce the amount of capacitance that we need to buy.

Based on this assumption, we can compute the real and reactive power into the synchronous motors.

$$P_2 = \frac{(200hp)1.2 \bullet 746w / hp}{.90}$$
$$= 198,933w$$

Since we know that it is supplying vars (leading), $Q_1 < 0$

$$Q_2 = -\sqrt{213,321^2 - 198,933^2}$$
$$= -77,016 \text{ var}$$

We need reactive of induction motor.

$$P_{IM} = \frac{(600hp)1.2 \bullet 746w / hp}{.85} = 631906$$

$$\begin{aligned} Q_{IM} &= P_{IM} \tan\{\cos^{-1} pf\} = 631906 \tan\{\cos^{-1} .80\} \\ &= 473930 \end{aligned}$$

Note P_{IM} is greater than before because it is 20% more.

Induction motor pf stays the same at 0.8 lag; because P_{IM} increase, Q_{IM} must also increase (relative to what it was before).

$$\begin{aligned}\text{So } P_{\text{total}} &= P_{\text{IM}} + P_{\text{HL}} + P_{\text{SM}} \\ &= 631906 + 100000 + 198933 \\ &= 930,839 \text{ watts}\end{aligned}$$

$$\begin{aligned}Q_{\text{total}} &= Q_{\text{IM}} + Q_{\text{HL}} + Q_{\text{SM}} \\ &= 473930 + 0 - 77016 \\ &= 396914\end{aligned}$$

$$\tan \theta = \frac{Q}{P} = \frac{396914}{930839} = 0.4264 \Rightarrow \theta = 23.09$$

$$pf = \cos \theta = \cos 23.09 = 0.92$$

A pf of 0.95 lagging requires:

$$\tan^{-1} \left[\frac{396,914 + Q_c}{930,839} \right] = \cos^{-1}(.95) = 18.19^\circ$$

$$Q_c = -396,913 + 930,839 \bullet \tan(18.19) = -90,961 \text{ var}$$

What is Bc and C necessary to supply this reactive power?

We need to know

**The voltage! Assume that it is 13.8 kV L-L.
Recall that it will be delta connected.**

$$Q_c = \frac{|V_c|^2}{-X_c} \Rightarrow X_c = \frac{|V_c|^2}{-Q_C} = \frac{13800^2}{90961} = 2093.6$$

$$X_{c\Delta} = 3X_c = 6280.9$$

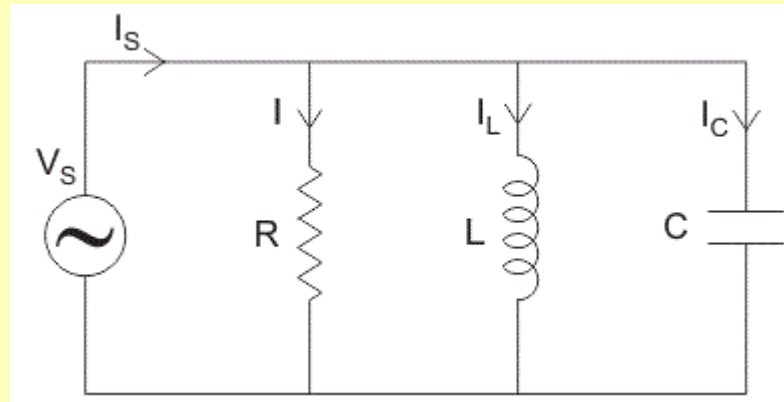
$$X_{c\Delta} = \frac{1}{\omega C}$$

$$C = \frac{1}{\omega X_{c\Delta}} = \frac{1}{377(6280.9)} = 0.4223 \mu\text{f}$$

Final comment on power factor correction

Resonance occurs when an RLC circuit is excited by a frequency ω such that the impedance seen by the source is purely resistive.

For example, consider the below RLC circuit:



The impedance seen by the source is given by $Z=R//j\omega L//-j/\omega C$,

which is:

$$\frac{1}{Z} = \frac{1}{R} + \frac{1}{j\omega L} - \frac{\omega C}{j} = \frac{1}{R} - \frac{j}{\omega L} + j\omega C$$

$$= \frac{\omega L - jR + j\omega^2 CRL}{\omega RL} = \frac{1}{\omega RL} \left[\omega L + j(\omega^2 CRL - R) \right]$$

Final comment on power factor correction

For this impedance to be entirely real, we have that

$$\omega^2 CRL - R = 0 \Rightarrow \omega^2 CL = 1 \Rightarrow \omega^2 = 1 / CL$$

Which implies that the resonant frequency is

$$\omega = 1 / \sqrt{LC}$$

Note also that

$$\begin{aligned} \omega^2 = 1 / CL &\Rightarrow \omega L = 1 / \omega C \\ &\Rightarrow X_L = X_C \end{aligned}$$

So resonance occurs when in the above circuit $X_L = X_C$, i.e., when the reactive consumption of the inductor is exactly compensated by the reactive supply of the capacitor. This is 100% compensation, or, 1.0 power factor condition.

Final comment on power factor correction

Conclusion:

Resonance is the condition under which the frequency causes the circuit to exhibit 1.0 power factor.

Or...unity power factor condition is the condition for which resonance occurs in an RLC circuit.