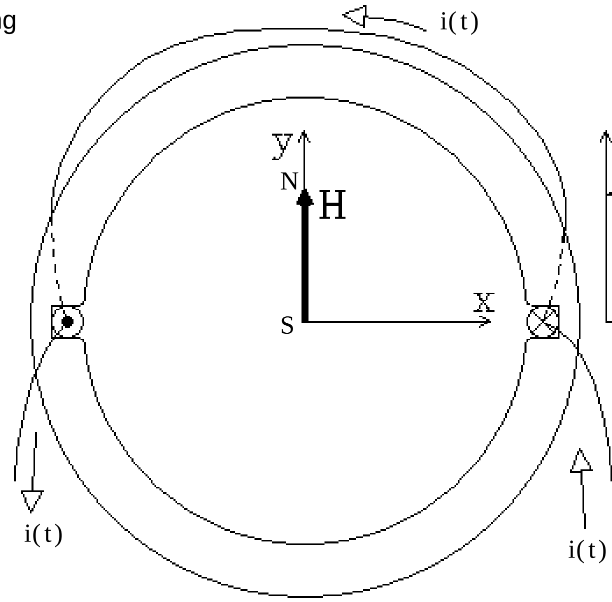
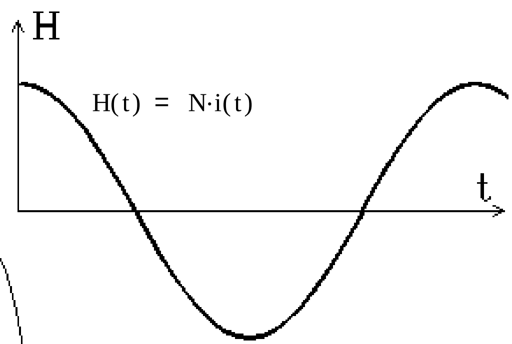
ECE 3600 Single-Phase Induction Motors

A Stolp
3/9/23,
11/2/23

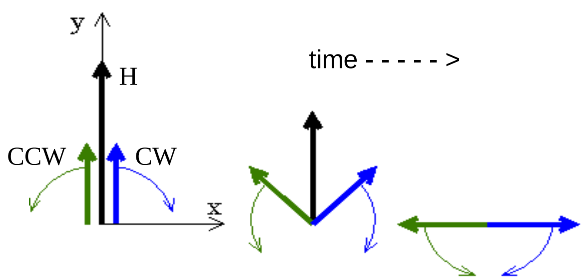
A single-phase winding on the stator of an induction motor.

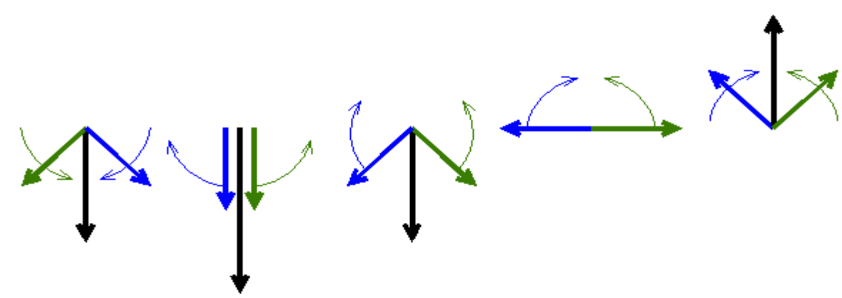




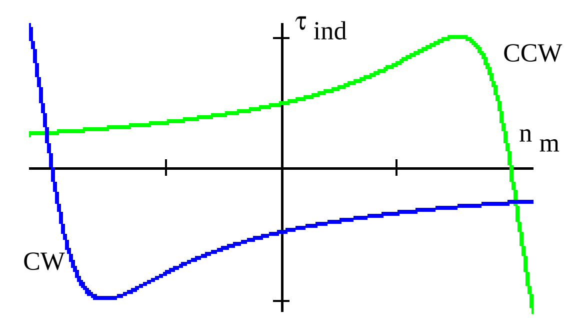
Field goes up and down-- no rotation.
A single phase of current cannot produce a rotating magnetic field.
So, does this motor have a torque-speed curve??

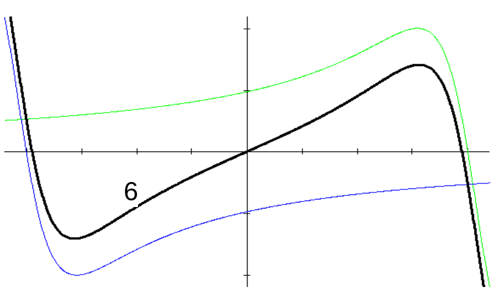
Yes it does. Think of the magnetic intensity vector, H, as being made up of two vectors half as large and rotating in opposite directions. The green (CCW) vector and the blue (CW) vectors shown below add up to be the H vector.





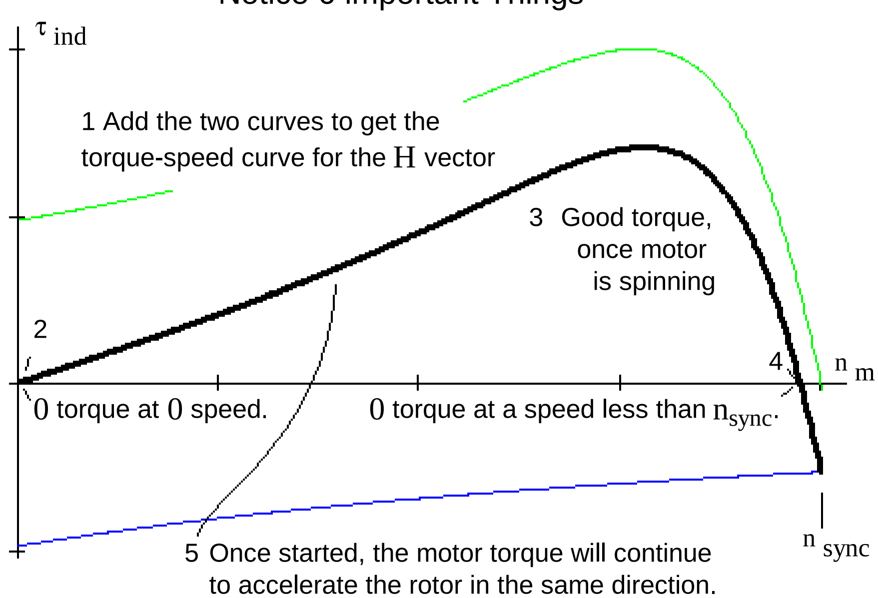
The two counter-rotating magnetic-field vectors would cause two simultaneous torque-speed curves for the rotor.





6 Motor will spin equally well in reverse, if you can just get it started that way.

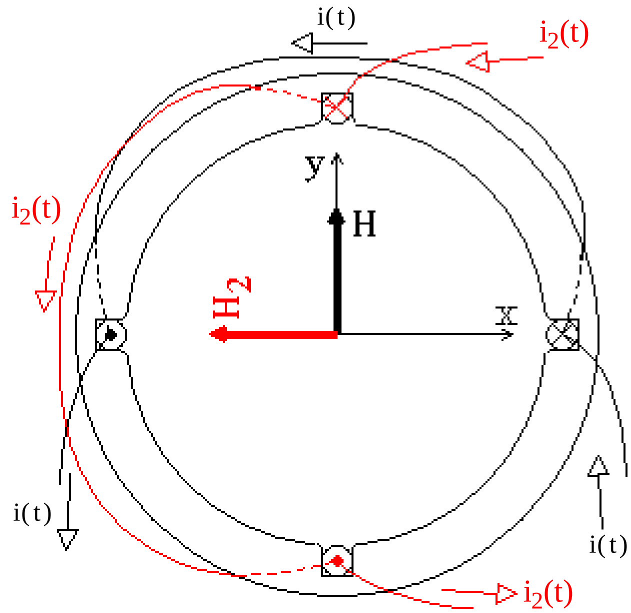
Notice 6 important Things



Think back to the first lab. Isn't that exactly what we saw in that lab?

So, how can we get this motor started?

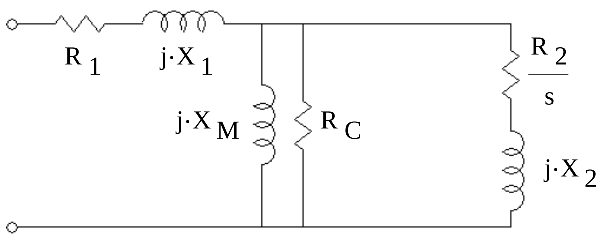
Adding a second winding might help, but only if the timing (phase) of $i(t)$ and $i_2(t)$ are not the same. If the phase of $i(t)$ and $i_2(t)$ are the same, then there is no net field rotation. But, if $i_2(t)$ can be delayed a little from $i(t)$, then there would be some net field rotation in the counter-clockwise (CCW) direction. Alternatively, if $i_2(t)$ could lead $i(t)$, then there would be some net field rotation in the clockwise (CW) direction.



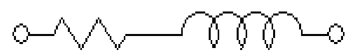
Unless you want to manually start the motor...

The motor NEEDs a second winding to get started, AND the phase of the two currents NEED to be different in order to get some net rotating magnetic field. No net rotating field -- means no starting torque.

Each winding can be modeled in the same way as a single phase of a 3-phase winding.



But are often shown as a single resistor and inductor.

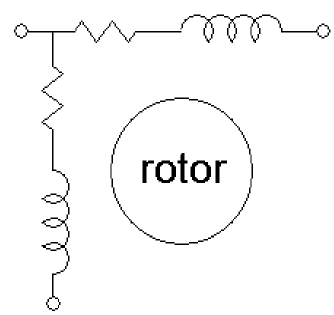


The values of the resistor and inductor would only be valid at one value of slip (s).

Sometimes the windings may be shown as something that looks like a single inductor, but it MUST have both resistance AND inductance.

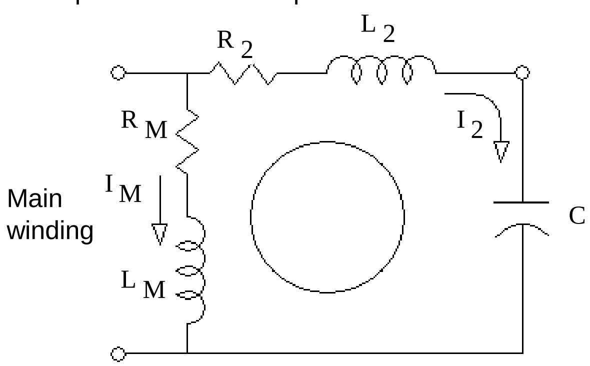
The two windings may also be shown like this, to indicate that they are placed at a 90^o angle to one another with respect to the rotor.

(Note: the actual angle would be less if it's not a 2-pole motor)



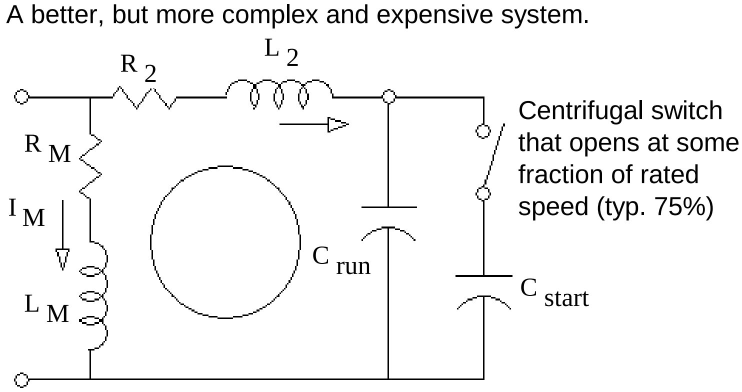
Capacitor-Run Motor

A capacitor is hooked up in series with one winding of the motor.



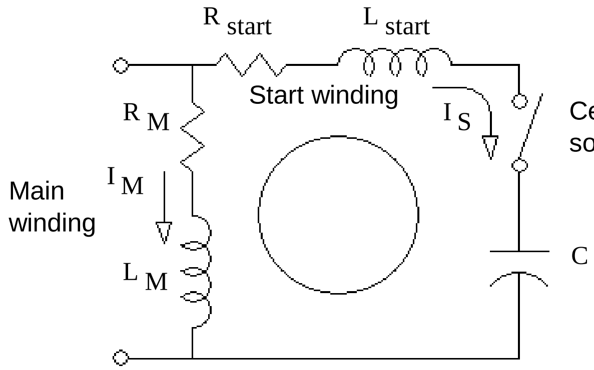
Ideally, choose a capacitor so that the current through the second winding (I_2) leads the current through the main winding (I_M) by 90^o. Unfortunately, that will only be possible at one motor speed (or slip).

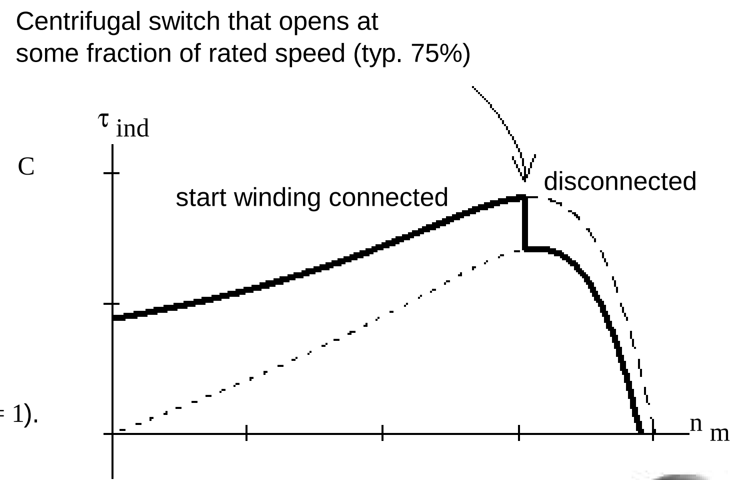
A better, but more complex and expensive system.



Now choose C_{run} to be ideal at normal operation and $C_{run} + C_{start}$ to be ideal at startup.

Capacitor-Start Motor





Ideally, choose a capacitor so that the current through the second winding (I_S) leads the current through the main winding (I_M) by 90º at startup ($s = 1$).

Note: An alternative to the centrifugal switch is a **P**ositive **T**hermal **C**oefficient thermistor (PTC or PTC relay). At room temperature it's resistance is low, but current flowing though it heats it and it's resistance increases to where only a small current flows through the start winding. These are common in refrigerators and freezers. They do have a problem in that the motor cannot be restarted until the PTC cools down.

PTC

Capacitor Calculation For a specific slip

V_T is the terminal voltage

$$\mathbf{Z_M} = R_M + j\cdot\omega\cdot L_M \qquad \mathbf{I_M} = \frac{V_T}{\mathbf{Z_M}}$$

$$\mathbf{Z_S} = R_S + j\cdot\omega\cdot L_S \qquad \mathbf{I_S} = \frac{V_T}{\mathbf{Z_S}}$$

$$\mathbf{Z_S} + \mathbf{Z_C} = R_S + j\cdot\left(\omega\cdot L_S - \frac{1}{\omega\cdot C}\right)$$

$$\mathbf{I_{SC}} = \frac{V_T}{\mathbf{Z_S} + \mathbf{Z_C}}$$

How much phase-angle difference do you get??
ϕ = angle difference between the currents.

$$\phi = \underline{/\,\mathbf{I}_{SC}} - \underline{/\,\mathbf{I}_M} = \arg(\mathbf{I_{SC}}) - \arg(\mathbf{I_M})$$

$$= \arg(\mathbf{Z_M}) - \arg(\mathbf{Z_S} + \mathbf{Z_C})$$

$$\phi = \operatorname{atan}\left(\frac{\omega\cdot L_M}{R_M}\right) - \operatorname{atan}\left[\frac{\omega\cdot L_S - \frac{1}{\omega\cdot C}}{R_S}\right]$$

90º is the optimal ϕ

Refer to the examples to see how you get 90º.

Motor Starting Torque

Proportional to the current magnitudes and the sine of the phase angle difference between the winding currents.

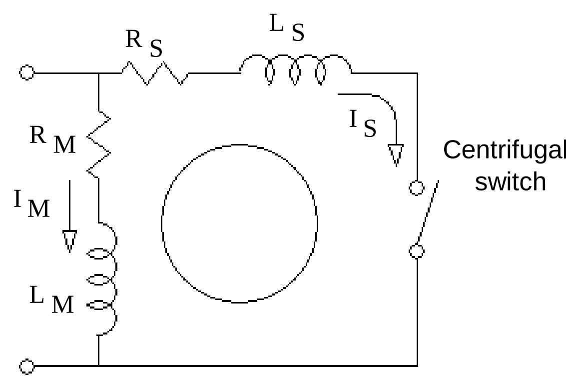
$\left(I_M\cdot I_S\cdot\sin(\phi)\right)$ Where ϕ is the angle difference between the currents (or impedances).

Split-Phase Motor

The run winding has a large inductance and little resistance.

The start winding has little inductance and lots of resistance.

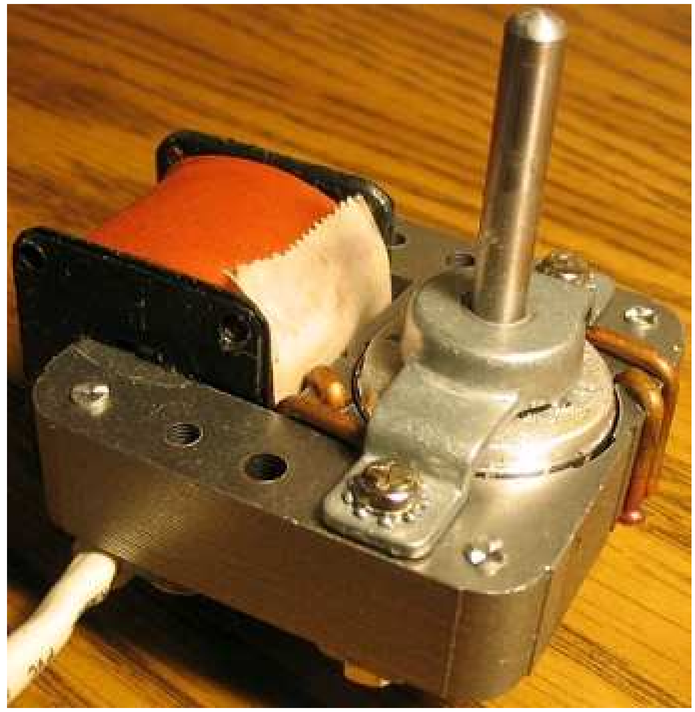
Cheap, but can only get about 30º of phase difference between currents, so starting torque is not that great.



Start Direction (All motors):
Reverse the leads to either of the windings to get the motor to start in the opposite direction.

Shaded-Pole Motor

Small, low-power, cheap induction motors
with a special starting method.



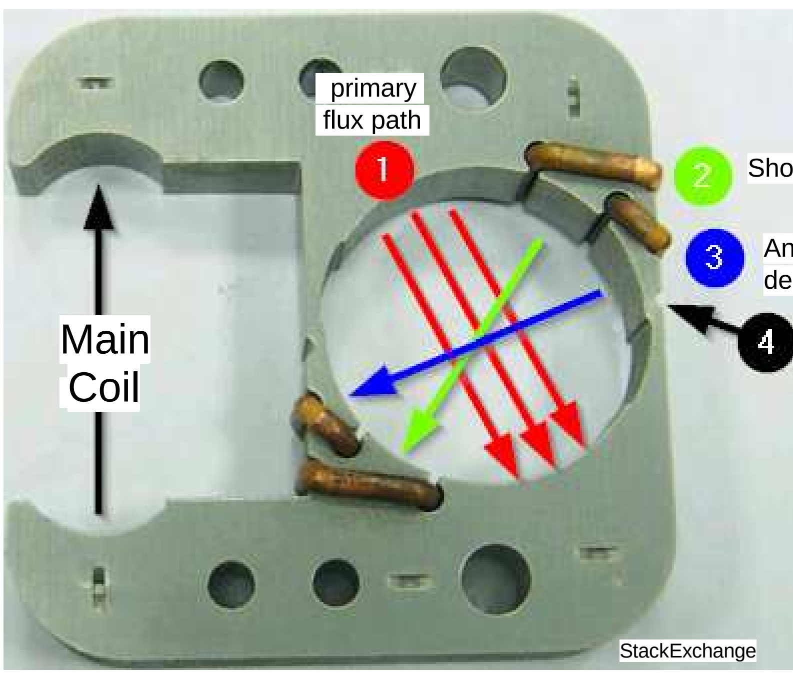
StackExchange

Advantages

- Simple construction
- Reliable and maintenance-free
- Long life
- Low cost
- Extremely rugged
- Self-starting
- Low starting current

Disadvantages

- Low starting torque
- Not Reversible
- Poor power factor
- Low efficiency
- Low power
  - Typically less than 1/20 hp
  - Rarely as much as 1/3 hp



2 Shorted coil delays magnetic flux

3 Another shorted coil delays the flux even more

4 Undesirable flux path here and on other side.

The core is manufactured in one piece to avoid an assembly step (keep it cheap). But notice the small cross-sectional area at this point and the other side. There is just enough metal for mechanical strength without being large enough for all the flux. The core will saturate at these points and force most of the flux to pass through the rotor.

The net effect of the delays is to produce a partially rotating flux in CW direction.

Common Uses

- Cheap, small fans
- Small water pumps
- Toys
- Advertising displays

If you disassemble an old, cheap record player or tape recorder, you will probably find one of these motors.

ECE 3600 Single-Phase Induction Motor Examples

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11/18/19

Ex. 1 From Fin F11. A Single-phase, 1/3-hp, 120-V split-phase motor draws 5 A in its main winding, and 3 A in its start winding when it is first switched on. The two currents lag the supply voltage by 40° and 15°, respectively.

a) Find the initial start-up current (magnitude) and power.

$\omega := 377 \cdot \frac{rad}{sec}$

$\mathbf{I_L} := 5 \cdot A \cdot e^{-j \cdot 40 \cdot deg} + 3 \cdot A \cdot e^{-j \cdot 15 \cdot deg}$ $\quad |\mathbf{I_L}| = 7.822 \cdot A$ $\quad arg(\mathbf{I_L}) = -30.672 \cdot deg$

$P_{start} := 120 \cdot V \cdot |\mathbf{I_L}| \cdot \cos(arg(\mathbf{I_L}))$ $\quad P_{start} = 807.36 \cdot W$

b) To improve this motor, you want to add a capacitor in series with the start winding so that currents will be 90° out of phase with each other. Find the value of the required capacitor.

The original: $\mathbf{Z_{start}} := \frac{120 \cdot V}{3 \cdot A \cdot e^{-j \cdot 15 \cdot deg}}$ $\quad \mathbf{Z_{start}} = (38.637 + 10.353j) \cdot \Omega$

The start winding current should now lead the voltage by 50°.

$X_{start} + X_C = -38.637 \cdot \Omega \cdot \tan(50 \cdot deg) = -46.046 \cdot \Omega$

$X_C := -46.046 \cdot \Omega - 10.353 \cdot \Omega$ $\quad X_C = -56.399 \cdot \Omega = -\frac{1}{\omega \cdot C}$ $\quad C := \frac{1}{-X_C \cdot \omega}$ $\quad C = 47 \cdot \mu F$

c) The new start winding current is about 2 A. The motor starting torque is proportional to the sine of the angle between the winding currents. It is also proportional to the magnitudes of the currents. How much bigger is the starting torque with the additional capacitor?

$$\frac{(2 \cdot A) \cdot (5 \cdot A) \cdot \sin(90 \cdot deg)}{(3 \cdot A) \cdot (5 \cdot A) \cdot \sin(40 \cdot deg - 15 \cdot deg)} = 1.577$$

Ex. 2 From Fin F12. A 1/4-hp, 120-V, 60-Hz, single-phase, capacitor-run, induction motor has two identical windings set 90º apart in the motor housing. Each winding draws 3 A at 30° lag when the rotor is locked and 1.5 A at 40° lag when the motor is running at its rated speed.

a) Find the ideal capacitor to place in series with one of the windings at startup.
Note: the ideal capacitor would create the ideal phase difference between the winding currents.

$\mathbf{Z_{start}} := \frac{120 \cdot V}{3 \cdot A \cdot e^{-j \cdot 30 \cdot deg}}$ $\quad \mathbf{Z_{start}} = (34.641 + 20j) \cdot \Omega$

$X_{start} + X_C = -34.641 \cdot \Omega \cdot \tan(60 \cdot deg) = -60 \cdot \Omega$

$X_C := -60 \cdot \Omega - 20 \cdot \Omega$ $\quad X_C = -80 \cdot \Omega = -\frac{1}{\omega \cdot C}$ $\quad C := \frac{1}{-X_C \cdot \omega}$ $\quad C = 33.2 \cdot \mu F$

b) Find the ideal capacitor to place in series with one of the windings at rated speed.

$\mathbf{Z_{run}} := \frac{120 \cdot V}{1.5 \cdot A \cdot e^{-j \cdot 40 \cdot deg}}$ $\quad \mathbf{Z_{run}} = (61.284 + 51.423j) \cdot \Omega$

$X_{run} + X_C = -61.284 \cdot \Omega \cdot \tan(50 \cdot deg) = -73.035 \cdot \Omega$

$X_C := -73.035 \cdot \Omega - 51.423 \cdot \Omega$ $\quad X_C = -124.458 \cdot \Omega = -\frac{1}{\omega \cdot C}$ $\quad C := \frac{1}{-X_C \cdot \omega}$ $\quad C = 21.3 \cdot \mu F$

c) Find a compromise capacitor to place in series with one of the windings. Choose this capacitor to make the current magnitude in the two windings exactly the same at rated speed. (Don't worry about the phase angles.)

$X_C := -2 \cdot 51.423 \cdot \Omega$ $\quad X_C = -102.846 \cdot \Omega = -\frac{1}{\omega \cdot C}$ $\quad C := \frac{1}{-X_C \cdot \omega}$ $\quad C = 25.8 \cdot \mu F$

d) Find the input power at rated speed with the compromise capacitor in place.

$\mathbf{I_L} := 1.5 \cdot A \cdot e^{-j \cdot 40 \cdot deg} + 1.5 \cdot A \cdot e^{j \cdot 40 \cdot deg}$ $\quad |\mathbf{I_L}| = 2.298 \cdot A$ $\quad arg(\mathbf{I_L}) = 0 \cdot deg$

$P_{start} := 120 \cdot V \cdot |\mathbf{I_L}| \cdot \cos(arg(\mathbf{I_L}))$ $\quad P_{start} = 275.8 \cdot W$