Independent control of active and reactive power flows from an inverter.

Introduction

Consider the following situation:
A wind turbine is situated in a remote part of the country such as north west Donegal where the impedance of the local grid is relatively high. The power factor of the local load is poor which leads to a local drop in voltage. A nearby wind farm feeds power on to the grid using an inverter. Can the wind farm supply reactive power to raise the voltage in the area without affecting its active power delivery?

Before looking at the solution to this in detail we need first to examine two mathematical transforms: the abc to dqo transform and the dqo to abc transform.

DQO to ABC transform

The DQO to ABC transform is as shown in equation 1 below.

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos(\omega t) & \sin(\omega t) & \frac{1}{\sqrt{2}} \\ \cos(\omega t - \frac{2\pi}{3}) & \sin(\omega t - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\omega t + \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} V_d \\ V_q \\ V_o \end{pmatrix} \quad \ldots.(1)$$

This equation is obtained from the consideration of the power flow to a three phase load.
Question: If a 3 phase load consists of three 1 ohm resistors connected in star formation, what must the phase-neutral voltage be to deliver 1W (in total) to the load?
Answer: If the total three phase power is 1W, then the power per phase must be 1/3 W.

$$P_{ph} = \frac{1}{3} = \frac{V_{ph}(rms)^2}{R}$$

$$\frac{1}{3} = \frac{V_{ph}(rms)^2}{1}$$

$$V_{ph}(rms) = \sqrt{\frac{1}{3}} V$$

This is an rms value so the amplitude is $\sqrt{\frac{2}{3}}$ V. The three phase voltages are therefore represented by three sinusoids displaced by an angle of 120 degrees. Substituting '1' for Vd in equation 1 and 0 for Vq and Vo we get:

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos(\omega t) & \sin(\omega t) & \frac{1}{\sqrt{2}} \\ \cos(\omega t - \frac{2\pi}{3}) & \sin(\omega t - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\omega t + \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos(\omega t) \\ \cos(\omega t - 2\frac{\pi}{3}) \\ \cos(\omega t + 2\frac{\pi}{3}) \end{pmatrix}$$

This equation represents three sinusoids (actually cosines) that have a phase of zero,-120 degrees and +120 degrees respectively.

Now what happens when we set Vd = 0 and Vq = 1. We now get

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \sin(\omega t) \\ \sin(\omega t - 2\frac{\pi}{3}) \\ \sin(\omega t + 2\frac{\pi}{3}) \end{pmatrix}$$

These also represent three sinusoids but shifted 90 degrees relative to the first case. What if Vd and Vq are both set to 1? We now end up with a net 45 degree phase shift. By varying Vd and Vq we can vary the phase of the resultant three phase system.

If these three sinusoids are now used as modulating waves for a three phase inverter we can deliver an output voltage with a phase varying between 0 and 90 degrees (relative to the local grid).

ABC to DQO transform

The compliment of the dqo to abc transforms is shown below. This transform will output a set of steady (DC) values representing the in phase (Vd) and quadrature (Vq) components of a three phase current or voltage set.

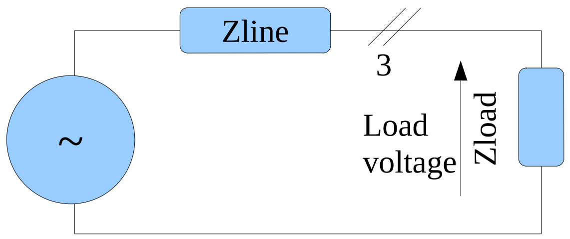
$$\begin{pmatrix} V_d \\ V_q \\ V_o \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3}) \\ \sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad \ldots.(2)$$

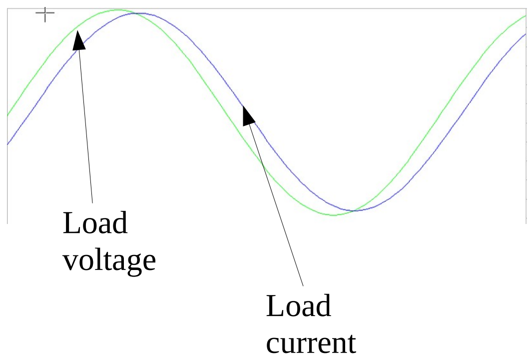
Exercise: Study the LTSpice model dqotest in your BrightSpace module and note the effect of varying Vd, Vq.

Control applications.

The transforms in equations 1 and 2 can be used in conjunction with “standard” P/PI/PID controllers as they represent active and reactive power flows using DC values. These DC values can be compared with setpoints for active and reactive power flows and adjusted to suit. Thus an inverter control can be used to output vars to a local grid independent of its power delivery.

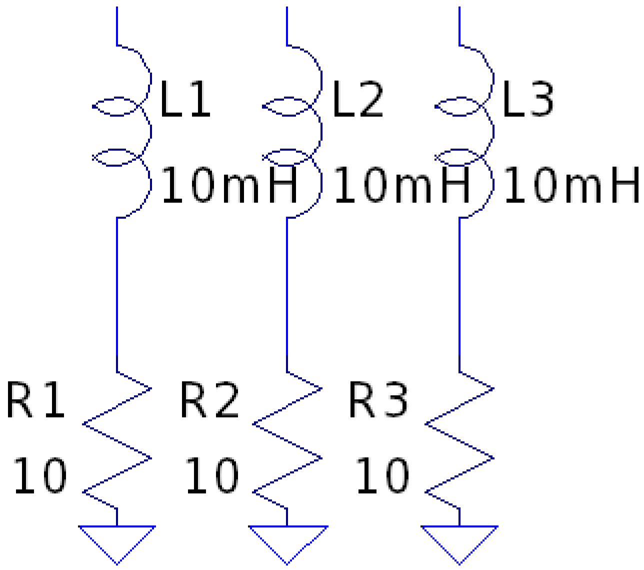
Consider a 3 phase load R-L load connected to a power transmission line with a non-zero impedance.





The load draws a lagging current as shown above. We can model the load as a simple RL pair as follows:

L1,L2, and L3 represent the inductive components of the load while R1,R2,R3 represent the active or resistive components of the load. Current drawn by the parallel inductors do not perform useful work but must nevertheless be supplied by the electricity network.



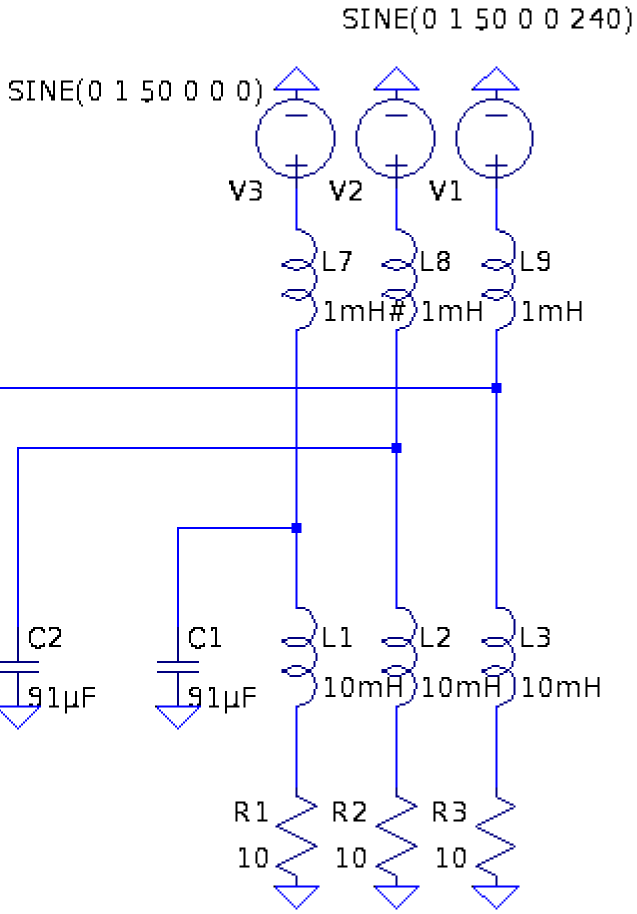
The per-phase impedance is 10.0000 + 3.1416i.
If we get the inverse of this impedance we get the load admittance : 0.091017 – 0.028594i
Can we add a component who’s admittance will compensate or cancel out the imaginary component? We, a capacitor’s admittance is 2pifC so if we should be able to calculate C as follows:

$$2\pi f C = 0.028594$$

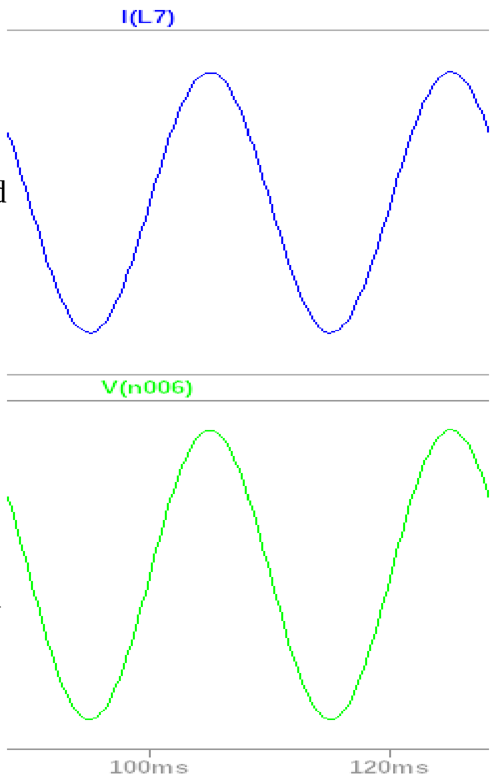
$$C = \frac{0.028594}{2\pi f}$$

$$C = 91\mu F$$

This can be modelled in LTSpice as follows:



This leads to these line current and voltages. As can be seen, they are now in phase. The capacitors have compensated for the inductance of the load.



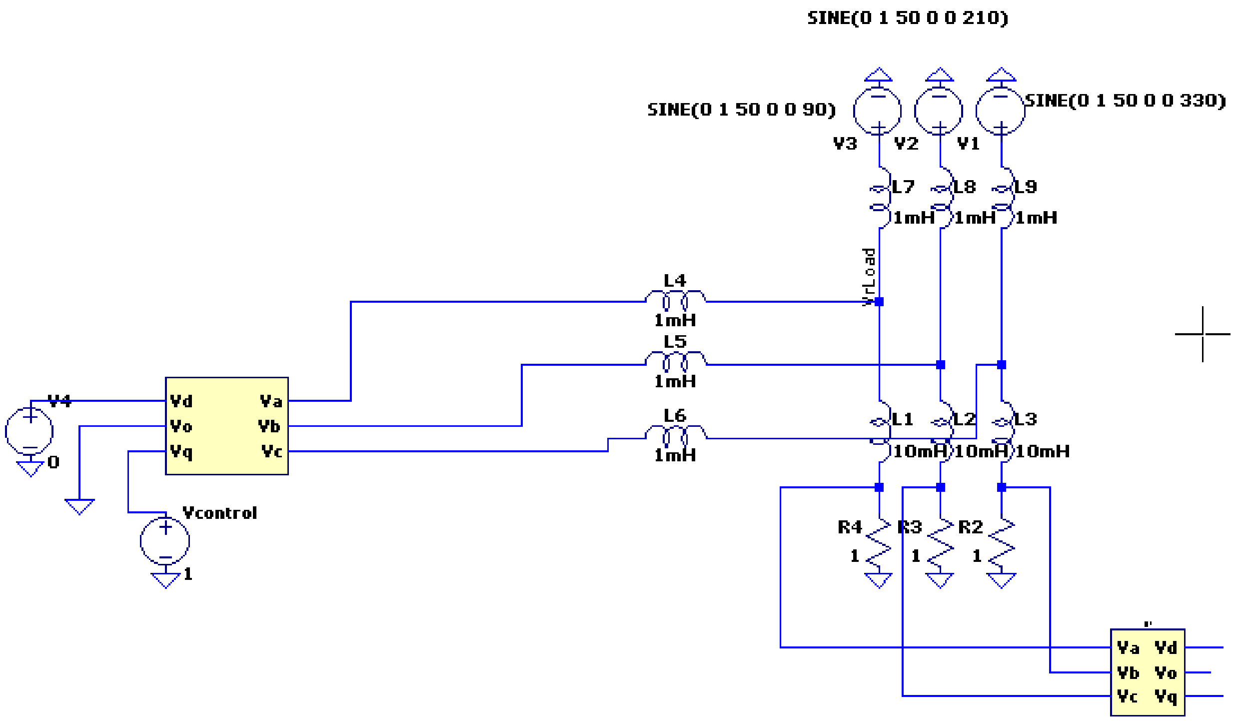
This is known as power factor correction and it it usually carried out by adding capacitor banks.

There are some problems with this:

Capacitors are usually of a fixed size so it compensation is only perfect for one particular load level.

Capacitor banks can be expensive and require maintenance.

Active VAR compensation can correct for power factor problems in continuous fashion thus keeping supply current in phase with supply voltage over a range of loads.



The figure above shows an idealized situation where a dqo controlled inverter is coupled to the local supply and is used to inject in VARS to compensate for a load with poor power factor. The control voltage for the dq0-abc block is fixed here but could be derived from feedback obtained from an abc-dqo transform connected to a current sensor. The signals involved are DC in nature and are amenable to traditional P,PI,PID control techniqies.