In power systems, equivalent impedance of the load typically has both a real (resistive) and a positive imaginary (inductive) component, shown in Fig. 1a. When an ac voltage is applied to the load, the current that flows into the load is out-of-phase with the voltage dropped across the load. Thus, the real and reactive powers are non-zero. The power factor, PF, is the ratio of the real power divided by the apparent power, the phasor magnitude of the complex power, delivered to the load. If the load is entirely inductive, power is stored by the load and the power factor is 0. it is 1 if the load impedance only has a resistivity component. Thus, the maximum power is transfer to the load when the voltage across the load and the current flowing into the load have the same phase angle and PF = 1. To achieve this, a capacitor, Cpf, is added in parallel to the load to balance as much as possible the inductive component of the load – a technique known as power factor correction, PFC (Fig. 1b).

Unfortunately, this balance is only achieved at or close to a specified frequency. Since the frequency of power systems tends to be extremely stable and rarely varies more than +/- 3 Hz, this technique is commonly used to eliminate the inductive component of the load. Additional resistance is added in series or in parallel to the load to then match the Thévenin resistance of the voltage source to maximize the power transferred.

When the frequency of the voltage applied to a load varies over a wide range, multicomponent matching networks, rather than a single capacitor, are used to insure that the maximum power is transferred to the load when the impedance of the load is not equal to the impedance of the source. There are many different matching network topologies, or the form that is made by the components. Three of them are the “L”, “T”, and “Π” or “PI” matching networks, shown in Figure 2a, b, and c, respectively. Note that the impedances in each of these networks are not shown as capacitors, inductors, or resistors as any combination of these can be used in a particular topology. However, resistors are rarely used as the real power delivered to the load would suffer. [One way to look at the capacitor used in power factor correction is that it is an “L” matching network where Zm1 = 0 Ω.]

The purpose of this experiment is to determine the power delivered to a load with no matching network, a load with a power factor correction capacitor, and a load with a T network that is designed to allow dc currents to pass to the load. You are allowed to use any of the online filter design packages such as the RF Impedance Circuit Solver available at http://www.eeweb.com/toolbox/ to help you design the T filter. Another tool that may be of interest is FilterPro by Texas Instruments. To gain access to this tool, you have to register at www.ti.com and then download and install the program. Lastly, there is a write-up on designing broadband matching networks with MATLAB code on Mathwork’s RF Toolbox/Videos and Examples site (http://www.mathworks.com/products/rftoolbox/examples.html).
Analysis:

1. Calculate the voltage transfer function $H(\omega) = V_1/V_S$ for the circuit shown in Figure 1a, where $R_S = 100 \, \Omega$, $R_L = 220 \, \Omega$, and $L_L = 10 \, mH$, and the load voltage $V_L$ is the voltage across the series combination of $R_L$ and $L_L$. Using the transfer function, $t_f$, in MATLAB, generate a plot of the magnitude and phase of $H(\omega)$ from 40-60 kHz. Calculate the power delivered to the load, the series combination of $R_L$ and $L_L$, in phasor notation at a frequency of $50 \, kHz$.

2. Calculate the value of the capacitor $C_{pi}$ that should be used in Fig. 1b to minimize the imaginary component of the load impedance and to keep the voltage across the load and the current through the load in phase (or as close as possible). Calculate the power delivered to the load, the series combination of $R_L$ and $L_L$, in phasor notation at a frequency of $50 \, kHz$.

3. Using the online filter design tool on the EEWeb site, design three low-pass impedance matching networks. As low pass filters, $L$, $T$, and $\Pi$ impedance networks should be designed to pass DC current – i.e., there is one or more inductors between $R_S$ and the load. The Q factor for the $T$ and $\Pi$ networks should be high enough so that there are real, positive solutions for the components in the matching network and then adjusted slightly so that the component values are reasonably close to individual components in the parts kit or can be constructed using a series or parallel combination of two components. Record the values of the inductors and capacitors and the Q factor for each design.
   a. Note that the tolerances associated with the inductors and most of the capacitors in the parts kit are +/- 10%. Also, the Q factor does not have to be an integer.

4. Mouse over the plots of the Mag & Phase and Real & Complex. This is the equivalent impedance of the matching network and load in series with $V_S$ and $R_S$. Record the values of the magnitude and phase and the real and imaginary components at $50.0 \, kHz$. (For at least one of the plots, I was unable to move the cursor to exactly $50.00 \, kHz$, but was able to obtain information at $50.01 \, kHz$.)
   a. If the equivalent impedance of the matching network and load has an imaginary component (the phase angle is not zero) at $50 \, kHz$, find the frequency where the equivalent impedance is only resistive. Record the frequency and equivalent impedance. (Again, there may be cases where you cannot move the cursor to a frequency where the phase angle is $0^\circ$. If so, find the frequency at which the imaginary component is as small as possible.)

5. Determine the voltage transfer function $H(\omega) = V_1/V_S$ for the $\Pi$ network. Using the $t_f$ function in MATLAB, generate a plot of the magnitude and phase of $H(\omega)$ from 40-60 kHz. Calculate the power delivered to the load, the series combination of $R_L$ and $L_L$, in phasor notation at a frequency of $50 \, kHz$. Compare the result of this calculation with the values obtained in Steps 1 and 2.

Modeling:

6. In PSpice, simulate the transient and frequency response of the circuit in Fig.1a.
   a. For the transient analysis, the frequency of the sinusoidal voltage source should be $50 \, kHz$ and the amplitude should be $1 \, V$. Print the graph of the voltage across the load and the current flowing through the load, $R_L$ in series with $L_L$, where 3-5 cycles are displayed. How quickly does the output voltage stabilize to its steady state value?
   b. For the frequency response, the amplitude of the AC voltage source should be $1 \, V$. The AC Sweep should be performed from 10 kHz to 100 kHz. Obtain a graph of the magnitude and phase angle of the voltage across the load and the current flowing through the load, $R_L$ in series with $L_L$. Using the cursors, determine the magnitude and phase angle of the voltage and current at $50 \, kHz$.
   c. Determine the power generated by the voltage source and the power delivered to the load at $50 \, kHz$.

7. Simulate the transient and frequency response of the circuit with the $\Pi$ network.
   a. For the transient analysis, the frequency of the sinusoidal voltage source should be $50 \, kHz$ and the amplitude should be $1 \, V$. Print the graph of the voltage across the load and the current flowing through the load, $R_L$ in series with $L_L$, where 3-5 cycles are displayed. How quickly does the output voltage stabilize to its steady state value?
   b. For the frequency response, the amplitude of the AC voltage source should be $1 \, V$. The AC Sweep should be performed from 10 kHz to 100 kHz. Obtain a graph of the magnitude and phase angle of the voltage across the load and the current flowing through the load, $R_L$ in series with $L_L$. Using the cursors, determine the magnitude and phase angle of the voltage and current at $50 \, kHz$.
   c. Determine the power generated by the voltage source and the power delivered to the load at $50 \, kHz$.
Measurements:

8. Construct the circuit in Fig. 1a. The arbitrary function generator should be set to a sinusoidal output at 50 kHz with an amplitude of 1V. Rs is the sum of the equivalent resistance of the arbitrary function generator and another resistor. The value of the resistor connected to the arbitrary function generator should not be 100 Ω; it should be 100 Ω minus the equivalent resistance of the arbitrary function generator, which is roughly 40-50 Ω.

9. Measure the voltage outputted by the arbitrary function generator and the voltage across the load impedance, $R_L$, in series with $L_L$. Determine the current flowing through the load impedance.
   a. Since the order of $R_L$ and $L_L$ is not important, consider switching the order of the two components and calculate the current through the load impedance by measuring the voltage across $R_L$ and then applying Ohm's Law.

10. Determine analytically the magnitude of $V_s$, the power generated by $V_s$, and the power delivered to the load impedance at 50 kHz. Calculate $H(50 \text{ kHz}) = \frac{V_l}{V_s}$.

11. Obtain a Bode plot of the magnitude and phase of the voltage across the load impedance and of the voltage across $R_L$, the magnitude of the latter is proportional to the magnitude of the current flowing through the load while the phase angle will be equal to the phase angle of the current flowing through the load. Each of the Bode plots should be made using the voltage output from the arbitrary function generator as the reference signal. The frequency range for the Bode plots should be 10 kHz - 100 kHz.

12. Modify the circuit to include the $\Pi$ matching network that was designed in Step 3.

13. Measure the voltage outputted by the arbitrary function generator; the voltage at the node between the resistor connected to the arbitrary function generator, $Z_{m1}$, and $Z_{m2}$; and the voltage across the load impedance, $R_L$, in series with $L_L$. Determine the current flowing through the load impedance.

14. Using the value of power generated by $V_s$ calculated in Step 10, calculate the power delivered to the load impedance at 50 kHz and $H(50 \text{ kHz}) = \frac{V_l}{V_s}$.

15. Obtain a Bode plot of the magnitude and phase of the voltage across the load impedance and of the voltage across $R_L$, the magnitude of the latter is proportional to the magnitude of the current flowing through the load while the phase angle will be equal to the phase angle of the current flowing through the load. Each of the Bode plots should be made using the voltage output from the arbitrary function generator as the reference signal. The frequency range for the Bode plots should be 10 kHz - 100 kHz.

16. Determine the frequency where the impedance of the load is matched to $R_s$. Calculate the percent difference between the design frequency and the measured frequency.

17. Comment on why the Bode plots obtained in Steps 11 and 15 do not match the MATLAB plots of the transfer function.

18. Compare the power delivered to the load with and without the matching network determined analytically, from the circuit simulations, and the calculated power from the measurements. Provide an explanation for any differences.

19. Comment on the differences between using a circuit to perform a power factor correction and an impedance matching network.

20. Given your knowledge of ideal and real components, explain why the operation of the low-pass $\Pi$ network should be closer to the predicted operation when compared to the low-pass T network. Similarly, why should the operation of the low-pass $\Pi$ network should be closer to the predicted operation when compared to the low-pass L network?

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