Lab 6: Power Factor Correction in Black Box Circuit

Or How I Stopped Worrying About Unknown Loads and Learned to Optimize Them

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Project Objective:

The objective of this project is to determine the correct power factor to use so that we can balance the circuit. The lab is completed in two parts:

1. We are given a black box with no knowledge of its contents, only the signals received from it. We are to analyze those signals and determine the equivalent circuitry inside of it.
2. We are to find the existing power factor of the black box, and then determine a means to correct the power factor.

Introduction:

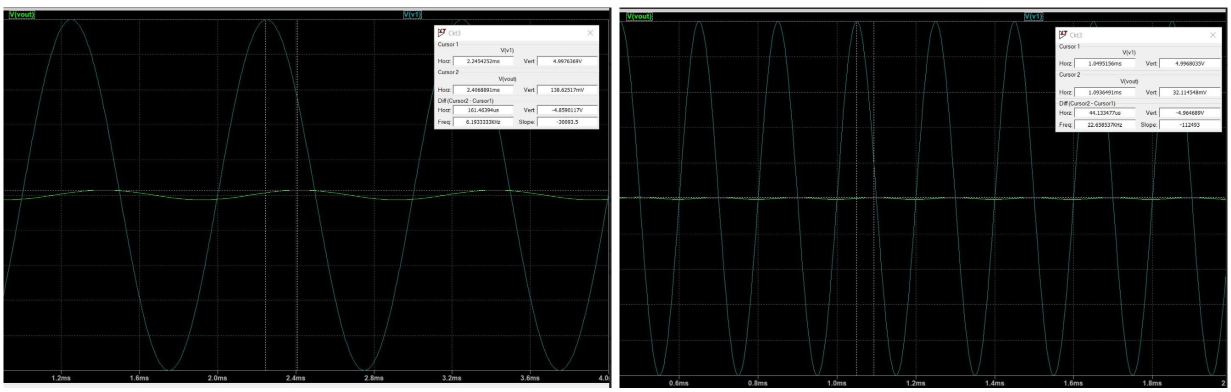

Fig 1: Voltage over time graphs for black box circuit [left: 1kHz, right: 5 kHz].

In part one, we are given two screenshots from the output of a black box with no knowledge of the internal circuitry. The two screenshots provided show signals from the circuit at 1kHz frequency and at 5kHz frequency. The possible contents are either RC or RL, and with the components either in series or parallel. We use Ohm's Law to analyze the circuit, and LTSPICE to model our hypothesized circuit and compare the simulated signals to the output from the black box for verification. Parts used in the LTSPICE model are actual values of real world circuit components which can be purchased commercially to build a physical circuit. Once the contents of the black box are confirmed, the power factor is analyzed for correction. The power factor is increased by adding a capacitor in parallel with the black box. The value of the capacitor should be the inverse of the impedance of the circuit. Increasing the power factor reduces power losses. The goal is to get the power factor as close to 1.0 as possible.

Part One: Black Box Analysis

Experimental Procedure:

Given: Two screenshots of signals from the black box and four possible configurations: RC series or parallel and RL series or parallel.

Step 1: Determine if the circuit is inductive or capacitive. With the screenshots provided, the current is calculated. The circuit's impedance is solved for with the input voltage and source current. If the current leads the voltage, the circuit is capacitive. If the voltage leads the current, the circuit is inductive. The form of the impedance will also tell if this is a RL or RC circuit.

$$I = \frac{v}{\sum_z}$$

Fig 2: Calculating current using impedance and source voltage.

Step 2: Determine if the circuit is in parallel or series. Examine how the voltage output changes when the frequency increases. If the phase angle decreases when the frequency increases, the circuit is either an inductive circuit in parallel with a resistor or a capacitive circuit in series with a resistor. If the phase angle increases when the frequency increases, the circuit is either an inductive circuit in series with a resistor or a capacitive circuit in parallel with a resistor. These two circuit types will act similar because of the formulas for adding impedances in series and in parallel.

Step 3: Determine the exact values of the components in the circuit. Find the total impedance by ohm's law. The real value of the impedance is the total resistor value in the circuit. The imaginary part of the impedance is the inductor or capacitor value of the circuit.

$$Z_{total} = Z_{res} + Z_{cap} + Z_{ind}$$

Where

$$\begin{aligned} Z_{res} &= R_{total} \\ Z_{cap} &= \sum \frac{-j}{\omega C} \\ Z_{ind} &= \sum j\omega L \end{aligned}$$

Fig 3: Finding total impedance.

Part Two: Power Factor Correction

Experimental Procedure:

Make a compensation plan to increase the power factor. To maximize the power factor, the inverse of the black box impedance is added in parallel to the circuit. After initial calculations show the desired capacitor value, it is modeled on LTSPICE to verify the effect. A capacitor of a larger size is chosen to get closer to a power factor of one. Power factor is important because it keeps voltage consistent to equipment and reduces power losses. It also saves money by lowering the electric bill.

Results:

Data:

Dataset	V(v1) (V)	V(vout)(V)	Pk-Pk Δ (s)	Freq kHz	Period (s)	Θ (°)
1k Ckt3	4.997	0.139	1.61E-04	1.00E+03	1.00E-03	58.13
5k Ckt3	4.997	0.032	4.41E-05	5.00E+03	2.00E-04	79.44
Dataset	**L/L**	**ω (rad/s)**	**I (A)**	**Z (j, Ω)**	**R Ω**	**ZL**
1k Ckt3	Current Leads Voltage - Inductive	6,283.185	131.735e-3 + j211.89e-3	380.87 - j612.62198	380	0.09720
5k Ckt3	Current Leads Voltage - Inductive	31,415.927	294.14e-6+j1.578e-3	569.78-j3.05e3	570	0.09708

Fig 4: Observed and calculated data from both output charts.

Results:

In step 1 of the experimental procedure we found the circuit's impedance to have a positive *j* value, which means it is inductive. The phase angle for the 1kHz frequency circuit is 58.1 degrees. The phase angle for the 5kHz frequency circuit is 79.4 degrees. This confirms that the circuit is inductive because as the frequency increases, the phase angle increases. This data confirms that the black box is an inductor in series with a resistor. The calculations made in steps one and two show the value of the inductor to be 100mH. Exact calculations show it to be about 97mH, but that's not a regular inductor size. The resistor for the 1kHz circuit is calculated to be about 380Ω.

In step 3, simulations on LTSPICE are done and the functional resistor value is 330Ω. The resistor for the 5kHz circuit is calculated to be 570Ω, but the closest real resistor value is 560Ω. To correct the power factor, a capacitor of at least 10mF should be used. The calculated size of capacitor needed was 0.006 F. This value was plugged into the LTSPICE simulation, and then the model was altered until the smallest error possible was found using real-world capacitor values. The price difference between the smallest capacitor needed to reach a power factor of 0.97, and the 10mF capacitor that was chosen is about 50 cents. For building one circuit, this price is not significant. If this was a mass produced circuit, further cost-benefit analysis would be performed.

The frequency changing gives more information about what is in the black box. In a capacitive circuit, when the frequency increases, the impedance decreases. In an inductive circuit, when the frequency increases, the impedance increases. This is the result of the equations for impedance for capacitors and inductors. The same capacitor can't compensate for both frequencies. Frequency is used to calculate omega (ω). When the frequency changes, the total impedance of the circuit changes.

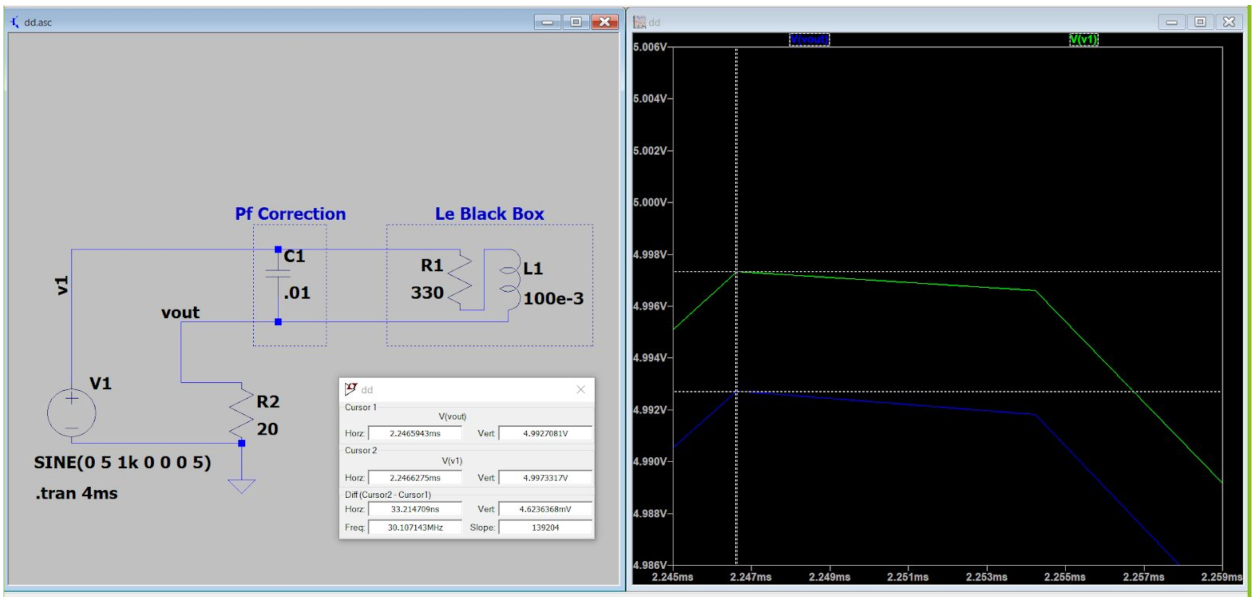

Fig 5: Final circuit and analysis for the power factor correction of the circuit.

Conclusion:

There have been some good learning points in the process of this project. Keeping equations in spreadsheets are important. It is important to take notes on how numbers were calculated. Results are not very useful if you can't explain how you got them. The most important step in the project was getting confirmation from Professor Lipski about the contents of the black box. This made it easy to proceed confidently.

The project requirements were easy to follow and mostly went as planned. Using qualitative techniques to identify the structure of the black box was tricky. It involved learning how the differences in load configuration might show up on a scope, while not explicitly being shown how this looks. The techniques in this lab reflect a simple, yet effective, tool in assessing how a circuits' load is configured. We may not always be given the structure of a load, and need to effectively balance it. Using this technique we knew only the variables that were accessible to us, voltage source, impedance of the sensing resistor, and the behaviour of the load as seen by an oscilloscope.

From these few data points, we were able to extrapolate the “overall” type of a load, and what the quantitative size of the resistive and inductive representation would be. Using this, we could easily implement a “solution” that might be sought after in industry, for a project, or during routine adjustment of circuits on a jobsite.