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How Transformer Impedance Affects Power Conversion System Ratings

C. Michael Hoff, TeraStor Energy

Introduction

There are a few losses to consider when sizing a power conversion system (PCS) in any energy storage system with transformers and transmission lines. Transformers especially, add impedance between the PCS and the point of interconnect (POI). Because of this, PCSs must be rated with a power capacity that is higher than the required power at the POI to overcome the effects of these components.

Simplistically, the battery delivers energy to the grid through a PCS and a transformer. The PCS creates ac voltage and current from the batteries dc voltage and current, and the transformer converts the PCS's output ac voltage to the grid's ac voltage. Figure 1 is a simplified diagram showing this exchange.
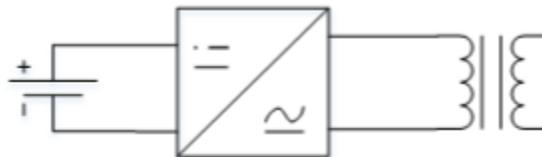

Figure 1: Simplified circuit diagram of the battery, PCS, and transformer

The battery and PCS can be modeled as a single ac voltage source and the transformer can be modeled, for the most part, by two main components, resistance and inductance (neglecting core losses for the moment), as shown in Figure 2Figure:
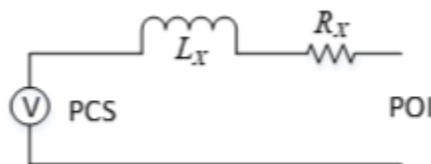

Figure 2: Simplified circuit model of a PCS and transformer

Power flowing into or out of any ac system, whether it be a PCS, a transformer, or a grid connection point contains two components: real and imaginary. Real power is that which is doing real work, and Imaginary is that which is flowing back and forth through the wires and not performing any work. Despite their names, they both contribute to real *current* flowing in and out of power devices and must be dealt with by current-handling devices. Real power is caused by resistive loads that draw current in phase with the voltage from generators. Imaginary power is caused by the presence of capacitances and inductances in an ac system that causes currents to flow 90 ° out of phase with the voltage.

The mathematical construct to represent these two power components is "complex" power, **S**. **S** is a vector in which the horizontal component (x-axis length) is the real component of power and the vertical component (y-axis) represents the imaginary component. The 90 ° geometrical configuration correlates to the 90 ° phase relationship between the currents associated with each. Hence the geometrical angle of any power vector represents the phase of the current or power it is representing.

The complex power, **S**, at the output of the PCS will be mathematically modeled as follows:

$$\mathbf{S}_{PCS} = \mathbf{S}_{POI} + P_x + jQ_x$$

Where j is an imaginary vertical vector with magnitude of 1.

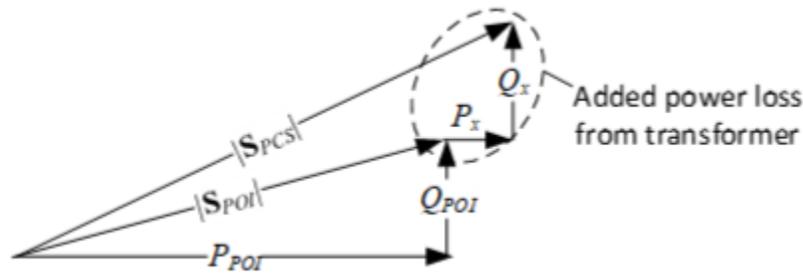Graphically, this can be shown as:

Figure 3: Vector diagram of the complex power losses between the PCS output and the POI

Where P_x and Q_x are the real and reactive losses inside the transformer.

The complex power at the POI, (**S**POI), is the vector sum of the real power delivered into the grid at the POI (PPOI) and the reactive "VARs" provided into the grid (QPOI). Often utilities will require generating assets, like turbines, windmills, PV arrays and batteries, to provide a certain amount of VAR support whenever they call for it. The ratio of PPOI and the magnitude of **S**POI (denoted as |**S**POI|) is the power factor (abbreviated PF). In general, PF is an indication of how much real work is being done by the current flowing in the lines.

In addition, since the PCS powers the system's auxiliary power (P_{aux}) and the transformer's core magnetization losses (P_{core}) while discharging, the real power output must include these extra components: $P_{aux} + P_{core}$.

The total complex power provided by the PCS under full power operation can be geometrically derived to be:

$$\mathbf{S}_{PCS} = P_{POI} \times \left(1 + \frac{R_X}{PF^2}\right) + P_{Aux} + P_{Core} + j\left[\frac{P_{POI}}{PF} \times \sin\left[\cos^{-1}(PF)\right] + P_{POI} \times \frac{L_X}{PF^2}\right]$$

Where $\mathbf{S}_{PCS}$ is the complex power at the PCS terminals, P_{POI} is the real power at the POI, R_x is the wiring resistance of the transformer, *PF* is the power factor at the POI, and L_x is the series reactive losses in the transformer.

As an example, if the grid load is maxed out at 100%, and has a 95% power factor, the complex power at the POI will be approximately 105% of rated real system power. However, if a transformer with 1% per-unit real losses, and 7% reactive impedance is inserted between the PCS and the POI, the total complex power at the PCS can be calculated to be:

$$\mathbf{S}_{PCS} = 1 + \frac{0.01}{0.9} + j\left[\frac{0.313}{0.95} + \frac{0.07}{0.9}\right] = 1.09\angle 22° \tag{0.1}$$

In this example, the required power at the PCS is nine percent larger than the nominally rated POI power. Therefore, it is important that the PCS and energy storage system be sized large enough to overcome the real and reactive losses between them and the POI while supplying the required real and reactive power to the grid.