Electric Vehicle On-Board Charger

An electric vehicle (EV) on-board charger (OBC) allows the EV battery to be charged using AC supply. As seen in Figure 1, the two main components of the OBC are the AC-DC converter and the isolated DC-DC converter.

In this publication, we have included three SPS examples: one example for each converter type and a third one simulating a 7.2-kW OBC.

A description of these models as well as simulation results are presented in the following pages.

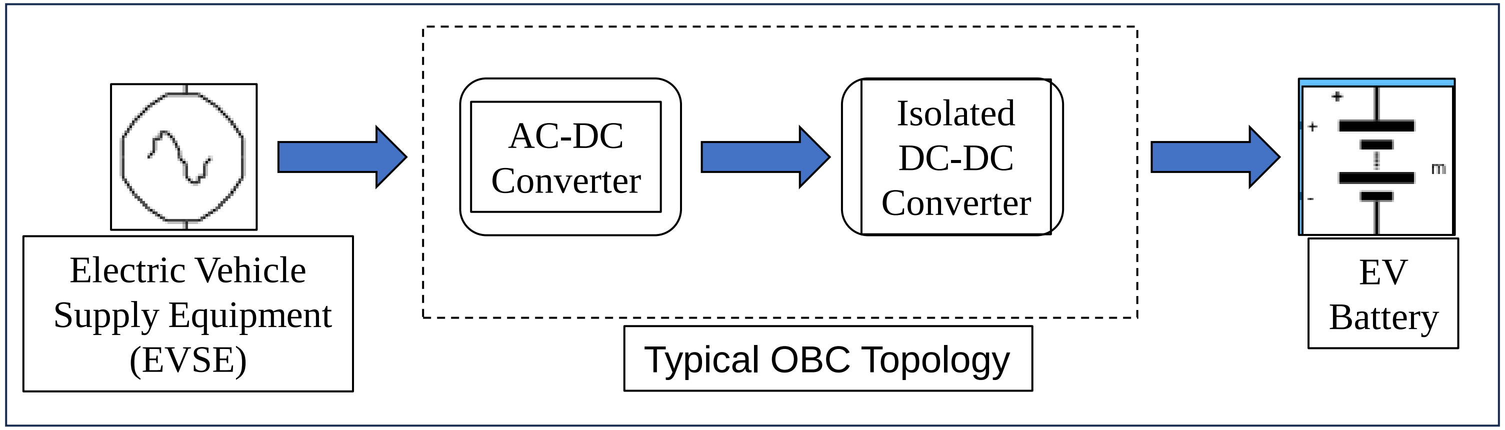

Figure 1

Design Goals

EV manufacturers have designed various types of converters to build their on-board chargers. In our SPS examples, we have chosen the *Totem-Pole Bridgeless PFC* topology for the AC-DC converter and the *Full-Bridge LLC Resonant topology* for the isolated DC-DC converter. See Figure 2.

Our design goals are:

- 7.2-kW unidirectional OBC
- AC-DC converter: Input 240V AC, 30 A, 60 Hz, output 400V DC, switching frequency of 100 kHz, power factor close to 1
- DC-DC converter: Isolated, variable output of 275-450V at full load, switching frequency of 120-250 kHz, Zero-Voltage switching (ZVS) capability

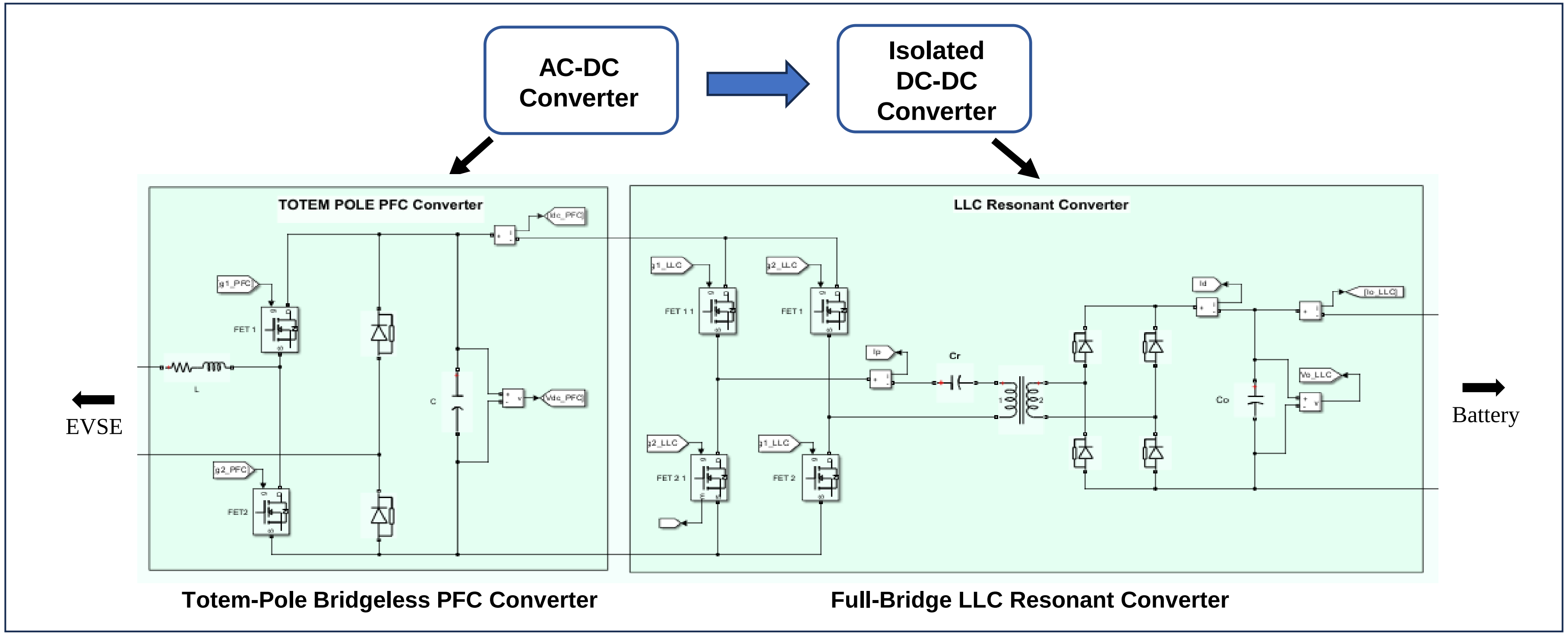

Figure 2

Bridgeless Totem Pole PFC - Power Components

TotemPole_PFC_v1.slx

A Totem-Pole Bridgeless PFC converter consists of a boost inductor and two switching arms (called totem-pole due to their arrangement). One arm is switched at high frequency (100 kHz in our example) and the other arm at low frequency (line frequency). The line frequency arm uses diodes, and the high-frequency arm uses fast FETs devices. Compared to the traditional AC-DC boost converter, this converter does not require a rectifying bridge. The SPS model of the PFC converter is shown in Figure 3.

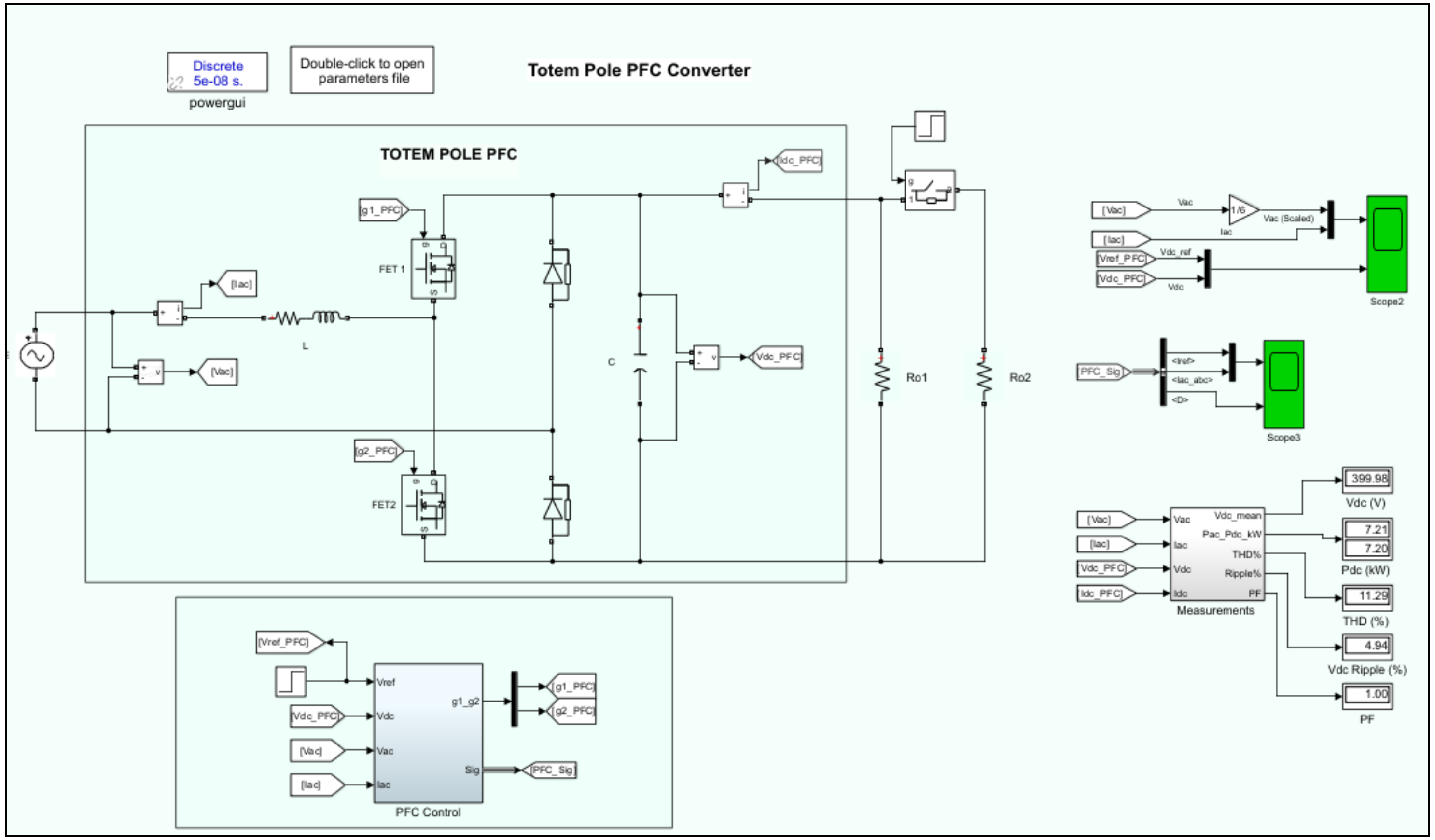

Figure 3: TotemPole_PFC_v1.slx

PFC Operation Mode

The converter operation is illustrated in Figure 4 below. As can be seen, the operation mode changes at each AC voltage zero-crossing. For the positive half-cycle, the bottom diode is conducting and FET2 is the active PWM switch (FET1 is complementary) . On the reverse, for the negative half-cycle, the top diode is conducting and FET1 is the active PWM switch (FET2 is complementary) .

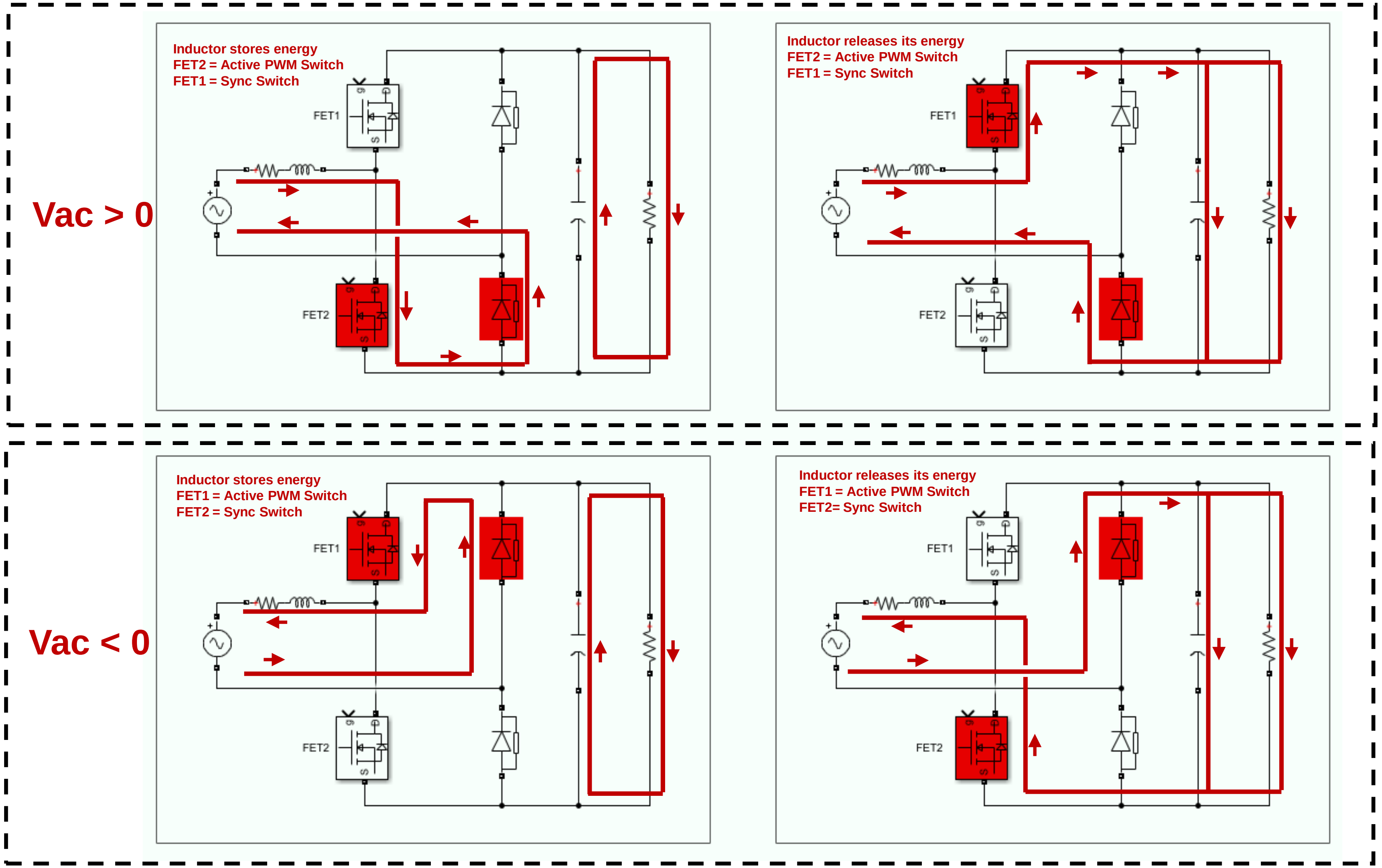

Figure 4

Bridgeless Totem Pole PFC - Control System

The PFC control system consists mainly of one Phase-Lock-Loop (PLL) and two control loops. The outer control loop is a voltage regulator using a *PI* controller. The inner control loop is a current regulator using a *Proportional Resonant* (PR) controller. The PLL job is to detect precisely the zero-crossing moment to determine the converter operating mode and to generate an image of the primary current required for the current regulator.

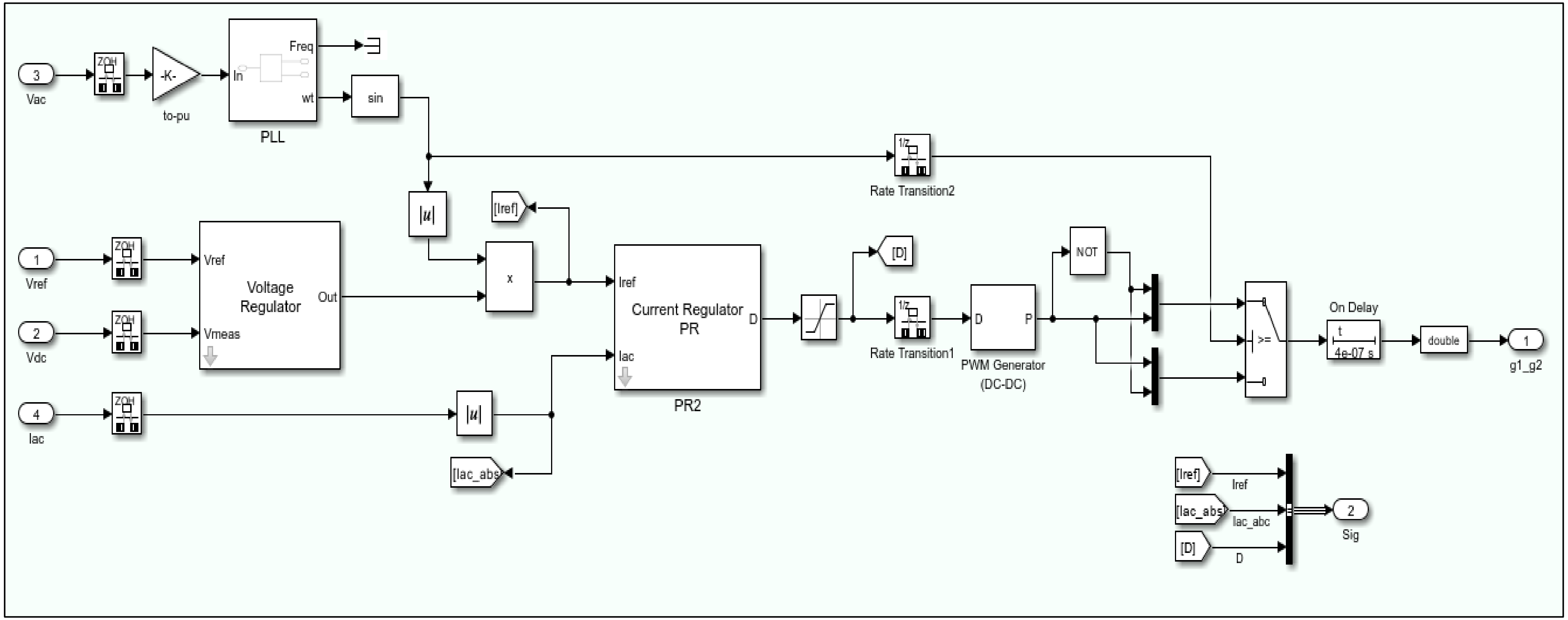

Figure 5

PFC Converter– Voltage Step Simulation Results

To validate the dynamics of the SPS model of the PFC converter, *Totem_Pole_PFC_v1.slx*, we run a 0.6 simulation with a reference voltage step occurring at 0.2 second, followed by a heavy-load switched-in at 0,4. The simulation results are shown in Figure 6a and 6b. We can then conclude that the system dynamics is good. In addition, looking at Figure 6c, we can see that at full load, the power factor (PF), Total Harmonic Distortion (THD) and ripple values are satisfactory.

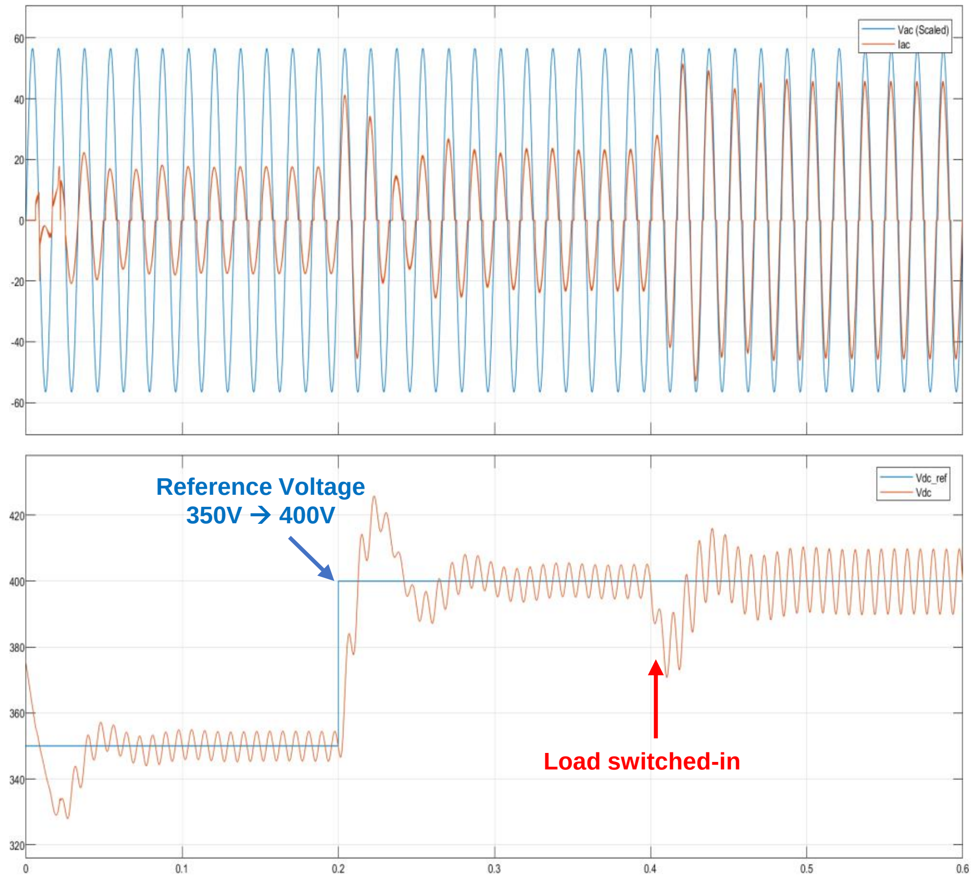

Figure 6a

(Zoom at full load)

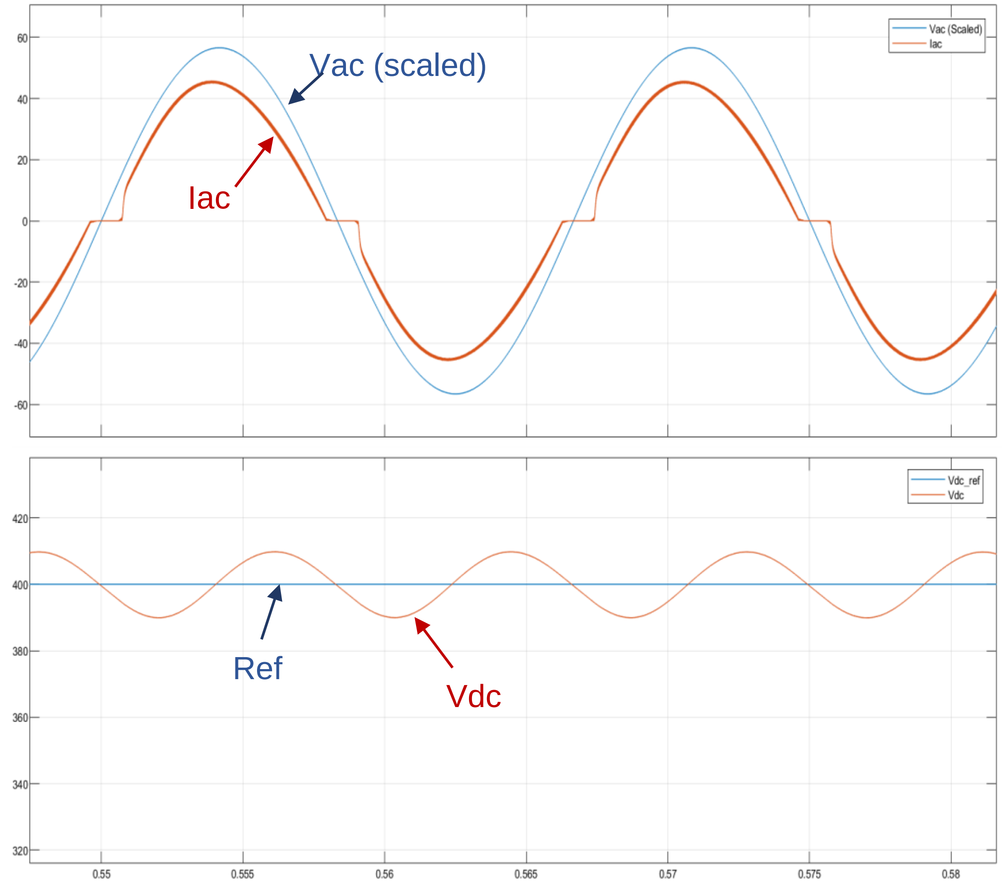

Figure 6b

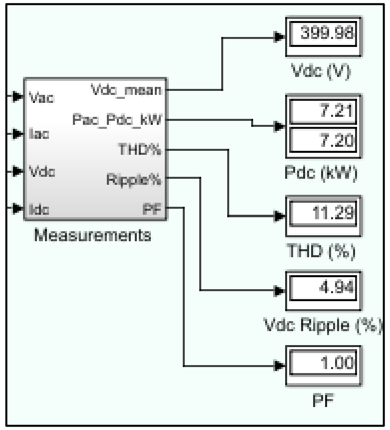

Figure 6c

Full-Bridge LLC Resonant Converter – Power Components

LLC_Resonant_Converter_1.slx

A full-bridge LLC resonant converter is an isolated DC-DC converter based on a resonant circuit. It consists of a full-bridge converter, a resonant tank, a full-bridge rectifier and an output filter. The resonant circuit reduces losses in achieving zero-voltage switching (ZVS) for the full-bridge converter. Our SPS model is shown in Figure 7

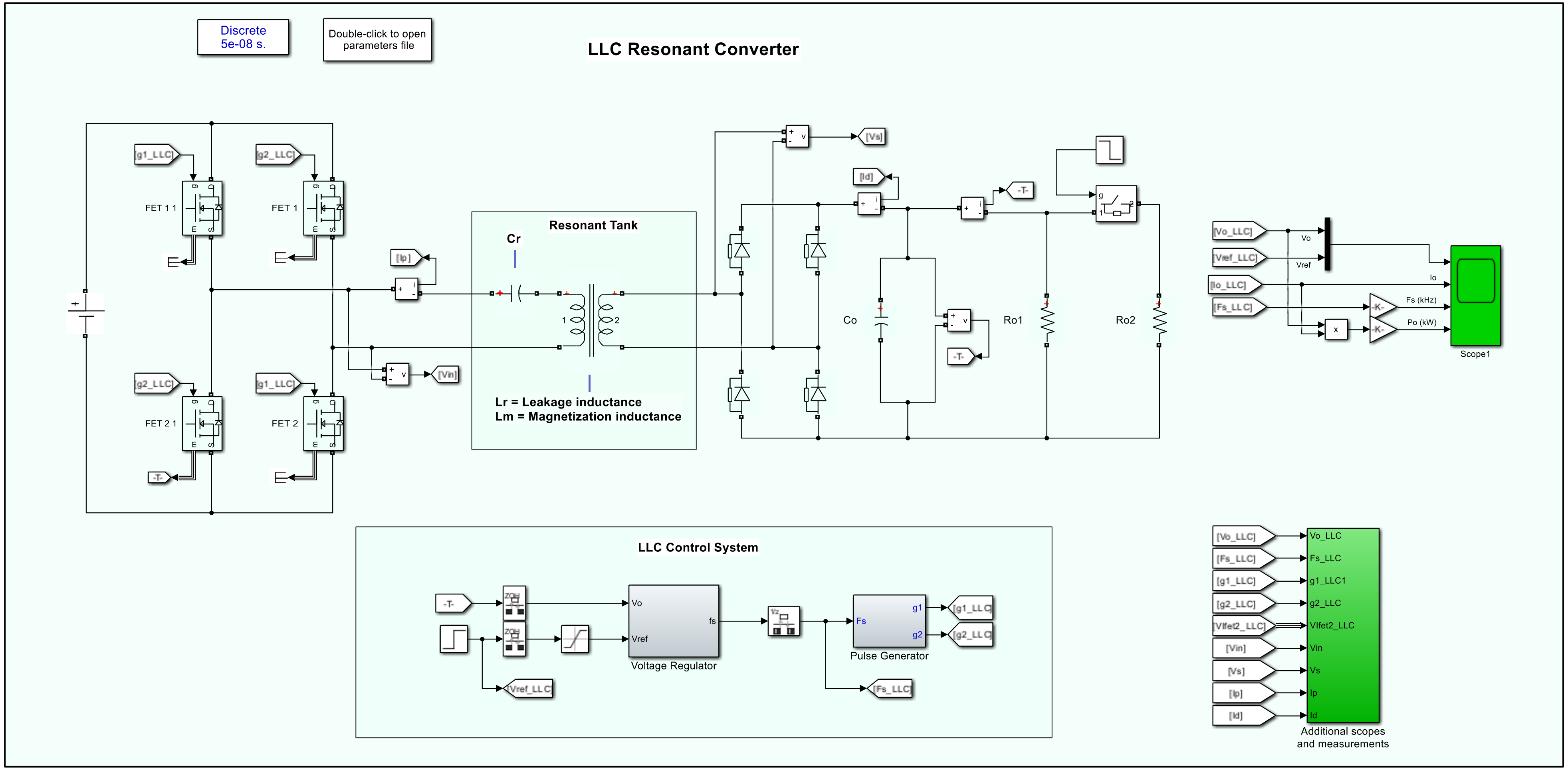

Figure 7: *LLC_Resonant_Converter_v1.slx*

Full-Bridge LLC Resonant Converter – Control System

LLC_Resonant_Converter_v1.slx

The basic control system of our LLC converter model is simply a voltage regulator using a PI controller and a pulse generator with a variable switching frequency. The voltage regulator allows a reference voltage range from 275V to 450V. The switching frequency can vary from 120 kHz to 250 kHz.

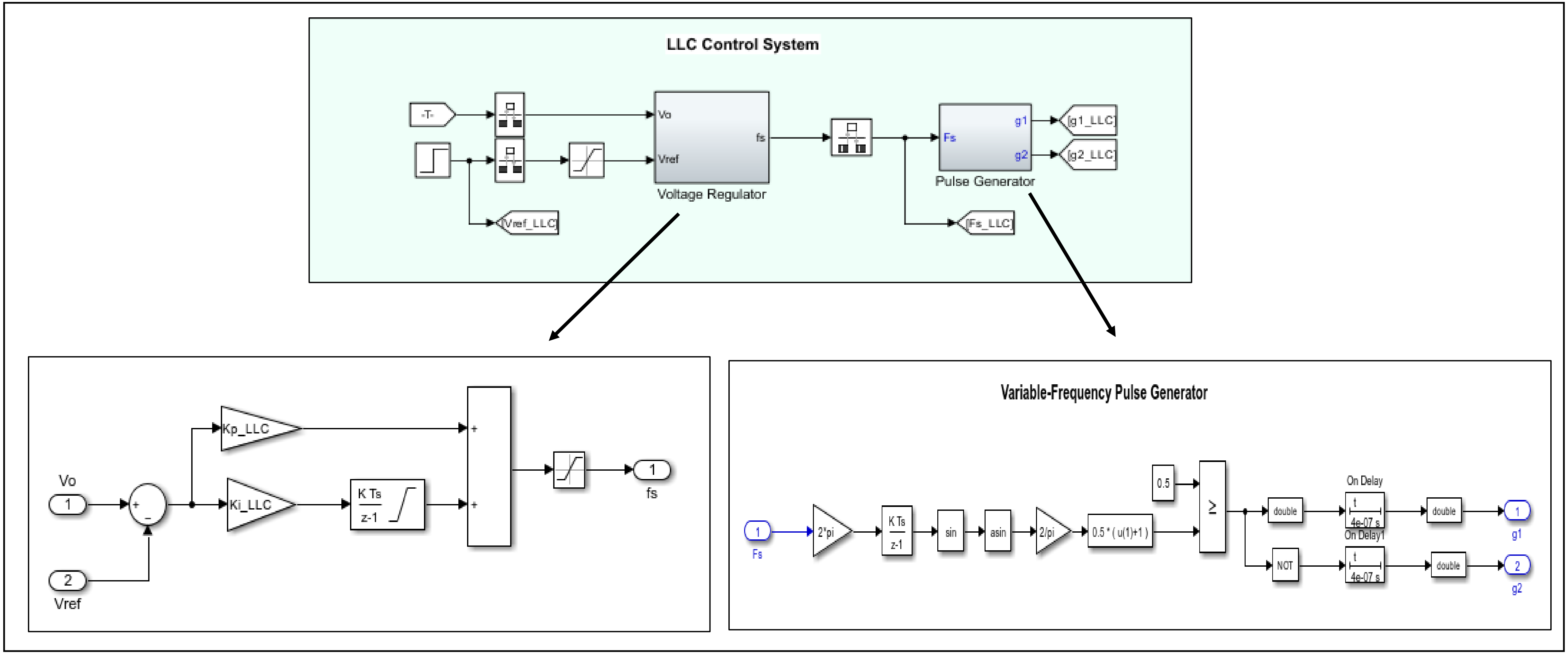

Figure 8

Resonant Tank Voltage Gain

The theoretical resonant tank frequency response of our example is shown in Figure 9. The resonant circuit gain is calculated as follows:

$$\left|\frac{Vout}{Vin}\right| = \frac{F_x^{2} * (m-1)}{\mathrm{sqrt}\left((m*F_x^{2}-1)^{2} + F_x^{2} * (F_x^{2}-1)^{2} * (m-1)^{2} * Q^{2} \right)}$$

Where:

F_x = normalized switching frequency = F_{sw} / F_r

F_r = resonant frequency = $1 / (2 * pi * \mathrm{sqrt}(L_r * C_r))$

Q = quality factor = $\mathrm{sqrt}(L_r / C_r) / R_{ac}$

R_{ac} = equivalent AC load resistance seen from the primary = $8/pi^2 * N^2 * R_o$ where N = Np/Ns = transformer ratio and R_o = DC load

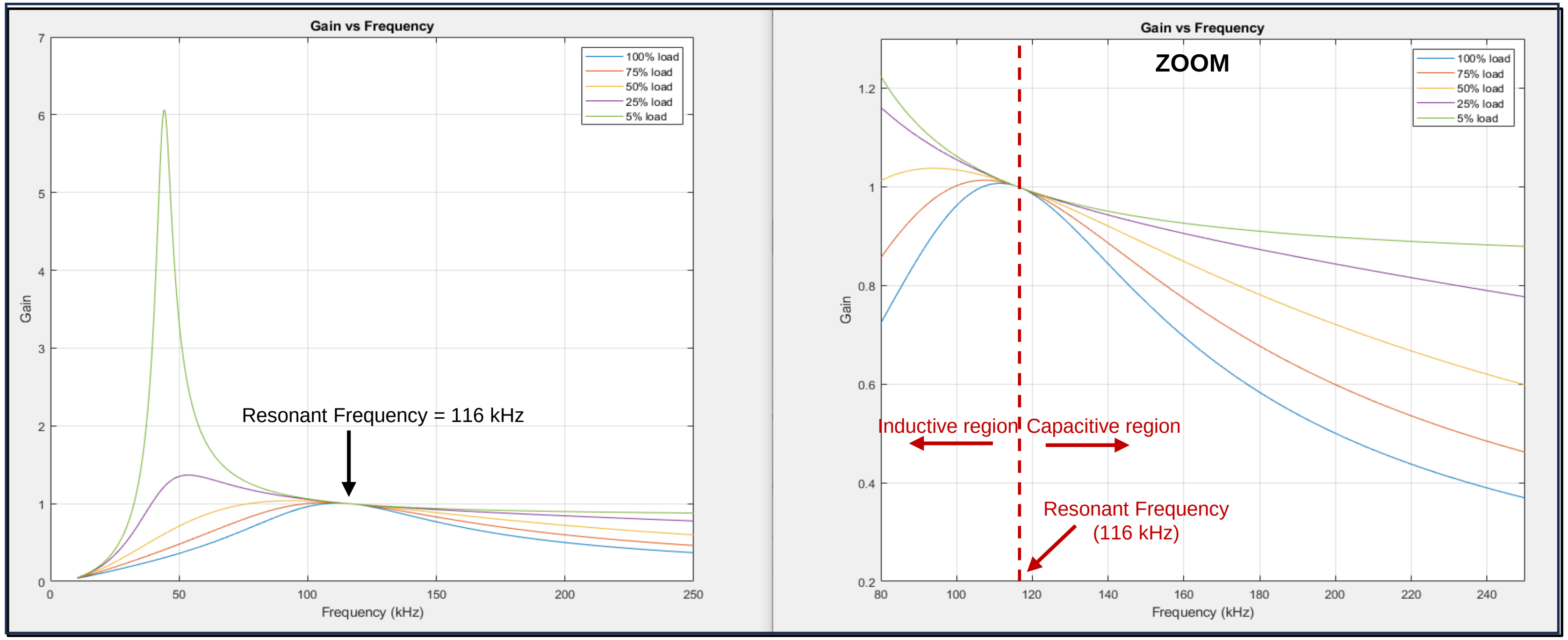

Figure 9

Note 1. The global voltage gain of the LLC converter will then be = *Switching bridge gain * Resonant tank gain * 1/Transformer ratio* where Switching bridge gain =1 and Transformer ratio = 1/1.2

Note 2. We will operate the LLC converter in the capacitive region to achieve ZVS.

LLC Resonant Converter – Simulation Results

Simulation results of the SPS model, *LLC_Resonant_Converter_v1.slx,* are given in Figure 10a and 10b. In Figure 10a, we can observe the converter dynamics as well as its voltage gain range. Figure 10b illustrates the ZVS operation occurring at the full-bridge converter and the 400 ns dead time.

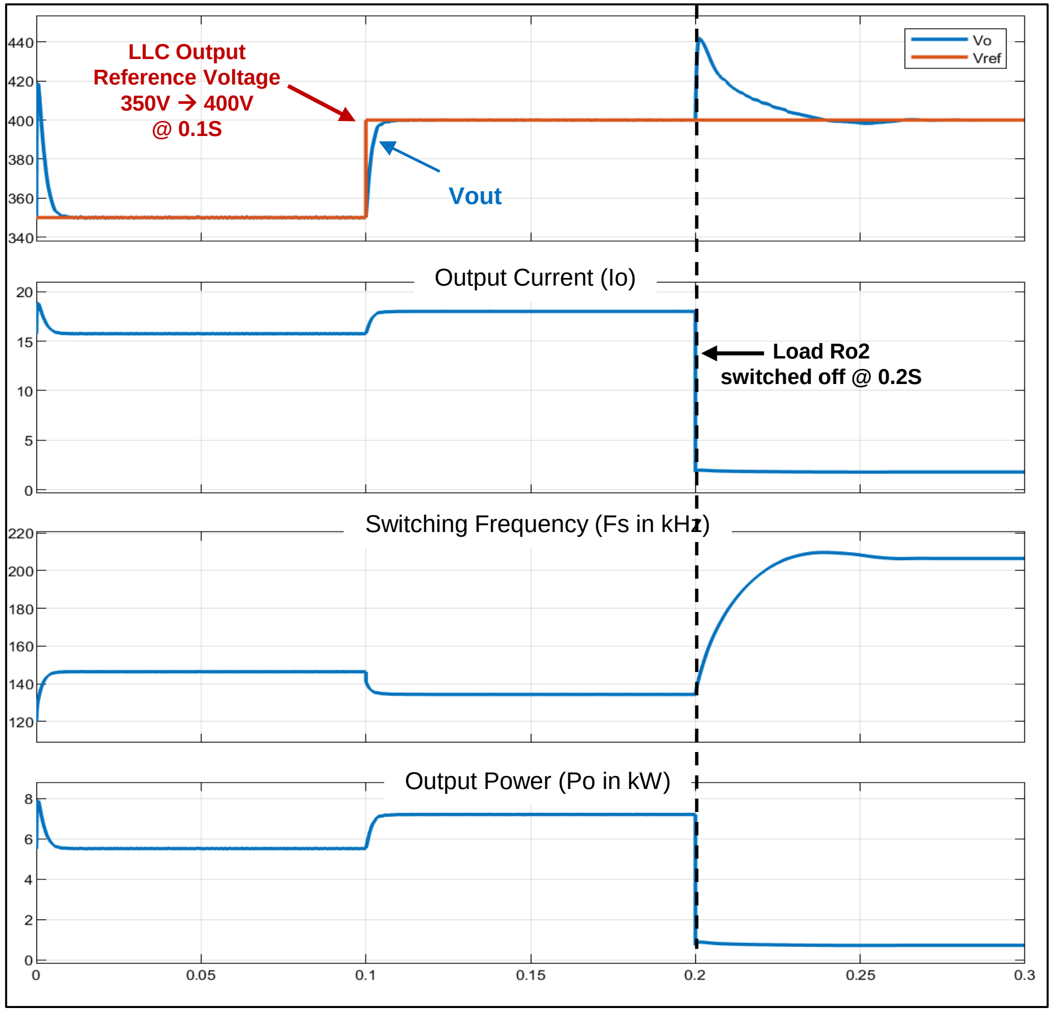

Figure 10a

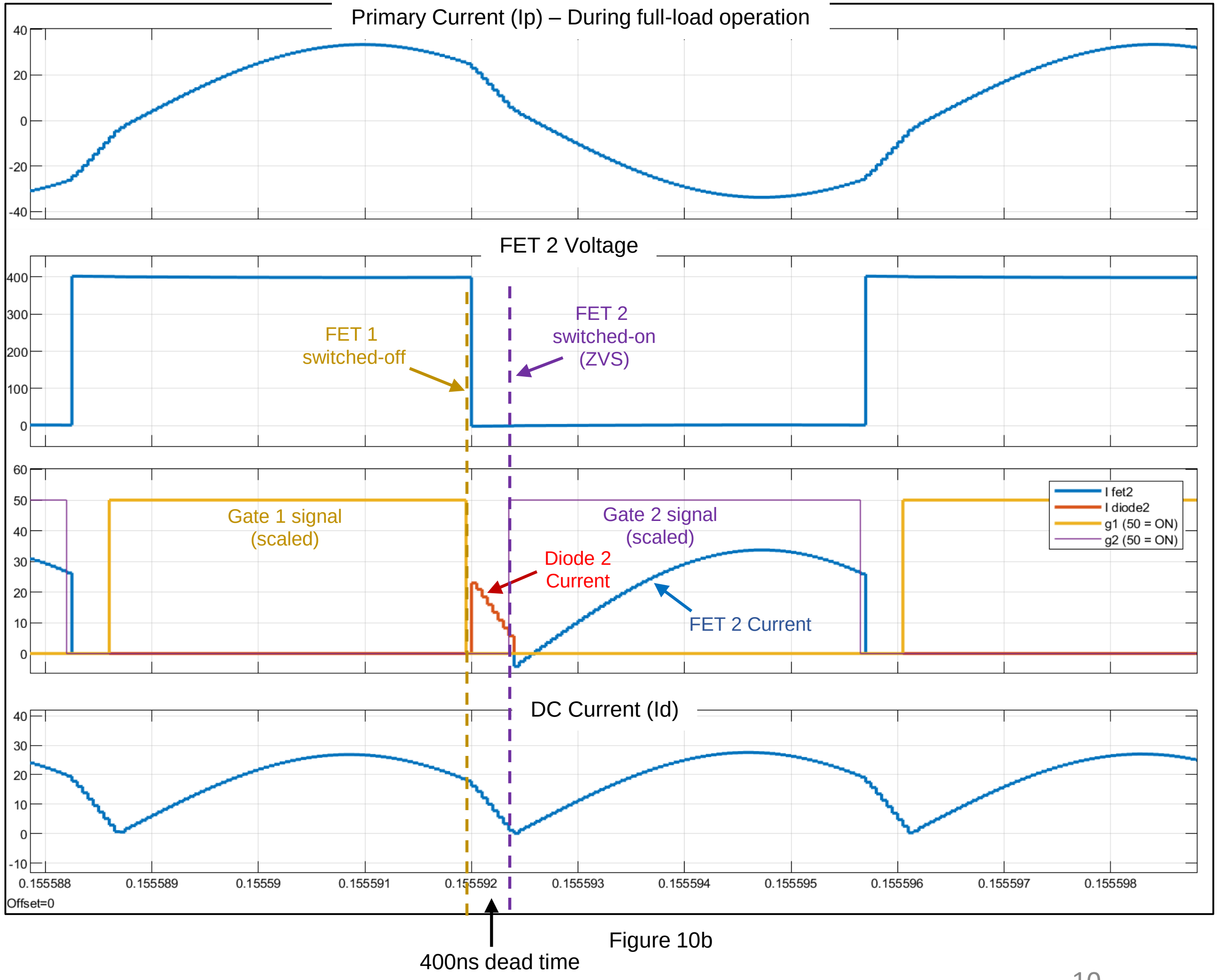

Figure 10b

7.2-kW Electric Vehicle On-Board Charger – SPS Model

OBC_v1.slx

The third SPS model of this publication is OBC_v1.slx. This model connects the two previous converters (described above) together to build the 7.2-kW on-board charger. A controlled current source is used to model the battery current demand. The model also includes additional Simulink blocks allowing to easily perform two different tests.

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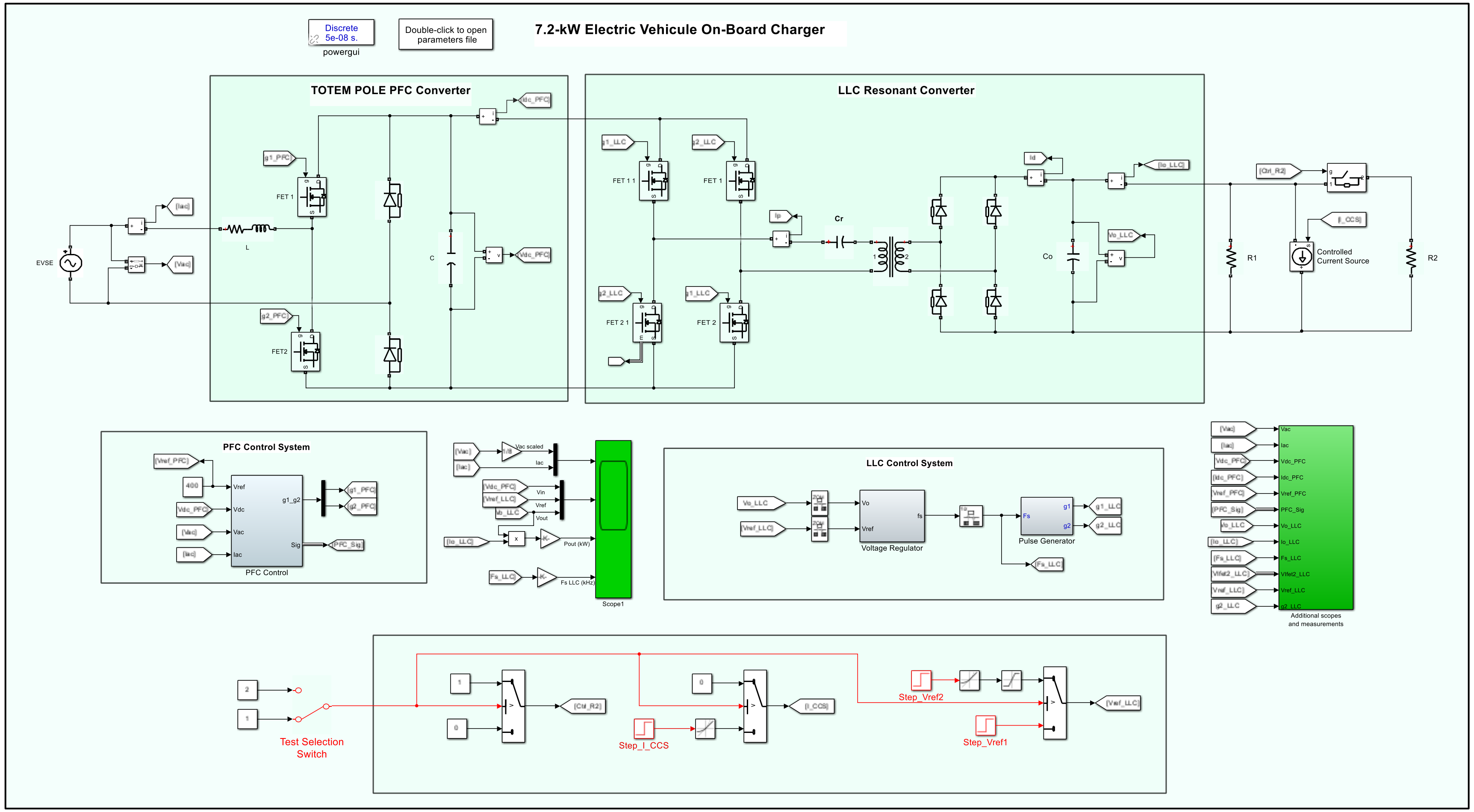

Figure 11: OBC_v1.slx

OBC Simulation results – Test 1

The first test demonstrates the good performance of the OBC converter for a step in the voltage output reference, followed by a ramping current demand up to the nominal load of 7.2 kW (see Figure 12). Figure 13 shows some PFC values during full-load operation.

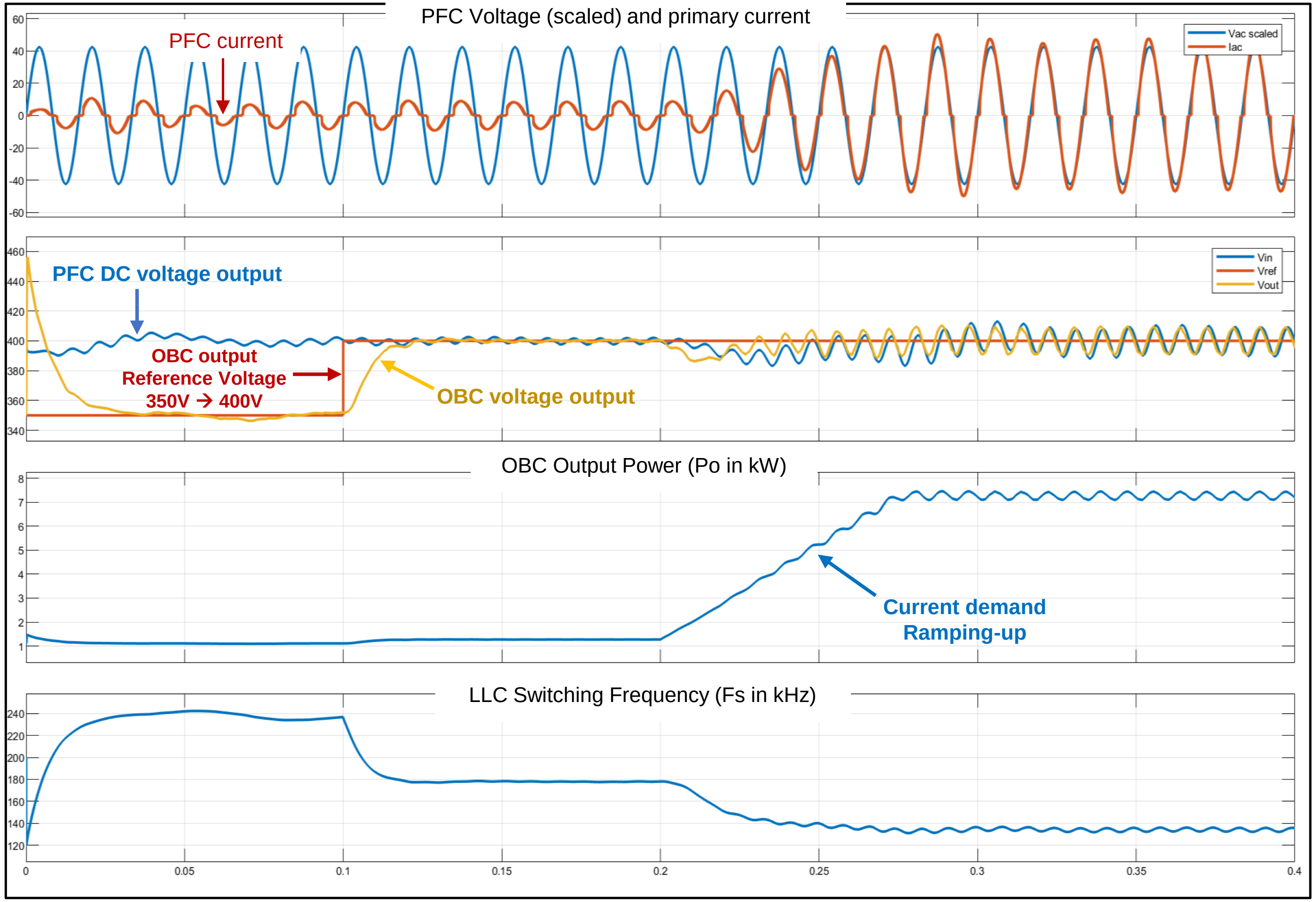

Figure 12

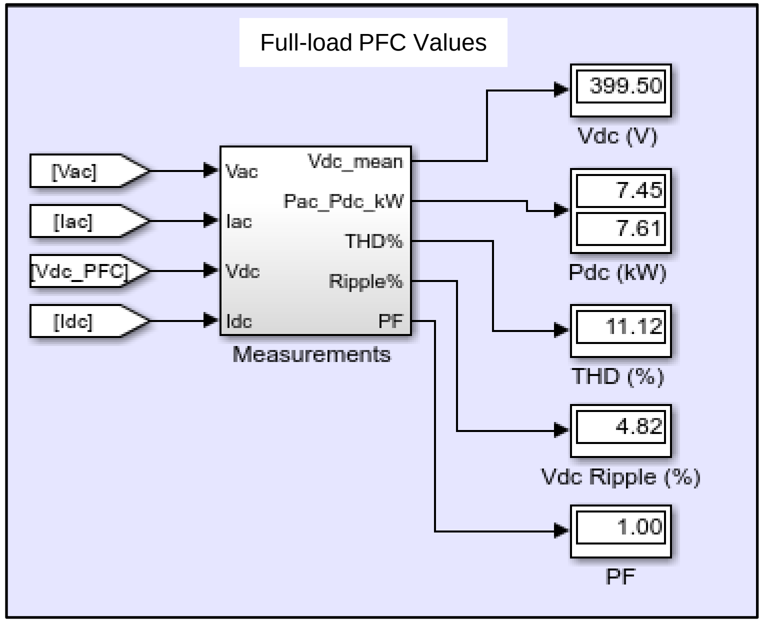

Figure 13

OBC Simulation results – Test 2

The second test (see Figure 14) demonstrates the voltage gain range of the OBC for a resistive nominal load. We can see that the OBC output correctly follows the reference voltage varying from 275V to 450V. To achieve that, the voltage controller varies the LLC switching frequency from about 185 kHz to 125 kHz. Note that the PFC DC output voltage is kept constant at 400V. For low current demand from the battery management system, the PFC DC output voltage may have to be reduced.

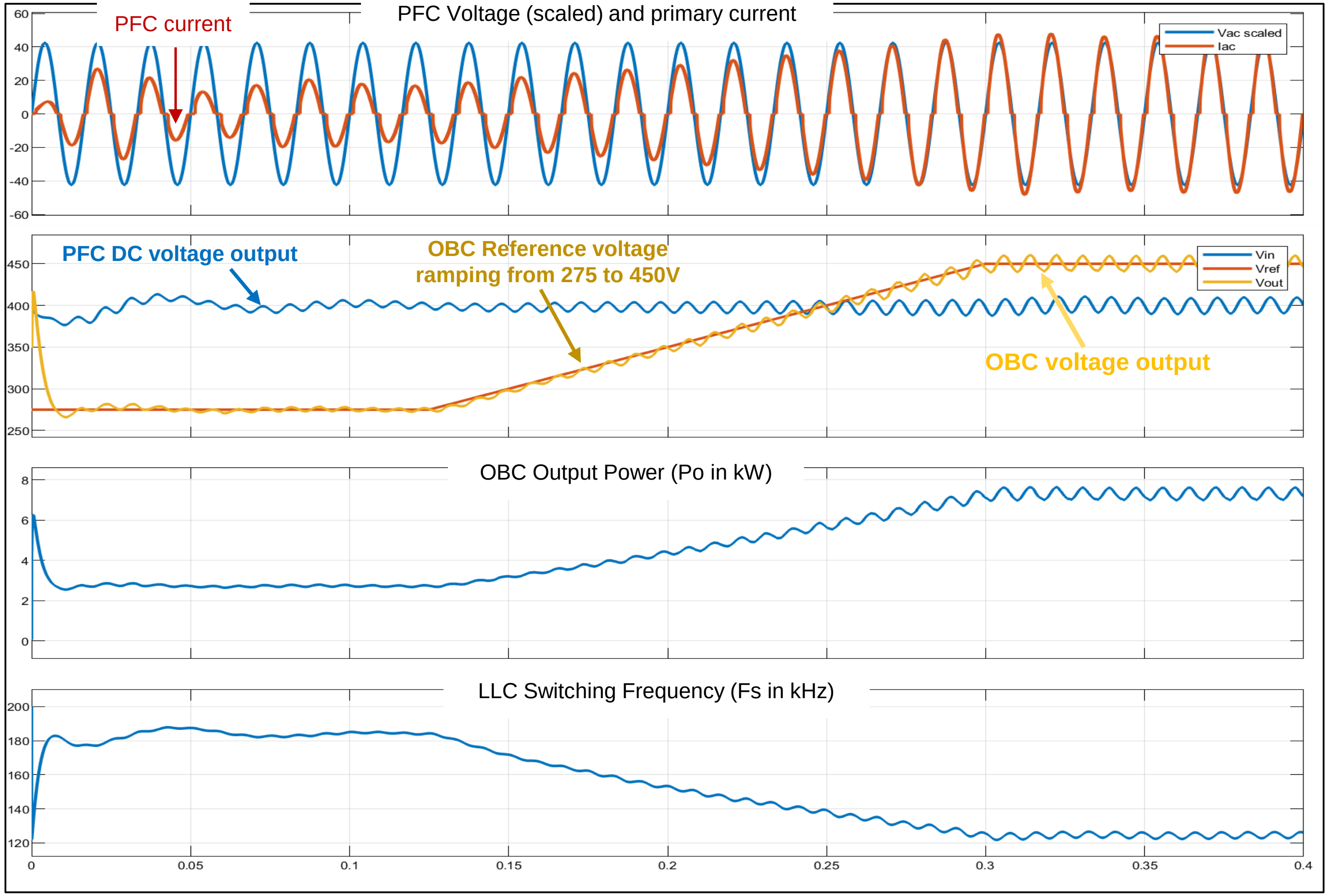

Figure 14

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