Impedance Models of Grid-Tied Converters

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***Abstract*—Due to the continuous growth in the number of grid-tied electronic power converters, it has become important to study how they can be represented from the point of view of the grid itself and the system-level problems that can arise once connected. This thesis uses linear analysis to obtain a small signal model of the converter to derive the equivalent impedance of a three-phase Voltage Source Converter (VSC). This impedance is analyzed to predict the converter behavior when it works as a generator (e.g. power generation from renewable plants) or when it it works as an active rectifier (e.g. battery charger). Such impedance can be then used in power system level stability studies, thanks to the Nyquist criterion.**

I. Introduction

Nowadays, electronic power converters are widely used to connect, for example, renewable energy plants or battery storage systems to the AC electric grid. In addition to that, the evolution of the power grid itself must be taken into account together with the electrification of transportation, with a resulting higher penetration of battery chargers. All this indicates a continuous growth of Voltage Source Converters (VSC) connected to the power grid. Although these converters are designed to be individually stable, once connected to the grid, due to the interactions between the harmonics produced by fast-switching power semiconductor devices and the grid, the system could weaken to the point of becoming unstable. This problem is determined by the dynamic interaction between the VSCs and the grid.

The objective of the thesis is to obtain, using linear analysis, a model which can be used for the analytical calculation of the equivalent impedance of the converters, Fig. 2. The obtaied impedance can be used either as a benchmark to evaluate the accuracy of other methods for measuring the equivalent impedance or for stability analysis using the Nyquist criterion.

My **personal contributions** made in this thesis are:

- Bibliographic research concerning the impedance models of converters obtained by linearization.
- Comprehensive description of the mathematical modeling.
- Obtaining a script to represent the equivalent impedance of a converter operating both with and without the voltage-loop.
- Comparison between two different types of converter operation.
- Show how the Phase-Locked Loop (PLL) affects the equivalent impedance.

II. System Under Study

The system, shown in Fig. 1, is representative for power converters for renewables or for battery chargers for plug-in electric vehicles,as shown in Fig. 2.

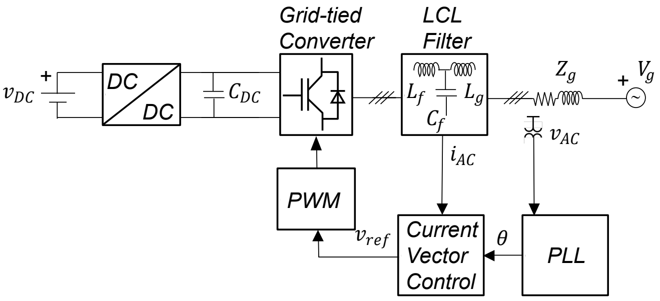

Figure 1: Single phase diagram of the analyzed system.

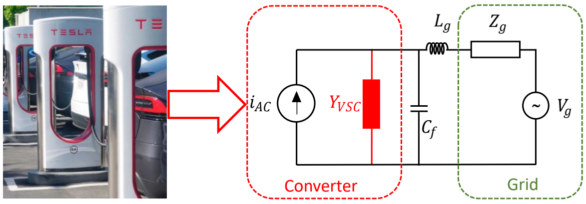

Figure 2: Norton equivalent circuit of the converter connected to the grid, where Y_{VSC} represents the equivalent admittance of the VSC.

III. Influence of the PLL

The PLL uses the $q-$axis component of the grid voltage to obtain the angle of the grid voltage vector. This angle is fed to the control so that the two reference systems, the physical one of the grid and that of the converter, are synchronous and coincident.

At steady state, the two domains are aligned; but, due to Small-Signal perturbations, the PLL will produce an output angle which will not perfectly coincide with that of the grid and therefore the angle θ_{PLL} will be different from the grid voltage vector angle, Fig. 3.

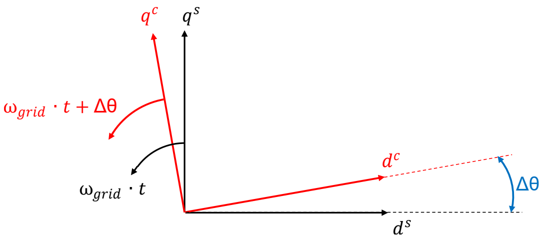

Figure 3: Difference between the two (d,q) frame domains: the converter reference frame and the system reference frame.

The two systems communicate with each other through the rotation transformation with angle $\Delta\theta$, i.e. the difference between the θ reconstructed through the PLL and the actual one of the physical system. As demonstrated below, the PLL has an important influence on system stability.

IV. ANALYTICAL DERIVATION OF IMPEDANCE

Considering only the first R-L impedance in series at the converter's output and by combining the voltage and current control scheme in (d,q) reference frame with the converter's average model, the equivalent circuit of the system for the study of the propagation of Small-Signal perturbations can be obtained (Fig. 4).

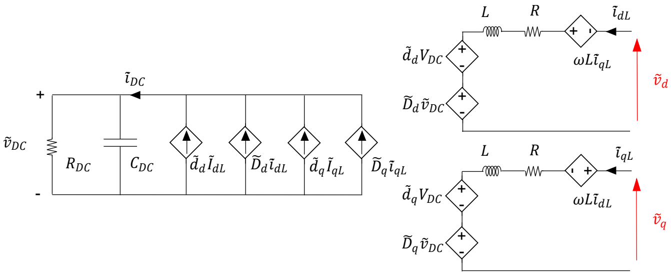

Figure 4: Small-Signal Circuit of the Grid-Tied Converter in (d,q) frame.

By means of this circuit, it can be found how the parameters are connected to each other within the system taken into consideration. Having analyzed a system in (d,q) reference frame, the impedance will be a 2×2 matrix. Since the system was considered as non-linear, it had to be linearized around an operating point which depends on the load, taking into account how the PLL interacts with the system and how it affects it through the presence of errors in the grid voltage measurement.

V. RESULTS

To minimize errors, a modular approach was used, increasing the complexity step-by-step. The results are two 2×2 impedance matrices: one considering an ideal voltage source, Fig. 5, with only current control, and the other also considering the voltage control. Despite the difference between the impedances Z_{dd}, Z_{dq} and Z_{qd} in the two cases, in both approaches it was possible to observe how the PLL had a strong influence on the impedance Z_{qq} which assumed, for a certain spectrum of frequencies, the form of a negative incremental resistance when the converter was working in Generator Mode.

As shown in Fig. 6, as the bandwidth of the PLL increases the impedance Z_{qq} has a greater frequency range for which it assumes a behavior of negative incremental resistance. This type of behaviour could lead to system instability causing a system shoutdown. In fact, the negative resistance behaviour, together with a weak grid, can lead to a negative resistance oscillator: for a Small-Signal voltage perturbation entering the converter at the PCC, the oscillation amplitude and energy grow exponentially with time. These factors can force the control current loop to open at some point, as it goes out of the controllability range.

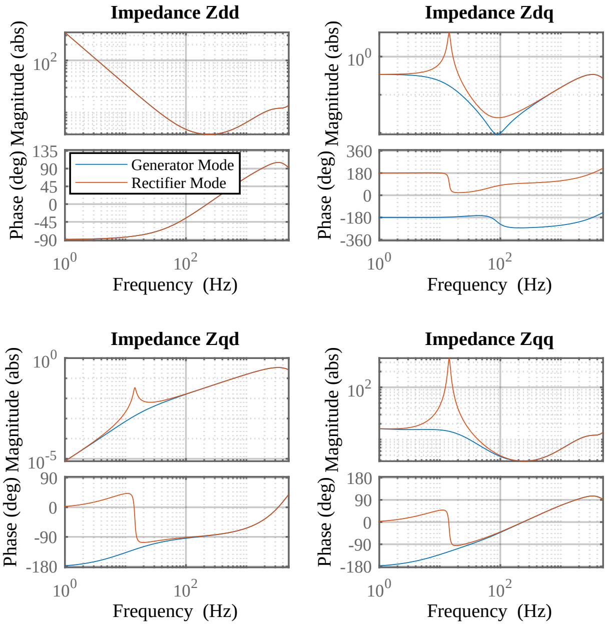

Figure 5: Confrontation between the impedance matrices calculated when the converter works as a Generator and when the converter works as a Rectifier.

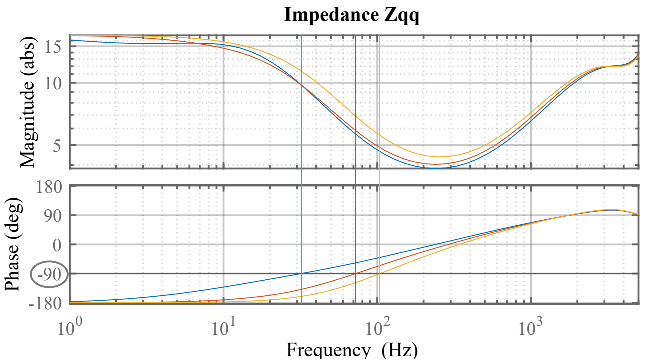

Figure 6: Impedance Z_{qq} with different PLL bandwidths when the converter works as a Generator.

VI. CONCLUSIONS

The model obtained it is capable of obtaining the equivalent impedance (or admittance) for Small-Signal perturbations of a converter by knowing its parameters. It can be used to validate experimental methods which calculate the equivalent impedance of the converter without actually knowing the value of the internal components and how the control had been structured. Another possible application is the verification of the stability of the network using the Nyquist criterion. Using the mathematical model obtained, it was also possible to observe that when the converter in analysis works by feeding energy into the grid, therefore when it works as an inverter connected to the network via the incoming signal from the PLL, the impedance Z_{qq} could destabilize the system due to its negative incremental resistance behaviour. It has also been seen how this penalizing behavior is influenced by the PLL.