Real-time grid parameters estimation for stability improvement of ultra-fast charging stations

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Abstract - The increasing prevalence of Electric Vehicles (EVs) requiring Ultra-fast Charging (UFC) stations is posing significant challenges for the operation of the electric power system. The goal of this work is the analysis, comparison and simulation of state-of-the-art solutions for real-time identification of grid parameters. A comprehensive literature review is conducted to identify promising solutions, followed by the development and implementation of robust identification algorithms. The methods are evaluated in the PLECS simulation environment. A two level three-phase active front-end (AFE) AC/DC converter model is implemented for this purpose. Selected estimation methods are implemented to verify their effectiveness and reliability. A final comparison of the methods under different grid conditions determines the best approach for varying scenarios. The thesis activities are carried out in collaboration with the Prima Electro R&D department, leveraging their resources and expertise.

I. Introduction

The exponential increase of charging stations installations, with projections anticipating over 270 million home chargers by 2035, poses significant technical and economic challenges. Indeed, the increase in grid-connected chargers raises challenges related to fluctuating network impedance and overall grid stability. The knowledge of network impedance value by embedding estimation algorithms into the active front-end (AFE) control helps mitigate instability issues, such as *Network characterization*, *Anti-islanding detection*, *Adaptive control of converters* and *LCL filter resonance avoidance*. Estimation techniques can be categorized into active and passive methods based on whether the perturbation is deliberately and periodically introduced. In particular, *Passive Techniques* utilise existing transients, caused by sufficiently large grid events, while *Active Techniques* deliberately introduce a controlled disturbance to enhance the amount of information obtainable from the network. In this thesis, only active techniques are analyzed, since they are uniquely capable of generating real-time estimation results with high accuracy and robustness. These techniques actively inject signals into the grid, allowing for immediate and precise measurement of grid parameters, which passive methods cannot achieve.

II. Grid and converter implemented model

The grid and converter model is implemented on *PLECS* and illustrated in Fig. 1. It consists of essential components for simulating the interaction between the inverter and the electrical grid. In particular, **Grid Model** includes a three-phase electrical network with parameters such as grid impedance (Z_g), grid voltage ($V_g = 400\ V_{rms}$) and grid frequency ($f_g = 50$ Hz). The **LCL Input Filter** attenutes high-frequency harmonics generated by the converter's pulse-width modulation (PWM). The **Voltage Source Inverter** (VSI) is modeled through ideal IGBT switches controlled by modulation signals (q_x). The DC converter side is connected to a constant voltage source (DC-Link) set at $V_{dc} = 800$ V. To conclude, the inverter is current controlled with PI regulators. All the controls are implemented in C-scripts. Additionally, the grid position θ_g is tracked through a SOGI-PLL (Second Order Generalized Integrator with Phase Locked Loop).

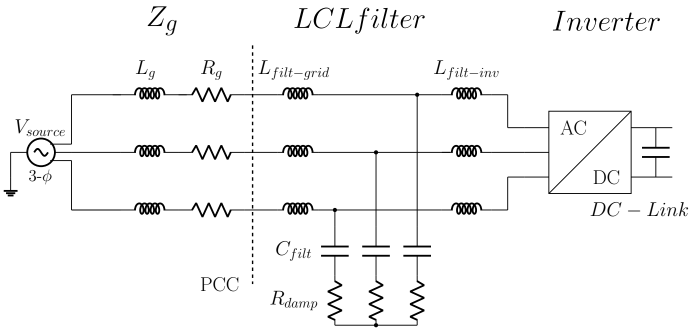


Figure 1: Block diagram of grid model

III. Impedance estimation through P/Q variations

The implemented method detects grid impedance by varying both active and reactive power provided by a grid-tied power converter. By altering the references adding ΔP and ΔQ, the resistive and inductive components of the line impedance can be detected. The signal references are illustrated in Fig. 2, where the appropriate moments for current and voltage measurements is shown. Two samples are necessary to obtain information from different working points. Taking the measurements of two operating points at the Point of Common Coupling (PCC), and assuming that $V_s(1) = V_s(2)$, the impedance can be calculated as:

$$R_g = \frac{(V_{q1} - V_{q2})(I_{q1} - I_{q2}) + (V_{d1} - V_{d2})(I_{d1} - I_{d2})}{(I_{q1} - I_{q2})^2 + (I_{d1} - I_{d2})^2} \quad (1)$$

$$\omega L_g = \frac{(V_{d1} - V_{d2})(I_{q1} - I_{q2}) - (V_{q1} - V_{q2})(I_{d1} - I_{d2})}{(I_{q1} - I_{q2})^2 + (I_{d1} - I_{d2})^2} \quad (2)$$

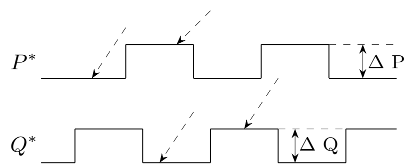


Figure 2: Signal references for P and Q

The method emphasizes ΔQ variations to induce phase angle deviations at the PCC. In particular, it has been decided to apply only ΔQ variations, under the limit of 10% of nominal active power, hence the grid active power is not disturbed. The results of the simulations shows that the estimation error is below 2% for L_g and below 10% for R_g.

IV. Impedance estimation with non-characteristic injections

This technique uses a non-characteristic frequency injection to estimate grid impedance without disturbing the operation at the fundamental frequency. The grid reactance is assumed linear in the entire frequency spectrum. This method has different approaches, such as voltage or current injections at different frequencies. Two methods will be compared: voltage injection and current injection. In Fig. 3 the diagram of the injection process for both methods.

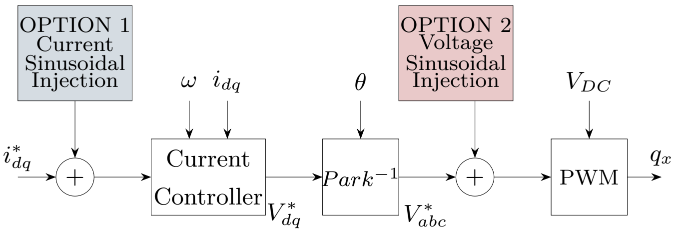


Figure 3: Block scheme for injection methods

The first method consists in injecting harmonic voltages through the inverter and by adding them to its reference. These injections occur at the zero voltage crossing point. Fig. 4a depicts the expected result with 400-600 Hz and 50 V amplitude signals. Then the mean absolute value of the current and voltage response is calculated. By evaluating grid impedance for the two points (using harmonics at different frequencies), and with some mathematical elaboration the grid resistance R_g and inductance L_g are computed as follows:

$$|Z_1|^2 = R_g^2 + (\omega_1 L_g)^2 \quad |Z_2|^2 = R_g^2 + (\omega_2 L_g)^2 \tag{3}$$

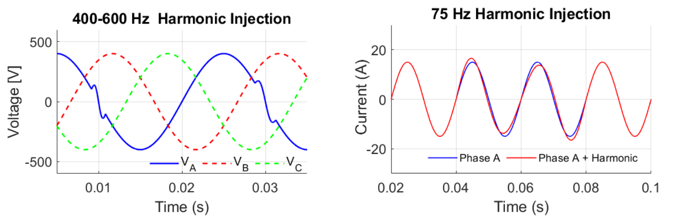
$$L_g = \sqrt{\frac{|Z_1|^2 - |Z_2|^2}{\omega_1^2 - \omega_2^2}} \qquad R_g = \sqrt{\frac{\omega_1^2|Z_2|^2 - \omega_2^2|Z_1|^2}{\omega_1^2 - \omega_2^2}} \tag{4}$$

It results that while L_g has a really low error (5%), R_g is not properly detected (30%). Instead, the second method uses current injection. A 2A current reference rotating at 75 Hz is added to the current references of the inverter control. It is illustrated in Fig. 4b. After injecting the signal, the estimation algorithm calculates the current and voltage responses specifically at the 75 Hz, using Discrete Fourier Transformation (DFT). In particular, the voltage and current vectors are calculated and then the impedance values can be extracted:

$$\hat{X}_h = \sum_{n=0}^{N-1} x_n \left(\cos\left(\frac{2\pi hn}{N}\right) - i \cdot \sin\left(\frac{2\pi hn}{N}\right)\right) \tag{5}$$

$$\hat{Z}_h = \frac{\hat{V}_h}{\hat{I}_h} \qquad R_g = re(\hat{Z}_h) \qquad \omega_h L_g = im(\hat{Z}_h) \tag{6}$$

The injected harmonic frequency is close to the fundamental frequency, which ensures high performance. Indeed, the current response is unaffected by the bandwidth of the control loop. The results indicate that this method achieves very low error rates for both R_g and L_g (below 5%).



(a) (b)

Figure 4: (a) Voltage injection at 400 and 600 Hz (b) Current injection 75 Hz

V. Performance Comparison

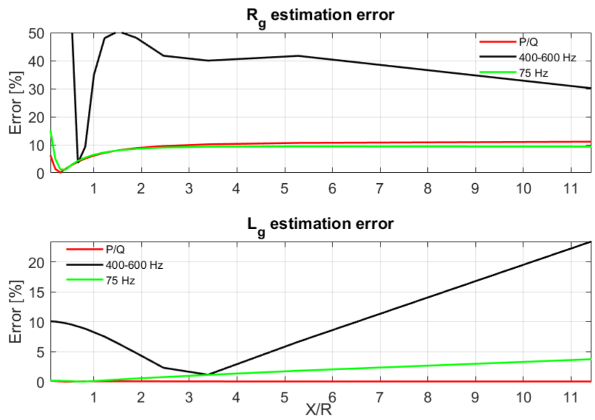


Figure 5: Comparison of the three methods varying X/R

Fig. 5 illustrates the comparison of all the methods for a simulation study in which the grid conditions vary in terms of X/R ratio and θ_g. Instead, The short-circuit ratio (SCR) of the simulated grid is kept constant at 10

$$SCR = \frac{Z_b}{Z_g} = 10 \tag{7}$$

P/Q variations and 75 Hz current injections methods results more robust than the Double injection method and able to estimate with low error for mostly all grid conditions. The Double injection method, is not able as well to estimate correctly R_g when the grid has a high-inductive or high-resistive behavior. Hence, it may be suitable for less extreme scenarios.

VI. Conclusions

The simulation study presented in this thesis aims to compare various methods for estimating grid parameters. The results demonstrate that methods based on P/Q variations and current injections are robust and exhibit significant adaptability to changes in grid characteristics, ensuring accurate estimation of Z_g. My personal contributions are:

- Literature research on the most suitable solutions
- Implementation on PLECS and on C-scripts of all the methods for testings and simulations.
- Final analysis and performance comparison for different conditions of the grid and the inverter.

Future work could focus on minimizing the network disturbances introduced by the effective P/Q variation and current injection methods, further enhancing their applicability and reliability.