**Facoltà di Ingegneria Civile e Industriale**

*Dottorato di ricerca in Ingegneria Elettrica, dei Materiali e delle Nanotecnologie (EMNE)*

**Dottorato di Ricerca in Ingegneria Elettrica, dei Materiali e delle Nanotecnologie**

<table>
<tr><td colspan="2">Relazione annuale A.A.:<br><br>2021-2022</td></tr>
<tr><td>Ciclo di Dottorato:<br><br>XXXVI</td><td>Curriculum:<br><br>Ingegneria Elettrica</td></tr>
<tr><td>Dottorando:<br><br>Mohamed Yahya Mohamed Elhag</td><td>Supervisore:<br><br>Prof. Giulio De Donato</td></tr>
</table>

**TITOLO DELLA RICERCA: Digital control of LCL-based inverters for grid-connected renewable energy systems**

## 1. Sintesi dell'attività di ricerca svolta

### 1.1. Introduction

Raw material shortages and environmental pollution due to conventional energy sources (e.g., coal and oil) are the main obstacles to global strategic sustainability plans [1]. In recent years, new energy sources such as wind and solar power generation are developing significantly, which has become an essential means to deal with environmental pollution and energy crises [2-3]. The markedly increased integration of renewable energy in the power grid is significant in the transition to a sustainable energy future. The grid integration of renewables will be continuously enhanced in the future.

According to the international renewable energy agency (IRENA), renewable technology is the main pathway to reaching zero carbon dioxide (CO2) emissions by 2060. Power electronics have played and will continue to play a significant role in this energy transition by providing efficient electrical energy conversion, distribution, transmission, and utilisation. Consequently, the development of power electronics technologies, i.e., new semiconductor devices, flexible converters, and advanced control schemes, is promoted extensively globally [1]. Grid-connected inverters have become a virtual interface for connecting distributed power generation systems. The grid-connected inverters play a vital role in ensuring that high-quality power is injected into the grid [4].

To control a three-phase voltage source inverter VSI, there are two control strategies: current control and voltage control. The voltage-controlled VSI uses the phase angle between the inverter output voltage and the grid voltage to control the power flow. Classical current control is classified as active power and reactive power control method. The grid frequency is tracked by a phase-locked loop (PLL) [5]. Voltage Oriented Control (VOC) is a control strategy for a three-phase grid-connected voltage source inverter that links a renewable energy source to the grid through an optimised LCL-type filter. This linear system has been decoupled into two different control loops corresponding to active and reactive power control. The power control of the grid converter is based on the instantaneous power theory. Typically the voltage-oriented control is based on a synchronous Reference Frame (dq) rotating at (ω) speed and oriented such that the d axis is aligned on the grid voltage vector. The reference current d component $i_d^*$ is controlled to manage active power exchange and typically to perform the DC voltage regulation. In contrast, the reference current q component $i_q^*$ is controlled to manage the reactive power exchange and to obtain a unity power factor. Similar results can be achieved in a stationary reference frame (αβ), but the relation between active/reactive power and the current vector components is more complex [6].

As a vital part of a grid-connected inverter, the output filter plays an essential role in filtering high-frequency switching harmonics caused by pulse-width modulation (PWM). A filter of a type such as the LCL filter can achieve a better filtering effect with smaller filter inductance, representing the developing trend of the output filter for the grid-connected inverter. The advantages of LCL filters are high attenuation, improved performance, cost-effectiveness, and less weight and size. The LCL filter offers good harmonic elimination with low values of inductors and capacitors. The switching harmonics produced by the inverter and current harmonics produced by the active/passive loads would create the system resonance and, consequently, the output current distortion and oscillation, as high-order LCL filters contain multiple resonant frequencies.

Integration of renewable energy sources into the utility grid offers technical challenges since the grid is a highly non-linear system. Power system power balance and grid operation are impacted by uncertainties and disturbances, which cause a huge frequency deviation, leading to the power system's stability. However, renewable energy sources are easily affected by uncertainties of the environment (solar irradiance, temperature, wind speed, etc.), making it challenging to control the output power, causing an imbalance in power between the source and the load and frequency fluctuation in the system, adversely affecting the power quality. Grid disturbances such as voltage fluctuations, harmonics, reactive power, low power factor, switching of resistive and inductive loads, tripping of feeders feeding the consumers, outage of generator and synchronization of generator affect the output parameters of the grid-connected renewable energy sources.

The project proposes investigating the active, reactive power control based on the nested loop, associated with an exact digital model for three-phase inverters in grid-tie converters for renewable energy systems, where it delivers improved dynamic performances, robustness, and system stability.

Currently, my work focuses on the design and implementation of state-of-the-art (current, power) control loops by using the approximate model and comparing it with the exact discrete-time models of the system that have been driven.

### 1.2 Research activities carried out during the $2^{nd}$ year

1.2.1 As a part of my PhD thesis, and during the second year, an exact discrete-time model of The LCL Filters connected to a grid in stationary and synchronous reference frames has been developed. The proposed model considers the inverter output current, grid side current, and capacitor voltage in addition to the damping resistor in series with the capacitor to achieve passive damping. The programs used for developing and debugging the equations are PSIM and MATLAB.

i. Discrete model equations for LCL-Filter (input current) with damping resistor in stationary (αβ) and synchronous (dq) reference frames (Fig.1):

$$\vec{I}_{1\alpha\beta}(z) = \frac{z^{-1}(hdot + jadot)}{(mdot - jodot)} * \vec{U}_{\alpha\beta}(z) + \frac{z^{-1}(sdot + jgdot)}{(mdot - jodot)} * \vec{i}_{2\,\alpha\beta}(z) - \frac{z^{-1}(edot + jddot)}{(mdot - jodot)} * \vec{V}_{c\alpha\beta}(z) - \frac{z^{-1}(ndot + jxdot)}{(mdot - jodot)} * \vec{e}_{\alpha\beta}(z)$$

$$\overrightarrow{I_1}_{dq}(z) = \frac{z^{-1}(hdot + jadot)}{(mdot - jodot)} * \overrightarrow{U}_{dq}(z) + \frac{z^{-1}(sdot + jgdot)}{(mdot - jodot)} * \overrightarrow{i_2}_{dq}(z) - \frac{z^{-1}(edot + jddot)}{(mdot - jodot)} * \overrightarrow{V}_{cdq}(z) - \frac{z^{-1}(ndot + jxdot)}{(mdot - jodot)} * \overrightarrow{e}_{dq}(z)$$

ii. Discrete model equations for LCL-Filter (output current) with damping resistor in stationary (αβ) and synchronous (dq) reference frames (Fig.2):

$$\overrightarrow{I_2}_{\alpha\beta}(z) = \frac{z^{-1}(hdot + jadot)}{(mdot - jodot)} * \overrightarrow{U}_{\alpha\beta}(z) + \frac{z^{-1}(sdot + jgdot)}{(mdot - jodot)} * \overrightarrow{i_1}_{\alpha\beta}(z) - \frac{z^{-1}(edot + jddot)}{(mdot - jodot)} * \overrightarrow{V}_{c\alpha\beta}(z) - \frac{z^{-1}(ndot + jxdot)}{(mdot - jodot)} * \overrightarrow{e}_{\alpha\beta}(z)$$

$$\overrightarrow{I_2}_{dq}(z) = \frac{z^{-1}(hdot + jadot)}{(mdot - jodot)} * \overrightarrow{U}_{dq}(z) + \frac{z^{-1}(sdot + jgdot)}{(mdot - jodot)} * \overrightarrow{i_1}_{dq}(z) - \frac{z^{-1}(edot + jddot)}{(mdot - jodot)} * \overrightarrow{V}_{cdq}(z) - \frac{z^{-1}(ndot + jxdot)}{(mdot - jodot)} * \overrightarrow{e}_{dq}(z)$$

iii. Discrete model equations for LCL-Filter (capacitor voltage) with damping resistor in stationary (αβ) and synchronous (dq) reference frames:

$$\overrightarrow{V}_{c\alpha\beta}(z) = \frac{z^{-1}(hdot + jadot)}{(mdot - jodot)} * \overrightarrow{U}_{\alpha\beta}(z) + \frac{z^{-1}(edot + jddot)}{(mdot - jodot)} * \overrightarrow{i_1}_{\alpha\beta}(z) - \frac{z^{-1}(sdot + jgdot)}{(mdot - jodot)} * \overrightarrow{i_2}_{\alpha\beta}(z) + \frac{z^{-1}(ndot + jxdot)}{(mdot - jodot)} * \overrightarrow{e}_{\alpha\beta}(z)$$

$$\vec{V}_{cdq}(z) = \frac{z^{-1}(hdot + jadot)}{(mdot - jodot)} * \vec{U}_{dq}(z) + \frac{z^{-1}(edot + jddot)}{(mdot - jodot)} * \vec{i}_{1\,dq}(z) - \frac{z^{-1}(sdot + jgdot)}{(mdot - jodot)} * \vec{i}_{2\,dq}(z) + \frac{z^{-1}(ndot + jxdot)}{(mdot - jodot)} * \vec{e}_{dq}(z)$$

1.2.2 The SYNDEM Smart Grid Research and Education Kit were used for the hardware implementation of the control and the discrete models. During the second year, different tests were done to configure the SYNDEM tool to test the ability and the limit of the kit, such as the DAC configuration in both MATLAB and PSIM software (Fig.4).

### 1.3 Timeline of planned Research

- $3^{rd}$ year (2022-2023)

a) Design the control loop.

b) Implement the control loop and the discrete model to the SYNDEM kit.

c) Experimental tests.

d) Six months of mobility in Illinois institution of technology to design and implement uncertainty and disturbance estimator UDE-based controller using the precise model of the three-phase LCL discrete model to improve the system stability and robustness.

e) Writing of the Thesis and related Research Papers.

## 2. Seminari, Corsi, Workshop e Scuole

- Participation in the "European PhD School-Power Electronics, Electrical Machines, Energy Control and Power Systems", 2021 Edition, Gaeta, Italy.

- Single Phase and Three-Phase Inverters Control, online course.

- Impedance Modeling and Stability Analysis of Grid-Interactive Converters, online course.

3. **Periodi trascorsi all'estero**

4. **Partecipazione a Congressi Nazionali e Internazionali**

5. **Pubblicazioni su atti di convegno (**prodotte o in corso di pubblicazione**)**

6. **Pubblicazioni su riviste (**prodotte o in corso di pubblicazione**)**

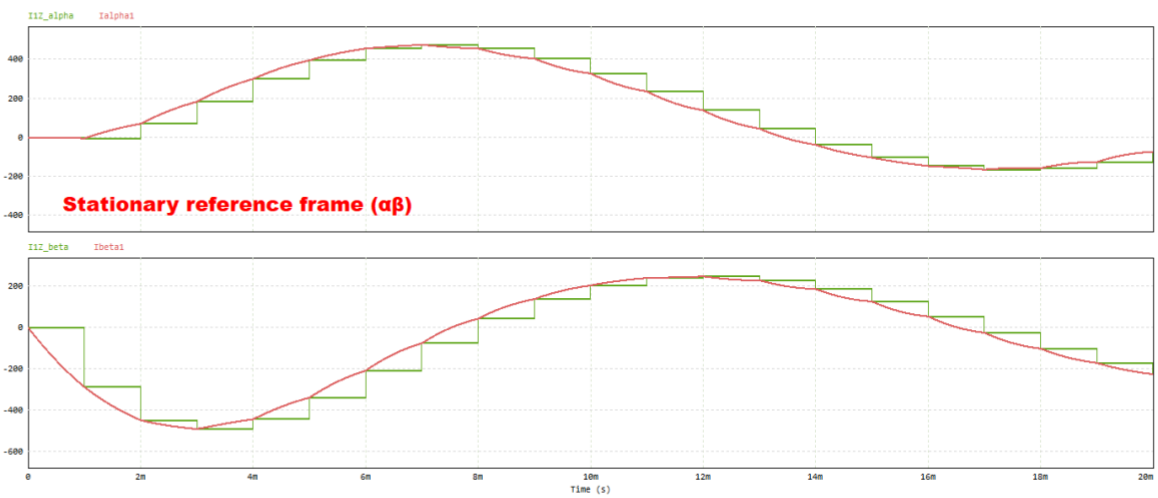


Fig.1. Discrete model for LCL-Filter (input current) in the stationary reference frame (αβ)

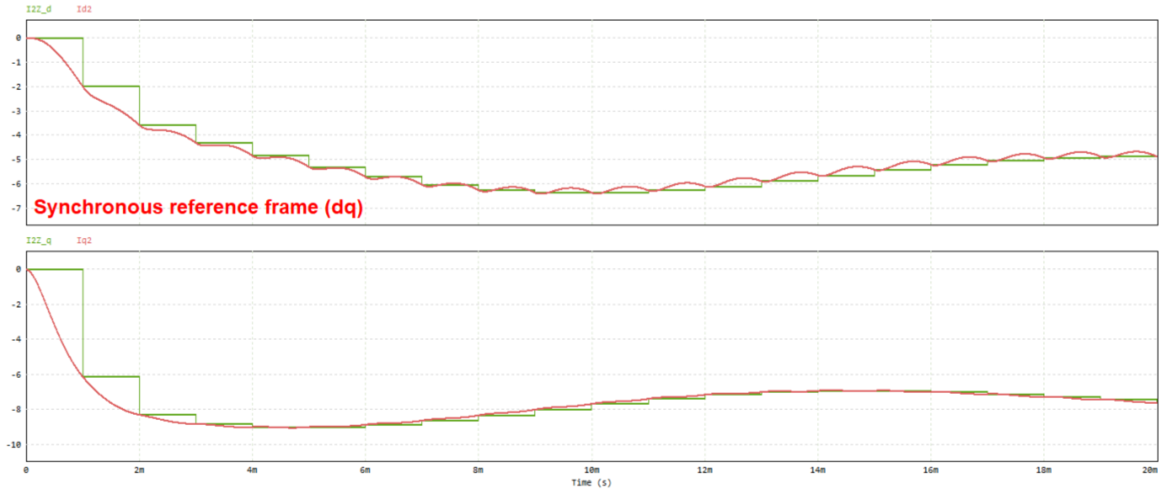


Fig.1. Discrete model for LCL-Filter (output current) in the synchronous reference frame (dq)

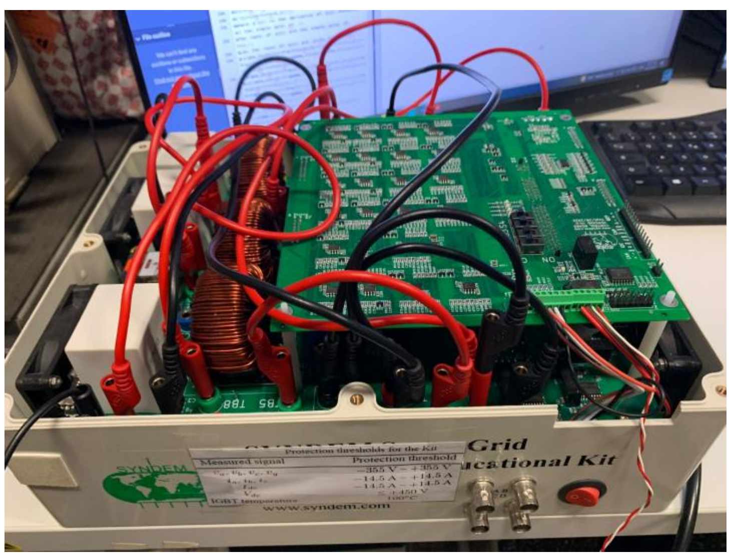


Fig.3. The SYNDEM Smart Grid Research and Education Kit.

## References

[1] Tang, Zhongting, Yongheng Yang, and Frede Blaabjerg. ”Power electronics: The enabling technology for renewable energy integration.” CSEE Journal of Power and Energy Systems 8, no.1 (2021): 39-52.

[2] Liserre M, Sauter T, Hung J. Future Energy Systems: Integrating Renewable Energy Sources into the Smart Power Grid Through Industrial Electronics[J]. IEEE Industrial Electronics Magazine. 2010, 4(1): 18-37.

[3] Wang Chengshan, Wang Shouxiang. Study on Some Key Problems Related to Distributed Generation System[J]. Automation of Electric Power Systems, 2008, 32(20): 1-4.

[4] Liu Hongda, Zhou Lei. A Multi-functional Grid-connected Inverter and Its Application in Micro- grid Access to Distribution System[J]. Proceedings of CSEE, 2014, 34(16): 2649-2658

[5] Arulkumar, K., K. Palanisamy, and D. Vijayakumar. ”Recent advances and control techniques in grid connected PV system–A review.” International Journal of Renewable Energy Research 6, no. 3 (2016): 1037-1049.

[6] Mahela, Om Prakash, and Sheesh Ram Ola. ”Impact of grid disturbances on the output of grid connected solar photovoltaic system.” In 2016 IEEE Students’ Conference on Electrical, Electronics and Computer Science (SCEECS), pp. 1-6. IEEE, 2016.