COURSE CONTENT FOR TRANSIT TRAINING

1.1 Modeling and Control of Grid Following Inverters for Renewables

1.1.1 Introduction

Power electronics play a crucial role in integrating renewable energy sources (RES) such as wind, photovoltaics (PV), battery energy storage systems (BESS), and electric vehicles (EVs) into the power grid. These technologies enable efficient energy conversion and management, ensuring that the power generated by RES can be effectively injected into the grid. Proper modeling and control of these systems are essential to maintain grid stability, power quality, and reliability, especially as the penetration of renewable energy increases.

This course delves into the significance of power electronics in RES integration and explores various power electronics converter configurations in different applications. The main focus of this course is to provide an in-depth understanding of the control of grid-following (GFL) inverters by analyzing the theory required for designing a fully controllable inverter for PV or BESS systems. The course also includes step-by-step guidelines on how to implement an inverter model in MATLAB/Simulink, where the inverter controller will be properly designed and integrated to achieve the development of a fully controllable GFL inverter through a hands-on example. Finally, the course offers insights into recent advancements in GFL inverter technology to enhance their grid support functionalities.

1.1.2 Power Electronics for RES integration

Power electronics is pivotal for the efficient integration of RES into modern power systems. They manage the energy conversion processes required for different RES, ensuring that the generated power is maximized while maintaining compatibility and synchronization with the main grid. Power electronics used high frequency switching components that are driven in a controllable manner to enable efficient energy conversion from direct (DC) to alternative (AC) current and vice versa considering different voltage or current level, frequency and phase angle at the input or output of each converter. Key applications of power electronics in renewable energy integration include:

- **Wind Power Systems**: Conversion from AC to DC to maximize the wind power extraction and from DC back to AC for synchronized injection of the produce power into the grid.
- **Photovoltaic Systems**: Conversion from DC to AC (or DC to DC and then to AC) to maximize the PV power extraction and to inject the produced power into the grid.
- **Energy Storage Systems**: Bidirectional conversion between DC and AC to charge and discharge the storage system in a controllable manner.
- **Electric Vehicle Chargers**: Conversion from AC to DC to charge the vehicle battery and occasionally from DC to AC for vehicle to grid (V2G) power transfer.

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- **Smart Appliances**: Conversion from AC to DC or AC to DC to AC for maximizing the appliances efficiency under any operating conditions.
- **High Voltage DC (HVDC) Transmission**: Conversion from AC to DC and back to AC for long-distance power transmission with reduced losses.

In this course, a particular emphasis is given in power electronics for RES, considering wind turbines, PVs and battery storage systems. In wind power systems, power electronics are used in both double-fed induction generators (DFIGs) and full-converter wind turbines to control turbine's rotational speed for maximum power extraction, regulate DC link voltage, and manage reactive power injection. For PV and BESS, power electronics enable maximum power point operation and ensure synchronized active and reactive power injection. Power electronics converters come in various configurations to meet the specific requirements of different RES applications. The choice of configuration depends on factors such as efficiency, cost, and the specific application requirements. Common configurations in wind or PV-storage applications are listed below:

i. **Wind Power Systems**:

   - **Double-Fed Induction Generators (DFIGs)**: This configuration is presented in Figure 1(a) where power electronics are used at approximately 30% of the rated power of the wind turbine to control the rotor currents, enabling variable speed operation in certain limits and reactive power support. This configuration is only valid for double-fed induction generators.
   - **Full-Converter Wind Turbines**: A fully converter wind power system is demonstrated in Figure 1(b) where power electronics are used at 100% of the rated power, allowing complete decoupling of the generator and grid, providing more flexibility and better grid support capabilities. This configuration is valid for any type of electrical generator connected to the turbine.

ii. **PV - Storage Systems**:

   - **DC Coupling**: A common DC bus is used with one inverter, to lower the overall cost and improve efficiency. This configuration, as shown in Figure 1(c), is suitable for integrating PV panels and BESS. An independent DC/DC converter is typically used for BESS and for PVs and some limitations are introduced when storage discharging and high PV generation are synchronized due to the restricted capacity of the common inverter.
   - **AC Coupling**: Independent systems connected at the same AC bus, requiring two inverters. A DC/DC converter is required for BESS, while it is optional for PVs. This configuration, see Figure 1(d), offers more flexibility in system design and is suitable for retrofitting existing systems, although a higher cost is typically needed.

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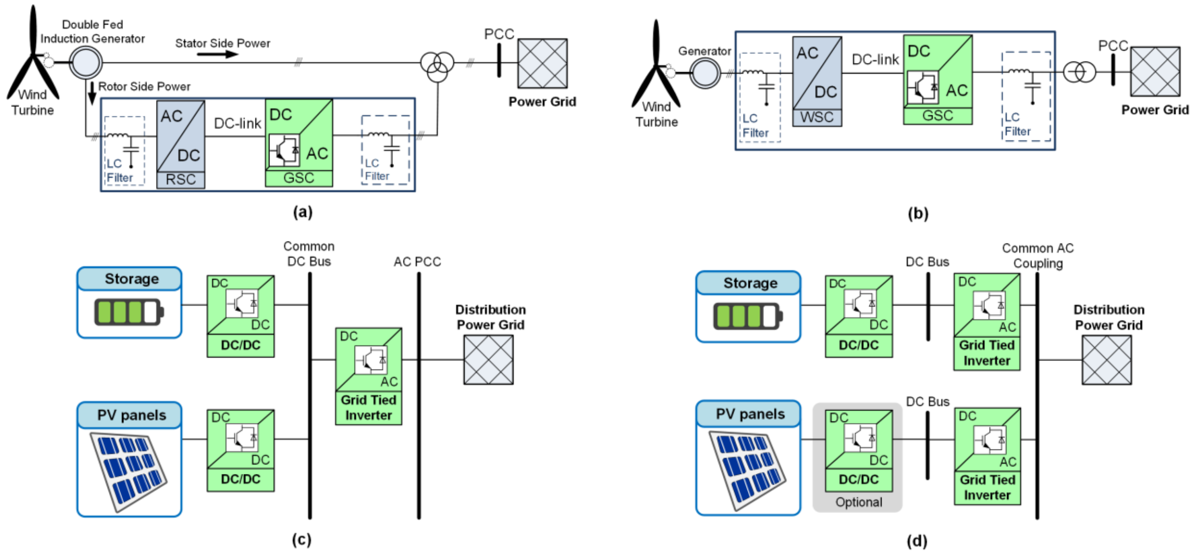

Figure 1: Power converter configurations for wind and PV-storage systems: (a) Wind turbine configuration baasde on double-fed induction generator and back-to-back power electronics converters in the rotor side of the generators; (b) Fully-converter wind power system where power electronics are handling the entire power flow; (c) DC coupling configuration for PV and storage systems based on a common inverter; (d) AC coupling configuration for PV and storage system with independent inverters.

In Figure 1, the converter located closest to the sources (e.g., wind turbine, photovoltaic panel) is typically responsible for maximizing power extraction. In wind power systems, the Wind Side Converter (WSC) or Rotor Side Converter (RSC) regulates the turbine's rotational speed according to varying wind conditions to continuously track the optimal speed, maximizing the turbine's power coefficient. Similarly, in a photovoltaic system, the DC/DC converter (if present, otherwise the grid-tied inverter) is responsible for regulating the DC voltage on the PV panel side to optimize power generation under varying solar irradiation and temperature conditions.

Furthermore, in all configurations depicted in Figure 1, the grid-tied inverter, also known as the Grid Side Converter (GSC), is a common component in wind, PV, or storage system designs. This converter is essential for integrating distributed energy resources into the grid in a synchronized manner while providing grid support functionalities as needed. The GSC also ensures that all the power produced by the RES is effectively injected into the grid by regulating the DC link voltage. Given that the grid-tied inverter is a critical element across all RES configurations, the remainder of this course will focus on the design of a controllable grid-tied inverter, operating in grid-following (GFL) mode.

1.1.3 Control of GFL inverters

In this section, all the essential elements for the controller design of a grid-tied inverter will be presented. While there are two main operating mode, grid-following (GFL) mode where the inverter relies on the existing grid to set the frequency and the voltage, and grid-forming (GFM) mode where

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the inverter can operate independently by establishing and regulating the grid voltage and frequency (like a traditional synchronous generator), this course will provide the design guidelines for a GFL inverter which is a most widely adopted approach.

The control of GFL inverters is crucial for the stable integration of RES into the grid. The overall inverter controller is presented in Figure 2 and relies on the following units: (a) Park's transformations that converters (abc/dq and vice versa) the sinusoidal three-phase (abc) voltage and current signals into "DC" (dq non-oscillating) signals enabling a simpler and decoupled control approach; (b) synchronization unit based on a phase-locked loop (PLL) approach to identify the grid voltage, phase angle and frequency; (c) active and reactive power (PQ), typically enhanced with DC link controllers and fault ride through (FRT) schemes, to regulate the power injection to the grid; and (d) current controller to generate the reference voltage signals (duty cycles) that drive the inverter switching element to control the current injection. More information about each of the controller units is provided in the following subsection.

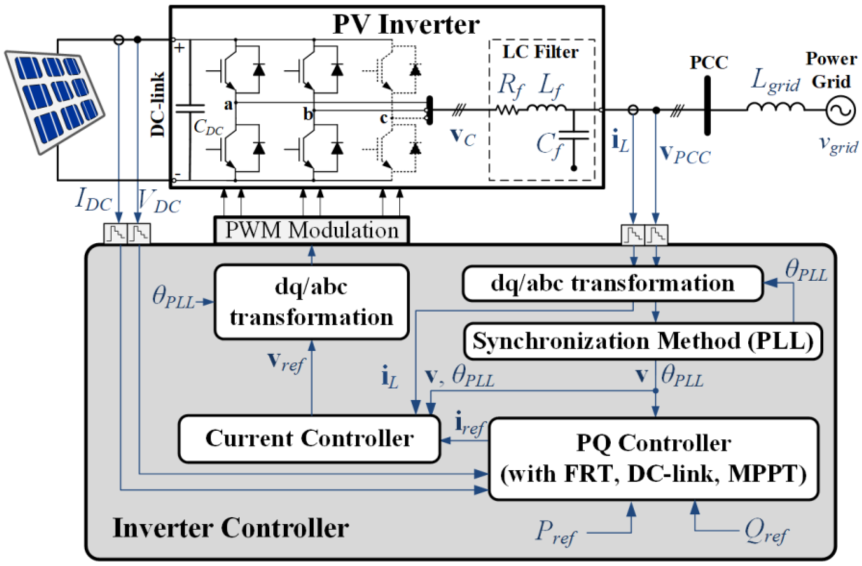

Figure 2: Grid tied inverter controller with its main units: park transformation, synchronization scheme, PQ controller and current controller.

1.1.3.1 Transformation theory

Transformation theory is fundamental in the control of power electronics, particularly for inverters in renewable energy systems. It involves converting the three-phase AC signals (*abc* phase), which are inherently time-varying and sinusoidal, into a different reference frame where they become easier to analyze and control. The most common transformations used are Clarke's transformation (*abc* to *αβ*) and Park's transformation (*αβ* to *dq*) [1].

Clarke's transformation (abc/αβ transformation), also known as the *αβ* transformation, converts the three-phase AC signals from their natural *abc* reference frame into a stationary two-axis *αβ* reference frame. This transformation simplifies the analysis of three-phase systems by reducing the complexity of the signals, making them easier to manage without losing any critical information. Park's transformation (abc/dq or αβ/dq) further converts these *αβ* signals (or the initial *abc* signals) into a rotating *dq* reference frame (rotating with the synchronous frequency of the grid voltage), aligning the d-axis with the vector of the grid voltage. In the *dq* frame, AC signals are transformed into DC-like quantities (non-oscillating signals), allowing for the use of simple proportional-integral (PI) controllers for tasks like regulating active and reactive power or regulating the current injection.

In addition, the alignment of the rotating d-axis with the rotating grid voltage vector (v_d=V and v_q=0), ensured by the synchronization/PLL unit, is crucial for decoupling the active and reactive power control since the active power is solely regulated by the d-axis current i_d while the reactive power is only regulated by the q-axis current i_q. This decoupling of the control of active and reactive power is a key advantage of using transformation theory, enabling precise control of inverters and improving the performance and stability of grid-connected RES.

It is noted that the theory related to Clarke's and Park's transformations, along with the forward and reverse transformation matrices for each case and the detailed power analysis at each reference frame is provided in the relevant slides of the course. Examples of voltage/current signals expressed at either *abc* frame, *αβ* or *dq* frame are also provided in the relevant slides of this course.

1.1.3.2 Synchronization method

The synchronization scheme for grid tied inverter is typically based on a Phase-Locked Loop (PLL) approach, allowing the inverter controller to track the phase angle, frequency, and amplitude of the grid voltage [2]. Accurate synchronization ensures decoupled control of active and reactive power crucial for stable operation (through the use of estimated phase angle in Park's transformation).

The basic principle of a PLL involves creating a feedback loop to synchronize the inverter output with the grid voltage. In this loop, the estimated phase angle (θ') is generated by using a PI controller to regulate $\Delta\theta$ to zero combined with an integrator that converter rotational speed to phase angle, as indicated in (1),

$$\theta' = \int \left(\omega_{nom} + K_p \Delta\theta + K_i \int \Delta\theta \ dt\right) dt \qquad (1)$$

where, ω_{nom} is the nominal grid frequency, $\mathrm{K_p}$ and $\mathrm{K_i}$ are the proportional and integral gains of the PI controller, respectively, and $\Delta\theta$ is the phase difference between the grid voltage θ_{grid} and the inverter estimated phase angle by the PLL θ'. The PLL adjusts the phase angle to minimize $\Delta\theta$, ensuring synchronization with the grid.

Since, the grid voltage phase angle θ_{grid} cannot be directly extracted by the voltage measurements, Park's transformation is used in practical applications to estimate the phase difference between the grid voltage phase angle and the estimated angle, since $v_q = V \cdot sin(\Delta\theta) \approx V \cdot \Delta\theta$ (for $\Delta\theta \approx 0$). Hence, for accurately estimating the voltage phase angle ($\Delta\theta = 0$), the PLL estimates θ' in order to achieve that v_q=0 and v_d aligns with the d-axis of Park's transformation. The practical design of the

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PLL is demonstrated in Figure 3, where the phase angle θ', the frequency $f'$and the amplitude V' of the grid voltage are estimated.

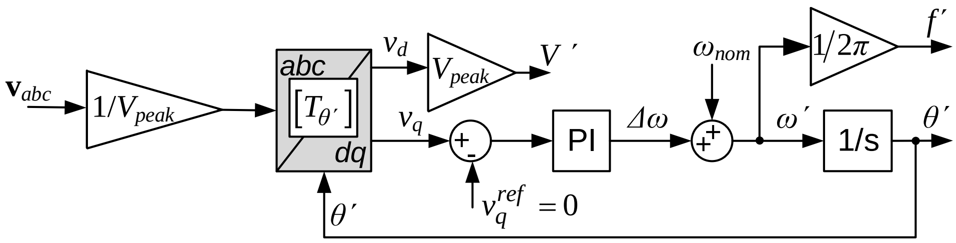

Figure 3: Synchronization unit design based on a PLL approach.

In this context, tunning of the PLL is a significant process to identify the K_p and K_i=1/T_i parameters of the PI controller for ensuring a fast and stable response. In this direction, small signal analysis is used to extract the transfer function of the PLL, which corresponds to a second order transfer function, given by,

$$H_\theta(s) = \frac{\theta'}{\theta_{grid}} = \frac{2\zeta\omega_n s + \omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{k_p \cdot s + \frac{1}{T_i}}{s^2 + k_p \cdot s + \frac{1}{T_i}} \qquad (2)$$

Considering the well know response of a second order transfer function, the natural frequency ω_n can be associated with the PLL parameters as $\omega_n = 1/\sqrt{T_i}$ while the damping coefficient ζ is related to PLL parameters as $\zeta = \left(k_p\sqrt{T_i}\right)/2$. For a second order transfer functions, the settling time (T_s) which is the required time in which the system stays within 1% of its steady state after a unitary step change of the input signal, can be calculated as $T_s = 4.6\tau$, where $\tau = 1/(\zeta \cdot \omega_n)$. Hence, by selecting the desired settling time of the PLL (e.g., 100 ms), the PLL tunning parameters can be calculated as,

$$k_p = 2\zeta\omega_n = \frac{9.2}{T_s} \quad \text{and} \quad T_i = \frac{1}{k_i} = 0.047 \cdot \zeta^2 \cdot T_s^2 \qquad (3)$$

1.1.3.3 PQ controller

The PQ controller plays a critical role in GFL inverters by managing the active (*P*) and reactive (*Q*) power injection. The controller operates in the *dq* reference frame where a decoupled control between active and reactive power can be achieved, since the synchronization unit (Section 1.1.3.2) ensures that v_q tracks zero. Under such conditions (where v_q is almost equal to zero), v_q can be ignored for the active and reactive power calculation and thus, a decouple management of active and reactive power is allowed. Hence, the d-axis current can be used to regulate active power (P=$1.5 \cdot v_d \cdot i_d$) and the q-axis current for regulating reactive power (Q=-$1.5 \cdot v_d \cdot i_q$).

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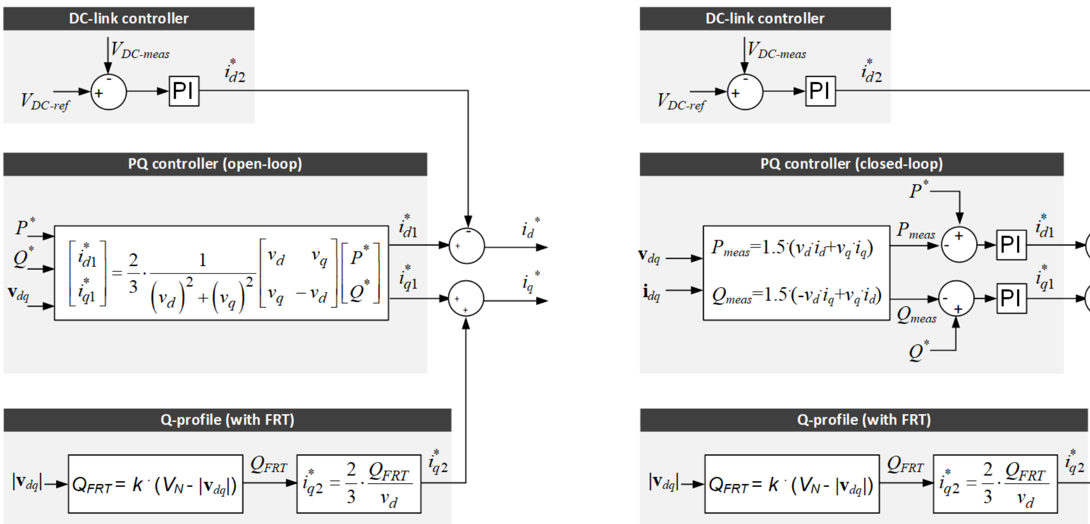
The PQ controller usually consists of several control loops that work together to regulate power output. The first loop is responsible for tracking the reference active power P^* and reactive power Q^*. The reference values (P^* and Q^*) can be set based on system requirements. In example the reactive power reference can be set to maintain a specific power factor during normal operation or to supporting grid voltage during fault ride through (FRT) operation according to the Q-profile requirements determined by the grid regulations. On the other hand, active power can be set to regulate the charging/discharging rate in a battery system configuration or to limit the PV power output during curtailments. The controller calculates the required d-axis and q-axis reference currents [1], according to (4).

$$\mathbf{i}_{dq}^* = \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} = \frac{2}{3}\frac{1}{{v_d}^2 + {v_q}^2}\begin{bmatrix} v_d & v_q \\ v_q & -v_d \end{bmatrix}\begin{bmatrix} P^* \\ Q^* \end{bmatrix} \quad (4)$$

These reference currents can either be directly provided to the current controller considering an open-loop configuration or can be regulated through additional PI controllers in a closed-loop approach.

Additionally, the PQ controller may incorporate a DC-link voltage control loop, which adjusts the total active power reference P^* to ensure that the DC-link voltage remains stable, further enhancing the inverter's ability to support the grid during varying operational conditions. In this case, when the power produced by the primary energy source (e.g., PV) is increased then the power balance at the DC link becomes positive and as a result the capacitor is charging, and the DC link voltage is increasing. Therefore, when the DC link controller (based on a PI controller) detects increasing voltage conditions, it increases the active power reference to maintain the power balance at the DC link. In this way, the DC link voltage remains stable and equal to the reference voltage while any deviation on the primary source generation is sensed by the grid tied inverter which adjust its active power accordingly. The two main PQ configurations, based on open-loop and closed-loop control approach are demonstrated in Figure 4.



(a) (b)

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Figure 4: (a) Open-loop PQ controller, (b) closed-loop PQ controller.

1.1.3.4 Current Controller

The current controller regulates the inverter's current injection by generating reference voltage signals that are fed to the Pulse Width Modulation (PWM) unit to drive the switching operation of the inverter. It ensures that the actual currents follow the reference currents (generated by the PQ controller – Section 1.1.3.3).

The current controller operates in the *dq* frame, where the control objectives are to ensure i_d tracks i_d^* and i_q tracks i_q^* by using two PI controller. The control law [1] can be expressed as,

$$v_d^* = v_d + i_q \omega L_f + K_p(i_d^* - i_d) + K_i \int (i_d^* - i_d)dt \tag{5}$$

$$v_q^* = v_q - i_d \omega L_f + K_p(i_q^* - i_q) + K_i \int (i_q^* - i_q)dt \tag{6}$$

where v_d^* and v_q^* are the reference voltages. These reference voltages are converted from *dq* frame to *abc* frame, using the backward Park's transformation matrices, in order to be fed to the PWM modulation unit for driving the inverter. The terms $(v_d + i_q \omega L_f)$ and $(v_q - i_d \omega L_f)$ in (5) and (6) respectively are feed-forward terms calculated according to the voltage droop across the inductor of the LC filter in order to set the controller closer to the operating point and make the PI controllers more effective [2]. The overall design of the current controller is presented in Figure 5.

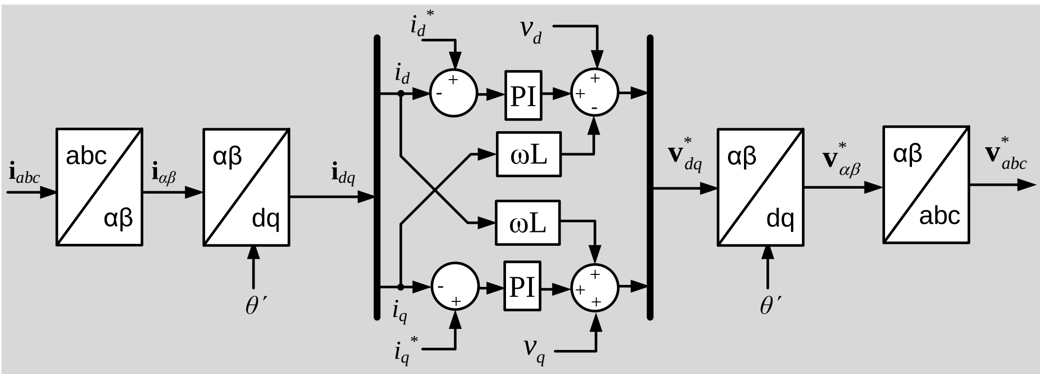

Figure 5: Structure of the conventional current controller.

To ensure the stability of the inverter, a proper tuning procedure is required for the current controller to adequately determine the k_p and k_i=1/T_i parameters of the PI controller. For the tuning process, the current controller transfer function is determined by considering the PI controller transfer function $G_{PI}(s)$, the transfer function of the inverter $G_D(s)$ where a small delay (T_d) is introduced to generate the converter voltage according to the reference voltage signals, and the transfer function of the LC filer $G_f(s)$. As a result, the overall current controller transfer function $H(s)$ is given below.

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$$H(s)=\frac{G_{PI}(s)G_D(s)G_f(s)}{1+G_{PI}(s)G_D(s)G_f(s)}=\frac{\left(k_p+\frac{1}{T_i s}\right)\left(\frac{1}{1+T_d s}\right)\left(\frac{1}{R_f+L_f s}\right)}{1+\left(k_p+\frac{1}{T_i s}\right)\left(\frac{1}{1+T_d s}\right)\left(\frac{1}{R_f+L_f s}\right)}$$

$$H(s)=\frac{\left(\frac{k_p T_i s+1}{T_i s}\right)\left(\frac{1}{1+T_d s}\right)\left(\frac{\frac{1}{R_f}}{1+\frac{L_f}{R_f}s}\right)}{1+\left(\frac{k_p T_i s+1}{T_i s}\right)\left(\frac{1}{1+T_d s}\right)\left(\frac{\frac{1}{R_f}}{1+\frac{L_f}{R_f}s}\right)} \tag{7}$$

However, the third-order transfer function of (7) is difficult to be tuned and thus, a zero-pole cancellation method is used, by selecting $k_p \cdot T_i = L_f/R_f$, to transform $H(s)$ into a second-order transfer function. Hence, by selecting the PI tuning parameters according to the LC filter parameters, $H(s)$ can be re-written as,

$$H(s)=\frac{\left(\frac{1}{R_f T_i s}\right)\left(\frac{1}{1+T_d s}\right)}{1+\left(\frac{1}{R_f T_i s}\right)\left(\frac{1}{1+T_d s}\right)}=\frac{\left(\frac{1}{T_i T_d R_f}\right)}{s^2+\left(\frac{1}{T_d}\right)s+\left(\frac{1}{T_i T_d R_f}\right)} \tag{8}$$

According to (8), $H(s)$ corresponds to a typical second-order transfer function with a natural frequency ω_n and damping coefficient ζ, as determined by (9).

$$\omega_n=\sqrt{\frac{1}{T_i T_d R_f}} \text{ and } \zeta\omega_n=\frac{1}{2T_d} \tag{9}$$

Therefore, the current controller can be tuned according to (10), by assuming optimal damping (ζ=0.07) and by considering the converter delay $T_d=T_{sampling}+T_{PWM}+T_{other}$ which is typically within a range between $1.5T_{sampling}$ and $5T_{sampling}$.

$$\omega_n=\sqrt{\frac{1}{T_i T_d R_f}} \text{ and } \zeta\omega_n=\frac{1}{2T_d} \tag{10}$$

The theory presented in this section is used in the following section to develop a controllable inverter model, as a hands-on example in MATLAB/Simulink.

1.1.4 Hands-on Example: Modeling a GFL Inverter in Simulink

In the previous sub-sections, the use of power electronics for integrating RES was analyzed, and the fundamentals for developing a controllable grid-tied inverter based on GFL mode were provided. This section presents a practical example of developing a fully controllable GFL inverter using MATLAB/Simulink.

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For this example, participants are provided with an initial Simulink model (GridTiedInverter.slx) that includes the overall power grid and power electronics configuration, where key simulation settings have already been established. In this model, the key inverter controller blocks are left intentionally empty. Participants are tasked with developing the inverter controller by following detailed, step-by-step instructions. The goal is that by the end of the training, each participant will have designed their own controllable grid-tied inverter.

The step-by-step guidelines are summarized below.

1. **Open the initial model (GridTiedInverter.slx) using MATLAB/Simulink**
    - If participants are not familiar with Simulink a quick tutorial is provided.
    - Otherwise, the participants are requested to get familiar with the Simulink environment, recognize the key components of the inverter model, and understand which blocks/subsystem needs to develop.
2. **Applying transformations (according to guidelines provided in Section 1.1.3.1)**
    - Design the forward (i.e., abc/dq, abc/αβ, αβ/dq) and reverse (i.e., dq/abc, αβ/abc, dq/αβ) transformation matrices and create general transformation blocks.
    - Use the transformation blocks to transform voltages and currents measurements.
    - Validate the transformation by comparing the results with theoretical calculations.
3. **Developing the synchronization method (according to information given in Section 1.1.3.2)**
    - Use voltage measurement and transformation blocks for developing the conventional dq-PLL to ensure accurate phase tracking and synchronization.
    - Tune the PLL parameters (Kp and Ki) according to the second order transfer function considering a desired settling time of 100 ms.
    - Validate the proper response of the PLL and if it can properly estimate voltage amplitude, phase angle and frequency.
4. **Developing the PQ controller (according to details provided in Section 1.1.3.3)**
    - Use active and reactive power equations and the transformed voltage and current measurements in *dq* frame to create a block that is able to calculate the power injection of the inverter.
    - Validate the active and reactive power calculated by your block with the power calculated by Simulink's Power (3ph, Instantaneous) module.
    - Implement the PQ open-loop controller as a block/subsystem using (4).

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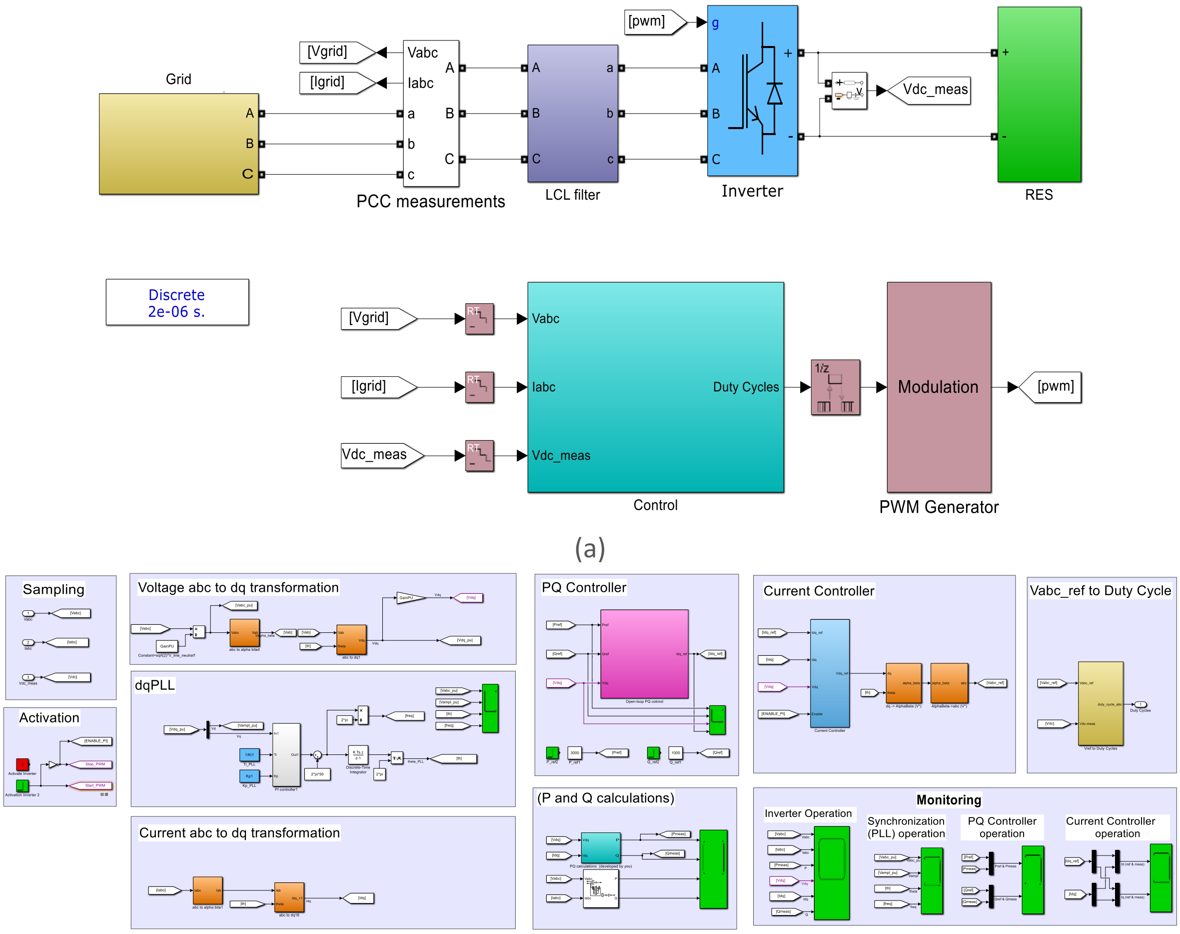
- Cross validate that the reference currents are properly generated according to different active and reactive power references.

5. **Developing the current controller (according to guidelines given in Section 1.1.3.4)**
    - Implement the current controller block according to Figure 5.
    - Tune the controller parameters according to zero-pole cancellation approach, as explained in Section 1.1.3.4 and described by (7)-(10).
6. **Integrating the inverter controller to create a fully functional grid tied inverter model**
    - Integrate the developed transformation blocks, PLL unit, PQ controller, and current controller to formulate a controllable grid tied inverter.
    - Validate the complete system by simulating various operating conditions and observing the performance.

By completing the hands-on example the inverter model and its associate controller should be similar to Figure 6, where all the subsystems (e.g., transformation blocks, dq-PLL, PQ controller, current controller) should be adequately designed according to the previous step-by-step instructions.



(b)

Figure 6: (a) Grid tied inverter model and (b) Inverter controller design in MATLAB/Simulink.

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If the system design is correct, then the participant will be able to observe the inverter operation, as indicated in Figure 7. The participants can change the active and reactive power set-points and observe the dynamic response of the inverter. They can also introduce grid disturbances (e.g., voltage fault, frequency deviation) in order to observe how the inverter will react.

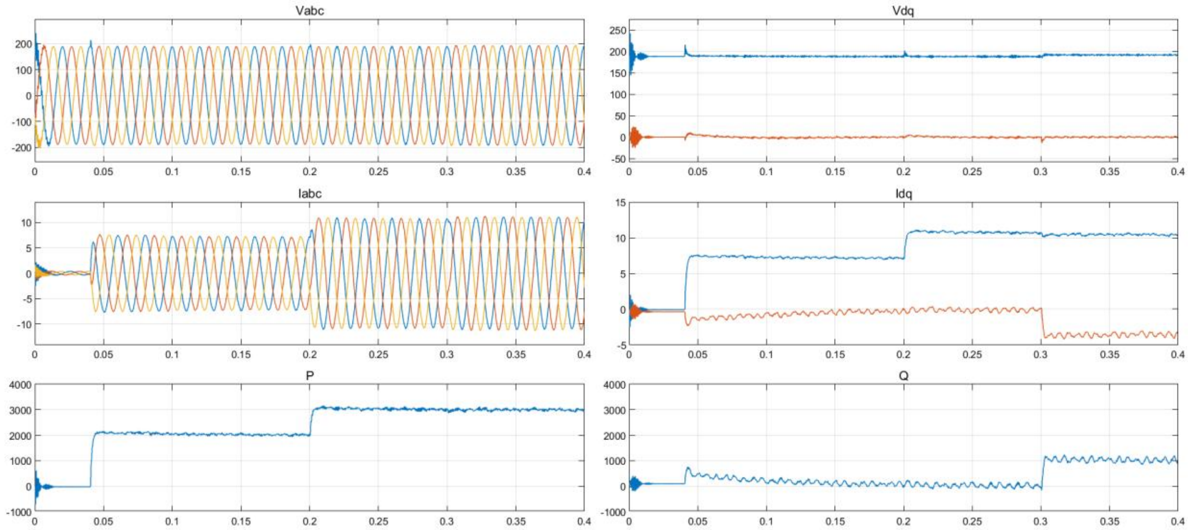

Figure 7: Inverter operation with step change on active and reactive power set-points.

This hands-on example highlights the practical aspects of inverter control, providing a detailed understanding of the modeling process and control design. The developed model represents a basic three-phase inverter with a conventional controller, while the participant can further extend this model to add more functionalities and ensure inverter robustness under any grid conditions.

1.1.5 Recent Advancements in GFL Inverters

The previous sub-sections have covered the overall theory and the practical aspects related to grid tied inverters and the design of their controller. This subsection will provide some recent advancement related to GFL inverter demonstrating how advanced control approaches can be used to enhance the inverter robustness, enable multi-functional operation, and allow grid support functionalities.

As the integration of RES into the power grid continues to grow, the demand for more robust, efficient, and flexible GFL inverters has become increasingly important. Recent advancements in GFL inverter technology focus on improving their synchronization accuracy, operational stability under abnormal grid conditions, and overall power quality. These developments enhance the inverters' ability to support the grid, even in challenging scenarios such as asymmetric faults and harmonic distortions. This section delves into some of the most notable recent advancements in GFL inverters, highlighting how these innovations contribute to the reliability and performance of modern power systems.

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1.1.5.1 Advanced Synchronization Techniques

One of the key advancements in GFL inverter technology is the development of more sophisticated synchronization methods. Traditional PLL techniques (e.g., dq-PLL presented in *Figure 3*) can struggle under conditions where the grid voltage is distorted or unbalanced, leading to inaccurate synchronization that compromise the overall inverter performance. In this context, decoupling network based PLLs have been introduced to provide accuracy under unbalanced voltage conditions (e.g., DDSRF-PLL [3]) or under unbalance and harmonic distorted conditions (e.g., DNαβ-PLL [4]) while ensuring a fast and dynamic response. Alternative PLL options based on moving average filters have also been proposed in [5] to increase synchronization units' robustness under abnormal grid conditions.

Experimental results in [4] demonstrates that fast and accurate synchronization is feasible even under asymmetric voltage faults or intense harmonic distorted conditions. During symmetrical or asymmetrical faults, proper and dynamic synchronization is important to enable the adequate fault ride through (FRT) operation of the inverter where voltage and frequency support needs to be provided to the grid, while during harmonic distorted conditions, precise synchronization, combined with enhanced current controller [6], can ensure a purely sinusoidal current injection by the inverter to improve the overall power quality of the grid.

1.1.5.2 Improved FRT Capabilities for supporting both voltage and frequency

Advancing the operation of GFL inverters requires the integration of advanced Fault Ride-Through (FRT) capabilities to support the grid during fault conditions. As grid codes become more stringent, inverters are increasingly required to remain connected and provide grid support during short-term voltage drops. Modern GFL inverters now feature enhanced FRT functions that allow them to maintain operation without disconnecting during such events. These capabilities are achieved through sophisticated control mechanisms that dynamically adjust the inverter's operation, enabling it to withstand and contribute to grid stability both during and after fault events. Such improvements are vital for maintaining grid integrity, particularly in systems with high penetration of RES.

In this context, grid codes mandate that during symmetric or asymmetric voltage sags, inverters must stay interconnected and prioritize the injection of reactive currents to enhance voltage stability. However, as the penetration of RES increases and the rotating inertia of modern power systems decreases, new requirements have emerged from system operators to ensure overall system stability. For example, in low-inertia systems like those in Ireland or Cyprus, prioritizing voltage support through reactive current injection during a voltage sag can inadvertently trigger cascading frequency disturbances [7]. To address this, alternative FRT support schemes have been developed for low-inertia grids, where the prioritization of active power is considered [7] to minimize the reduction of active power during a voltage fault, thereby avoiding cascading disturbances.

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Additionally, adaptive solutions have been introduced in [8] that dynamically adjust the intensity of voltage and frequency support based on real-time grid conditions, without relying on predefined prioritization approaches. In such cases, frequency support is provided through frequency droop control and virtual inertia support loops, while voltage support is ensured through reactive current injection. The intensity of each support function is adjusted in real-time according to the deviations in both grid voltage and frequency during disturbance events. As a result, these advanced inverter control schemes significantly enhance the overall stability of the power system.

Moreover, in some concepts the provision of both positive and negative voltage support is also explored for enhancing the voltage stability [9]. In this case, the injection of positive sequence reactive current increases the voltage level during a short-circuit event, while the injection of negative sequence reactive current can suppress the voltage asymmetries during an unbalanced fault. The intensity of each current injection can either follow a pre-defined droop approach or can be real-time adjusted according to the voltage conditions during the fault.

1.1.5.3 Multi-functional operation of RES inverters

As RESs become more prevalent in modern distribution grids, the role of inverters has expanded beyond merely converting and injecting RES power into the grid. Inverters are increasingly being tasked with providing additional grid support services [6], [10] to enhance overall power quality and system reliability. One significant advancement in this area is the development of multi-functional RES inverters capable of performing power factor correction, phase balancing, and active filtering [8]. These capabilities allow the inverter to address common power quality issues while simultaneously managing renewable energy generation.

Power factor correction (PFC) is a crucial function in maintaining the efficiency of power delivery in the grid. Traditionally, poor power factor is caused by inductive or capacitive loads that result in a phase difference between voltage and current, leading to inefficient power usage. RES inverters equipped with PFC capabilities can dynamically adjust the reactive power injection to improve the grid power factor [10]. By compensating for the reactive power drawn by local loads, these inverters ensure that the power delivered to the grid is predominantly active, thereby reducing losses and improving the overall efficiency of the power system.

Phase balancing is another critical service provided by advanced RES inverters, especially in distribution networks that may experience unbalanced loading conditions. Unbalanced loads can lead to voltage instability, increased losses, and reduced equipment lifespan. RES inverters can help mitigate these issues by actively balancing the phases of the power they inject into the grid. This is achieved by dynamically adjusting the power output across the three phases, compensating for any disparities [11]. In doing so, the inverter not only ensures that the power supplied to the grid is

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balanced but also improves the voltage stability and reduces the likelihood of equipment malfunctions caused by phase imbalances.

Active filtering is a more advanced capability that addresses harmonics, which are distortions in the electrical waveform caused by nonlinear loads such as power electronics, variable speed drives, and some types of lighting. Harmonics can lead to increased losses, overheating of equipment, and interference with communication systems. Multi-functional RES inverters with active filtering capabilities can detect and compensate for these harmonic distortions by injecting currents that counteract the harmonics, effectively "cleaning" the waveform [11]. This function not only improves the quality of the power supplied to the grid but also protects sensitive equipment and reduces the overall stress on the electrical infrastructure.

The integration of power factor correction, phase balancing, and active filtering capabilities into RES inverters marks a significant advancement in the role of these devices within the power system. By providing these additional services, RES inverters contribute to improved power quality, enhanced grid stability, and increased efficiency. However, the inverter reliability and lifetime expectancy may be affected by the provision of such additional services and therefore it is important to develop thermal management control schemes as well in order to ensure a proper balance between the provision of ancillary services and the lifetime degradation of the inverters [12].

1.1.6 Contribution to development of low carbon technologies, sustainability and circularity

The focus of this training course on modeling and controlling GFL inverters for RES directly contributes to the advancement of low-carbon technologies. By enhancing the integration of RES such as wind, PV, and BESS into the grid, GFL inverters play a pivotal role in reducing reliance on fossil fuels and decreasing greenhouse gas emissions. As these inverters facilitate the efficient and reliable incorporation of renewable energy, they enable the transition toward a more sustainable and low-carbon energy system. The improved control strategies discussed in this course not only enhance the performance of RES but also contribute to grid stability, ensuring that the increasing share of renewables can be managed effectively.

Furthermore, the course promotes the principles of sustainability and circularity by emphasizing the optimization of energy use and the extension of equipment life through advanced inverter controls. By improving power quality, reducing energy losses, and enabling grid support functionalities, GFL inverters help maximize the utilization of renewable energy resources. Additionally, by integrating functionalities such as active filtering, power factor correction, and phase balancing, these inverters reduce the need for additional grid infrastructure, minimizing resource consumption and waste. The course's hands-on approach equips participants with the knowledge and skills to design and implement inverter systems that contribute to a circular economy, where resources are used more efficiently and sustainably.

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1.1.7 Highlight on application in industry

The control and modeling techniques covered in this course have significant applications in various industries, particularly those involved in renewable energy generation, power electronics, and grid infrastructure. As industries increasingly adopt renewable energy solutions to meet sustainability goals and reduce operational costs, the ability to effectively integrate and control RES using GFL inverters becomes essential. This course equips participants with the skills needed to design, implement, and optimize GFL inverters for a wide range of industrial applications, from large-scale wind farms and solar power plants to distributed energy resources in smart grids.

In industrial settings, GFL inverters are crucial for ensuring that energy from renewable sources is efficiently converted and synchronized with the grid. This is particularly important in sectors such as manufacturing, where reliable power supply is critical, and in utilities, where maintaining grid stability is a top priority. Additionally, the advanced functionalities of GFL inverters, such as power factor correction, phase balancing, and active filtering, are directly applicable in industries where power quality is a concern. These features help industries comply with grid codes, reduce energy costs, and protect sensitive equipment from power disturbances. By mastering the content of this course, participants can significantly contribute to the deployment and optimization of RES in various industrial contexts, driving innovation and sustainability across multiple sectors.

1.1.8 Contribution to development of skills and competences

This training course is designed to develop essential skills and competences in the field of power electronics, renewable energy integration, and grid management. Participants will gain a deep understanding of the theoretical foundations and practical applications of GFL inverters, with a focus on control strategies, modeling techniques, and the latest technological advancements. The course's hands-on approach, including the development of inverter models in MATLAB/Simulink, ensures that participants not only learn the concepts but also acquire the ability to apply them in real-world scenarios.

By completing this course, participants will be equipped with a range of technical skills that are highly relevant to the renewable energy and power electronics industries. These skills include advanced modeling and simulation, control system design, and the ability to optimize inverter performance under various grid conditions. Moreover, the course enhances problem-solving abilities and critical thinking, as participants learn to address complex challenges such as grid stability, fault ride-through, and power quality improvement. The competences gained through this course will empower participants to contribute to the development and deployment of innovative solutions that support the transition to a sustainable energy future, making them valuable assets in their respective fields.

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1.1.9 References

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