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PHOTOVOLTAIC SYSTEMS: CONTROL STRATEGIES FOR GRID CONNECTION

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Abstract

Renewable energy is one of the best solutions for generating clean energy. Wind and solar installations have seen a huge increase in the last decades and will be the major power production technology in the future, phasing out classical power production such as coal and gas, which result in the increase of CO2 and other greenhouse gases. This article gives an overview on how grid connected renewable energy systems, like a photovoltaics, can play an important role in the energy supply of the future. Also it shows that such renewable energy sources need to be combined with storage in order to be able to comply with grid codes and make the energy system of the future clean and secure.

Keywords*: renewable energy, grid-connected, current control.*

1. Introduction

Renewable energy has been a very hot topic during the last two decades. Converter based renewable energy is mainly linked to wind and solar applications, where the wind turbine (WT) generator or the photovoltaic (PV) plant is connected to the electrical grid using power electronic converters. These converters are needed in order to convert the alternating current (AC) from the WT generator or the direct current (DC) from the PV plant into a fixed frequency AC electrical grid.

Looking into yearly installations there have been a total of 97.5GW of new WT installed worldwide in 2021 **[1]**. Though, this has been surpassed by new PV installations, since about 168 GW of new PV plants have been installed in 2021, according to **[2]**. Looking at the globally installed cumulative capacity of WT and PV installations, at the end of 2021 there were 837 GW of WT and 940 GW of PV installations worldwide.

Looking at PV plants, one would imagine a few PV panels installed on rooftops. This is true for systems installed in residential and commercial buildings, where such systems have a capacity from a few kWp to around hundreds of kWp, depending on building size.

Nevertheless, PV installations have reached GWp capacities and their peak production can match the production of traditional coal power plants or even that of nuclear reactors, given the fact that sunshine is available in the specific location.

The biggest PV plants are listed in **Table 1.** nevertheless there are many smaller PV systems in the range of up to several hundred kWp capacity either as residential or commercial installations. This means that nowadays a huge capacity of the electrical power production is now distributed over a wider area, while in the past electrical energy was produced in a central power plant and distributed over long transmission lines to the consumers, that could be several hundreds of km away.

PV plants are modular and are made up of thousands of PV panels connected in PV strings, these PV strings are then connected in parallel into PV arrays. These PV arrays are then connected to the electrical grid through a PV inverter. In most cases such PV plants use three-phase inverters and connect to the medium voltage (MV) voltage grid though a MV/LV transformer station **[3]**.

2. Grid codes and requirements

Grid connected systems need to comply with rules and requirements that are defined by the local electrical grid owner. These requirements define DC voltage injection, voltage imbalance, voltage amplitude, frequency deviation, faults and harmonics in a three-phase system in order to make sure that a grid connected unit will not disturb the grid and will not have a negative impact in grid voltage quality.

Looking into the IEEE 1547 Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces published by IEEE, back in 2003, one can read, that converters connected to the grid [4]:

- shall not actively regulate voltage;
- shall disconnect on abnormal voltage or frequency of the electrical grid.

This was the rule since at that time there were only 2.8 GWp of PV and 39GW of WT installations worldwide contributing only to a very small share in the total energy mix.

Table 1. *Largest PV plant installations worldwide*

Name	Country	Capacity MW_{DC} or MW_{AC}	Land size km^2	Year
Bhadla Solar Park	India	2,700	160	2020
Longvangxia Dam Solar Park	China	2,400		2015
Huanghe Hydropower Hainan Solar Park	China	2,200	50	2020
Pavagada Solar Park	India	2,050	53	2019
Benban Solar Park	Egypt	1,650	37	2019
Tengger Desert Solar Park	China	1,547	43	2016
Noor Abu Dhabi	United Arab Emirates	1,177	8	2019
Mohammed bin Rashid Al Maktoum Solar Park	United Arab Emirates	1,013		2020
Kurnool Ultra Mega Solar Park	India	1,000	24	2017
Datong Solar Power Top Runner Base	China	1,000		2016
NP Kunta	India	900		2020

With the increasing share of renewable energy in the energy mix, the grid codes have also evolved. In 2014, the IEEE 1547 standard was updated and mentioned that converters connected to the grid:

- may actively regulate voltage;
- may ride through abnormal voltage or frequency;
- may provide frequency response.

This means that grid connected systems are now capable of supporting the electrical grid with ancillary services, thereby making the electrical network stronger, better and safer.

With the continuous increase in the installed renewable energy systems, the IEEE 1547 grid code requirement has been updated again in 2018, where it is mentioned that grid connected systems are now required to fulfil the following:

- shall be capable of actively regulating voltage;
- shall ride through abnormal voltage/frequency;
- shall be capable of frequency response.

With these ancillary services, grid connected converters have taken an active part in the grid, not only injecting power in the grid, but also adjusting their behavior depending on the actual grid parameters, the same way traditional power plants would do.

3. Control of grid connected converters

Grid connected converters have several layers of control algorithms. The main control layer is the low-level control and is common for all grid connected converters. This is usually made up of a DC voltage control loop, grid synchronization and a current control loop. The theory about these loops can be found in many publications and books, such as [5], and will not be discussed here in detail. Grid current control focuses on THD limits imposed by standards, stability in case of grid impedance variations and ride-through grid voltage disturbances. DC voltage control deals with the adaptation to grid voltage variations and ride-through grid voltage disturbances. Finally, grid synchronization has the purpose of synchronizing to the grid using a phase locked loop (PLL) or frequency locked loop (FLL), required for grid connection or reconnection after a grid event, like a grid fault.

These control algorithms, shown in **Figure 2** are all needed for grid connected applications to

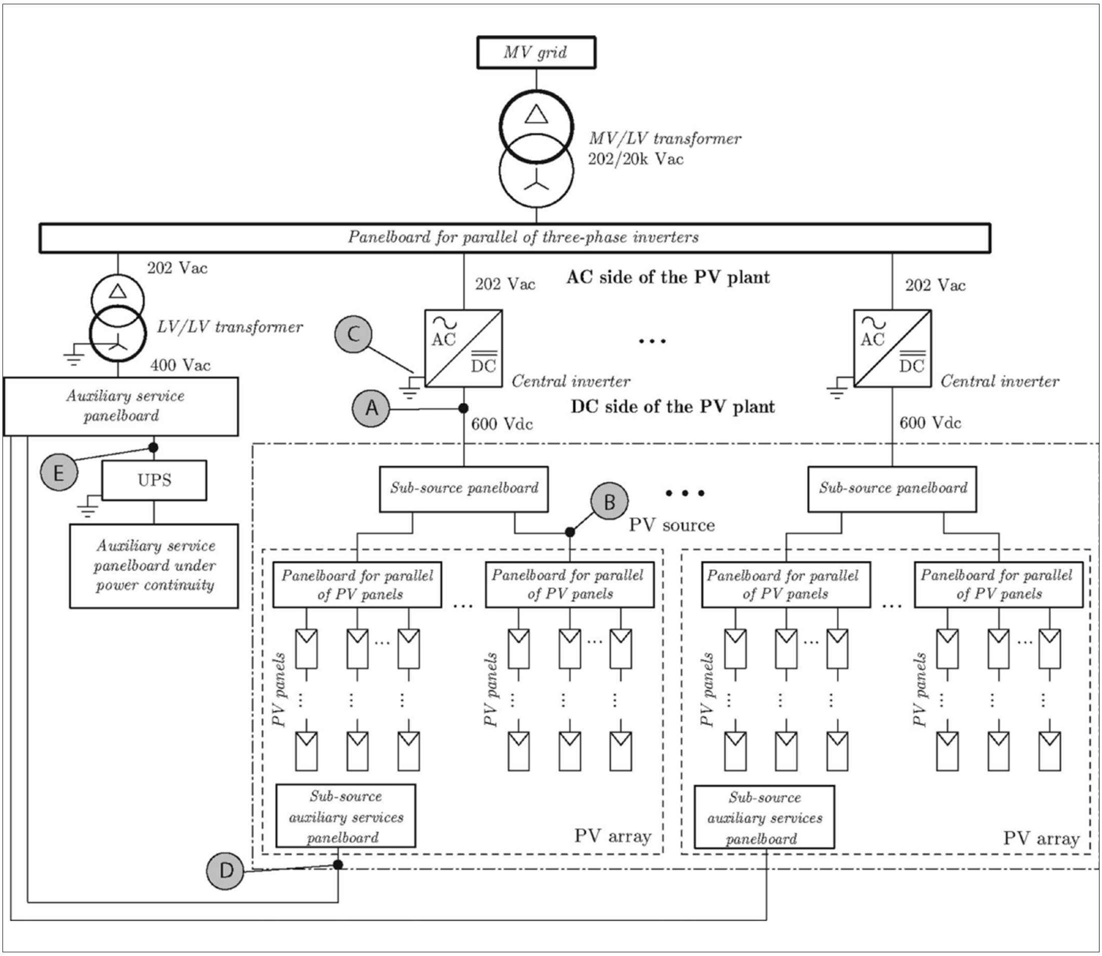

Figure 1. *Single line diagram of a PV plant.*

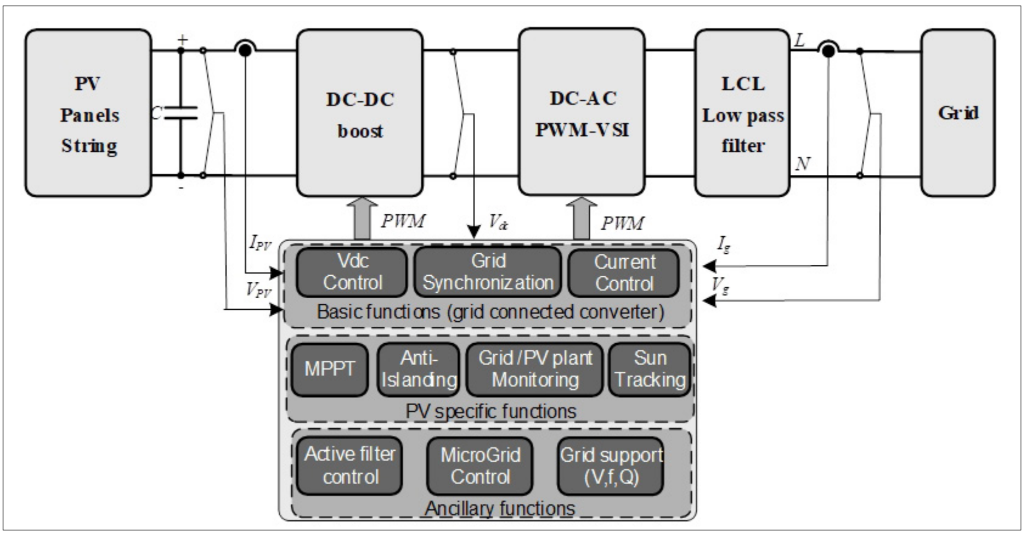

Figure 2. *Control loops in a grid connected converter application.*

make sure that grid requirements such as IEEE 1547 are followed.

In case of PV applications, there are specific PV functions, including:

- Maximum Power Point Tracking (MPPT), which requires a very high MPPT efficiency in steady state (typical > 99%), fast tracking during rapid irradiation changes (dynamical MPPT efficiency) and a stable operation at very low irradiation levels;
- Anti-Islanding (AI), to disconnect from the grid in case of specific grid events, if this is required by grid codes and standards;
- Grid Monitoring for operation at unity power factor and fast voltage/frequency detection as required by standards;
- Plant Monitoring with the scope of diagnostic of the PV panel array or partial shading detection.

Such specific PV related functions ensure that the PV array is operating at optimum conditions while also following the grid codes and requirements defined in the specific standards.

Controlling the power flow in a grid connected converter requires two loops. An outer power loop (PQ controller) shown in **Figure 3** that will calculate the required current references (id* és iq*) based on the P* and Q* reference values. Using the calculated current reference values, the inner loop (Current controller) shown in **Figure 3** then will calculate the required voltage references (Vd* and Vq*). These voltage references will be transformed to their three-phase equivalent values and used in the pulse width modulator (PWM). The PWM will generate the duty cycles that control each individual transistor in the three-phase power electronic converter, as also shown in **Figure 2.**

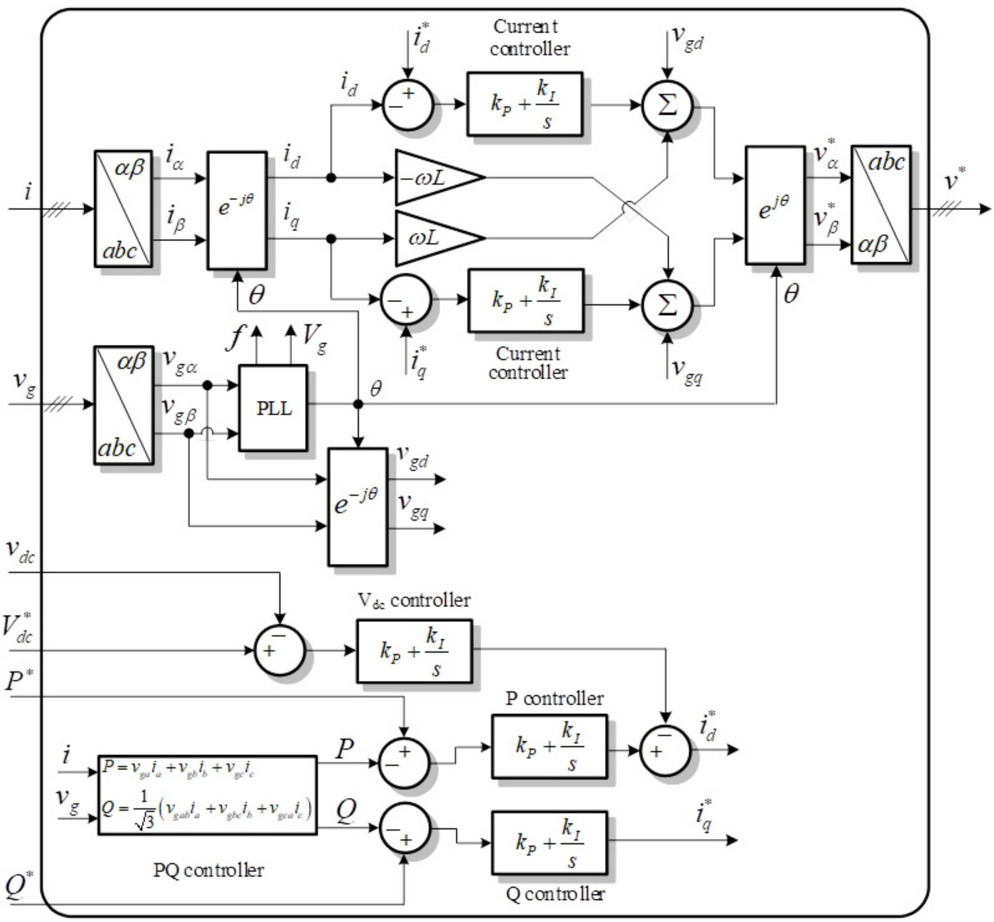

Figure 3. *Control of grid side current using a traditional PI controller and DQ transformations.*

Controlling the current and the power flow is just one of the tasks grid connected systems need to do. Grid codes also specify how fast the injected power is allowed to change, when connected to the grid. This is done in order to limit the power fluctuations that would influence grid security in a negative way. Taking into account that PV systems have no inherent inertia, any change in the received sunlight intensity will be directly visible on the output power of the converter and lead to very steep power fluctuations.

Simulating such a scenario has been achieved using a 5.7 kWp PV system. As can be seen in **Figure 5** the output power from the PV systems follows the sunlight pattern and will cause voltage fluctuations on the electrical grid. This is an unwanted side effect, and the power ramp rate needs to be limited. While the positive ramp rate can be limited in case of increasing power, just by limiting and clamping the power output of the converter, the negative ramp rate cannot be limited, since the energy stored in the power electronic converter is not enough. This means that during such scenarios the PV system will not match the grid codes and requirements.

Such power fluctuations can be limited using storage, in the form of a battery system. In this particular case, if a 10 kW and 2.5 kWh battery system is added, then, depending on the battery management system (BMS), the fluctuations can be limited to a level that is within the limits defined by the grid codes. The model of such a system is presented in **Figure 6.** and the results of the output power using the hybrid system, can be seen in **Figure 7**.

Comparing the results from **Figure 5** and **Figure 8** one can see the P_{out} reduces fluctuations when using storage since the battery filters and compensates these power fluctuations coming from the PV array. Also, if the impedance of the cables between the PV system and the low voltage (LV) distribution transformer is taken into account, then these power fluctuations will lead also to voltage fluctuations, that again are limited by the grid code. These voltage fluctuations are due to the increased active power (P) and can be compensated for using reactive power (Q). This means that the PV inverter needs to be sized accordingly, so that the current rating of the transistors will be able to carry the combined current both from the active and reactive power during all scenarios.

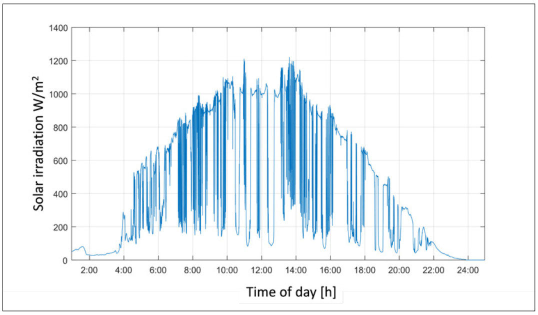

Figure 4. *Solar irradiation profile on a sunny day with passing clouds.*

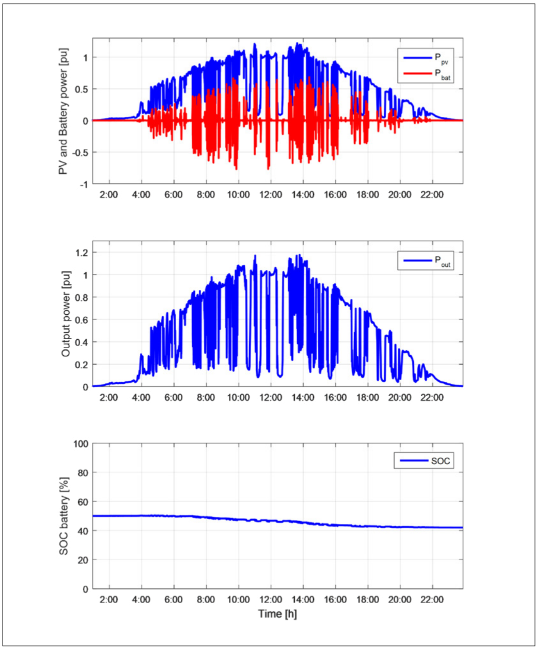

Figure 5. *PV system output power during sunny day with passing clouds shown by P_{out}.*

4. Conclusion

Renewable energy is one of the best solutions in generating clean energy. Wind and solar installations have seen a huge increase in the last decades and will be the major power production technology in the future, phasing out classical power production such as coal and gas, that result in the increase of CO_2 and other greenhouse gases. The intermittency of renewable energy, though, is a challenge. Therefore, different renewable energy sources need to be combined with energy storage solutions to make energy production a success in the future.

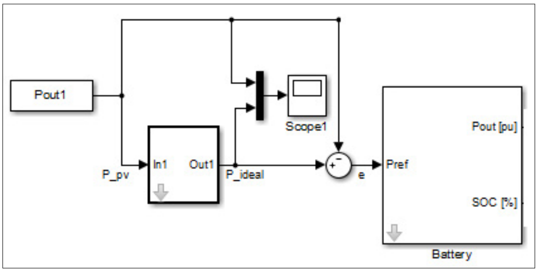

Figure 6. *PV production including battery model.*

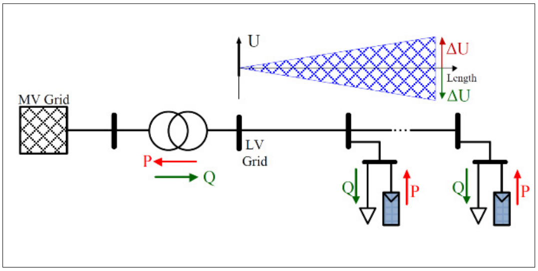

Figure 7. *Grid voltage influenced by grid impedance in the LV grid.*

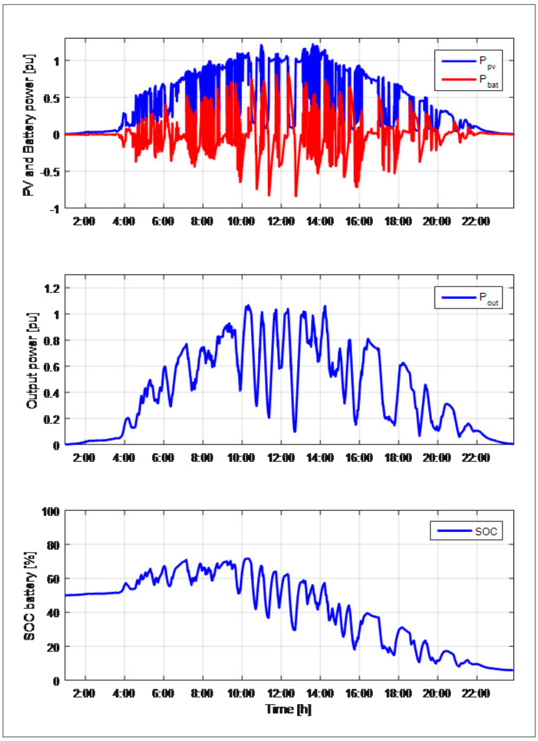

Figure 8. *Simulation results showing P_{PV}-PV power, P_{bat}-battery power, P_{out}-power injected in the grid and the battery state of charge (SOC)*

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