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Integration of photovoltaic sources and battery based storage systems – A DC analysis and distributed maximum power point tracking solution

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"It is better, of course, to know useless things than to know nothing."

Seneca the Younger

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Abstract

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Doctor of Philosophy

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In this thesis the integration of photovoltaic (PV) generation and energy storage into the electrical grid is discussed. Although the studied system is for grid tied applications, here the integration of the PV generation and the energy storage system (ESS) on the direct current (DC)-side of the system is addressed. The work contained in this thesis focuses on the integration of the DC-working parts before interfacing them with the grid through the use of an inverter and seeks an increasing in the energy that the system can deliver.

First, a study of classical systems that present well-differentiated parts is presented: PV generation, a lithium-ion battery based ESS, the utility grid and a residential electricity consumer. PV installations of 3 and 10kWp are considered together with storage capacities ranging from 1 to 9kWh. This yields interesting insights on how the system works based on the timing of the generation and consumption of energy. The results are used to highlight the weaknesses of the selected converter arrangement for the interfacing of the PV source and the ESS. Results show that the system is rather stiff and lacks from conversion efficiency when it needs to work in a wide range of powers, mainly due to low consumer power demand during battery discharge. In this first part of the thesis, three solutions to workaround the efficiency problem are proposed: reducing the difference between the ESS and the DC-bus voltages, using isolated converters to interface the ESS, or adopting a new arrangement of the parts of the system. One of the first two proposed solutions should be adopted if the same system topology is to be kept. These two solutions address the efficiency problem when the ESS is involved in the energy conversion. The third solution is proposed as alternative to the classical systems that use a DC-bus to exchange power with the different parts of the system.

The new proposed arrangement features a distributed maximum power point tracking (DMPPT) type system that includes storage at module level. DMPPT systems are able to track the maximum power point tracking (MPPT) of each panel separately by connecting a small power electronic converter (PEC) to each PV panel. They are specially useful when the PV installation receives uneven irradiance, i.e. shadows are present in some of the panels, increasing the annual yield of PV energy from 7 to 30% as reported in the literature. Unfortunately, this kind of systems cannot always handle high irradiance mismatches, and fail to track the maximum power point (MPP) throughout the whole installation in some cases. Including batteries at module level instead of connecting them to the DC-bus, allows for increasing the MPPT range of the system, virtually to any severity of irradiance mismatch (depending on the state of charge (SoC) of the battery pack), as well as adding storage capability to the system.

The novel proposed system is able to workaround the problems of using non-isolated converters, achieving PV energy conversion efficiencies from 86% (for at least 10% of the peak power) to 90% and storage charge/discharge efficiencies ranging from 86% to 95%. Besides, it brings the opportunity to exploit the synergies of having storage at module level in systems that combine renewable energies and storage. Moreover, DMPPT systems achieve superior PV generation under partially shaded conditions when compared to classical PV arrays increasing the PV generation when compared to classical or centralized PV installations up to 45% in power as reported in the literature.

In the second part of the thesis, the proposed novel DMPPT topology is presented. The whole system is fully designed from scratch, including PECs, sizing of the different parts of the modules, embedded control loops of the modules and supervisory control of the whole system. Finally, the results obtained from running the proposed system are shown and discussed, and suggestions given on how to operate and protect the system. Experimental results are obtained using a 1.5kWp PV power and 1.5kWh capacity test bench built for that purpose.

The proposed system is able to generate PV energy, store the energy coming from PV generation and inject the generated and stored energy into the grid. The proposed system extends the MPPT capability of storage-less series-connected DMPPT systems. This is achieved by using the batteries not only to store energy when required, but also to compensate the power mismatch across DMPPT modules of the same string when the output voltage of the modules becomes a limit. It also presents a modular and upgradable approach to PV systems including storage. This modularity also brings fault tolerance, and an ability to continue working after failure of one or more of the DMPPT modules by partially or completely isolating the faulty module (depending on the nature of the fault). Moreover, the addition of the DC-DC converters allows for the use of different PV panels in the system, i.e. from different manufacturers or technologies.

In conclusion, the presented system is very flexible, can be designed for a wide range of power levels and energy storage sizes, and presents improved reliability when compared to other series-connected DMPPT systems.

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