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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 workaroud 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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Contents

Abstract	v
Acknowledgements	vii
1 Introduction	1
I Storage and renewable energy generation system analysis	3
2 Introduction to Part I	5
3 Outline of the local-grid study	9
3.1 Case studies	9
3.1.1 PV generation	10
3.1.2 Load consumption	12
3.1.3 Energy storage system	13
3.2 Local-grid simulator	13
3.3 Energy management algorithms	14
3.4 Discussion	17
4 Modeling	19
4.1 Bidirectional boost converter	19
4.1.1 Switching model of bidirectional boost converter	20
Conduction losses in switching model	23
4.1.2 Classical averaged model of bidirectional boost converter	24
Conduction losses in classical averaged model	25
4.2 Half-bridge	26
4.2.1 Conduction losses in half-bridge averaged model	29
4.2.2 Switching losses in half-bridge averaged model	30
4.3 Three-level bidirectional boost converter	35
4.4 Dual active bridge converter	36
4.4.1 Steady-state average current calculation	38
4.4.2 Generalized averaged model of dual active bridge	41
4.5 Battery pack	42
4.6 PV panel	43
5 Results	45
5.1 PV generation results	45
5.2 Energy storage system results	48
5.3 Discussion	50

II	Distributed Maximum Power Point Tracking System including Storage at Module Level	53
6	Modules for the DMPPT system	55
6.1	Topology and sizing	59
6.1.1	Operation modes of the interleaved three-port boost converter	59
6.1.2	Sizing of the modules for the DMPPT system	61
6.2	Modeling of the PEC in the module	69
6.2.1	Three-port boost converter	69
6.2.2	Interleaved three-port boost converter	70
	Switched model	70
	Averaged model	71
	Small-signal model	72
6.3	Proposed modulation for the interleaved three-port boost converter . .	74
6.3.1	Trailing- and leading-edge modulation	75
6.3.2	Symmetrical modulation	75
6.4	Design and implementation	76
6.4.1	Power converter	77
	Snubber circuits	79
6.4.2	Measurements	84
6.4.3	Control	85
6.4.4	Power supplies	86
6.5	Control of the PEC	86
6.5.1	PV current control loop	87
6.5.2	PV voltage control loop	89
6.5.3	Battery current control loop	89
6.5.4	Protections	90
6.6	Command of the DMPPT modules	90
6.7	Discussion	91
7	DMPPT system with storage at module level	93
7.1	DMPPT system limits	93
7.2	DMPPT system control structure	97
7.3	DMPPT system control algorithm	97
7.3.1	DMPPT system initialization	99
7.3.2	Normal operation of the DMPPT system	103
	Supervisory control version 1	103
	Supervisory control version 2	105
	Supervisory control version 3	105
	Supervisory control version 4	107
	Supervisory control version 5	109
	MPPT function	109
	DC-bus voltage adaptation	117
7.3.3	DMPPT system stop	117
7.3.4	Recover a module from PWM tripping	119
7.4	Discussion	121
8	Simulation and experimental results	125
8.1	Results from DMPPT module design and testing	125
8.1.1	Control of module	125
8.1.2	Converter modulation	127

8.1.3	Module efficiency	130
8.2	DMPPT system control	130
8.2.1	DMPPT system initialization	133
8.2.2	DMPPT system stop	135
8.2.3	DC-bus voltage adaptation	141
8.2.4	Recovering a DMPPT module from PWM tripping	141
8.2.5	Operation of the DMPPT system under homogeneous irradiance	141
8.2.6	Operation of the DMPPT system under partial shading	146
8.3	Discussion	166
9	Conclusion	171
9.1	Summary of the main contributions	175
10	Future work	177
A	Converter design for local-grid simulation study	181
A.1	PV converters	181
A.1.1	2-level boost converter for 3kWp PV application	181
A.1.2	3-level boost converter for 3kWp PV application	182
Inductor design	183	
A.1.3	Boost converter for 10kWp PV application	185
A.1.4	Three-level boost converter for 10kWp PV application	185
A.1.5	Summary	185
A.2	Energy storage system converters	185
A.2.1	Boost converter for 50V battery pack	186
A.2.2	Boost converter for 150V battery pack	186
A.2.3	Three-level boost converter for 150V battery pack	187
A.2.4	Summary	187
B	Results of the study in Part I	189
B.1	PV generation results	189
B.2	Energy storage system results	192
C	PCB layout	203
D	DMPPT module efficiency measurement data	207
E	Nonlinear MIMO control using feedback linearization	211
E.1	Converter model	212
E.2	Proposed control strategy	212
E.3	State-feedback control design	213
E.4	Simulation results	215
F	Cost of the proposed DMPPT module	221