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Grid Support in Large Scale PV Power Plants using Active Power Reserves

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Publication date:
2014

Document Version
Publisher's PDF, also known as Version of record

[Link to publication from Aalborg University](#)

Citation for published version (APA):
Craciun, B-I. (2014). *Grid Support in Large Scale PV Power Plants using Active Power Reserves*. Department of Energy Technology, Aalborg University.

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Grid Support in Large scale PV Power Plants using Active Power Reserves

By

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Department of Energy Technology



DEPARTMENT OF ENERGY TECHNOLOGY
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Dissertation Submitted to

The Faculty of Engineering, Science and Medicine, Aalborg University in
Partial Fulfilment for the Degree of Doctor of Philosophy

September 2014

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Printed in Denmark by UniPrint
ISBN:

Thesis title: Grid Support in Large scale PV Power Plants using Active Power Reserves

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List of published papers:

- B-I Craciun, T. Kerekes, D. Sera, R. Teodorescu *Overview of recent Grid Codes for PV power integration; Proceedings of 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), 2012 Page(s): 959 – 965*
 - B-I Craciun, E. Man, V. Muresan T. Kerekes, D. Sera, R. Teodorescu *Improved voltage regulation strategies by PV inverters in LV rural networks; Proceedings of 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2012, Page(s): 775 - 781*
 - B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, Adrian Timbus, *Benchmark Networks for grid integration impact studies of large PV plants, Proceedings of 2nd International Workshop on Integration of Solar into Power Systems, 2012*
 - B-I Craciun, S. Spataru, T. Kerekes, D. Sera, R. Teodorescu *Power ramp limitation and frequency support in large scale PVPPs without storage, Proceedings of IEEE 39th Photovoltaic Specialists Conference (PVSC), 2013, Page(s): 2354 – 2359*
 - B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, R. Brandl, T. Degner, D. Geibel, H. Hernandez, *Grid integration of PV power based on PHIL testing using different interface algorithms, Proceedings of 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013, Page(s): 5380 – 5385*
 - B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, Adrian Timbus, *Benchmark Networks for grid integration impact studies of large PV plants, Proceedings of IEEE PowerTech (POWERTECH), 2013, Page(s): 1 - 6*
 - B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, U.D. Annakkage, *Active power reserves evaluation in large scale PVPPs Proceedings of 3rd International Workshop on Integration of Solar into Power Systems, 2013*
 - B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, U.D. Annakkage, *Frequency support functions in Large PV Power Plants with Active Power Reserves, IEEE Journal of Emerging and Selected Topics in Power Electronics Special Issue on Modeling and Control of Power Electronics for Renewable*
-

Energy and Power Systems, 2014

- B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, U.D. Annakkage *Power Ramp Limitation capabilities of Large PV Power Plants with Active Power Reserves, IEEE Transactions on Sustainable Energy, 2014 (submitted)*

This present report combined with the above listed scientific papers has been submitted for assessment in partial fulfillment of the PhD degree. The scientific papers are not included in this version due to copyright issues. Detailed publication information is provided above and the interested reader is referred to the original published papers. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty of Engineering and Science, Aalborg University.

Preface

The submission of this thesis marks the end of a wonderful period from 15 August 2011 to 15 August 2014 in which I was a PhD student in the Department of Energy Technology at Aalborg University. The PhD project was part of the PSO Forskel project number 10648 entitled Smart PV systems and was in cooperation with Danfoss Solar A/S and Gaia Solar A/S.

I can sincerely say that the entire PhD has been the most challenging experience encountered yet and I wish to express my deepest gratitude to those who gave me the strength and courage to evolve and move forward.

First of all, I am extremely grateful to my supervisors from Aalborg University: Professor Remus Teodorescu, Associate Professor Tamás Kerekes and Associate Professor Dezső Séra. Their valuable guidance, professional support and great enthusiasm made my PhD experience productive and stimulating.

I want to thank Søren Bækthøj Kjær and Dan Radu Lazăr, from Danfoss Solar A/S for their fruitful participation in the steering meetings and for their valuable and active support.

I am also grateful to Professor Udaya D. Annakkage from University of Manitoba for his kindness and invaluable technical support during my study abroad period from 1st of March to 1st of June 2013 at the Department of Electrical and Computer Engineering.

Many thanks to my colleagues from the Department of Energy Technology for their friendly guidance and professional debates. In particular, I thank Cristian Sântămărean, Emanuel Eni, Sergiu Spătaru, Daniel Stroe, Irina Stan and Cam Pham for their caring support and warm encouragements.

And last, but not least, I am deeply thankful to my entire family for their unconditional love and continuous support. I dedicate this thesis to my mother Maria, whose role in my life was, is and remains enormous. I also dedicate this thesis to the loving memory of my father Eugen. Without his priceless advices none of my achievements would have been possible.

Bogdan-Ionuț Crăciun
July 2014, Aalborg

Abstract

Photovoltaic (PV) systems are in the 3rd place in the renewable energy market having a global installed capacity of 138.9 GW in 2013, after hydro and wind power. The increased penetration of PV within the electrical power system has led to stability issues of the entire grid in terms of its reliability, availability and security of the supply. As a consequence, Large scale PV Power Plants (LPVPPs) operating in Maximum Power Point (MPP) are not supporting the electrical network. Several grid events and the increased number of downward regulation procedures have forced the European Network of Transmission System Operators for Electricity (ENTSO-E) to continuously upgrade their Network Codes (NCs), imposing grid stabilization features to LPVPP.

Considering the technical challenges present in nowadays power systems, the work presented in this thesis focuses on frequency and power ramp control strategies provided by LPVPPs with internal generated Active Power Reserves (APRs).

LPVPPs with frequency support functions such as Frequency Sensitive Mode (FSM) and Inertial Response (IR) are studied and analyzed, with the main goal of assessing their contribution in a system with increased level of PV penetration. Short-term and mid-term frequency stability analysis, based on time domain and statistical evaluation studies, demonstrate LPVPPs ability to improve the frequency stability during transients and their participation in the regulation process of overall frequency quality parameters. Furthermore, the analysis proves that LPVPPs can become active players in the power system, along with the conventional generation, can share part of their stabilizing responsibilities and consequently can allow higher PV penetrations.

Stringent power ramping obligations imposed by TSOs with increased levels of renewables, such as Puerto Rico Electric Power Authority (PREPA), represents the second topic of this thesis. Power fluctuations created by the variable and intermittent nature of the irradiance, are smoothed out by a proposed power ramp limitation (PRL) control architecture, which considers the spatial distribution of LPVPPs and minimizes the power mismatches by using optimal curtailed APRs.

The proposed PRL method targets the limitation of the power fluctuation directly at the production site and, consequently, reduces the ramping stress of the participating plants.

The aforementioned ancillary services rely on the use of APRs, a crucial element in their security of the supply. The thesis examines the use of internal generated APRs, realized by curtailment, and their deployment during frequency and irradiance transients. The reserves are dynamically deployed in accordance with meteorological conditions present at the production site and in accordance with the requirements imposed by the ENTSO-E.

In order to validate the performance of the frequency support functions, a flexible grid model with IEEE 12 bus system characteristics has been developed and implemented in RTDS. A power hardware-in-the-loop (PHIL) system composed by 20 kW plant (2 x 10 kW inverters and PV linear simulator) and grid simulator (RTDS) has been developed and used to validate the frequency support functions.

Dansk resumé

Solceller system(PV) er den tredje størst i vedvarende energi marked, føret af vand og vind kraft.

Den øgede indtrængning af PV inden for elforsyningen har ført til stabilitets problem for hele el-net i form af dens pålidelighed, tilgængelighed og sikkerhed for forsyningen. Som følge deraf, stor skala PV kraftværk (LPVPPs) som arbejder i Maximum Power Point(MPP) støtte ikke forsyningsnet, da flere el-net udløse hændelse eller stigende antal af nedregulering procedurer har tvunget European Network of Transmission System Operators for Electricity (ENTSO-E) til konstant opgraderer deres netværk forskrifter(NCs) og flytte deres fokus til el-net stabilisering funktioner.

Tage i betragtning af de tekniske udfordringer i nu om dagens elforsyning system, arbejdet som fremlægger i denne afhandling fokuser på frekvens og effekt rampe kontrol strategier givet af LPVPPs med intern generering Active Power Reserves (APRs).

LPVPPs med frekvens understøtte funktioner såsom Frequency Sensitive Mode (FSM) og Inertiel Response (IR) er undersøgt og analyseret, hvor hovedformål er at demonstrere deres fornødenhed i et system med øgede niveau af indtrængning. Short-term og mid-term frekvens stabilitet analyser baseret på tidsdomain og statistisk evaluering undersøgelse påviser LPVPPs evne til at forbedre frekvens stabilitet under transient og dens medvirke i regulering forløb af overordnet frekvens egenskab parameter. Ydermere, analyser vise at LPVPPs kan spille en afgørende rolle i elforsyning sammen med konventionel produktion og kan dele en del af dens stabilisering ansvar.

Skrappere effekt rampelse forpligtelse pålagt af TSO som for eksempel Puerto Rico Electric Power Authority(PREPA) med øgede niveau af vedvarende energi udgør det andet emne af denne afhandling. Strøm variationer skabt af skiftende og uregelmæssigt forhold af irradians er glattet ud af den foreslået power ramp limitation (PRL) kontrol arkitektur, som tage hensyn til LPVPP spatial fordeling og minimere effekt uoverensstemmelse ved at anvende optimum indskrænket APRs. Den foreslået PRL metode rette sig mod begrænsning

af strøm variation direkte ved produktionssted og som konsekvens begrænser rampe stress af de medvirkende værker.

Den førnævnte hjælpe-service afhængig af anvendelse af APRs, et afgørende element i dens sikring af forsyningen. Afhandlingen kigger på brugen af intern genererer APRs realiseret af indskrænkning og dens implementering under frekvens og irradians transiente. Reserven er dynamisk givet jævnført af metrologisk forhold ved produktionssted og ifølge af krav pålægger af ENTSO-E.

For at validere ydelsen af frekvens støtte funktioner, et fleksible el-net model med IEEE 12 bus systems karakteristika er udviklet og implementeret i RTDS. En Power Hardware-In-The-Loop (PHIL)system består af 20kW værk (2 x 10kW vekselretter og PV lineært simulator) og el-net simulator (RTDS) er udviklet og anvendt til frekvens støtte funktioner.

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Nomenclature

List of abbreviations:

AC	– Alternative Current
ADC	– Analog to Digital Converter
AGC	– Automatic Generation Control
aAPR	– auxiliary Active Power Reserves
APR	– Active Power Reserves
AVR	– Automatic Voltage Regulator
CPP	– Conventional Power Plant
DAC	– Digital to Analog Converter
DC	– Direct Current
DIM	– Damping Impedance Method
DK1	– West Danmark Power system
ENTSO-E	– European Network of Transmission System Operators for Electricity
FCR	– Frequency Containment Reserves
FRR	– Frequency Restoration Reserves
FRT	– Fault Ride Through
FSM	– Frequency Sensitive Mode
HV	– High Voltage
HUT	– Hardware Under Test
iAPR	– internal Active Power Reserves
IA	Interface Algorithms
IR	– Inertial Response
ITM	– Ideal Transform Method
LV	– Low Voltage
LVRT	– Low Voltage Ride Through
LPVPP	– Large scale PV Power Plants
MPP	– Maximum Power Point
MPPT	– Maximum Power Point Tracking
MV	– Medium Voltage
NC	– Network Codes
PCC	– Point of Common Coupling
PFC	– Primary Frequency Control
PHIL	– Power Hardware In the Loop
PI	– Proportional Integrator
PREPA	– Puerto Rico Electric Power Authority

PRL	– Power Ramp Limitation
PV	– Photo Voltaic
PU	– Per Unit
RR	– Replacement Reserves
ROCOF	– Rate Of Change Of Frequency
RTDS	– Real Time Digital Simulator
RTS	– Real Time System
RTW	– Real Time Workshop
SRF	– Standard Frequency Range
STC	– Standard Test Conditions
TD	– Time Delay
THD	– Total Harmonic Distortion
TSO	– Transmission System Operator

List of symbols

α_i	– AGC sharing coefficients
$\tau_{\text{filtering}}$	– Time constant specific to LPVPP spatial distribution
τ_{PRL}	– Time constant specific to PRL service
ω_m	– Mechanical speed
$\pm\Delta P_s$	– Upward and downward APR
Δf_1	– Steady state frequency error
Δi_{APR}	– Internal generated APR
ΔP_{demand}	– Total active power mismatch
ΔP_{DCcap}	– Active power stored in the DC capacitance
ΔP_{IR}	– APR during IR
ΔP_{PRL}	– APR during PRL service
ΔV_{DC}	– Voltage difference in the DC capacitance
$d\omega/dt$	– Rate of change of frequency
ha	– Hectares
$i_{\alpha}^*, i_{\beta}^*$	– References in stationary reference frequency
s	– DC voltage sensitivity analysis
A	– LPVPP area
G	– Irradiance
H_i	– Generator inertia
H_{syn}	– Synthetic inertia
I_{MPP}	– DC current at MPP conditions
J_i	– Generator inertia momentum
K_i	– Integrative constant in single area AGC
$N_{\text{PV inv}}$	– Number of central inverters in LPVPP
$P_{\text{AC}}^{\text{meas}}$	– Central inertia measured active power
P_{LG1}	– Generator loading in single are AGC
P_{LPVPP}	– LPVPP produced active power

P_{\max}	– Maximum available power in LPVPPs
P_{TSO}	– TSO downward regulation power
R_{FSMi}	– FSM droop characteristic
R_{PVPP}	– Inertial response ramp rate
Q_{LPVPP}^*	– Reactive power reference of LPVPP
Q_{meas}	– Measured reactive power
S_{base}	– Base apparent power
T	– Temperature
T_{G}	– Governor specific time constant
V_{MPP}	– DC voltage at MPP conditions
Z^*	– Hardware impedance
Z_{H}	– HUT impedance
Z_{S}	– Simulated grid impedance
Z_{SH}	– Linking impedance

PART I – Report

Chapter 1

Introduction

This chapter presents the background and the motivation of PhD thesis, continues with problem formulation, objectives and limitations encountered and ends with the list of the main contributions brought to this project along with a short presentation of the thesis outline.

1.1 Background and motivation

The entire power system suffers severe paradigm changes in its hierarchy and control due to the total cumulative renewable energy installed in the last years causing the lower parts of the grid to become more active.

It is a well-known fact that Photovoltaic (PV) power is predominant on LV side of the power system, but trends and recent ongoing projects show that PV industry moves towards large scale installments having total peak installed capacity of hundreds of MWs.

Until now, PV power had a rapid growth based on the availability of subsidies under different forms of national incentives focusing on the economic benefits which can be obtained from the maximization of the extracted power [1-3].

To increase even more the PV power penetration into the grid means that the entire grid has to become more flexible since the nature of PV power is variable and intermittent. This makes the base motivation for the Transmission System Operators (TSO) to upgrade their requirements and enhance PV systems with more responsibilities that can increase the grid integration and in the same time to enforce the grid in terms of stability, reliability and security of the supply [4, 5].

Recent developments of the Network Codes (NCs) (see Figure 1-1) show an increased interest over the technical requirements of every grid

connected application during transients which means that the NC are evolving, moving their focus from local instabilities (e.g. voltage support in the LV feeders, harmonic compensation, unbalances, flicker, etc.) to grid stabilizing features (e.g. Inertial Response (IR), Primary Frequency Control (PFC), Active Power Reserves (APRs) voltage control, zero Low Voltage Ride Through (LVRT), black start, etc.)[6]

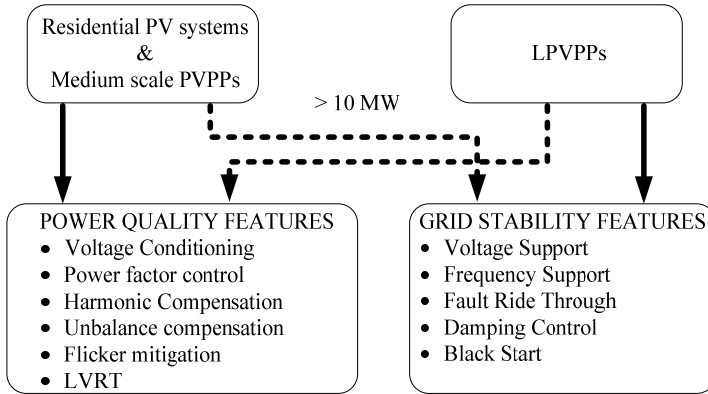


Figure 1-1 Functionalities of grid connected PV systems depending on their level of installed capacity

As a proven fact, European Network of Transmission System Operators for Electricity (ENTSO-E) NCs development starts to require the supply of ancillary services which is a new feature added to the future grid connected medium and Large scale PV Power Plants (LPVPPs). Furthermore, NCs are encouraging plant owners to perform different availability analysis and to start sharing responsibilities such as:

- *System management*: LPVPPs should perform security analysis for forecast improvement, availability analysis in power production and ancillary services; give information about temporary unavailability, to perform according to schedules.
- *Frequency stability*: LPVPPs should contribute to frequency stability with APRs.
- *Voltage stability*: To keep the voltage in the safety limits, LPVPPs should provide reactive power support.
- *System robustness*: LPVPPs have to have a robust operation during grid disturbances.
- *System restoration*: After a disturbance or even blackout LPVPPs have to restore the voltage or to control it if their implementation is technical feasible [7, 8].

1.2 Problem formulation

The PV industry moves towards a mature technology mainly driven by the political strategies of several countries towards fossil fuel free energy production or due to environmental concerns trending it to large scale installations. This accelerated growth of PV power raises technical and economic challenges which have to be overcome by future installments in order to increase the penetration and reach the desired goal.

The fast increase of PV power is noticed also in the development and evolution of NCs since the power mismatches introduced by PV are no longer negligible. Thus, in the beginning, the operation of LPVPPs was permitted in a well-defined deadband, focusing only on the maximization of energy extracted from their primary energy resource. This has now changed and recently more grid support functions are requested and encouraged. A secondary aspect of this evolution is that the attention of TSOs moved from local grid instabilities or power quality concerns towards a more harmonized grid operation in which LPVPPs have more responsibilities.

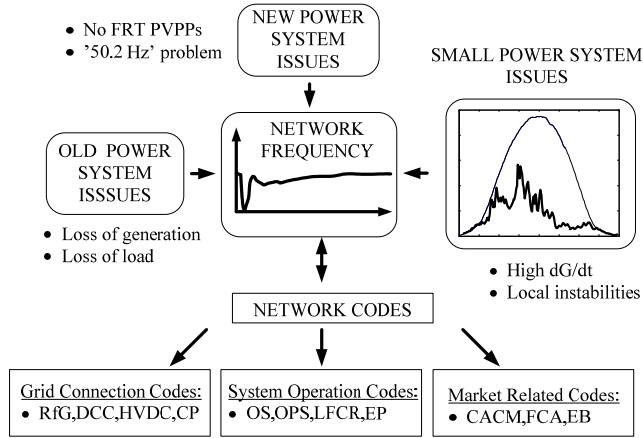


Figure 1-2 Network frequency divided among problems and stabilizing features

LPVPPs with APRs and frequency support functions are becoming a reality in the near future since the grid frequency experiences increased deviations and erosions caused by PV power. Frequency excursions are illustrated in Figure 1-2 and are mainly caused by:

- Old power system issues: loss of generation, loss of load, line tripping

- New power system issues: LPVPPs with no Fault Ride Through (FRT) support, LPVPPs with no retrofitting to new NCs
- Small power system issues: high slopes in irradiance can cause generator tripping in the system.

The aforementioned features are game changers in the PV industry, thus the Maximum Power Point (MPP) mode has to suffer several transformations in order to provide frequency stabilizing characteristics. To be able to accomplish this, LPVPPs have to operate with APRs, a hot topic for:

- LPVPP owners - interested only in maximizing their profit
- TSOs - interested to ensure the security of the power supply without being forced to down regulate and curtail the production
- Energy markets for ancillary services and avoidance of periods with high negative bids.

Downward regulation by means of power curtailment for LPVPPs is not seen as a viable solution because TSOs have to compensate the affected plants for the lost energy, although increases the percentage of hosting capability of the power system for renewable energy. This is necessarily a drawback since the curtailed power can be used in other purposes such as APRs where LPVPPs can participate on the reserve energy markets.

LPVPPs with APRs can be achieved either by adding extra equipment such as batteries - added cost to the initial investments, long maintenance and limited lifetime or by power curtailment - LPVPP provides the reserve directly from its PV panels by operating at a lower point than its MPP. Power curtailment in LPVPPs is seen as an advantage since it reduces the necessity of storage devices avoiding additional costs.

1.3 Project objectives

In accordance with the challenges present in nowadays power system and the immediate need of ancillary services which have to be provided by LPVPPs, the project proposes to have the following objectives:

- Develop a HV grid benchmark (e.g. the Generic IEEE 12 bus system) and evaluate it over a real time platform (RTDS)

- Develop synthetic governor functions in LPVPPs to improve grid stability and share responsibilities with CPP.
- Develop frequency support functions and prove LPVPP can become active players in the power system
- Develop power ramp limitation functions in central inverter based LPVPPs
- Perform availability analysis of internal and auxiliary APRs in LPVPPs
- Develop a fully programmable PHIL test bench for PV applications in order to test the proposed grid support concepts

1.4 Project limitations

In the project development process several limitations had to be considered. Thus, the most important limitations of this project are summed up as it follows:

- The frequency stability studies and the entire modeling of the system was realized in real time domain application and evaluated over RTDS
- The $N - 1$ contingency plan was considered to be the loss of 2 p.u. of active power in one of the generators
- PV penetration levels were considered to be as single large scale units connected in a single HV point of the network.
- Power converters were modeled as average source since switching converter models could not be implemented at a larger scale and would increase the calculation effort.
- To reach the desired penetration levels scaling coefficients were used to increase the installed capacity of LPVPPs
- In the modeling process of PV panels, ageing and partial shadowing effects were neglected since they were not the topic of this research project
- Due to limitation in the installed power of laboratory equipment the LPVPPs were downscaled to a PHIL PV system of 20 kW

1.5 Main contributions

The main contributions of the thesis are listed below:

- A complete overview of most recent NC focused on frequency stabilization features and power ramp capabilities;
- Development of new HV grid benchmark (generic IEEE 12 bus system) implemented over a real time framework (RTDS) with adaptable parameters (e.g. PREPA characteristics);
- Analysis of short-term and mid-term frequency stability based on real time domain and statistical studies of LPVPPs with FSM and IR considering different levels of penetration. The study is performed on a realistic Danish load profile with the n-1 contingency criteria included. The results show the necessity of FSM and IR, in the case of increased PV penetration, and highlights the advantages brought by these ancillary services;
- A control method for limiting power fluctuation in LPVPPs due to high irradiance changes has been proposed. The method smooths out the power mismatches, contributes to NC fulfillment and optimally uses the internal generated APRs;
- Optimal sizing of APRs based on PRL methodology and prioritization of APR deployment between internal APRs and storage units;
- Analysis of APRs availability in LPVPPs provided by curtailment based on central inverter studies;
- Hardware implementation of FSM, IR and PRL control architecture on downscale PHIL 15 kW PV central inverters;
- Real-time evaluation of PHIL LPVPPs with frequency support functions and PRL capabilities over a flexible AC grid test bench with generic IEEE 12 bus system characteristics.

1.6 Thesis outline

The presented work is divided into two parts: PART I – Report and PART II – Publications. PART I sums up the work that has been carried out during the research period, structured in eight chapters and PART II lists all the publications that have been presented in international conferences and journals.

In Chapter I entitled INTRODUCTION, the background and motivation of this research is realized. Moreover, the problem formulation is defined, the objective and limitation of this project are listed, the contributions are emphasized and finally the thesis outline summarizes the structure and content.

Chapter II – GRID SUPPORT WITH LPVPPs – introduces the concept of synthetic governor in LPVPPs a necessary achievement for present and future installments. Compared with the classical use of a governor in synchronous generator-based conventional power plants (CPP), the synthetic governor in LPVPPs has to consider also the irregularities of irradiation and for this issue; APRs are seen as an essential element.

Chapter III – SYSTEM MODELING gives an introduction to the modeling process of the entire system which is composed by a generic IEEE 12 bus system having connected LPVPPs. A brief description with the complete model of the proposed power system is presented in the first part followed up by modeling guidelines which consider both electric and spatial distribution characteristics of power converter based LPVPPs. The chapter ends with a detailed analysis of APR availability in LPVPPs realized by curtailment and their application for different ancillary services requested by the TSO.

Charter IV – MANAGEMENT OF ACTIVE POWER RESERVES IN LPVPPs – presents the APR requirements proposed by the newest ENTSO-E NCs and their technical implementation in PV central inverters. The chapter ends with an availability analysis which gives the opportunity for LPVPPs to further evaluate the time periods in which they could have the maximum impact on the reserves power markets.

Charter V – FREQUENCY SUPPORT IN LPVPPS WITH ACTIVE POWER RESERVES – presents the control architecture of LPVPPs that can provide frequency support functions. Time domain and

statistical analysis are carried out with the main purpose of proving the benefits and to highlight the advantages brought by the supplied ancillary services in case the PV penetration level reaches higher levels.

Chapter VI – RAMPING OBLIGATIONS OF LPVPPS – In this chapter a PRL method is proposed and evaluated. The proposed test cases for the PRL method highlight its flexibility in terms of APR deployment and show a prioritization among multiple APR sources. The proposed PRL method has a predictive nature and leads to optimal sizing of APRs needed to fulfill the ramping requirements. Considering the ramping obligations of LPVPPs in small power systems, the PRL method takes into consideration every smoothing characteristics present in LPVPPs: spatial displacement, curtailment and auxiliary storage.

Chapter VII – EXPERIMENTAL EVALUATION OF A FLEXIBLE AC TEST BENCH – links the advantages of real time domain simulations with the benefits brought by the Power Hardware In the Loop (PHIL) testing and opens the possibility of hardware implementation. Interface algorithms are investigated to bridge the gap between the simulation environment and the flexible AC grid emulated by a linear amplifier. The algorithms are used to improve overall system stability and to be able to safely reproduce every situation present in the nowadays power system. The experimental tests confirm the simulation results and prove the hardware applicability of the proposed LPVPP control structures.

Chapter VIII – CONCLUSIONS – draws the main conclusions of this thesis based on the applied theory, simulation results and experimental data obtained. Furthermore, the ideas for the future work are listed.

PART II of the thesis entitled PUBLICATIONS presents the complete list of articles that were realized and published during this research period.

1.7 List of publications

- I. B-I Craciun, T. Kerekes, D. Sera, R. Teodorescu Overview of recent Grid Codes for PV power integration; Proceedings of 13th International Conference on Optimization of Electrical and

- Electronic Equipment (OPTIM), 2012 Page(s): 959 – 965
- II. B-I Craciun, E. Man, V. Muresan T. Kerekes, D. Sera, R. Teodorescu Improved voltage regulation strategies by PV inverters in LV rural networks; Proceedings of 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG), 2012, Page(s): 775 - 781
 - III. B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, Adrian Timbus, Benchmark Networks for grid integration impact studies of large PV plants, Proceedings of 2nd International Workshop on Integration of Solar into Power Systems, 2012
 - IV. B-I Craciun, S. Spataru, T. Kerekes, D. Sera, R. Teodorescu Power ramp limitation and frequency support in large scale PVPPs without storage, Proceedings of IEEE 39th Photovoltaic Specialists Conference (PVSC), 2013, Page(s): 2354 – 2359
 - V. B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, R. Brandl, T. Degner, D. Geibel, H. Hernandez, Grid integration of PV power based on PHIL testing using different interface algorithms, Proceedings of 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013, Page(s): 5380 – 5385
 - VI. B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, Adrian Timbus, Benchmark Networks for grid integration impact studies of large PV plants, Proceedings of IEEE PowerTech (POWERTECH), 2013, Page(s): 1 - 6
 - VII. B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, U.D. Annakkage, Active power reserves evaluation in large scale PVPPs Proceedings of 3rd International Workshop on Integration of Solar into Power Systems, 2013
 - VIII. B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, Frequency support functions in Large PV Power Plants with Active Power Reserves, IEEE Journal of Emerging and Selected Topics in Power Electronics Special Issue on Modeling and Control of Power Electronics for Renewable Energy and Power Systems, 2014
 - IX. B-I Craciun, Tamas Kerekes, Dezso Sera, Remus Teodorescu, U.D. Annakkage Power Ramp Limitation capabilities of Large PV Power Plants with Active Power Reserves, IEEE Transactions on Sustainable Energy, 2014 (second review)
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Chapter 2

Grid support with LPVPPs

This chapter introduces the concept of synthetic governors in LPVPPs, presents the challenges and particularities of PV power in their implementation and demonstrates the APR necessity in future installations.

The main objective of the system operator is to ensure the system security with a high level of reliability, availability and quality from the transmission level, to distribution and finally down to the end customers situated on the low voltage levels of the network [9].

The security of the system is maintained only if there is a close cooperation between the generating plants, consumers and network operator. Having more installed PV power distributed all over the network and less conventional generation, the security and stability of the system is a primary concern for future power systems.

For this purpose the system operator has to include renewable power in its planning, permitting a better system management. An improved behavior is achieved only if the LPVPP is able to preserve the system stability taking into consideration the issues presented in Figure 2-1.

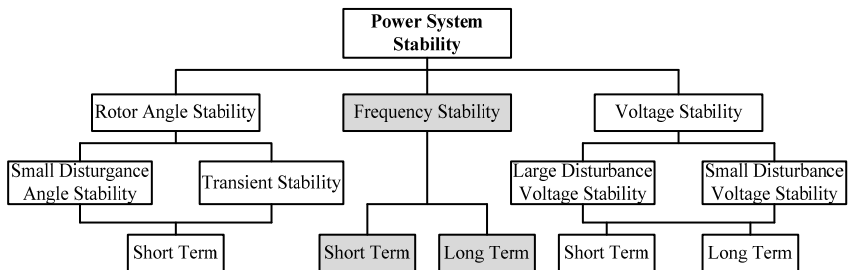


Figure 2-1 Classification of the power system stability [10]

Until now LPVPPs did not have any responsibilities in the operation of the network, because the installed power was seen as negative load and in case the threshold limits of voltage and frequency were exceeded

they were forced to disconnect from the grid.

This changed when the stability of the grid was affected due to sudden disconnection of large amounts of PV power due to specific events in the power system and now the LPVPP have to participate in the stabilization process and provide more than just green energy.

2.1 Synthetic governors in LPVPPs

In a conventional power plant the stable operation of the turbine is obtained by the use of a governing system which regulates the variations encountered in the shaft speed. The governor operates after a power-speed characteristic, changes the valve position (c_{valve}) with its specific time constant (T_G) and regulates the mechanical power fed into the turbine accordingly as shown in Figure 2-2. Consequently, the variations in the electric frequency (Δf) of the network are transduced into active power variations (ΔP) at the output of the generator [11].

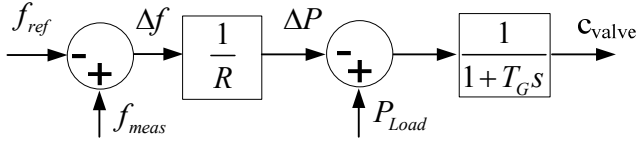


Figure 2-2 Governing system in CPPs

In case of a frequency event in the network, the inertial power stored in the rotational masses is released limiting the nadir of the frequency, followed up by a recovering period which takes a longer period and is taken care of by the governing system (see Figure 2-4). In this period, the APR in the conventional power plant (CPP) is deployed in order to bring the frequency back to its rated value, which means that the plant operator has to increase the fuel consumption (e.g. coal, oil, gas) from its well dimensioned stack supplies [9, 11, 12].

Compared with the classical evaluation towards a CPP, modern power systems start to have LPVPPs as the main suppliers of power which present different supply characteristics depending mainly on the meteorological conditions. Thus, system operators gradually started to demand grid stabilization features that have to be synthetically implemented in the LPVPPs.

The need of ancillary services forced TSOs to demand the Frequency sensitive mode (FSM) – a droop based operation which synthetically reproduces the behavior of a governing system used in a CPP during the frequency regulation process. In consequence, LPVPPs have to be prepared to deploy their APR (curtailed or storage) and have to actively participate in this process.

A more recent concern which is directly related with the nature of the power produced by the LPVPP arises due to the variable and unpredictable nature of the irradiance that produces large power fluctuations in the output of the LPVPP. Thus, the synthetic governor in the LPVPP has to be adapted in order to compensate the mismatches between the produced power and the imposed ramps by the use of APRs. An important advantage of the LPVPP is its spatial distribution over a large area which has a smoothing character and partially facilitates the ramping requirements.

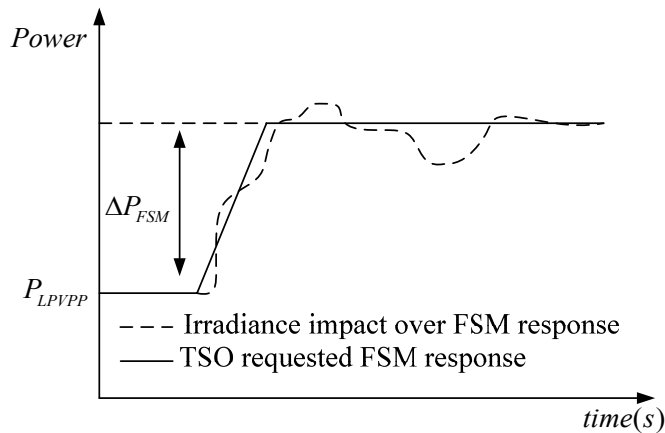


Figure 2-3 LPVPP synthetic governor with FSM and power ramping capabilities

Compared with the conventional governing system where the fuel reserves are able to support changes in the turbine admissions of steam/water dictated by the governor, in LPVPPs the synthetic governor has to share the total APR between two fundamental operations which are situated in the same time range (seconds). The same APR has to be shared during frequency deviations when FSM is activated and in the same time the APR is used to correct the power fluctuations present at the production level of the LPVPP as seen in Figure 2-3.

2.2 Frequency support with LPVPPs

Frequency is one of the fundamental characteristics in a power system and in normal operating conditions has a constant value. A constant frequency value indicates a balance between the generation and consumption but during grid events the frequency experiences deviations.

The frequency starts to experience deviations from its nominal values due to various reasons. The worst scenario is considered to be in case the system experiences loss of significant generation (N-1 contingency plan) and the frequency violates the safety limits affecting the operation of the entire system as shown in Figure 2-4. Another situation when the frequency deviates from its rated value is due to heavy loading that might appear during daily operation causing mismatches between the forecasted and the real power demand [13, 14].

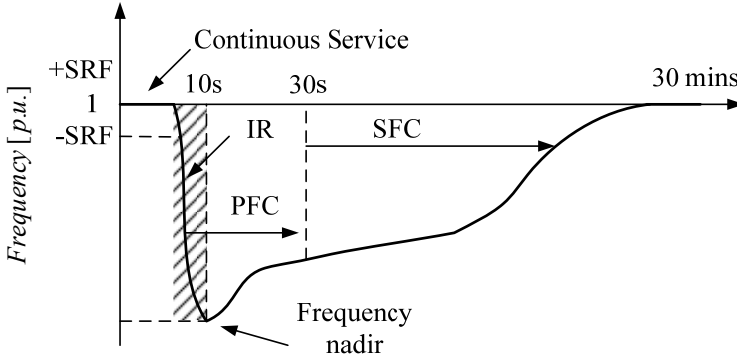


Figure 2-4 Frequency control phases during an event

After an event as shown in Figure 2-4, all the synchronous-based CPPs start to maintain their synchronism and start to release the inertial power. During this stage, the change of the active power at the output of the generator depends on the H and $d\omega/dt$. It can be understood as the time, in seconds, that it would take to replace this stored energy when operating at rated mechanical speed (ω_m) and rated apparent power output (S_{base}). The total system inertia (H_T) includes the combined inertia of most of spinning generation and load connected to the power system [15, 16].

$$H_T = \sum_{i=1}^N H_i ; H_i = \frac{1}{2} \frac{J_i \omega_m^2}{S_{base}} \quad (2.1)$$

A more stringent demand had been noticed recently in the IR in the power system since the penetration levels of renewables especially wind and PV are reducing this damping characteristic. It is well known that PV power is completely interfaced by power electronic converters and doesn't have any rotating masses in the system that can contribute to the systems inertia. Hence, modern solutions showed that IR added to the system had to modify the existing technology and nevertheless had to include supplementary control loops in LPVPPs control architectures in order to synthetically create it and in the same to take into consideration the encouragements provided by the TSOs as shown in Figure 2-5[17].

LPVPP's fast response abilities and fast APR restoration processes without the possibility of complete shutdown, a situation present in large wind power plants, establish them as feasible candidates to provide these fast response frequency support functions.

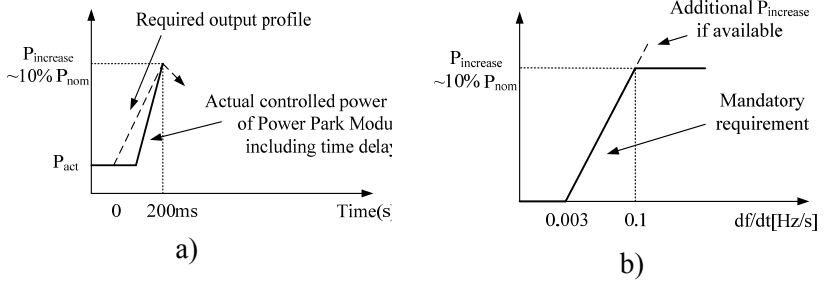


Figure 2-5 IR requirements for large scale renewable power plants: a) Time domain requirements of LPVPPs for IR b) ROCOF requirement and APR deployment [18]

After the generators, including LPVPPs, have concluded the IR phase setting the nadir of the frequency, the recovery phase begins, which means the governors start to change the output power of the participating plants. Depending on a preset dead band, the imbalance is eliminated by the use of a droop characteristic as shown in Figure 2-6 which defines the magnitude of the change in frequency when the output is modified between zero APR and full APR deployment.

Figure 2-7 proves how primary frequency control (PFC) and secondary frequency control (SFC) act on the restoration process of frequency in the system and within the stability regions in case the load demand has increased.

2.3 Power ramping obligations in LPVPPs

Ramp rate control in large scale renewable plants is a mandatory condition in island power systems after the penetration percentages of renewable energy and their intermittent nature started to affect the stability of the system.

Power ramping capabilities in LPVPPs represents a key element in their integration into a small power system since the effect of the changing irradiance and consequently the injected power has to follow up specific ramping requirements. To smooth the fluctuations, LPVPPs have to use mainly upward and downward APRs as shown in Figure 2-8 [19, 20].

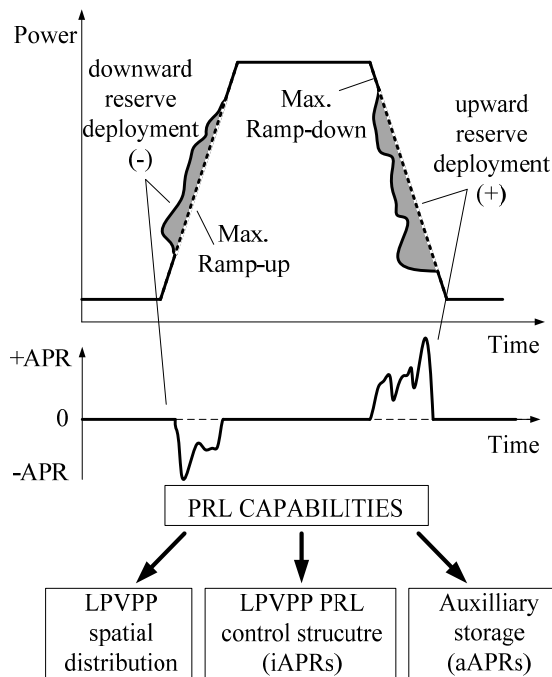


Figure 2-8 Power ramping obligation in LPVPPs

This is achieved taking into consideration several decisive factors as following:

- Plant size and spatial distribution (ha)
- Plant control and curtailment (iAPR)
- Auxiliary storage capacity (aAPR)

The first step is to correct LPVPP characteristics by imposing well-defined production ramps implying that LPVPPs power fluctuations should be initially solved at the production level and not entirely by the participating plants.

To reduce the power fluctuations of LPVPPs (see Figure 2-8), TSOs have imposed mandatory ramp rates transforming LPVPPs from units focused on the maximization of energy extraction into grid participating plants. To accomplish this, plant owners have to reconsider the provision and availability of APRs which fulfill the requirements [21-24].

2.4 Summary

LPVPPs have to become more active since in the near future they have to become a reliable energy source. In this chapter, the concept of synthetic governor in LPVPPs was introduced and several particularities compared with the conventional governor present in the CPP were analyzed.

The synthetic governor main functionality has to be sensitive to frequency changes in the grid deploying upward and downward APRs but in the same time has to consider the active power variation induced by the nature of the irradiance.

Frequency support in terms of IR and FSM along with smoothing characteristics in terms of power ramp rate control are solved by the use of APR which are supplied by curtailment or by auxiliary storage and are considered a main priority in the future development of LPVPPs.

Chapter 3

System description

The chapter presents the entire modeling process of a proposed HV grid having LPVPP as one of the main energy suppliers and is divided in two main parts. The first part presents the modeling and control process of the generic HV IEEE 12 bus system, with a study case of the PREPA power system followed up by the modeling and control of LPVPPs taking into consideration all their specific characteristics.

Trends predict an even larger PV power penetration in the near future and consequently, LPVPPs have to provide more grid support. In this case valid benchmark networks model have to be developed and evaluated in order to investigate the integration process of LPVPP into the grid. This process starts with accurate model development of every component present in the electrical network which can be able to precisely reproduce the behavior of the entire system commencing at the power system level with its characteristics and control architectures down to the inverter level present in the LPVPP.

The proposed benchmark model along with the LPVPP model and its controls are validated and tested on a RTDS platform. The real time platform used proves to meet the necessities in terms of calculation effort and opens the possibility to develop new control structures for recent and future requirements.

3.1 Power system modeling

To perform grid integration studies and to develop future concepts of grid stabilization features in LPVPPs, an appropriate network model has to be selected and used. The chosen grid benchmark is the generic IEEE 12 bus system since the model presents a tradeoff between the

complexity (e.g. IEEE 118 bus system, IEEE 68 bus system) and the limitations encountered in other much simpler proposed multi machine benchmarks (e.g. 9 bus system, 2 area 4 machine system) [12, 25, 26].

3.1.1 Power system model

The layout of the generic IEEE 12-bus system presented in Figure 3-1 shows an isolated 4 area power system in which the generation is divided between thermal and hydro. All the CPPs used in the proposed model rely on the power production of synchronous generators. The rest of CPPs component models which are divided into electrical (e.g. AVR, exciter) and mechanical (e.g. governor, steam turbine, hydro turbine) are presented in Appendix A.

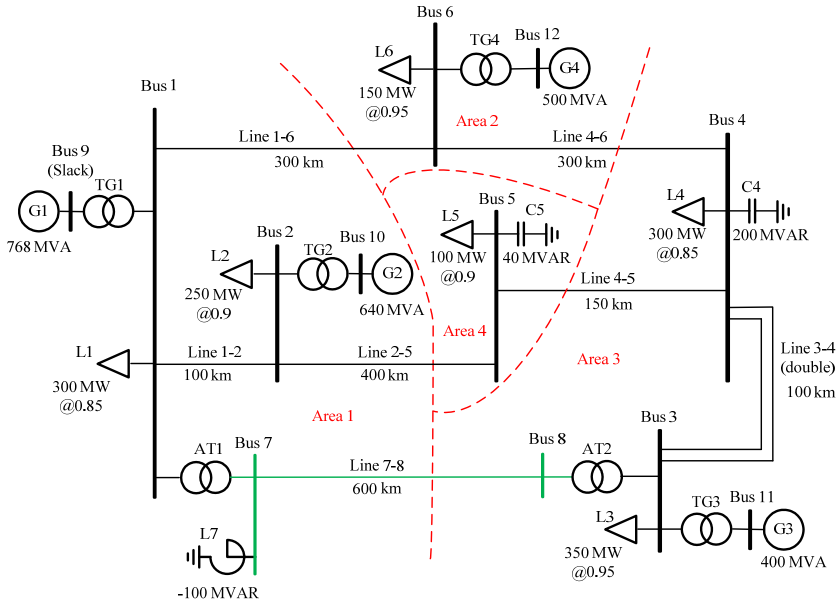


Figure 3-1 Generic IEEE 12-bus system layout (single line diagram)

The generic IEEE 12 bus system proposed benchmark contains:

- Area 1 – has the biggest thermal generation found in the system (generators G1 and G2) with high density load
- Area 2 – has mainly hydro generation (generator G4) and low density load
- Area 3 – has a heavily loaded area and part of the consumption is supplied by a thermal plant (generator G3)
- Area 4 – it is a load area without any local generation

Area 1 has the biggest generation unit (G1) in the system, which makes this CPP to be the reference for the entire system. The generic IEEE 12-bus system is designed to fulfill the N-1 contingency criterion (loss of 200 MW in G2) and the system has to maintain its stability.

In steady state operation, the system frequency has a constant value which means the systems consumption and generation is balanced. The bus voltages are kept within the limits by the AVRs of the generators, along with the use of shunt devices which provide proper reactive power compensation [12, 25, 26].

The generic IEEE 12 bus system offers flexibility in terms of modeling grids with different characteristics since all the components are fully configurable. Furthermore, to adapt the proposed grid benchmark model to a real island power system, several adjustments had to be made.

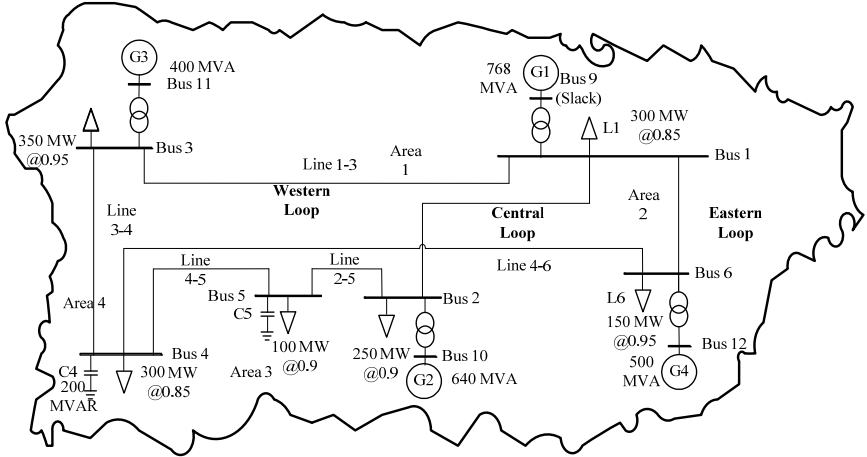


Figure 3-2 Adaptation of the generic IEEE 12 bus system to PREPA power system (single line view)

The chosen power system for these studies is PREPA (see Figure 3-2), since the power level, nature of generation and layout (Western Loop, Central Loop and Eastern Loop) present similar characteristics with the generic IEEE 12 bus system. To adapt the benchmark to PREPA power system model, the following modifications were performed:

- All line lengths were adapted to that of PREPA power system characteristics
- G3 was modified from steam plant (medium response) to gas turbine plant (fast response)
- G4 was modified from hydro plant (fast response) to steam plant (medium response)

- Line 7 – 8 (345 kV in the generic IEEE 12 bus system) has been modified to 230 kV line and the autotransformers and line reactors were removed
- The load on bus 1 was increased since in PREPA is heavy load area[27]

The complete list of the parameters used for the modeling of the generic IEEE 12 bus system is provided in Appendix B.

3.1.2 Power system control architecture

The control objective of the proposed power system control architecture has to maintain the frequency within the limits during operation due to the variability of the load. A more recent concern that has to be added to this matter is the variability and the intermittent nature of PV power since LPVPPs depending on their size and level of penetration in the power system, have the ability to cause considerable mismatches between generation and consumption [11, 28].

To perform integration studies for the proposed grid benchmark, realistic load profiles have to be attached to the system loads. Giving the size of the power system, a Danish load profile from West Denmark power system (DK1) on a winter day was considered as shown in Figure 3-3 [29].

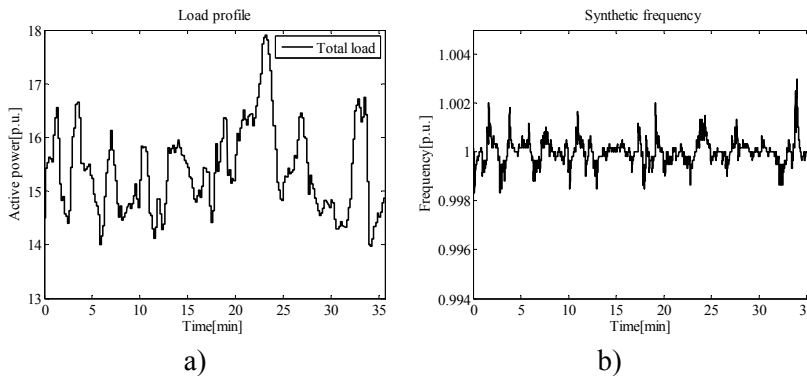


Figure 3-3 The generic IEEE 12 bus system characteristics: a) Selected Danish load profile b) Generated synthetic frequency

The load profile is distributed between all the loads present in the system and the generators along with Automatic Generation Control (AGC) system have to compensate the power mismatches.

The entire procedure, involving the generator dynamics, prime mover

time constants and AGC performance lead to the generation of the synthetic frequency of the system. Furthermore, depending on the PV penetration level into the system the AGC system may suffer several changes.

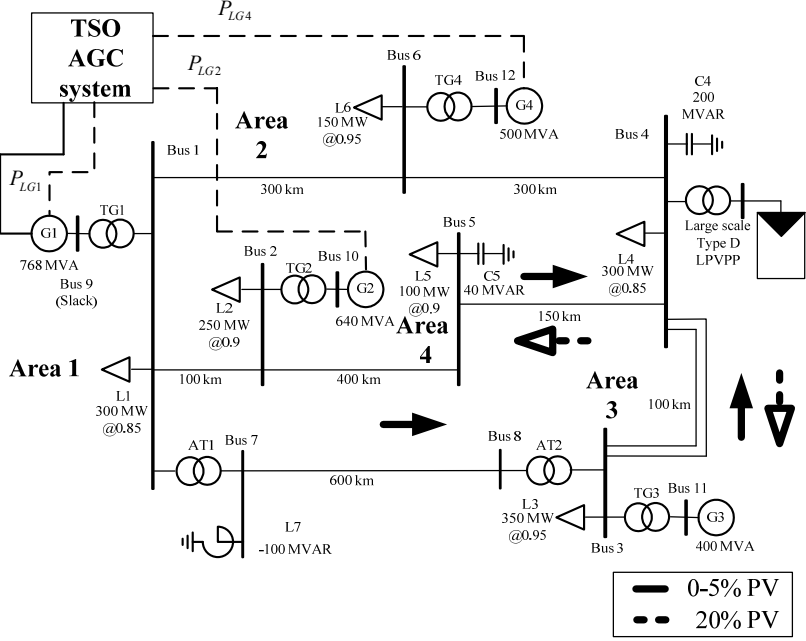


Figure 3-4 AGC changes due to different PV penetration scenarios

Until a certain percentage of penetration ($< 10\%$ PV penetration) the largest generator (G1) was chosen to be responsible of regulating the frequency as expressed in the bellow equation:

$$P_{LG_1}(s) = (f_{ref} - f_{meas}) \cdot \frac{-K_f}{s} \quad (3.1)$$

To increase even more the penetration scenario and to prove the need of ancillary services provided by LPVPPs without increasing the load, the AGC system is modified as shown in Figure 3-5 since several issues appeared:

- G1 reaches the loading limit
- Line loading and reverse power flow into the system

In the AGC system, G2 and G4 were added to participate in the frequency regulation process and they had to share G1 responsibilities according with a decided sharing factor [9, 28].

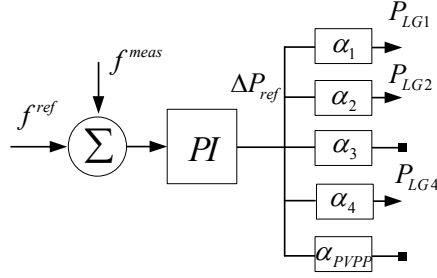


Figure 3-5 AGC changes for the generic IEEE 12 bus system

The complete list of the parameters used for AGC systems for different penetration scenarios are provided in Appendix A.

3.2 LPVPP modeling

The modeling process of LPVPPs starts from the basic statement that the plant has to accurately reproduce the effects induces by the irradiance and temperature in the injected active power. Thus, beside the electric characteristics of power electronic converters that are used to extract the energy and which are dependent on the meteorological conditions, the plant size and its spatial distribution has also a direct impact on the quality of the produced active power.

For this purpose, these two characteristics have to be combined in the modeling process of the LPVPP and have to be taken into consideration in order to develop new control concepts of synthetic governors.

3.2.1 LPVPP model

The design of LPVPPs shown in Figure 3-6 starts from the power production level –the PV panels, which are modeled as current sources sensitive to irradiance and temperature changes, while for the PV central inverters, average voltage sources are used to reproduce their response and to reduce the calculation effort.

The LPVPP layout consists of multiple MV feeders to which central inverter stations are connected and can handle the power extracted from the panels and through a MV/HV transformer, inject the produced power

into the HV grid [30]. A complete list of the parameters used in the LPVPP modeling process can be found in Appendix B.

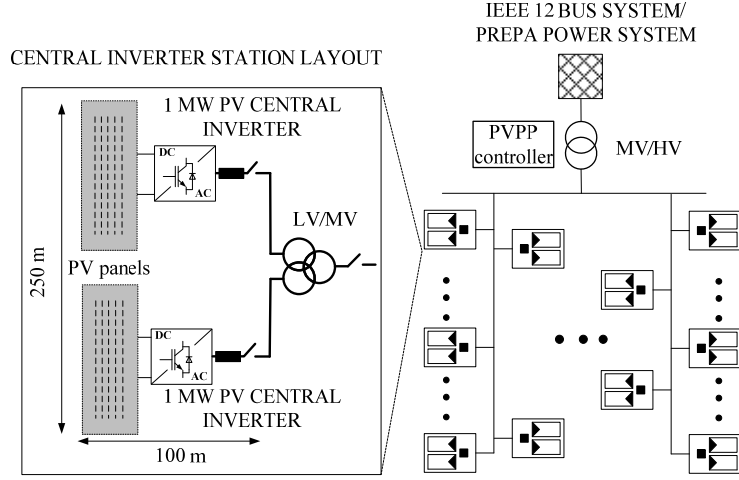


Figure 3-6 Layout of LPVPPs with central inverter stations (single line diagram)

The design procedure of the LPVPPs has to consider the filtering effect caused by its spatial distribution. A direct consequence of LPVPPs smoothing effect is that it has the ability to reduce the output power fluctuations since the fast changing conditions of irradiance is moderated by the entire area of the LPVPP. The filtering effect brought by LPVPPs spatial distribution, beginning from the irradiance change and ending with the power injected into the grid can be expressed as the following transfer function [21, 23, 31]:

$$\frac{P_{LPVPP}(s)}{G(s)} = \frac{N_{PV\ inv}}{1 + \tau_{filtering}(\sqrt{A}) \cdot s} \quad (3.2)$$

where,

P_{LPVPP} – The active power produced by the LPVPP

G – The irradiance present at the PV panel side of the LPVPP

N – The scaling factor of the plant, proportional with the number of central inverter stations

$\tau_{filtering}$ – The time constant in filtering effect brought by LPVPPs spatial distribution

A – Area covered by the entire LPVPP

Giving the size, type and penetration scenario into the proposed HV grid benchmark, the response times induced by their spatial distribution are presented in the table below.

Table 3-1 LPVPPs evaluation based on plant type, size and penetration scenario

Penetration scenario [%]	ENTSO-E Plant Type	Plant Size [MW]	Spatial Distrib. [ha]	Filtering effect τ_{LPVPP} [s]
3	Type C	60	165	102.2
5	Type D	100	275	132
10	Type D	200	550	186.6
15	Type D	300	825	228.6
20	Type D	400	1100	239.9

3.2.2 LPVPP control architecture

The LPVPP control objective is to provide the plant with protection, to guarantee maximum energy extraction from the primary energy resource and in the same time to provide the grid support functions. For these purposes the LPVPP control architecture has to be divided mainly in two separate layers:

- Central inverter control handling local functionalities (e.g. grid synchronization, current regulation, maximization of energy extraction, iAPR generation, etc.)
- Centralized LPVPP control providing grid support functionalities and performing system management actions (e.g. provision of ancillary services, references for central inverter units, APR management, cooperation with TSO, etc.)

The central inverter control presented in Figure 3-7 and Figure 3-8 uses proportional resonant controllers for regulating the current in the stationary reference frame (i_α and i_β reference frame) and proportional integrator controllers for the outer loops which are responsible with the control of active and reactive power. Using the inverse matrix applied in the instantaneous power theory, the link between the two control loops is successfully realized. Moreover, the local functionality presented in Figure 3-7 of the central inverter controller is to maximize PV power extraction (P_{MPP}) and in the same time to fulfill the APR requirement (ΔP) [32, 33].

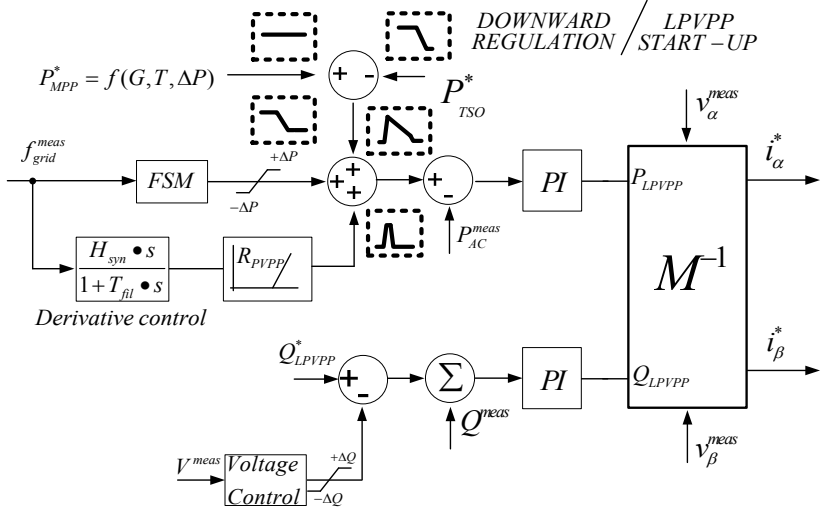


Figure 3-7 Implementation of control layers in PV central inverters

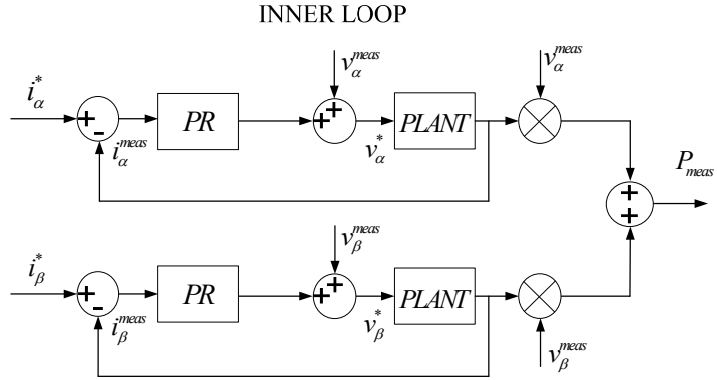


Figure 3-8 Inner loop control structure in PV central inverters

LPVPP control represent the highest level in the control hierarchy, meaning that the plant controller has to take the responsibilities of dividing the active and reactive power references (P_{LPVPP} and Q_{LPVPP}) needed for ancillary service (FSM power, IR power, PRL power), forward the downward regulation procedure down to the central inverter station (P_{TSO}) and most important has to perform system APR management for all central inverter station, to guarantee a secure APR deployment at the PCC during frequency events(f_{meas}).

3.3 Summary

In this chapter, the description of the modeling phase of the entire system has been performed. The entire system can be roughly divided into two parts:

- Modeling and control of the power system
- Modeling and control of LPVPPs

The development of the proposed power system model is realized by using the generic IEEE 12 bus system; which can accurately reproduce the behavior of a realistic power system and facilitates the development of realistic grid integration studies of LPVPPs for different PV penetration scenarios.

The opportunity to add the AGC system on top of the grid benchmark opened the possibility of performing both short-term and midterm frequency analysis. By applying realistic load profiles to the system (e.g. DK1 load profile), synthetic grid frequencies can be obtained and evaluated with the main purpose of proving the necessity of ancillary services from LPVPPs in case the penetration reaches high levels.

The second part of the chapter presents the modeling procedure of LPVPPs and takes into consideration their electrical characteristics along with the spatial distribution features created by their size.

The proposed models of HV grid and LPVPPs are valuable assets that can be used to develop new concept of synthetic governors applied to LPVPPs.

The entire system has been modeled, tested and validate over the RTDS platform, a tool that offers great advantages in terms of flexibility and calculation effort [26]. Moreover, RTDS open the possibility for PHIL testing which means that the proposed models can be implemented in laboratory facilities.

Chapter 4

Management of active power reserves in LPVPPs

The chapter focuses on a technical evaluation of internal generated APRs in central inverter-based LPVPPs. The study involves a DC voltage sensitivity analysis which targets to improve the operation of the power electronics converters supplying iAPRs and combines it with an availability analysis which shows LPVPP potential participation on the reserve power market.

To provide frequency and ramp rate support, LPVPPs need to have APRs that can be supplied from storage or by curtailment.

LPVPPs with internal generated APRs providing the aforementioned services are limited by the condition of their primary energy resource but they can have a positive impact over the auxiliary storage demand. The added storage to the system increases the cost of the total installment but removes part of inconveniences created by the nature of the irradiation and has the potential to increase the security of the provided reserve.

4.1 APR requirements

Having APRs generated internally represents a much simpler and cheaper solution compared with the auxiliary storage solution which means that the entire plant has to operate under its MPP. This proves to be a challenging task since all plant owners want to avoid this in order to get the maximum economic benefit.

On the other hand, TSOs are starting to demand more grid support from LPVPPs in order to improve the quality of the frequency

parameters (see Figure 4-1) which means that TSOs have to manage all power imbalances and have to guarantee that the corresponding area in which the LPVPP is connected has to share and ensure a part of the requested APR.

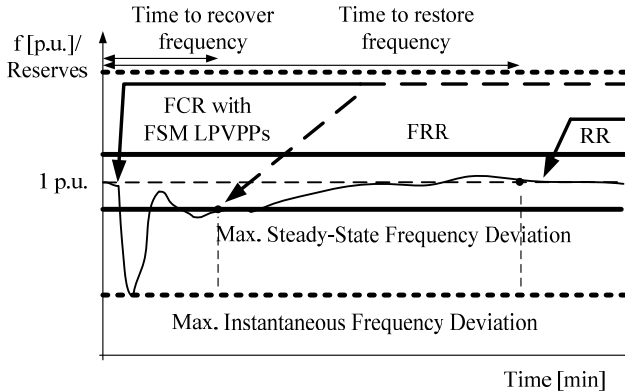


Figure 4-1 LPVPPs with APRs during network frequency event

This is achieved by determining the exact amounts of reserves needed for the specific area, to distribute the reserves among the units which are participating in the frequency support and in the end to organize the availability. A necessary condition in reserve dimension is considered to be a good cooperation between the TSO and the participating units.

Knowing the nature of the LPVPP and the fact that are fully interfaced by power electronic converters, these characteristics offer them net advantages in terms of fast response times and establishes them as suitable candidates for ancillary services such as inertial response and to participate with Frequency Containment Reserves (FCR) in the process of primary frequency control as shown in Figure 4-1 [34].

4.2 Internal generated APRs

In the LPVPPs layout, single stage central PV inverters are used to process the power and are directly connected at the DC output of the panels. The PV power along with the magnitude of the DC voltage processed by the converter depend on the type and the configuration of the panels, thus an equivalent characteristic of the system is obtained (see Figure 4-2).

Depending on the MPPT algorithm used to extract the maximum power (P_{MPP}) by controlling the DC voltage at the input of the converter (V_{MPP}), the PV panels produce a power directly proportional with the present condition of irradiance and temperature.

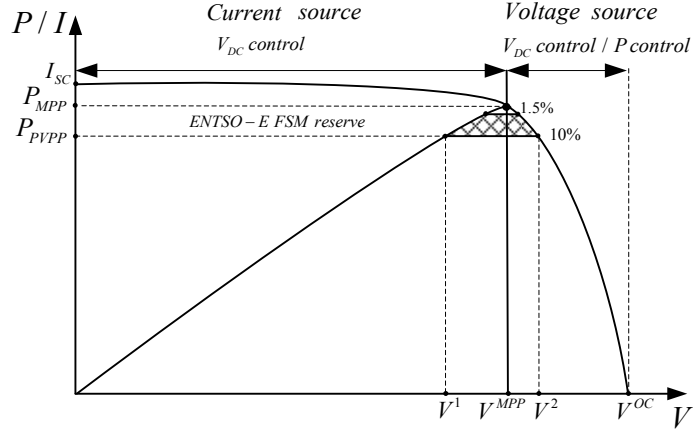


Figure 4-2 P-V curve profile of central inverters with APRs

To provide APR demanded by ENTSO-E NCs (between 1.5%-10% from P_{max}/P_{MPP}) for ancillary services such as the FSM, without involving any other auxiliary storage devices, the LPVPP system operator has to generate them internally by dividing the total APR requirements among the total number of central inverters in the plant. The iAPR can be produced in two ways [35]:

- To set the DC voltage reference of the central inverter below the MPP voltage of the PV panels (V_1). The set DC voltage forces the panels to act as a current source with the major disadvantage that during high slope irradiance conditions, the produced current and the deployment of APR for different ancillary services (FSM and PRL) can cause the DC voltage to experience large fluctuations and even converter tripping.
- To set the DC voltage reference of the central inverter above the MPP voltage of the PV panels (V_2). The set DC voltage reference gives the opportunity to operate the PV panels as voltage sources without inducing large fluctuations in the DC voltage during APR deployment. Operating at higher voltages than the V_{MPP} opens the possibility of controlling the panels directly in power and in this case the DC voltage becomes an intrinsic characteristic.

The evaluation and deployment of iAPRs was conducted on two different grid support services that compose the synthetic governor functionality delivered by the LPVPP.

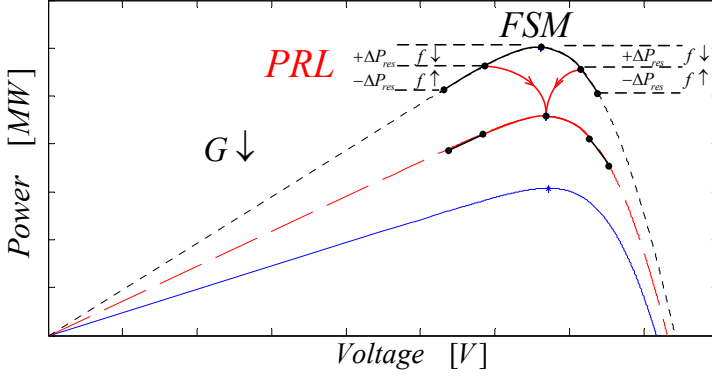


Figure 4-3 P-V characteristics and APR deployment of central inverters during frequency changes (FSM) and high irradiance slopes (PRL)

To evaluate the iAPR deployment during frequency deviations, the first study concentrated over the FSM operation (see Figure 4-3). At constant irradiation FSM central inverters adjust their output power in accordance with nature of the frequency disturbance modifying the value of the DC voltage. Moreover, with the PRL service activate, meaning the panels are experiencing high slopes of irradiance, the DC voltage experiences high fluctuations in case the central inverter operate at a DC voltage below MPP conditions. In other words during frequency and irradiance changes while the central inverter's output power has to increase, also the DC voltage level has to increase which means it needs an increased current to maintain the reference and consequently introduces a higher stress over the synthetic governor controls [35].

The added stress can be avoided in case the converter operates at a higher DC voltage than the MPP conditions and the converter is able to deploy the APR in a more straight forward manner decreasing its DC voltage until it reaches the MPP conditions. Thus, performing at an increased DC voltage increases the stability of the converter and avoids the possibility of converter tripping.

4.3 PV central inverter technical analysis

To have a better understanding and to decide between the available solutions for iAPR generation, a technical analysis of the central inverter has to be made in terms of losses, efficiency, active power sensitivity analysis and DC capacitor energy storage evaluation during constant power production [35].

The technical analysis for iAPR generation was conducted under ENTSO-E FSM requirements and APR supply conditions. Thus, the analysis was made for different APR levels (ΔP_{res}) and in order to simplify the calculation and to ignore mainly the ageing effect of the PV panels, the Standard Test Conditions (STC) conditions at steady state were chosen. As presented in Figure 4-3 the iAPR can be delivered in both ways and the results for the technical analysis of the converter can be examined in the below table.

Table 4-1 Converter studies for different APR conditions

V_{DC}	ΔV	I_{DC}	I_{AC} RMS	Duty cycle peak value	η	iAPR	s
V	V	kA	A	pu	%	%	MW/V
669	105	1,350	336	1.04	98.38	10	-0,0009
693	81	1,348	346	1.00	98.39	7	-0,0008
709	65	1,345	354	0.98	98.40	5	-0,0007
737	37	1,335	365	0.95	98.40	2	-0,0005
774	0	1,296	371	0.91	98.41	MPP	0
805	31	1,222	362	0.87	98.43	2	0,0006
821	47	1,161	351	0.86	98.44	5	0,0010
829	55	1,126	344	0.85	98.41	7	0,0012
839	65	1,076	332	0.84	98.35	10	0,0015

Analyzing the converter in decreased DC voltage operation, the P-V characteristic starts to move towards a constant current operation and decrease in the efficiency of the converter is encountered given the fact that the conduction losses in the converter are directly proportional with the injected current.

Operating at a higher DC voltage, the PV panels act as current controlled voltage sources, slightly increasing the efficiency of the entire

system. In such conditions the converter experiences a decrease in the duty cycle giving the fact that the duty cycle is directly related with the value of the DC voltage. It is worth mentioning that in the steady state conditions, for almost the same voltage difference (ΔV) a double amount of iAPR is generated in case the converter operates at a higher DC voltage.

The converter technical analysis is continued by the active power sensitivity analysis for both operation scenarios. The sensitivity analysis focuses on the contribution of the DC voltage level to the energy stored in the DC capacitor related with the amount of iAPR needed for FSM operation. The sensitivity analysis is expressed as:

$$s = \frac{\Delta iAPR - \Delta P_{DCcap}}{|\Delta V_{DC}|} \quad (4.1)$$

From Table 4-1 it can be remarked that by operating at a lower DC voltage the converter decreases its sensitivity and proves once again that during transient states when the irradiation or the frequency changes the converter has to recover the energy difference stored in the capacitor created by large DC voltage fluctuations. The operation of the central inverter in such conditions shows that the converter has to support a higher energy effort while for DC voltages above the MPP conditions the reserve of energy stored in the capacitor is naturally released improving its operation [35].

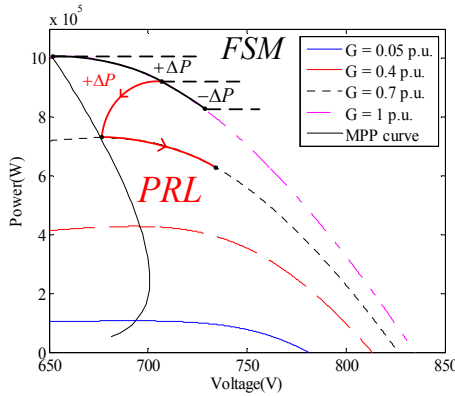


Figure 4-4 Central inverter operation at increased DC voltage level for iAPR generation and its deployment during FSM and PRL request

It can be concluded that operating at an increased DC voltage level as shown in Figure 4-4 the central inverter increases its flexibility and gains more benefits in terms of iAPR generation and deployment

consequently improving its performance and efficiency. A complete table with the technical specification can be found in Appendix C

4.4 Availability analysis of iAPRs in LVPPs

In case LPVPPs participate in the total FCR capacity, they have to overcome a fundamental system planning issue of proper APR allocation which implies a trade-off between:

- Low amount APRs and low FSM participation
- High amount of APRs and excessive increase of costs due to added storage or high energy losses created by curtailment

Compared with the CPPs, LPVPPs are strongly dependent on the nature of their primary energy resource. This dependency proves that LPVPPs are energy-limited sources, but in several meteorological conditions their operation can be associated with the supply iAPRs and can become appropriate candidates to supply short-term and midterm ancillary services such as FSM and IR. This capability is once again accentuated by the fact that LPVPPs have only electro-magnetic constants in the system, fully operated by power converters giving them a net advantage in matters of time response [35].

The evaluation of iAPRs in LPVPPs without any support from storage units has to take into consideration two different scenarios based on the irradiance profile evolution. The characteristics presented in Figure 4-5a show two days with different irradiation profiles which have a direct impact over the power production and the supply of iAPRs. From this point of view it can be stated that LPVPPs participating in frequency support with iAPRs have to rely mostly on the weather conditions and especially on the weather forecast, in order for maximize the time period in which the above mentioned ancillary services are provided [36].

The supply of ancillary services with LPVPPs is also affected by the quantity of the iAPRs and the time frame in which it is supplied. In this case a 10% of iAPRs from the available maximum power production was considered giving the fact that it is the upper limit permitted by the ENTSO-E NCs.

The duration curve presented in Figure 4-5b shows that the highest participation factor with iAPRs is realized during days with favorable weather conditions. The amount of iAPRs has to be delivered in accordance with the time period corresponding with the time frame imposed by the energy market for ancillary services and with the minimum threshold of reserve allowed by the NCs [37].

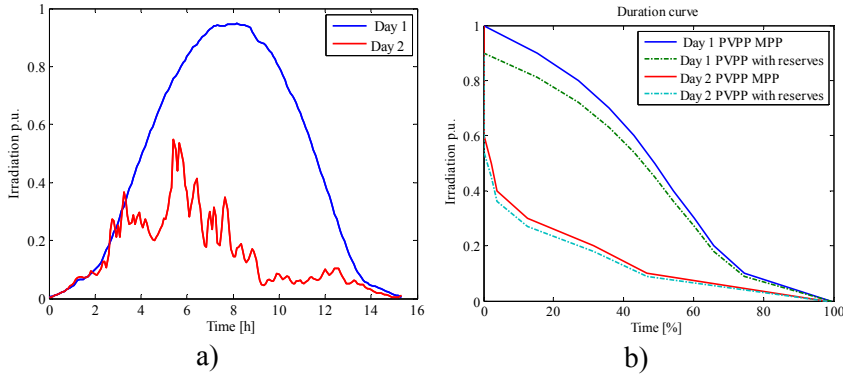


Figure 4-5 Availability of energy production: a) irradiation profile b) duration curves and the availability of 10 % of reserves

4.5 Summary

The APR demand for LPVPPs becomes a necessity in order to increase the percentage levels of penetration into the grid. In consequence, plant owners have to manage their development either by curtailment either by adding extra equipment to the LPVPP.

This chapter analyzes the APR management in LPVPPs by curtailment and their implementation in central inverters. The technical analysis of iAPR performed on the central inverter units shows that iAPRs implementation has a better approach for voltages higher than the MPP voltage where the converter gains more flexibility, manages to deploy it during transients without the possibility of tripping due to high slopes irradiance.

Another aspect treated in this chapter consists on the availability of the APR which is highly dependent on the meteorological conditions. To have a secure iAPR with such dynamic character and to be able to participate on the reserve power market, forecasting and cloud prediction algorithm would have decisive impact over the reliability of the iAPR.

Chapter 5

Frequency support in LPVPPs with active power reserves

This chapter investigates the impact of LPVPPs supplying mandatory FSM enhanced with high sensitivity IR over the frequency quality parameters. Therefore, a time domain evaluation combined with a statistical analysis of the generated synthetic frequency is performed in order to prove the short term and midterm benefits brought by the added ancillary services.

Load variability, a classical power system concern, along with variability of PV power, a modern power system concern, adds up even more the stress on the CPPs which are used by the TSOs to cover up the mismatches between generation and consumption. In consequence, the need for ancillary services can no longer be neglected and TSOs start to request more grid support and more responsibilities from LPVPPs.

The decentralized power production by means of LPVPPs implies a strong TSO process of grid reinforcement, but sharing the responsibilities, part of the extra costs can be saved. Therefore, grid support functions such as frequency control become a topic of interest in LPVPPs since several frequency triggering effects generated by the total installed capacity of PV power has showed that this energy resource has the potential to create frequency instabilities [1].

5.1 Network requirements

TSOs moved their focus towards the entire grid stability and its harmonization with renewable power, therefore they started to consider LPVPPs and their potential to offer grid stabilization features. In consequence, NCs for frequency support developed by ENTSO-E show

an outstanding resemblance with the classical governor actions in CPPs. This means, the TSOs target is to synthetically enforce LPVPPs with frequency support functions such as the FSM operation. To be able to fully implement FSM in LPVPPs as shown in Figure 5-1a, LPVPPs need to have upward and downward APRs.

Giving the droop-based character (s_1 and s_2) of FSM, LPVPPs have to deploy their iAPR (ΔP_1) based on their available power (P_{\max}) and considering the nature of the frequency disturbance (Δf_1). The entire FSM service has to start no later than 2 seconds (t_1) after the fault occurred and has to be fully activated in 15 seconds (t_2) as shown in Figure 5-1b.

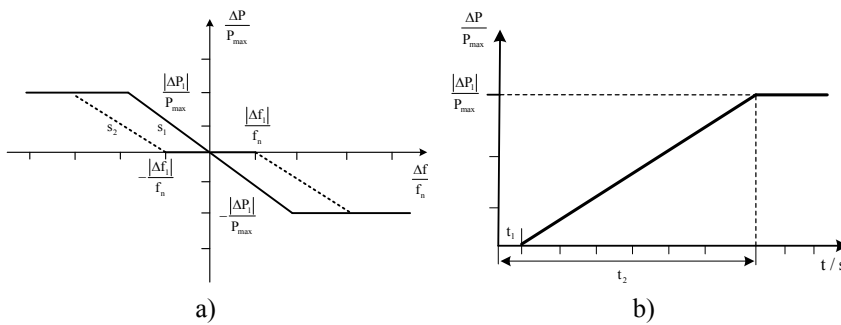


Figure 5-1 ENTSO-E requirements for FSM operation of LPVPPs; a) iAPR deployment b) LPVPP FSM time response [6, 7]

Another ancillary service which is highly encouraged by the TSO to which LPVPPs are seen as valid candidates is the supply of IR. Although this service is only recommended by ENTSO-E, other countries have proposed requirements of operation for large scale renewable plants in terms of synthetic inertia linked with their operation. The requirements can be observed in Table 5-1. Moreover, the concern for frequency stability made ENTSO-E define frequency quality parameters which are listed in Table 5-2.

Table 5-1 IR requirements in different countries

REE Spain	Encouraged df/dt (no requirement)
Hydro Quebec	Equivalent response as provided by a synchronous machine with a inertia constant, $H=3.5$ s
UK	A current draft suggest a primary control with +10 % APR deployment over 5 s, and 1 s max delay time
Denmark	Similar to Hydro Quebec
ENTSO-E NC	The TSO shall have the right to require an equivalent delivery related to the rate of change of frequency

Table 5-2 ENTSO-E NC for frequency quality parameters

	Baltic	CE	GB	IRE
Nominal Frequency	1 pu	1 pu	1 pu	1 pu
Standard Freq. Range	± 0.001 pu	± 0.001 pu	± 0.004 pu	± 0.004 pu
Max. Instant. Freq. Deviation	0.016 pu	0.016 pu	0.016 pu	0.02 pu
Max. steady state Freq. Deviation	0.004 pu	0.004 pu	0.01 pu	0.01 pu
Time to Recover Freq.	not def.	not def.	1 min	1 min
Freq. Range Within Time To Rec. Freq.	not def.	not def.	± 0.01 pu	± 0.01 pu
Time To Restore Freq.	15 min	15 min	10 min	20 min
Freq. Range Within Time To Res. Freq.	not def.	not app.	± 0.004 pu	± 0.004 pu

Beside the technical requirements for short term frequency response of LPVPPs, ENTSO-E NCs have shown an increased interest in the complete analysis and evaluation of frequency. The NCs proposed a statistic evaluation of the measured frequency by means of: mean value, standard frequency deviation, percentiles and time outside the Standard Frequency Range (SFR). The purpose of these parameters is to investigate the mid and long term frequency stability, to observe the impact of ancillary services provided by LPVPPs and to have the opportunity to require in advance more frequency support from LPVPPs in case the targets for frequency quality parameters are not met.

5.2 Synthetic frequency support with LPVPPs

The synthetic frequency generated by the proposed power system benchmark model is subject to LPVPPs which can provide synthetic governor functions. To provide these functions, the central inverters in the LPVPP have to consider the time response encounter during the supply of these services. Giving the fact that frequency support functions are placed in the seconds range, the contribution of the LPVPP to these

services is realized in the outer loop control architecture of the central PV inverter used in the plant (see Figure 5-2). Thus, the central inverter outer loop control architecture is as it follows:

- The active power produced by the PV panels highly depends on the meteorological conditions along with the amount of APRs that have to be supplied from curtailment;
- The downward regulation power imposed by the TSO;
- Start-up procedures imposed by the plant operator;
- To supply ancillary services during frequency disturbance: FSM – mandatory requirement and IR – encouraged requirement but with high sensitivity (no deadband) even to light load changes;

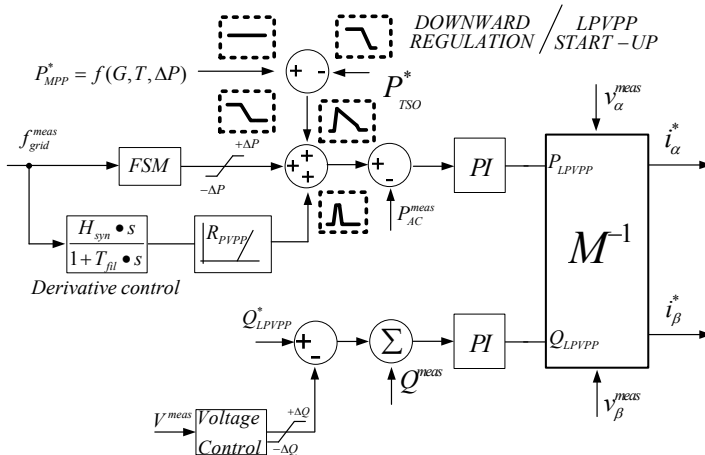


Figure 5-2 LPVPP central inverter control architecture - frequency sensitive synthetic governor concept

A. LPVPPs with FSM

The rated power of a central inverter used in the LPVPP is 1 MW and to provide FSM, the iAPR percentage is realized by curtailment from its MPP. The APR is dynamically calculated depending on the meteorological conditions and the amount of reserve required by the TSO (see eq.(4.2),(4.3) and(4.4)).

$$P_{mpp}(G,T)=I_{MPP}(G,T)\cdot V_{MPP}(G,T) \quad (4.2)$$

$$P_{pvp}(G,T)=P_{MPP}(G,T)-\Delta P_{FSM}(\%) \quad (4.3)$$

$$\Delta P_{FSM} = (P_{mpp}(G, T) - P_{pvpp}(G, T, \Delta P)) \cdot \frac{f_N - f_{meas}}{\Delta f_{FSM}} \cdot R_{FSM} \quad (4.4)$$

The FSM implemented in the control structure of the inverters fulfills the requirements proposed by ENTSO-E based on the frequency

measurements delivered by the TSO or based on the PCC measurements. The LPVPP releases its dynamic APR in the permitted range of $R_{FSM} = 2 - 12\%$ taking also into consideration the set frequency band of operation Δf_{FSM} . In other words, the FSM operation symbolizes the first part of the proposed synthetic governor (sensitive to frequency changes) which recently became a mandatory requirement for LPVPPs.

B. LPVPPs with IR

To complete the FSM operation and to have a better iAPR usage the, IR is added to the central inverter control architecture. The control structure chosen for the IR in LPVPP is based on the derivative control (see Figure 5-2) which has the purpose to determine the Rate of Change of Frequency (ROCOF) during normal operation and especially during events [38, 39].

The IR delivered by LPVPPs with APRs can be expressed as:

$$\Delta P_{IR} = -2H_{syn} \cdot f \cdot \frac{df}{dt} \quad (4.5)$$

The iAPR deployment takes into consideration the following aspects:

- T_{fil} – a low pass filter is used to filter the noise from the measured frequency data
- H_{syn} – synthetic inertia constant equivalent to a synchronous generator.
- R_{PVPP} – rate of change of iAPR delivered by LPVPP imposed usually by NCs.

During frequency deviations the maximum IR released by the LPVPP depends on the available iAPR and limited by the FSM response. The available iAPR used by the IR can be expressed as:

$$\Delta P_{IRmax} = \Delta P_{FSM} \cdot \left(1 - \frac{f_N - f_{meas}}{\Delta f_{FSM}} \cdot s\right) \cdot (-2H \cdot f_{meas} \cdot \frac{df_{meas}}{dt}) \quad [pu] \quad (4.6)$$

available reserve after FSM scaling factor

$$\Delta P_{IRmax} = (k_1 k_2 f_{meas} - k_1 k_3 f_{meas}^2) \cdot \left(\frac{df_{meas}}{dt}\right) \quad [pu] \quad (4.7)$$

where,

$$k_1 = \frac{\Delta P_{FSM} \cdot (-2H)}{\Delta f_{FSM}} \quad , \quad k_2 = \Delta f_{FSM} - f_N \cdot k_3 \quad , \quad k_3 = R_{FSM} ;$$

Eq. (4.6) and (4.7) show that IR power is depending on the linear nature of the droop based FSM operation and the maximum available iAPR. IR has a nonlinear character depending on the ROCOF which transforms it into an impulse power ancillary service.

5.2.1 Short-term synthetic frequency analysis

To evaluate the improvement brought by LPVPPs supplying frequency based ancillary services, a 20 % penetration scenario was chosen which means that the LPVPP installed capacity was of 4 p.u. at a system base value of 100 MVA. The tests were performed at a constant power production, LPVPPs having 10% iAPRs and the generated synthetic frequency (see Figure 5-3) was evaluated under two different cases: light load step and generator event.

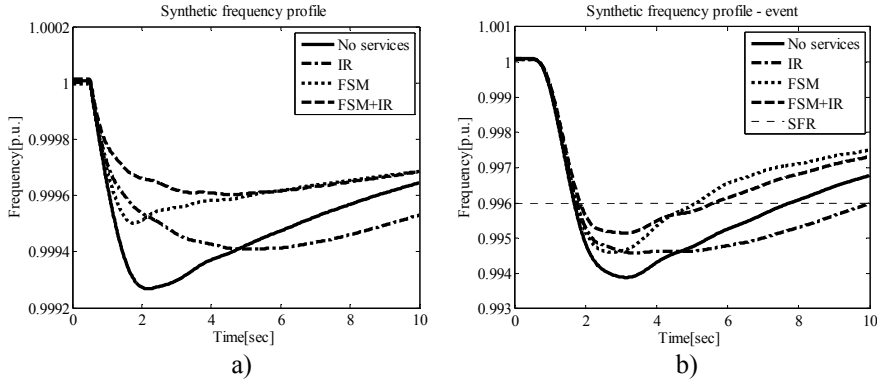


Figure 5-3 Short term evaluation: a) synthetic frequency - light load step b) synthetic frequency - frequency event

In the first case (see Figure 5-3a), the results show a frequency snapshot during a normal load step when the frequency experiences small deviations but remains within the SFR. The generated synthetic frequency presents different profile characteristics depending on the services provided by the LPVPP.

It can be noticed that an enhanced response is achieved only in case FSM and IR are used together since both services are targeting different characteristics during frequency excursions. Using IR with high sensitivity enables the possibility for LPVPPs to respond to light loading conditions of the network, thus in these conditions the LPVPP can cover a wider range of disturbances and responds in the same way a CPP does.

In the second case, the generic IEEE 12 bus system is subject to a frequency event (loss of 200 MW in G2) only this time the generated synthetic frequency exceeds the SFR (see Figure 5-3b). It can be seen that LPVPPs with IR and FSM services have an improved impact over the network frequency since IR releases the inertial energy pulse, reduces the ROCOF and the frequency nadir while the synthetic governor action of FSM operation contributes to the frequency recovery.

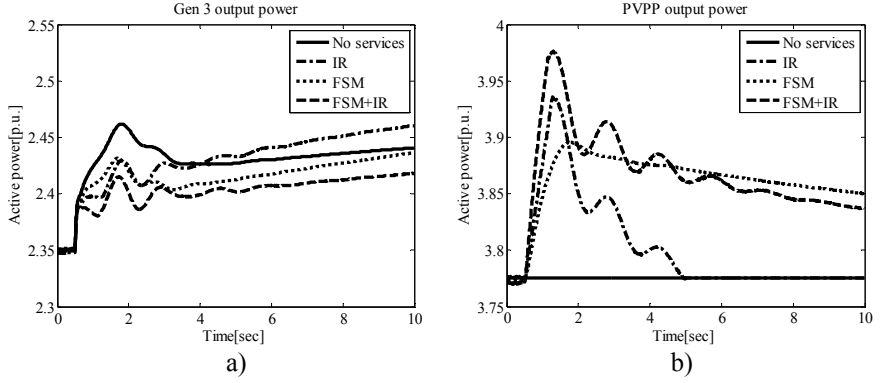


Figure 5-4 Time domain evaluation of the generating: a) LPVPP response with different frequency support functions activated b) G3 output power response during frequency event

Figure 5-4a presents the behavior of G3, a thermal plant, during a frequency event. It can be noticed that once again LPVPPs with FSM and IR services (see Figure 5-4) have a better impact over the output power of a participating generator. LPVPPs with IR reduce the IR stress over G3 while the FSM decreases the active power demand during frequency recovery. This proves once more that LPVPP with frequency support functions are valuable assets and can successfully share part of the responsibilities with the CPPs.

5.2.2 Mid-term synthetic frequency analysis

The mid-term evaluation of the synthetic frequency implies to observe the impact of LPVPPs with frequency support functions over longer period ranges (minutes). The load profile and AGC system presented in Figure 3-3 a and Figure 3-5 forces the participating CPPs in the grid to cover the power mismatches in order to keep the system at its rated frequency as seen in Figure 5-5.

Depending on the penetration level of PV power concentrated into LPVPPs (e.g. 5 % and 20%), the AGC system is modified, thus the generation profiles of all generators change as shown in Figure 5-6. LPVPPs with an installed power corresponding with 5% of penetration (1 p.u. installed capacity) are not equipped with any frequency support function since the power level and impact of ancillary services have a reduced effect and G1 (see Figure 5-6a).

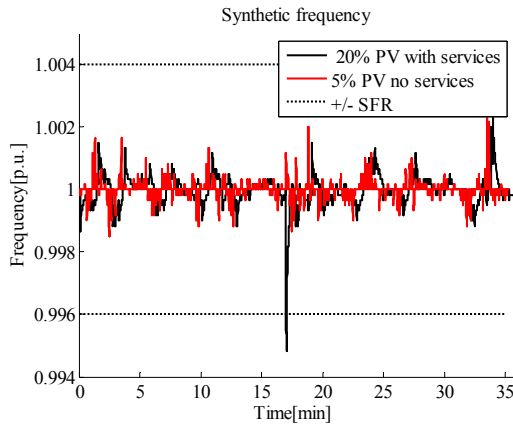


Figure 5-5 The generated synthetic frequency based on Danish load profile and different LPVPPs penetration scenarios

In the second case, LPVPP's installed capacity reaches 20% of penetration (4 p.u. installed capacity) and in this case G2 and G4 are added to the AGC system since G1 was not able anymore to regulate the frequency by itself. From this point on, LPVPPs become active players in the system and start to share also part of the responsibilities in terms of FSM operation enhanced with high sensitivity IR. The system was tested during a frequency event and the response of the entire system is shown in Figure 5-6b where LPVPPs have an intensified frequency response towards deviations.

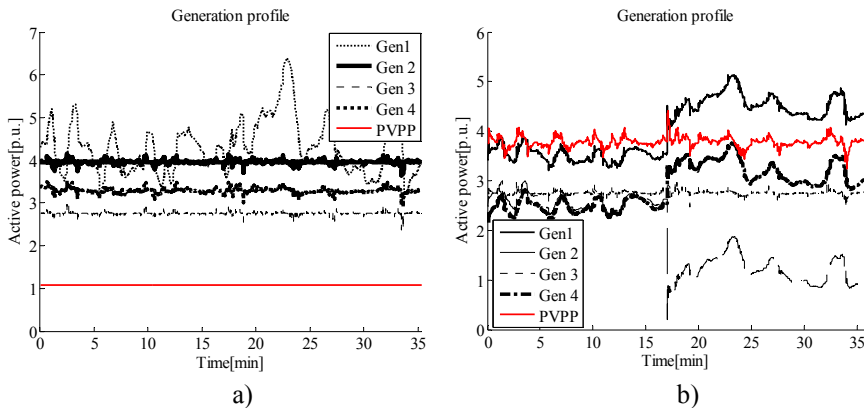


Figure 5-6 Generation profile of IEEE bus system: a) 5% penetration, b) 20% penetration and LPVPPs with frequency support functions

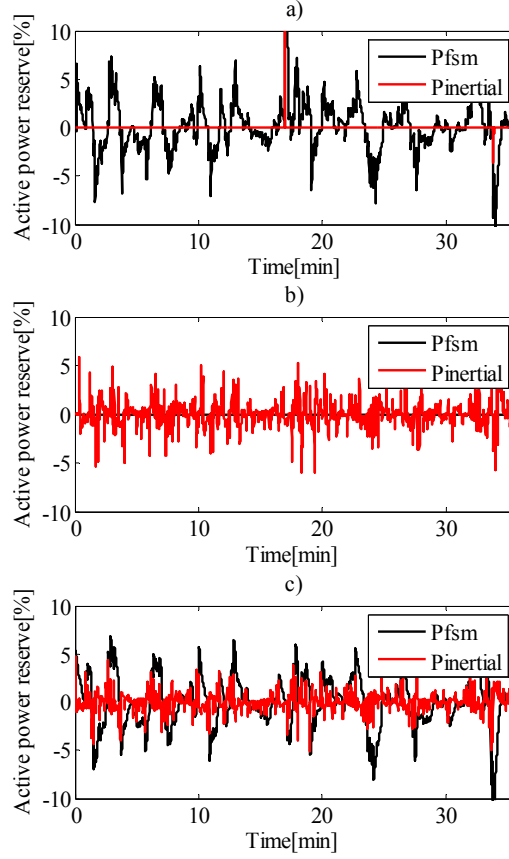


Figure 5-7 LPVPP iAPR deployment: a) FSM and IR only in events b) IR increased sensitivity c) FSM and IR increased sensitivity

Figure 5-7 shows the deployment of the iAPR in different cases when the LPVPP has different ancillary services activated. Figure 5-7a highlights the LPVPP iAPR deployment only during mandatory FSM operation and in this case LPVPP's IR has a limited operation due to an imposed deadband. As it can be seen the IR is used only during frequency events and heavy load situations when the synthetic frequency ROCOF experiences large deviations.

In Figure 5-7b, the FSM operation is deactivated and IR has an increased sensibility. This feature is present in the conventional generation where the kinetic energy is stored in the rotating masses of the plant and released during every power mismatch in the system. This intrinsic characteristic is synthetically adopted in the LPVPP which in this case is sensitive also to light load steps and has the ability to release its IR faster.

In the third scenario which is seen in Figure 5-7c, the LPVPP uses an enhanced FSM with high sensitivity IR. The LPVPP with APRs is sensitive to all scenarios which appear in the grid and artificially emulates the behavior of a CPP. In consequence, the high sensitivity IR improvement added to the mandatory FSM imposed by the TSO achieves better iAPR utilization and provides a faster response during power mismatches.

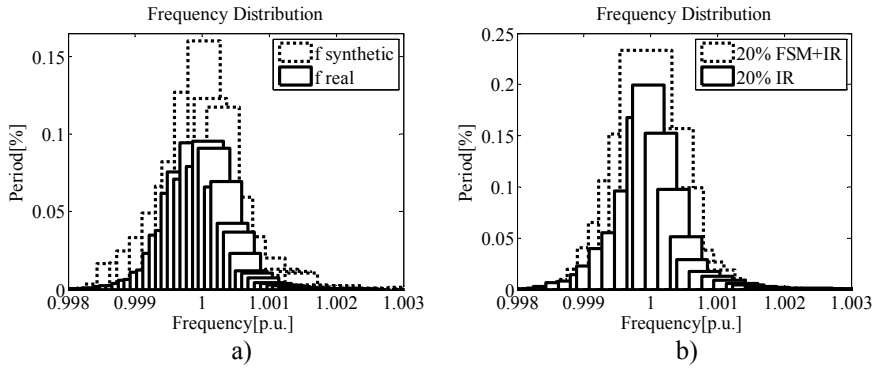


Figure 5-8 Normal distribution of the synthetic frequency: a) Comparison between real and synthetic frequency distribution b) Comparison of different synthetic frequency distributions with LPVPPs providing ancillary services

Midterm frequency analysis gives also the opportunity for statistic evaluation of the frequency quality parameters as shown in Figure 5-8.

Figure 5-8a shows the normal distribution of the synthetic frequency which is validated with the real frequency measurements taken from the Danish power system DK1 and Figure 5-8b shows the impact and improvements of the frequency distribution in case the proposed grid benchmark reaches 20% of PV penetration. As expected with every added ancillary service to the LPVPP, the frequency distribution increases, strengthens the system and leads to overall mid-term stability.

On the other hand, the quality evaluation criteria of the synthetic frequency consists on gathering the synthetic frequency information over a well-defined period and calculates a series of global indicators which in the end reveal the health status of the power system with each penetration scenario.

The statistical characteristics of the generated synthetic frequency with 20% study case of PV penetration are presented in Table 5-3. LPVPPs with APR and ancillary services show an overall improvement in the quality parameters since now it is an active player in the system.

Table 5-3 Evaluation of the synthetic frequency quality parameters

Freq. Param.	Mean Value [p.u.]	Std Dev [p.u.]	Per 99 [p.u.]	Per 90 [p.u.]	Time outside the SFR[s]
20% no services	1	4.9e-04	4.8e-04	4.4e-04	10
20% with services	1	4.7e-04	4.72e-04	4.2e-04	9

The standard deviation used in combination with the mean value of the frequency measurements is the most important global indicator which assesses the control errors and instabilities present in the measured frequency. In the scenario with 20% PV penetration, where the LPVPP supplies ancillary services for frequency support, the standard deviation experiences corrections even on a global scale. In consequence, LPVPP with APRs becomes a reliable participant for the long term evaluation of frequency stability.

The percentiles provide additional information about frequency deviation meaning that if for example the 90th percentile is equal with 4.2e-4 p.u. this means that 90% of the time the frequency data is less than 4.2e-4 p.u. and 10% of the time is higher.

The quality parameter of time outside the SFR shows the power system's sensitivity to frequency violations. This parameter gives TSOs the possibility to require more ancillary services from LPVPPs in case the evaluated frequency quality parameters are not matching with the targets which they are imposing, a topic which is under development.

5.3 Summary

This chapter performs for the first time a time domain evaluation combined with statistical analysis of the IEEE 12 bus system synthetic frequency. LPVPPs with APR which share the responsibilities of frequency control with the conventional generation show to improve the overall system response and reduce the short-term and long-term stress over the synchronous generators in the system.

LPVPPs supplying mandatory FSM enhanced with high sensitivity IR have a direct impact also over the global indicators of frequency quality: decrease the standard deviation, percentiles and reduce the number of

SRF violations.

In consequence, in future PV penetration scenarios, LPVPPs have to supply ancillary services in order to improve the frequency stability, reduce the number of downward regulation procedures and to save part of the investments in grid reinforcement.

Chapter 6 Ramping obligations of LPVPPs

The chapter proposes a PRL control structure for dynamic APR sizing and deployment. The PRL method along with the LPVPPs spatial displacement act as smoothing characteristics against irradiance changes and reveal the LPVPP size for which only iAPRs are used to meet the ramp-rate requirements.

Severe meteorological conditions in matters of high slopes of irradiance have a direct impact over the power production profile in LPVPPs. In power systems with low levels of PV penetration, the variability of PV is usually compensated by the CPP. This fact changes with increased PV power introduced into the system since LPVPPs power fluctuations start to become significant and increase the compensation stress over the participating CPPs.

In strong power systems having low penetration of PV power this effect is not seen as an urgent matter, but in small power systems such as islands, large fluctuations of LPVPPs active power output can cause frequency instabilities and even blackouts. During high slopes of irradiance, the generators in small power systems cannot compensate the power mismatches by means of their limited capabilities of active power recovery causing accidental tripping which leads to a chain reaction endangering the security of the supply [24, 40-42].

Power ramp rate control requirements are seen as the next step to correct LPVPPs power fluctuation and are already demanded in island power systems. This implies that LPVPPs power fluctuations should be initially solved at the production level and not entirely by the CPPs. To compensate the LPVPPs have to have PRL capabilities that can fulfill the imposed ramping requirements, thus the use and deployment of APRs (iAPR or aAPR) becomes a necessity [43-45].

6.1 Network requirements

PRL capabilities are already in force in island power systems and they clearly specify the ramping obligation of every renewable energy source based on its installed capacity and level of connection to the grid. Moreover, ENTSO-E NCs do not impose any PRL obligations, instead it leaves it at the latitude of the local TSOs to require ramping capabilities. A list of the most relevant NC requirements is presented below:

Table 6-1 TSOs power ramp rate requirements [7, 46, 47]

	Positive ramp	Negative ramp	Instant. ramp
HECO (Hawaii)	2MW/min 1MW/min	2MW/min 1MW/min	1MW/2s
PREPA (Puerto Rico)	10%/min	10%/min	No Req.
EIRGRID (Ireland)	30MW/min	No Req.	No Req.
Germany	10%/min	No Req.	No Req.
ENTSO-E	No Req.	No Req.	No Req.

Fluctuations present in the output power of the LPVPP are compensated by the positive and negative deployment of APRs, which smoothens out the power production according to the imposed ramp. The APR is dynamically deployed during the transient period and restored after the disturbance disappears. The ramp rate can be calculated as the difference between two points at any 60s interval or can be imposed by defining the minimum and maximum value between two points within a given time interval.

6.2 Power ramp limitation in LPVPP

Constant slope control represents the most straightforward method but the simplicity of this method presents flexibility limitations and is not able to prioritize the deployment of APRs from different sources.

The proposed PRL method represents the second part of the proposed synthetic governor in LPVPPs since the governing action of LPVPPs which takes into consideration frequency deviations has to take also into account the variations generated by the primary energy

resource.

The LPVPP PRL concept is evaluated on the generic IEEE 12 bus system having PREPA power system characteristics which is subject to different PV penetration scenarios.

6.2.1 Static PRL

The proposed static PRL control strategy presented in Figure 6-1 has to fulfill the ramping requirements imposed by the TSO based on the active power measurements delivered by the PV panels [30].

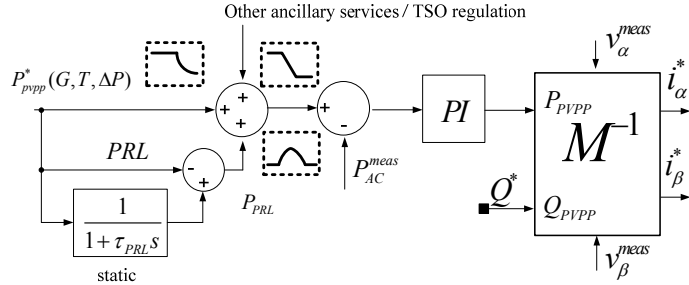


Figure 6-1 LPVPP control structure with static PRL

For this purpose iAPR have to be obtained by setting the LPVPP below its MPP conditions (I_{mpp} , V_{mpp} , P_{mpp}) and has to release the reserve during transients (ΔP_{PRL}). Giving the fact that the value of the controller (τ_{PRL}) is fixed the static PRL releases its dynamic iAPR in an uncontrolled manner without considering any ramp requirement (see Equations (5.1), (5.2) and (5.3)).

$$P_{mpp}(G, T) = I_{mpp}(G, T) \cdot V_{mpp}(G, T) \quad (5.1)$$

$$P_{pvpp}(G, T, \Delta P) = P_{mpp}(G, T) - \Delta P \quad (5.2)$$

$$\Delta P_{PRL}(s) = (P_{mpp}(G, T) - P_{pvpp}(G, T, \Delta P)) \cdot \frac{1}{1 + \tau_{PRL} \cdot s} \quad (5.3)$$

where,

P_{pvpp} – actual power produced by the LPVPP taking into consideration the MPP power and the total amount of curtailed iAPR (ΔP) agreed with the TSO

ΔP_{PRL} - the iAPR used by the PRL control structure during irradiance transients

τ_{PRL} - the proposed PRL control architecture fixed time constant used for iAPR deployment

The static PRL control architecture sums up the power produced by the PV panels (P_{pvpp}) with the deployed iAPR (ΔP_{PRL}) activated by the PRL method, compares it and regulates it by the use of a Proportional Integrator (PI) controller with the injected power (P_{AC}^{meas}). Based on the Instantaneous Power Theory the regulated active and reactive power is transmitted to the inner current control loop, where the current regulation is realized in the stationary reference frame (i_α and i_β).

Figure 6-2 shows the response of a central inverter station with a static PRL. The figure points out the corrective action of the static PRL method and in the same time confirms the fact that the iAPR is released unconditionally, does not consider any ramp and does not consider the duration of the transient state.

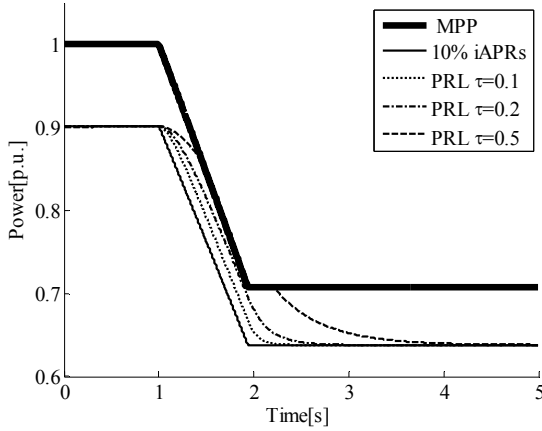


Figure 6-2 The response of static PRL method implemented in LPVPP's central inverter units

6.2.2 Dynamic PRL

The limitations brought by the static PRL are overcome by the use of the dynamic PRL (see Figure 6-3) which invokes a dynamic τ_{PRL} . The time constant used in the dynamic PRL method is dynamically modified based on the power mismatches created by the LPVPP power fluctuations generated by severe irradiance conditions and the imposed ramp rate by the TSO.

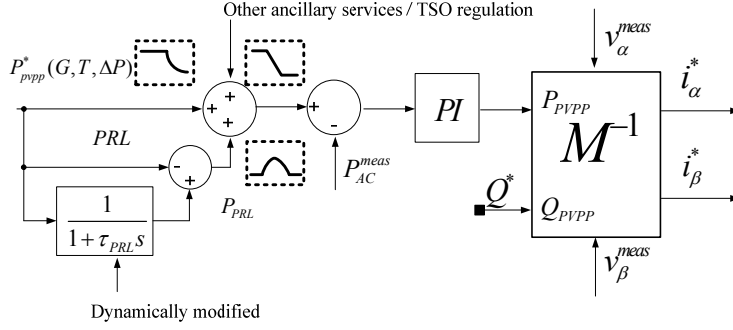


Figure 6-3 LPVPP control structure with dynamic PRL

As it can be seen from Figure 6-3 the dynamic PRL gives the opportunity for APR prioritization during its deployment since in the beginning the APR is extracted from the panels and in case the extracted energy is not sufficient the service deploys it from the aAPR.

Figure 6-4 shows the methodology which describes the dynamic variations that τ_{PRL} experiences during the periods when the PRL service is activated. In the beginning, the PRL method uses a sample delay on the PV panel power production (P_1 and P_2) in order to detect any violation in the imposed power ramping requirements (P_{syn_ramp}). In case this limit is exceeded the PRL method is activated and the variation of the dynamic τ_{PRL} begins.

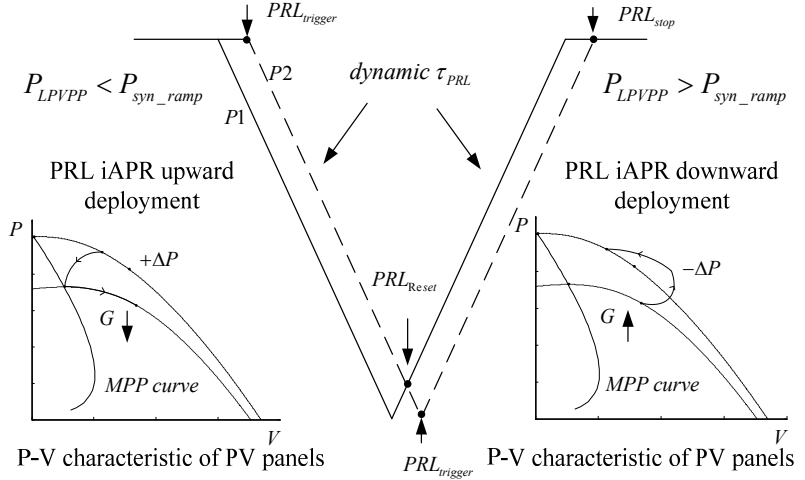


Figure 6-4 Dynamic PRL concept and methodology

For example, during ramp down procedures, the dynamic τ_{PRL} starts from an initial predefined value (τ_{init}) which is dynamically adapted in

order to deploy the iAPR and to meet the power ramp-rate requirements.

It is worth mentioning that the slope and duration of the negative ramp encountered in the LPVPP output power remains unknown and the nature of dynamic PRL service has to become predictive. Therefore, the τ_{PRL} is changed based on the premises presented in Equation(5.4):

$$\tau_{PRL} = \begin{cases} \tau_{PRL} = \tau_{init} , P_{LPVPP}(G, T) \geq P_{syn_ramp} \\ \tau_{PRL} = \tau_{LPVPP} , P_{LPVPP}(G, T) < P_{syn_ramp} \end{cases} \quad (5.4)$$

In case the output power of the LPVPP output power complies the imposed ramping requirements, the value of τ_{PRL} remains at the initial conditions defined by τ_{init} . Thus, the value of τ_{init} has to provide the PRL service with fast characteristics, sensitive to the LPVPP output power conditions and has to avoid the unnecessary iAPR deployment in case the imposed power ramp requirement is not exceeded (see Figure 6-6a).

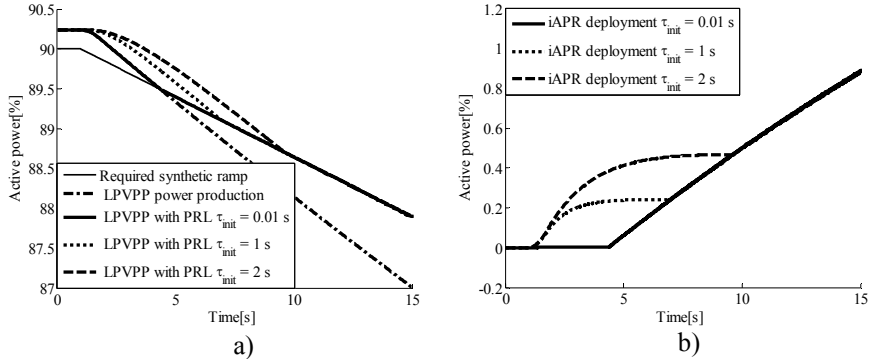


Figure 6-5 LPVPP with dynamic PRL during negative ramp: a) LPVPP output with different τ_{init} conditions, b) iAPR deployment for different values of τ_{init}

In case the LPVPP output power is not able to fulfill the requirements imposed by P_{syn_ramp} , the value of τ_{PRL} changes to τ_{LPVPP} which takes into consideration the effect of its spatial distribution as presented in Table 3-1. In other words, the LPVPP spatial distribution which is reflected in τ_{LPVPP} is used to decrease the sensitivity of the PRL service and forces the LPVPP to deploy the iAPR until the requirements are met (see Figure 6-6b).

The PRL service is stopped or reset and the iAPR is dynamically restored in case the power mismatch between P_1 and P_2 is lower than the imposed ramp or in case the LPVPP experiences ramp-ups. During ramp-ups the same PRL procedure is followed and the LPVPP has to deploy downward iAPR in order to fulfill the ramping requirements.

In Figure 6-4 it can also be observed the iAPR deployment during ramp-down and ramp-up. The maximum allowed upward iAPR is defined by the MPP curve which is dictated by the present irradiation conditions while for downward iAPR, the PRL has no limitations. Moreover, the flow chart presented in Figure 6-6 creates an overview of the entire dynamic PRL process during negative and positive power ramps experienced during high slopes of irradiance present at the production level of the LPVPP.

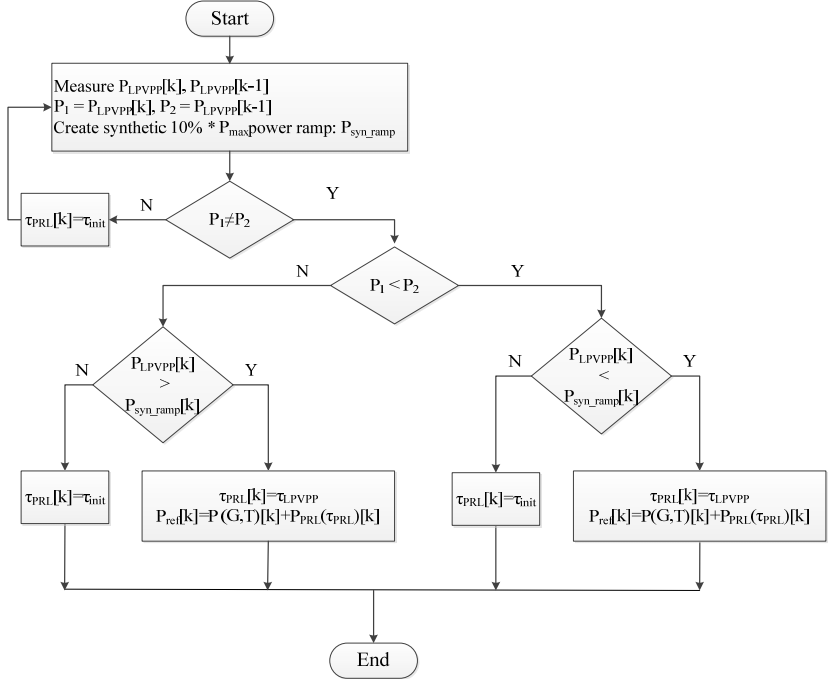


Figure 6-6 Flow chart of the proposed dynamic PRL method

The PRL capabilities of LPVPPs with iAPR were subject to the worst case scenario of 50% drop-off in the power production due to changes in the meteorological conditions (class IV and class V irradiation conditions) for penetration scenarios of 1%, 10% and 20% (see Figure 6-7). The main goal of such tests was to evaluate the APR necessities for ramping requirements of 10%/min taking in consideration LPVPPs spatial displacement which is described in Section 2.3 and Section 3.2.1. The studies had the purpose to investigate the impact of the proposed control architecture over the generating units of the modified IEEE 12 bus system with PREPA characteristics [48-50].

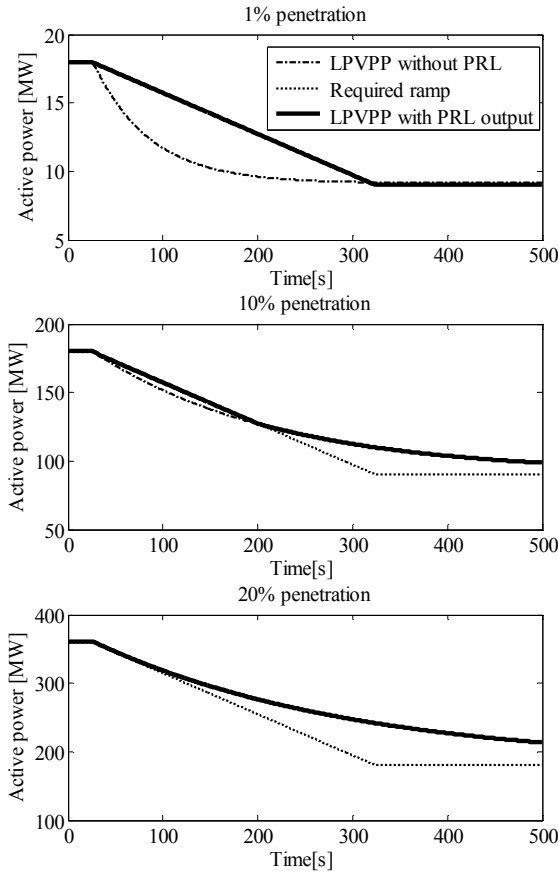


Figure 6-7 LPVPP response for 50% power reduction

The PRL control strategy becomes active in the moment the produced power exceeds the ramping limit and deploys iAPRs accordingly. For the 1% LPVPP penetration case, it can be noticed that the PRL requires an increased amount of APRs since the spatial distribution of such plant is limited and the PRL service has to require an increased amount of reserves to accomplish the ramp requirements. The spatial distribution of LPVPPs and their filtering effect can be observed of a penetration scenario of 10% and 20% (see Figure 6-7) where part of the ramping requirements are covered by the PRL service and part are dissolved by the spatial distribution reducing the APR needs.

The PRL starts by using the iAPRs obtained from the curtailed power and they are used until the LPVPP reaches its MPP. In case the APR requirement persists, they are supplied from other sources such as auxiliary storage units (aAPRs).

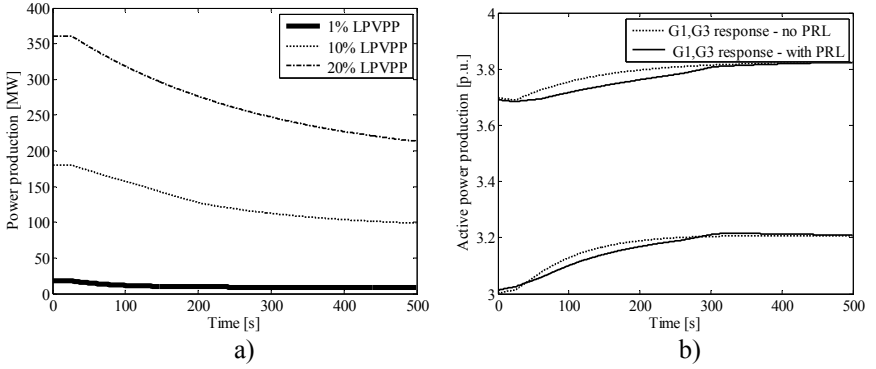


Figure 6-8 LPVPP with dynamic PRL: a) LPVPP's output for different penetration scenario, b) 10% LPVPP with PRL penetration scenario impact over the PREPA power system generators

As it is expected, the ramp rate requirements are dependent on the plant size and the APRs involved (see Figure 6-8a). This means that the PRL services become more active for small and medium size LPVPPs while for LPVPPs the ramp rate necessity is reduced due to their spatial distribution.

The investigation of PRL proposed control architecture was also tested over the proposed power system with an increased interest over the generating units and their ramping response. For this case, a 10% LPVPP power penetration was considered having 10% iAPRs. During the power fluctuations created by high irradiance changes, the conventional generators compensate the power mismatches by regulating their power production as shown in Figure 6-8b considering a 100 MVA base value.

LPVPPs with PRL and iAPRs limit their own power according to the set ramp rate and in this way share the ramping responsibilities with the participating plants, reducing their ramping stress.

The PRL services are also investigated over the scenario of negative and positive production fluctuations emulating cloud passage over the plant. For this case (see Figure 6-9a) a downward step of 30% of power production was investigated over a 10% LPVPP penetration into the system with iAPRs brought by 10% of power curtailment.

The deployment of iAPRs is observed in Figure 6-9b during ramping periods where upward and downward APRs are released by the plant. Once again it can be noted the flexibility of the proposed PRL control structure since it is applied at the plant level and immediately releases the reserves created by the curtailed power. Figure 6-9b shows that the

iAPRs are sufficient to fulfill the requirement and does not necessitate the deployment of aAPRs.

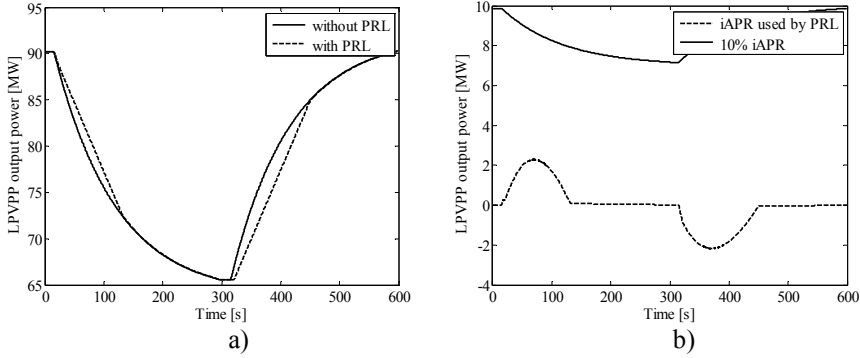


Figure 6-9 LPVPP response during cloud passage: a) PRL effect on LPVPP's output, b) iAPR deployment during dynamic PRL

6.3 APR dimensioning

A synthesis of APR deployment with PRL control structure for different percentage of PV penetration into the proposed power system is presented in Figure 6-10a. It is worth mentioning that the APR created by curtailment also has a dynamic nature since they depend on the irradiation profile.

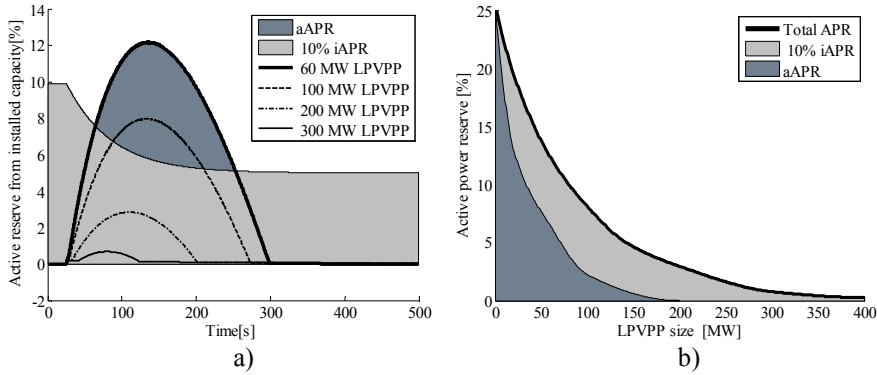


Figure 6-10 Dynamic PRL optimal APR sizing: a) APR time domain evaluation during worst case scenario, b) APR requirements depending on LPVPP size

The evaluation of APRs was subject to the worst case scenario considered which defines the maximum amount of reserve needed to fulfill the ramping requirements. From Figure 6-10a it can be observed that smaller LPVPPs require higher percentages of APRs from their

installed capacity since the distribution characteristics limit the filtering process of power fluctuations. The minimum required APRs for different percentages of penetration with LPVPPs are presented in Table 6-2.

Table 6-2 LPVPPs with APR requirements

Penetration scenario [%]	ENTSO-E Plant type	Plant size [MW]	APR percentage [%]	APR Value [MW]
1	Type B	20	19.2	3.84
3	Type C	60	12.1	7.26
5	Type D	100	7.9	7.9
10	Type D	200	2.8	5.6
15	Type D	300	0.6	2
20	Type D	400	0.2	0.8

Figure 6-10b summarizes the APR requirements considering LPVPPs with different APR endowment. It is shown that 10 % curtailment has a significant impact over the storage requirements, thus storage necessities become more essential for smaller plants. PRL defines once again the necessities of APRs and has the flexibility to deploy them from different sources. Ramping requirements can be fulfilled directly by iAPRs with the main disadvantage of energy loss in the curtailment process or by aAPRs which means extra costs of the installations.

6.4 Summary

Power ramp rate control of LPVPPs are a necessity in small power systems since the active power mismatches created by large power fluctuations of LPVPPs cannot be recovered by the generating plants in the system.

To fulfill the ramping requirements with LPVPPs, it is necessary to combine the electrical characteristics with the size and spatial distribution deciding the minimum requirements of APRs.

The proposed PRL control strategy overcomes the challenges created by large output power fluctuations of LPVPPs and decides the minimum necessities of APRs. PRL services provide flexibility in terms of APR

usage since the control architecture can be implemented in the production area at the central inverter station level but proves to have a better appliance at the plant level where the APR management is realized.

Chapter 7

Experimental evaluation of a real time PHIL test bench for PV applications

This chapter summarizes the experimental validation of the proposed control concepts for frequency and ramp rate support over a fully programmable laboratory PHIL test bench.

PHIL testing combines the features of both pure hardware and pure software methods by running a mathematical model of the well-known components of a system in pure software environment. In this way, the gap between software simulation and hardware testing is bridged, leading to novel advantages hardly seen in former simulation technologies. Consequently, the use of PHIL is no longer optional, but rather seen as a necessity giving the opportunity to develop new grid support concepts that can boost up the integration process of LPVPPs into the grid [51-53].

The main objective of this chapter is to present a fully programmable PHIL test bench that is able to reproduce the behavior of a HV grid having connected LPVPPs, using a scaled laboratory platform. Thus, Figure 7-1 shows an overview of the proposed test bench which can be divided in two main parts: flexible AC grid with proposed HV characteristics and PHIL LPVPPs with fully programmable parameters including the meteorological conditions.

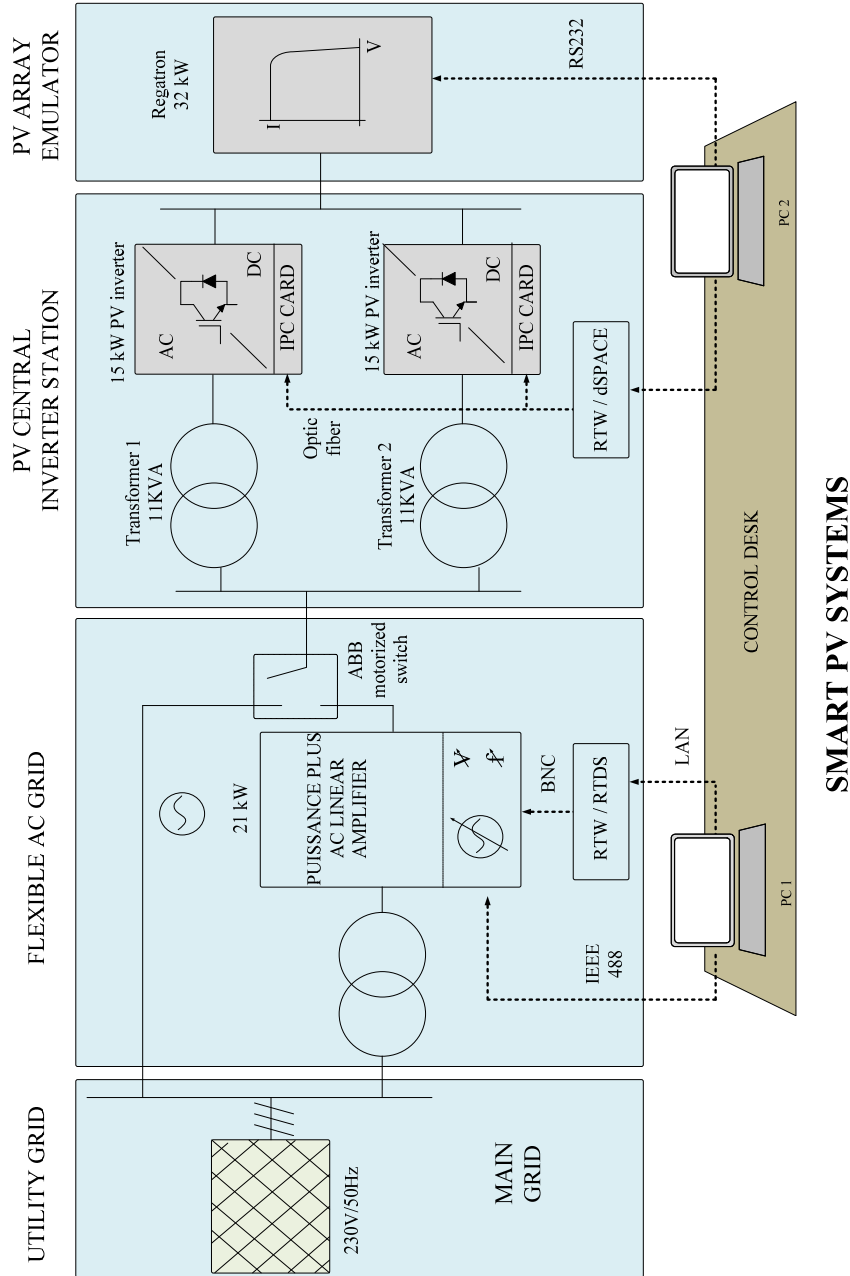


Figure 7-1 Real time PHIL test bench for PV applications (single line diagram)

7.1 Flexible AC grids prepared for PHIL LPVPPs

To successfully perform stable PHIL tests, IAs are used to couple hardware and software environments. The IA contains different elements that enable the possibility to exchange different signals between the Hardware under Test (HuT) devices and the Real Time System (RTS) at the desired power level.

The setup configuration presented in Figure 7-2 displays the open-loop test procedure of a RTS generated voltage applied to a linear power amplifier. The open loop test is used to estimate the time-delay in the loop and to evaluate the accuracy in the amplified voltage by the controllable power supply.

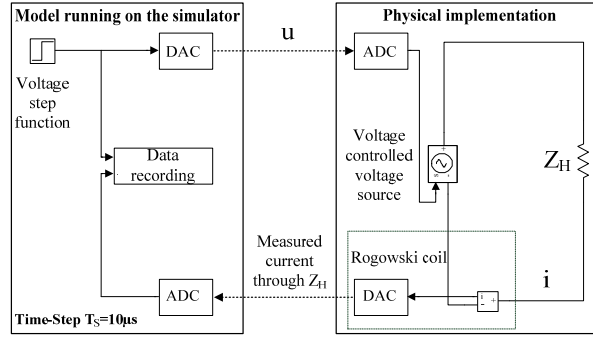


Figure 7-2 Open-loop test setup block scheme

To test new concept of grid support functions in central inverter based LPVPPs, the PHIL evaluation of such systems has to consider two main features: accuracy and stability. For this purpose, the selection process of an appropriate IA is considered critical since the chosen IA applied to the linear amplifier determines the performance of the application [54, 55].

The Ideal Transformer Method (ITM)

The ITM is a straightforward method for PHIL implementation. The method shown in Figure 7-3 is known to have moderate stable operation, low implementation effort and consists of two basic operations: voltage amplification (RTS simulated u is amplified to u'') and current feedback (measured current i'' is fed back to the RTS environment).

A real implementation of the ITM interface contains non-ideal components that affect the stability of the application, as they introduce

time delays in the loop. Thus, extra time delays are added by the RTS which requires a certain amount of computation time of the simulated model based on the preset time step, time delays added by the measurements which are fed into the RTS and time delays specific to the linear amplifier. These delays are lumped to a single time delay, which can be estimated to be twice the value of the time-step $T_D=2T_s$ [51].

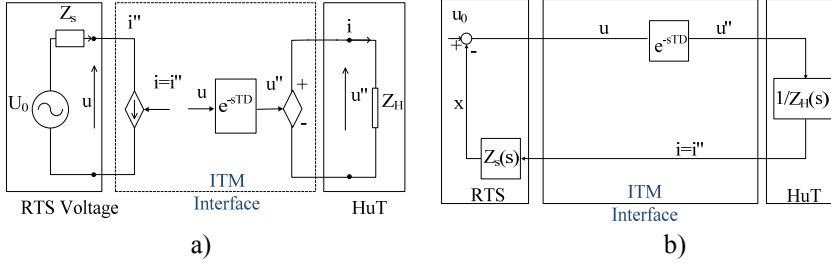


Figure 7-3 ITM interface: a) ITM PHIL implementation b) ITM block diagram

The ITM open-loop transfer function is obtained as follows:

$$-F_0(s) = \frac{x}{u} = e^{-sT_D} \times \frac{Z_s(s)}{Z_H(s)} \quad (6.1)$$

As it can be deduced from Equation (6.1) the radius of the circle of the Nyquist plot is given by $|Z_s/Z_H|$. For magnitudes smaller than one, the point $[-1; 0j]$ is not be encircled, which means a stable operation (Figure 7-4 – System A) while for magnitudes bigger than one, the point $[-1; 0j]$ is encircled, which means that the system is unstable (Figure 7-4 – System B) [54, 55].

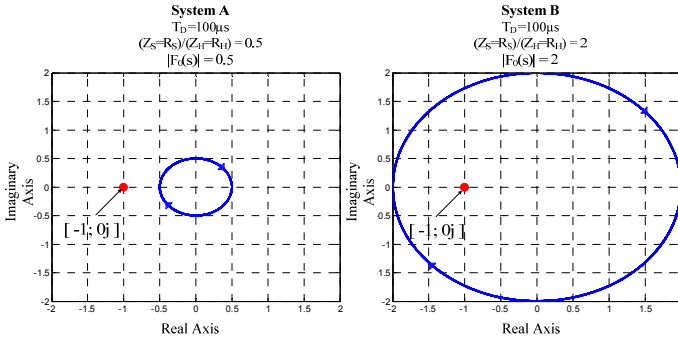


Figure 7-4 Nyquist plot of PHIL ITM interface having different $|Z_s/Z_H|$ ratios

The Damping Impedance Method (DIM)

The DIM interface proposes to improve the poor stability properties of the ITM interface by adding a time delay compensation mechanism

consisting of Z^* and of linking impedances Z_{SH} which are inserted both in software and in hardware environments (see Figure 7-5a).

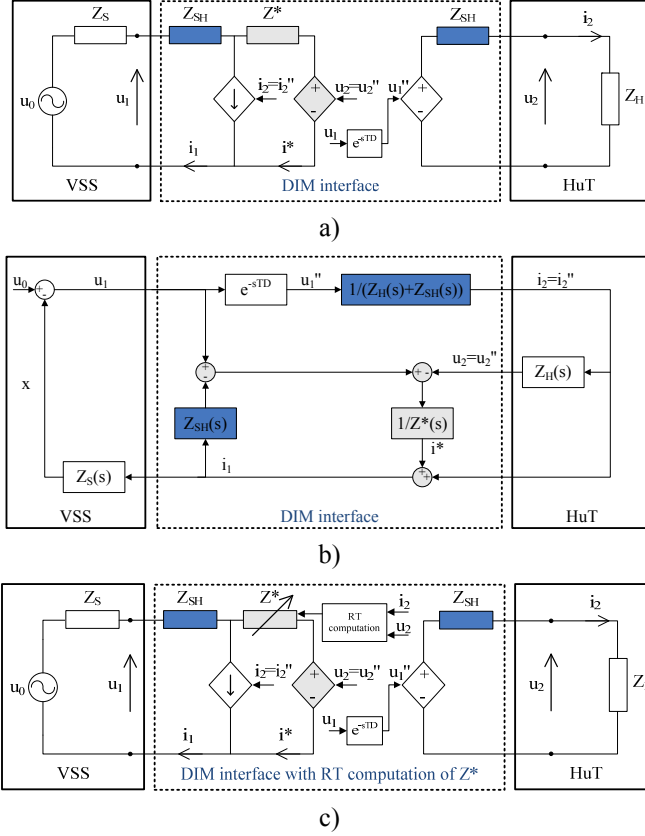


Figure 7-5 DIM interface: a) DIM PHIL implementation b) DIM block diagram representation c) DIM PHIL implementation with RT computation of Z^*

The acting mechanism of the DIM method for the ideal cases when the damping impedance matches the hardware impedance ($Z^* = Z_H$) can be observed in Figure 7-5b and is mathematically expressed in Equation (6.2) where the open-loop transfer function's magnitude becomes zero. This means that the PHIL testing procedure becomes stable, even for large $|Z_S/Z_H|$ impedance ratios.

$$-F_0(s) = \frac{x}{u_1} \approx e^{-sT_D} \times \frac{Z_S(s)(Z_H(s) - Z^*(s))}{(Z_H(s) + Z_{SH}(s))(Z_S(s) + Z_{SH}(s) + Z^*(s))} \quad (6.2)$$

Another possibility to implement the DIM interface algorithm and to suppress the effect of the added time delays that can affect the PHIL stability is to calculate in real time the value of the damping impedance based on the fed in measurements. In this case, the real-time Z^* is calculated, so that it is always have a value close to the value of Z_H . This

IA is referred to as DIM method with real-time computation of Z^* and its schematic is presented in Figure 7-5c [54, 55].

In case the damping impedance is not matched to the hardware impedance ($Z^* \neq Z_H$), the DIM method continues to have a stable operation, as it is easier to keep the magnitude of the open-loop transfer function below one (see Figure 7-6).

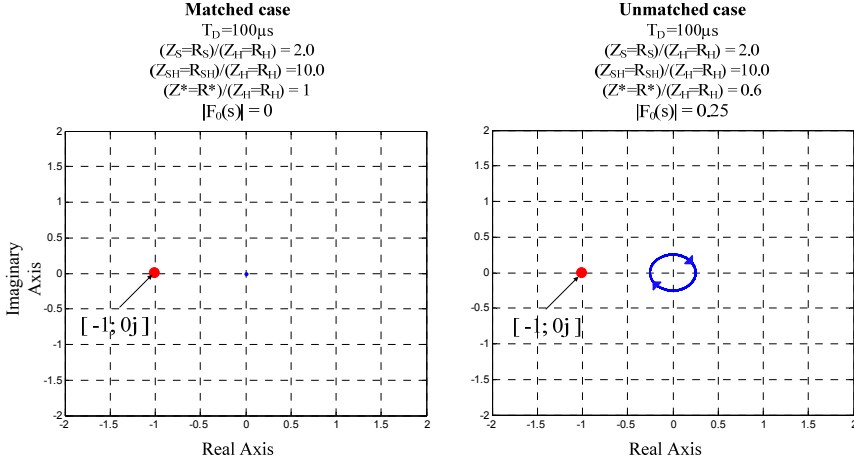


Figure 7-6 Nyquist plot of PHIL DIM interface having different $|Z_S/Z_H|$ ratios

For both IAs, the experiments are divided into following parts:

- Variation of Z_S for constant Z_H
- Variation of Z_H for constant Z_S

Variation of Z_S for constant Z_H

In this test case, the PHIL evaluation was made in closed-loop conditions and Z_S was linearly modified for a constant value of $Z_H = 53 \Omega$ in order to simulate dynamic conditions of the RTS.

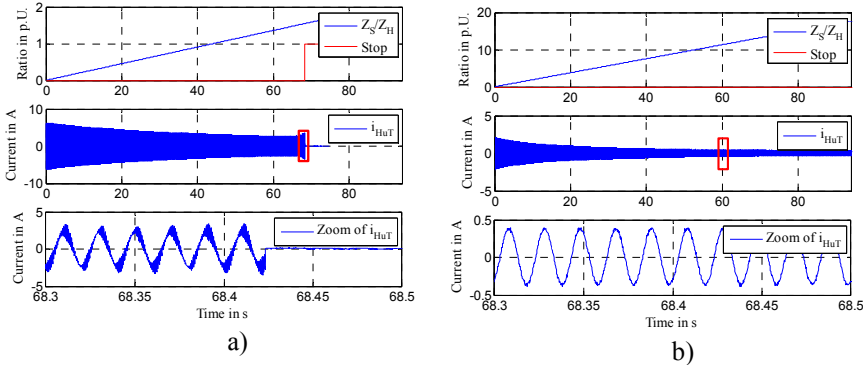


Figure 7-7 Variation of Z_S for constant Z_H for a) ITM and b) DIM

The results are shown in Figure 7-7, where the value of $|Z_S/Z_H|$ and the current flowing through the HuT are depicted. In the case of the ITM study case (see Figure 7-7), the simulations were interrupted since the computed Total Harmonic Distortion (THD) level of the measured current in the model running on the RTS went beyond the safety limits. The THD is used as an indication to quantify the harmonic content of the measured current. This is important to indicate possible interferences, which could harm the hardware components. Furthermore the current and voltage will also be recorded as an additional protection.

Moreover, Figure 7-7 shows that the ITM method performs stable only for $|Z_S/Z_H| < 1.5$, whereas the DIM method shows a stable behavior for the whole testing range ($0 < |Z_S/Z_H| < 20$).

Variation of Z_H for constant Z_S

Similarly to the above study case, the behavior of the two IAs was evaluated for variations in the value of Z_H . In this case, the value of Z_S was kept constant and the value of Z_H was dynamically modified emulating the conditions of a PV based HuT (see Figure 7-8).

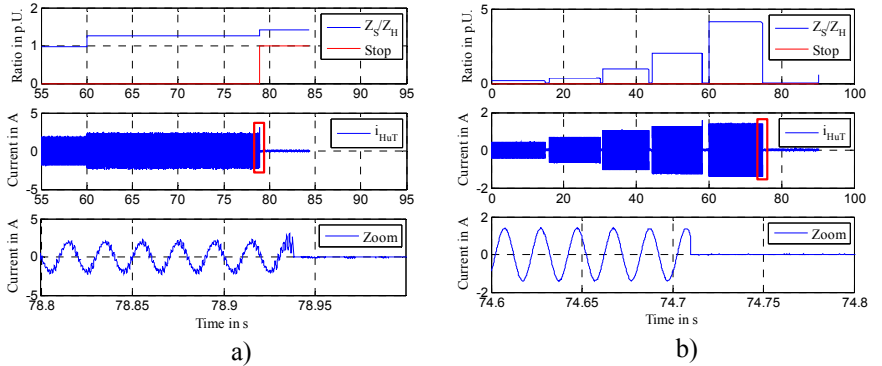


Figure 7-8 Variation of Z_H for constant Z_S a) ITM b) DIM

From Figure 7-8 it can be observed that the results are similar to those of Figure 7-7 as the ITM showed a stable behavior only for $|Z_S/Z_H| < 1.5$, whereas the DIM method has a stable performance for the entire testing range, even in cases with high variations of $|Z_S/Z_H|$.

In conclusion the selection process of the appropriate IA should be chosen according to the application and to the estimates of the worst case values of Z_S (grid impedance) and Z_H (PHIL LPVPP impedance conditions). Thus, the results have shown that the DIM interface offers a good alternative to the limited stability of the ITM method, as it is stable even for a wide range of $|Z_S/Z_H|$ ratios. Furthermore, for the matched case

($Z^* = Z_H$), the DIM method shows a stable performance regardless of $|Z_S/Z_H|$. For this reason, the DIM represents a more suitable choice for having stable PHIL grid test benches involving linear power amplifiers.

Flexible AC grid with generic IEEE 12 bus system characteristics

The opportunity to operate in a stable manner with PHIL linear amplifiers as demonstrated above, enables the possibility to link the flexible PHIL AC grid with the real time simulated generic IEEE 12 bus system. In this way, depending on the PCC HV bus connection, the characteristics of the proposed HV grid can be downscaled at the same power level and successfully reproduced by the flexible AC grid as shown in Figure 7-9.

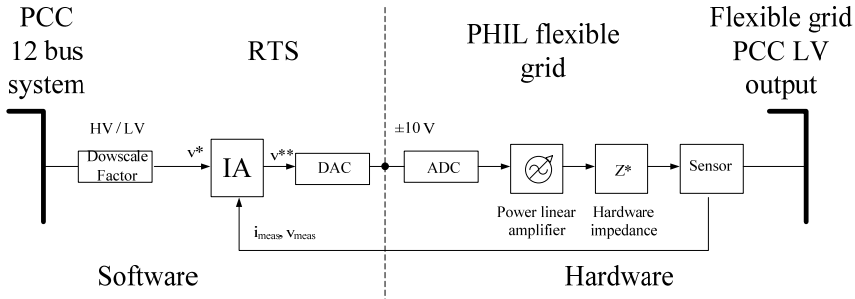


Figure 7-9 Flexible AC grid with fully programmable IEEE 12 bus system parameters

From this point on, the fully programmable PHIL AC grid gives the opportunity to test and evaluate the response of real PV systems or enables the possibility to test central inverter –based LPVPP prototypes with novel grid support functions.

7.2 PHIL evaluation of LPVPPs with grid support functions

The second part of the flexible PHIL laboratory test bench is represented by a 2x10 kW PHIL PV plant. The PV plant shown in Figure 7-1 and detailed in Appendix E uses a 32 kW PV linear amplifier to create the desired meteorological conditions and offers the possibility to emulate the technology of any desired PV panel technology.

Depending on the selected configuration of series and parallel connected PV panels, the levels of DC voltage and DC current can be adjusted in order to meet the power requirements needed by the used grid connected converters. As a consequence, the PV linear amplifier

produces a DC power directly proportional with the present conditions of irradiance and temperature and feeds it into the DC input of the downscale PHIL PV plant.

The configuration of the PHIL PV plant consists of two grid connected converters which are responsible to process the produced PV power and to inject it into the flexible PHIL AC grid.

Both grid connected PV inverters are controlled by a dSPACE RTS at a switching frequency of 10 kHz. The dSPACE RTS is responsible for the data acquisition, converter control and PWM generation.

The control architecture used by the dSPACE RTS has a double loop configuration. The inner loop is realized in the stationary reference frame controlling the current injected into the grid while the outer loop is responsible with the control of the active and reactive power delivered by the PHIL PV plant. The PHIL PV parameters are in Appendix E.

7.2.1 PHIL LPVPPs with frequency support functions

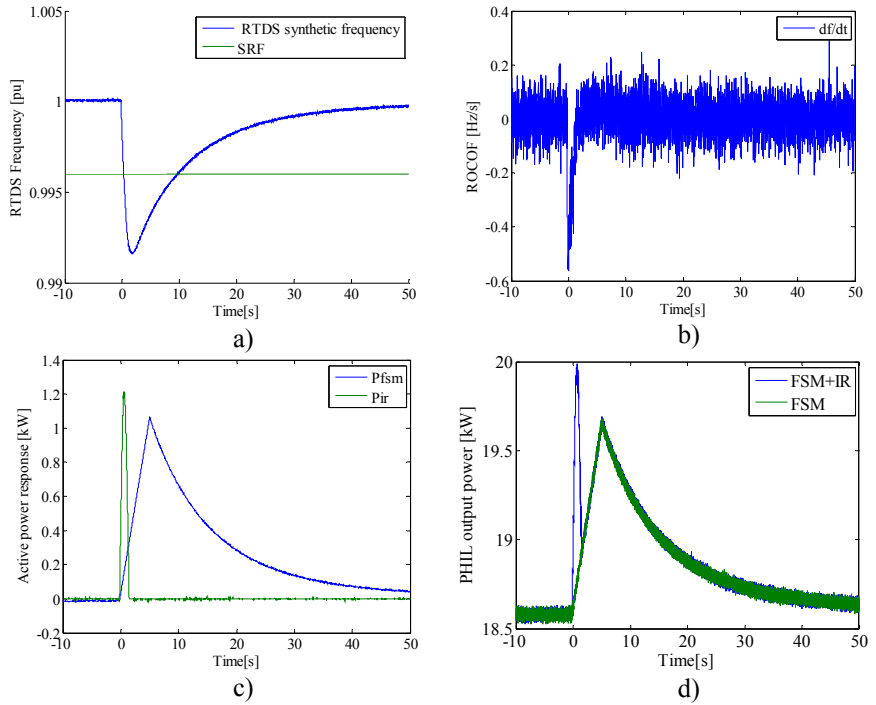


Figure 7-10 Frequency support in PHIL PV plants: a) RTDS generated synthetic frequency b) Measured ROCOF c) iAPR deployment during IR and FSM d) PHIL PV plant response with FSM and FSM+IR

Having the entire laboratory test bench linked together with the flexible PHIL AC grid, the possibility of testing the proposed synthetic governor functions delivered by PHIL PV plants appears.

For this purpose the generic IEEE 12 bus system was subject to a frequency event meaning the loss of 2 p.u. of generation which determined the frequency to deviate from its rated parameters and to exceed the SFR as shown in Figure 7-10a. During the frequency disturbance, the measured ROCOF (see Figure 7-10b) enables the synthetic inertia modeled in the PHIL PV plant and causes the inverters to react by means of their iAPR which for this study case the amount of iAPRs were considered to be in the range of 10% at STC power production (see Figure 7-10c).

In case the PV system is equipped only with FSM, the converters release the iAPR according to the pre-set value of the droop and take in consideration only the frequency mismatch in their iAPR deployment as shown in Figure 7-10d.

7.2.2 PHIL LPVPPs with power ramp capabilities

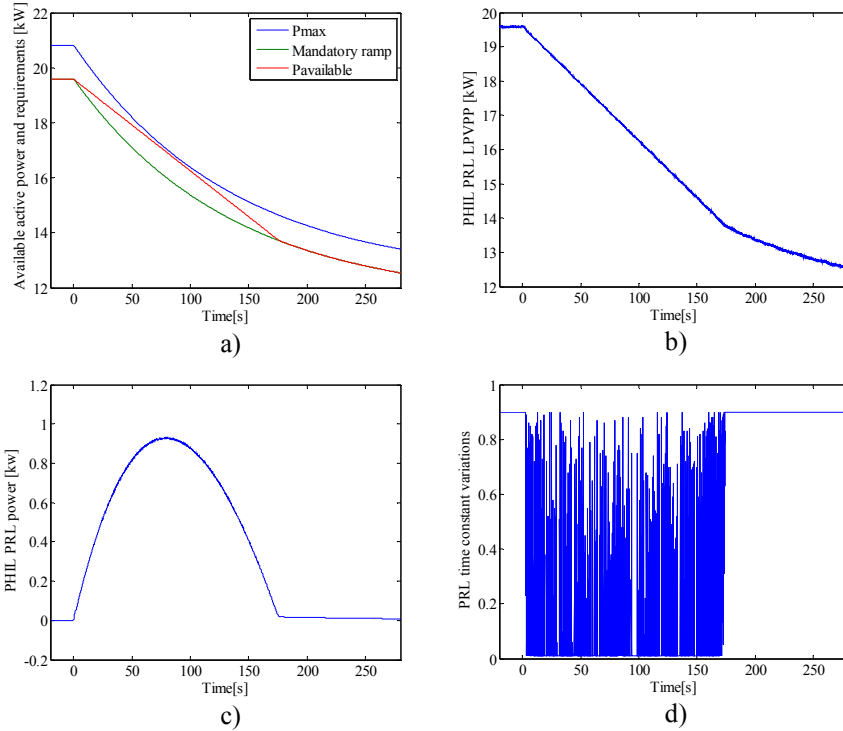


Figure 7-11 PHIL PV plant response during ramp rate control: a) Power output cases b) PHIL PV plant output, c) PRL deployment d) Dynamic tau during PRL

The second part of the proposed synthetic governor function which was tested on the PHIL PV plant is the PRL service that can be supplied during high slopes of irradiance.

For this study case, the 20 kW PV plant was tested at the worst case scenario of 50% drop off in the irradiance starting from STC state down to 500W/m².

The downscale PHIL PV plant emulates the behavior of a 100 MW LPVPP having 10% iAPRs and the power mismatches produced by the above mentioned condition can be observed in Figure 7-11a. It can be stated that the PRL action of the proposed synthetic governor is enabled in case the ramping requirement are not met (see Figure 7-11b) and for this purpose iAPR(see Figure 7-11c) are dynamically deployed in order to compensate any power difference that occurs.

The dynamic character of the proposed PRL method is observed in Figure 7-11d where the time constant is dynamically changed during high power ramp rates which means adapting the iAPR needs to the imposed ramp-rate requirements.

7.3 Summary

The entire grid evolves within each year and TSOs are constantly forced to update their NCs and to require more grid support from renewable power plants. In consequence, PHIL testing of the entire system acts as a necessity since every scenario present in the grid and each grid support function implemented in LPVPPs has to be tested and evaluated.

The real time PHIL test bench developed on a laboratory scale proposes to address these issues and consists of two main parts: the 21 kW flexible AC grid and the 20 kW PV plants in which the proposed synthetic governor functions are implemented.

The entire PHIL platform has a stable operation in case the DIM interface is used allowing the power amplifier to operate over a wider range of impedance ratios and enables the possibility to successfully test the proposed control architectures implemented in the PHIL PV plant.

Chapter 8

Conclusions

The main conclusions of the thesis are underlined in this chapter along with several recommendations for future work regarding areas that could be further investigated.

8.1 Thesis summary

The work developed during the entire PhD period and summarized in this thesis focuses on frequency support and active power ramp capabilities of LPVPPs with internal generated APRs.

The main motivation of the presented work has been driven by the significant growth of PV power integrated into the system, in the last period and its potential to create instabilities at a larger scale.

In the same time the trends of several countries to reach almost complete autonomous operation from the conventional methods of producing electricity, have made TSOs to start involving LPVPPs in their planning, imposing more responsibilities in order to ensure the stability and reliability of the supply.

In these circumstances, ancillary services in terms of frequency support functions and active power ramp-rate features become a hot topic for LPVPPs since the advantages brought by their nature can have a positive impact in the short term dynamics of the grid caused by frequency events or by fast changing meteorological conditions.

In consequence, the goal of this work was to develop new grid support concepts that can successfully be implemented in LPVPPs and can actively contribute to overall system stability.

- To accomplish these objectives and to create valid test cases which can be used to analyze the short term and long term improvements brought by the proposed LPVPP control concepts, first the development of suitable HV grid benchmark models have to be achieved. For this

purpose, the generic IEEE 12 bus system was selected, giving the fact that the model represented a trade-off between flexibility and complexity and proved to be a reliable platform to perform LPVPP grid integration studies. The advantages of the proposed model were once emphasized since the model showed similar characteristic with the PREPA power system and the real island power system characteristics were easily reproduced improving even more the accuracy of the obtained results.

- The entire modeling process of the proposed HV grid benchmark having LPVPPs with their electrical and spatial distribution characteristics was realized over RTDS platform, which overcame the challenges in terms of calculation effort and proved to be an adequate simulation tool.

- Performing real time simulations with valid HV grid models opened the possibility to analyze the short term and midterm stability of a synthetic generated grid frequency created by the participating CPPs as a response to a realistic Danish load profile. Thus, the possibility of analyzing different LPVPP penetration scenarios supplying ancillary services was carried out in order to prove their benefits over the short term frequency stability in case the penetration becomes relevant. The time domain analysis revealed that LPVPPs providing the mandatory FSM enhanced with high sensitivity IR represent the proper solution for frequency support since both FSM and IR target different characteristics of frequency and in this way enhance the LPVPP with synthetic governor functions.

- Beside the short term evaluation of the synthetic frequency, a mid-term analysis combined with a statistical evaluation was considered. The main focus of this analysis was to observe the iAPR deployment of LPVPPs and their positive impact over the frequency quality parameters in terms of reducing the value of the standard deviation, percentiles, and even the time outside the SFR in case the frequency experiences deviations. These quality parameters are considered global indicators and could be used in the future to justify the need for more ancillary services and more APRs in case the target values are not met.

- Enhanced FSM with high sensitivity IR is only a part from the proposed synthetic governor which was intended to be used in LPVPPs. As was demonstrated, this part is mostly sensitive to grid frequency disturbances and is able to deploy the APRs accordingly. The second part the proposed synthetic governor considers the power fluctuations

brought by extreme irradiance conditions. For this purpose, the proposed PRL method is used in order to meet the TSO ramping requirements and in the same time manages to optimally size the total APR need. Compared with the conventional ramping methods, the PRL presents net advantages in terms of flexibility since it is able to manage and dispatch the APRs from different sources.

- The management of APRs and their deployment in order to fulfill different NCs has to be evaluated first at the plant level followed up by a dispatch process over the production units. Hence, the technical analysis performed over the PV central inverters showed that iAPRs can be generated by operating under the MPP conditions, with an improved system response at DC voltages above the MPP voltage. In this way, the iAPR can be deployed without the risk of converter tripping and enhances the possibility to easily implement the proposed control architectures

- To validate the performance of LPVPPs providing frequency and ramp-rate support with internal generated APRs, a fully programmable flexible PHIL system composed by a 20 kW PV plant and a 21 kW grid simulator has been developed and used.

- The entire laboratory platform can be divided into two specific parts, thus a main part of the setup consists of the flexible AC grid which reproduces the characteristics of the proposed IEEE 12 bus system simulated in RTDS RTS. To perform stable study cases and to emulate every power system condition, different IAs were used to overcome this challenge. It was demonstrated that DIM interface had a superior performance compared with the IA interface and was able to operate the AC linear power amplifier over a wide range of impedance ratios.

- The second part of the PHIL platform consists of a downscale 20 kW PV plant composed by 2 x 10 kW inverters and a PV linear amplifier that can reproduce every meteorological condition and can offer the possibility of testing different PV panel technology. The proposed control architecture was implemented over the inverters which were controlled by the dSPACE RTS and has showed its hardware applicability in terms of frequency support and ramp rate control.

8.2 Future work

The possibility for future work remains and the work can advance in several directions. The main lines of research areas that could be interesting to be explored are listed as it follows:

- Different irradiance profile in inverters to have a more accurate APR profile prepared for the worst case scenario
- Short term predictions for irradiance can improve the nature or the provided services and the security of APRs
- Optimization of APR taking into consideration multiple grid events(frequency events, number of downward regulations) for different irradiation profiles
- Development of central inverter DC voltage control strategies dedicated to APR internal generation
- Development of methodology to predict LPVPP time response considering the size and spatial displacement
- Prioritization methods for FSM and PRL in the process of iAPR deployment.
- Economic analysis of iAPR and aAPR and reserve market revenue

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Appendix A

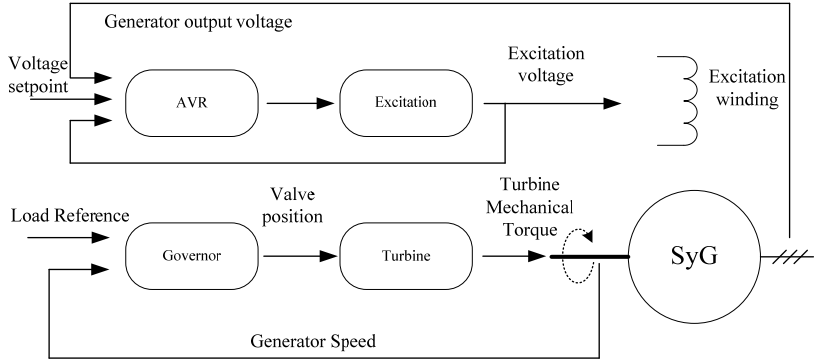


Figure A-1 Synchronous generator control scheme

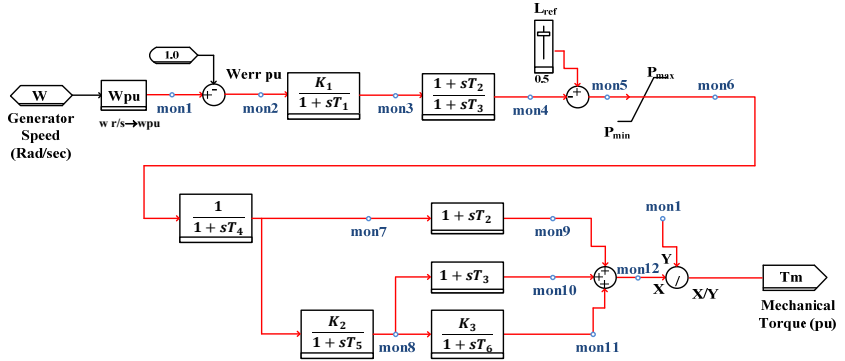


Figure A-2 RSCAD standard IEEE governor/turbine model [56]

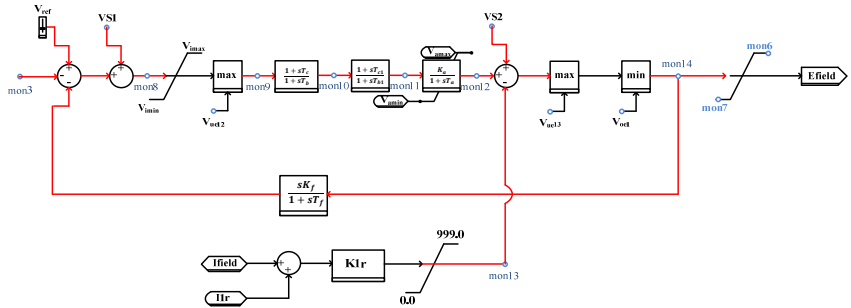


Figure A-3 RSCAD model of the IEEE type ST1A exciter and AVR [56]

Appendix B

TABLE B-1 Generic IEEE 1 2bus system data with LPVPPs

CPP units	Gen type	Exciter type	Governor type
G1 x 6	F6	H13	F10
G2 x 4	F8	H13	F5
G3 x 2	F9	F8	F7
G4x 4	H15	ST1A	H16
Line	R [pu]	X [pu]	B [pu]
1-2	0.01131	0.08998	0.18377
1-6	0.03394	0.26995	0.55130
2-5	0.0453	0.3599	0.7351
3-4	0.0057	0.0450	0.3675
4-5	0.0170	0.1350	0.2757
4-6	0.03394	0.26995	0.55130
7-8	0.0159	0.1721	3.2853
Transformer	MVA	U_k %	Voltage[kV]
1-7	500	13	230/345
1-9	800	12	15.5/230
2-10	700	12	15/230
3-8	500	13	230/245
3-11	400	10	18/230
6-12	500	11	13.8/230
4-PVPP	400	10	11/230
PV data	Units	Central Inverter	Units
P _{mpp} [W]	218.4	MVA	1
I _{mp} [A]	8.16	C _{DC} [mF]	10
V _{mpp} [V]	30.12	Filter	
V _{OC} [V]	30.94	L _{filter} [mH]	1
I _{Sc} [I]	8.61	Trafo LV/MV	U_k [%]

Panels in series	22	2 [MVA]	10
Rows in parallel	185	Voltage [kV]	0.48/11
AGC			K_{IAGC}
α_1	α_2	α_4	-0.05 (5% PV)
0.4	0.3	0.3	0.07(20 % PV)
Central inverter control			
K_{PI}	K_{II}	K_{PP}	K_{IP}
3	1500	0.3	200
ΔP [%]		Δf [Hz]	FSM [%]
10		0.5	12
IR	$H_{syn}[s]$	$T_{fil}[s]$	$R_{PVPP}[pu/s]$
	3.5	0.01	0.1

Appendix C

TABLE C-1 PV central inverter data

PV panel characteristics	Units	Inverter	Units
P_{mpp}	218.4[W]	Rated power	1 [MW]
I_{mp}	8.16 [A]	Number of conv.	4 x 250 [kW]
V_{mp}	30.12 [V]	DC cap.	10[mF]
Panels in series	26	IGBT module	SKM 500GA123D
Rows in parallel	157		Si device

Appendix D

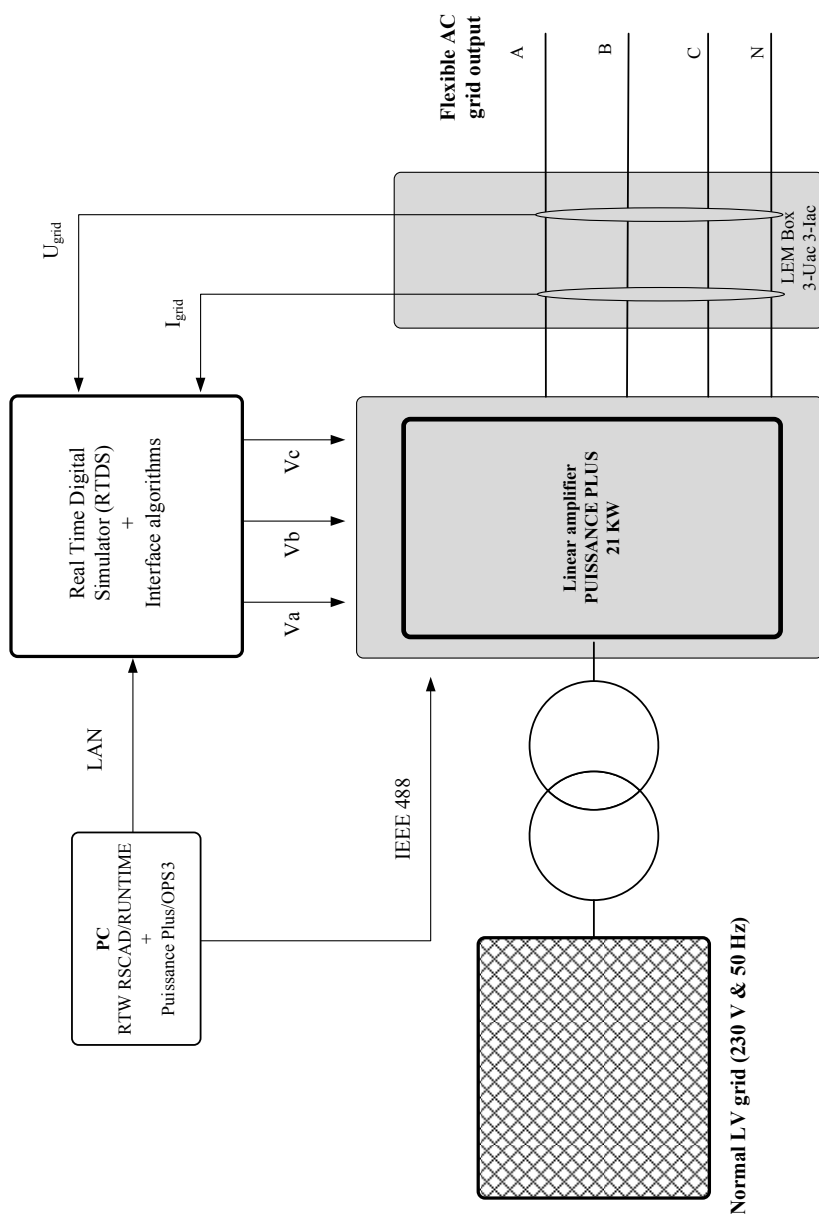


Figure D-1 Laboratory diagram of PHIL flexible AC grid

Appendix E

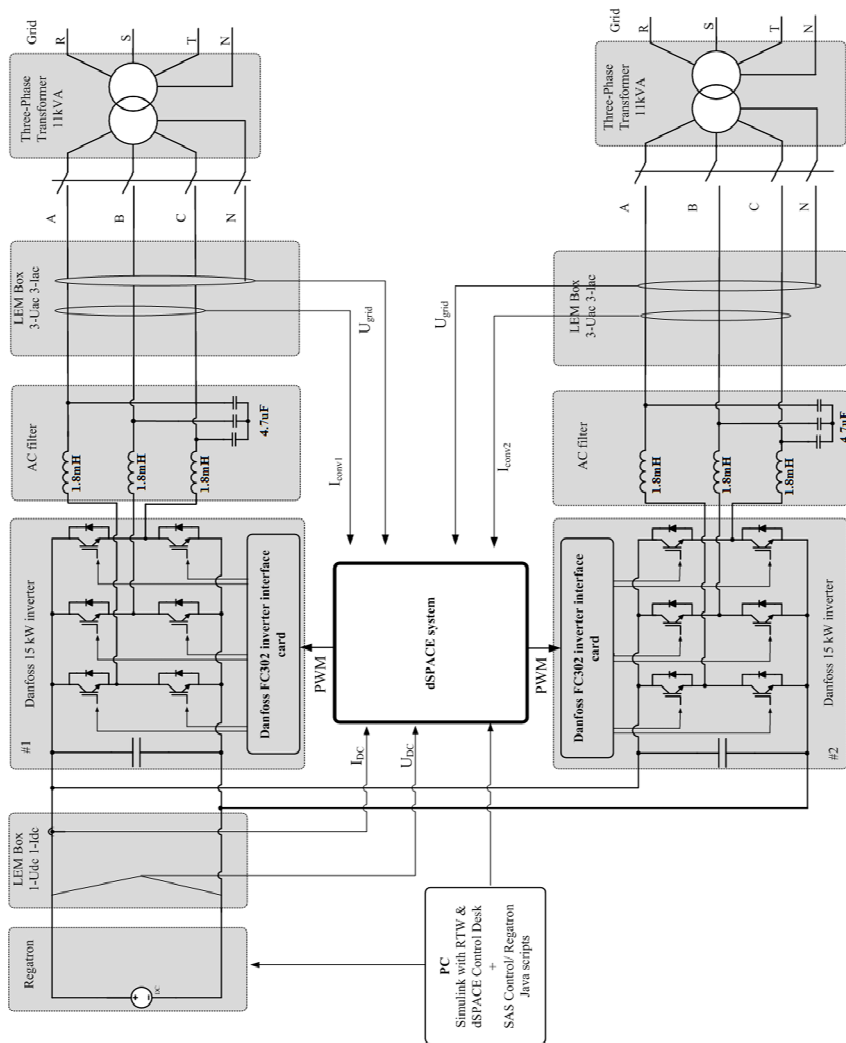


Figure E-1 Laboratory diagram of PHIL 20kW PV plant

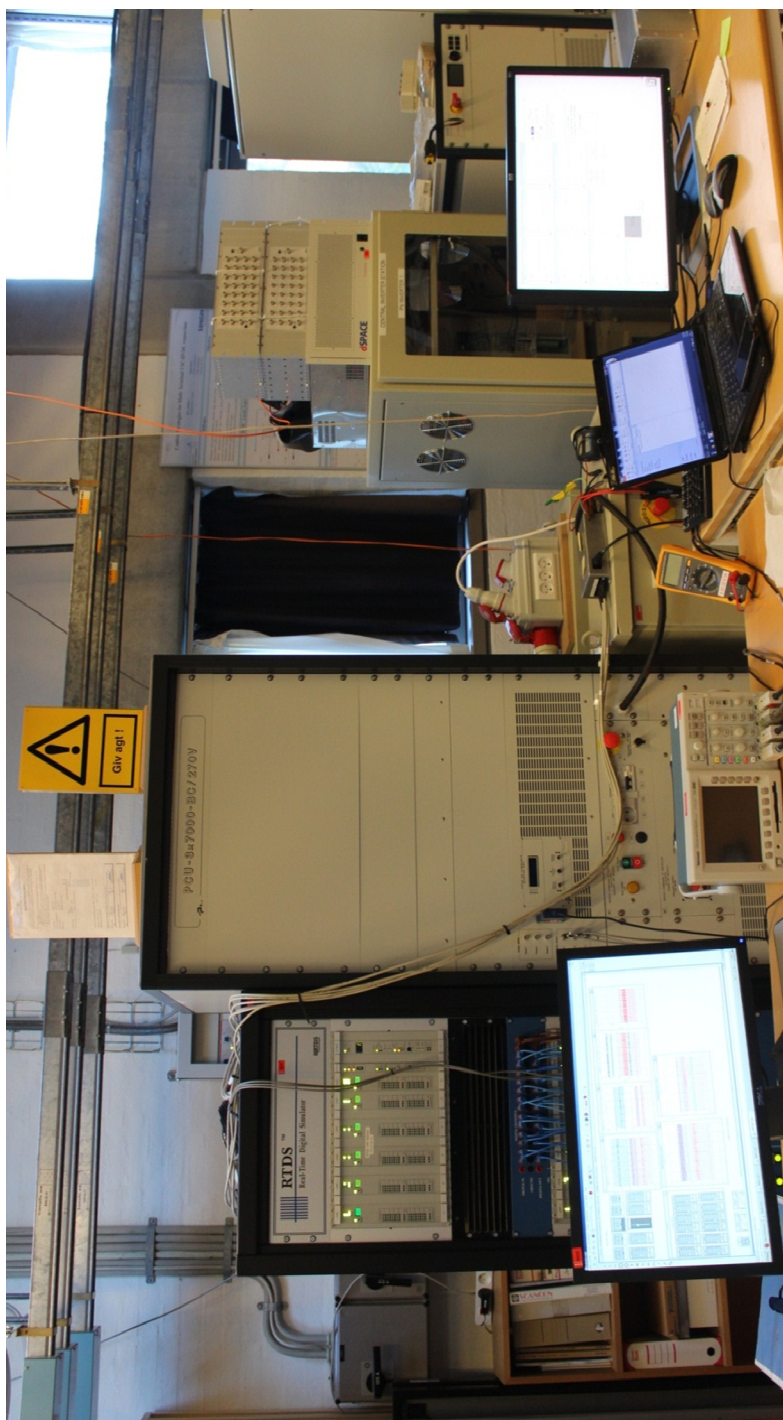


Figure E -2 Laboratory infrastructure of flexible AC grid

TABLE E-1 Real time PHIL test bench for PV applications

PHIL test bench – hardware specifications			
PV array emulator		Regatron 32kW/40A/1000V	
PV panel		CHSM6612P – 285W	
PV inverters		2 x VLT FC302/15kW	
Grid filter		1.6mH, 10uF	
Grid switch		ABB OTM 40F3CMA230V	
Grid impedance		1.8mH ± 10%, ± 20% 2.8mH ± 10%, ± 20% 32 A/400V	
Grid Transformer		2 x 11kVA / U _k = 3%	
Flexible AC grid		Puissance Plus PCU 3X7000-BC/270V	
Control desk/dSPACE RTS		DS1103/10kHz	
Runtime/RTDS RTS		2x6 GPC/ 50uS	
AC DC current sensors		LEM LA55-P	
AC DC voltage sensors		LEM LV25-P	
PV Central Inverter control			
K _{PI}	K _{II}	K _{PP}	K _{IP}
4.6	1500	0.5	200
ΔP [%]	Δf [Hz]		FSM [%]
10	0.5		12
IR	H _{syn} [s]	T _{fil} [s]	R _{PVPP} [pu/s]
	3.5	0.01	0.1

