Active Power Control of Photovoltaic Power Systems

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Outline

I. **Motivation behind APC of PV**
II. **Basics of frequency regulation and inertial response**
III. **Potential application environments**
IV. **Summary of related work**
V. **Research directions**

Motivation

Typical PV systems operated at maximum power point (MPP)

Active power control (APC) involves operating below MPP in order to provide margin for up-regulation (without storage)

Why throw away energy like this?

Answer: APC enables several useful functions

- Grid frequency regulation (FR) / frequency support
- Inertial response
- Bi-directional power ramp-rate control
- Power reference tracking

These functions become important at high PV penetrations (at grid-level)

Motivation

Current PV systems can be problematic for grid operators

- PV systems have been shown to increase the moment-to-moment mismatch between generation and load, increasing the need for FR services.
- PV systems displace the conventional generators that traditionally provide FR
- PV-based FR can turn remove these liabilities and replace them with a new asset

Smart inverters are beginning to address many integration problems (e.g. volt-VAr control)

- APC can complete the suite of smart inverter features, bringing PV closer to a truly dispatchable resource

Inverter-based APC/FR can react much faster than mechanical machine controls

- FERC Order 755 recognizes greater value of fast-ramping FR for system stability, requiring higher compensation

Motivation: analogy to wind power

APC of wind plants is already required in some countries with high penetrations

Similarities between APC of wind and PV:

- Opportunity cost of operating below MPP
- Dependent on weather conditions
- Very fast response

Advantages of PV over wind for APC

- Wind has limits on how much APC can down kinetic energy of blades
- Wind must allow blades to re-accelerate after performing APC
- Wind APC limited by mechanical loading

Disadvantages of PV relative to wind

- Not available outside daylight hours
- Technological development wind-based APC is much more mature

As PV penetrations increase it is likely that APC will be desired/required as it is for wind today

Basics of frequency regulation

When load increases, frequency drops slightly, and vice versa

Frequency stability depends on instantaneous balance between load and generation

Total generator rotational inertia determines how fast frequency changes for a given load step

Generators work together to regulate frequency by modulating their power output

Primary frequency control consists of the inertial response and droop-based autonomous power modulation

Secondary frequency control is achieved through a communication signal (AGC) that changes generator setpoints to bring frequency back to normal

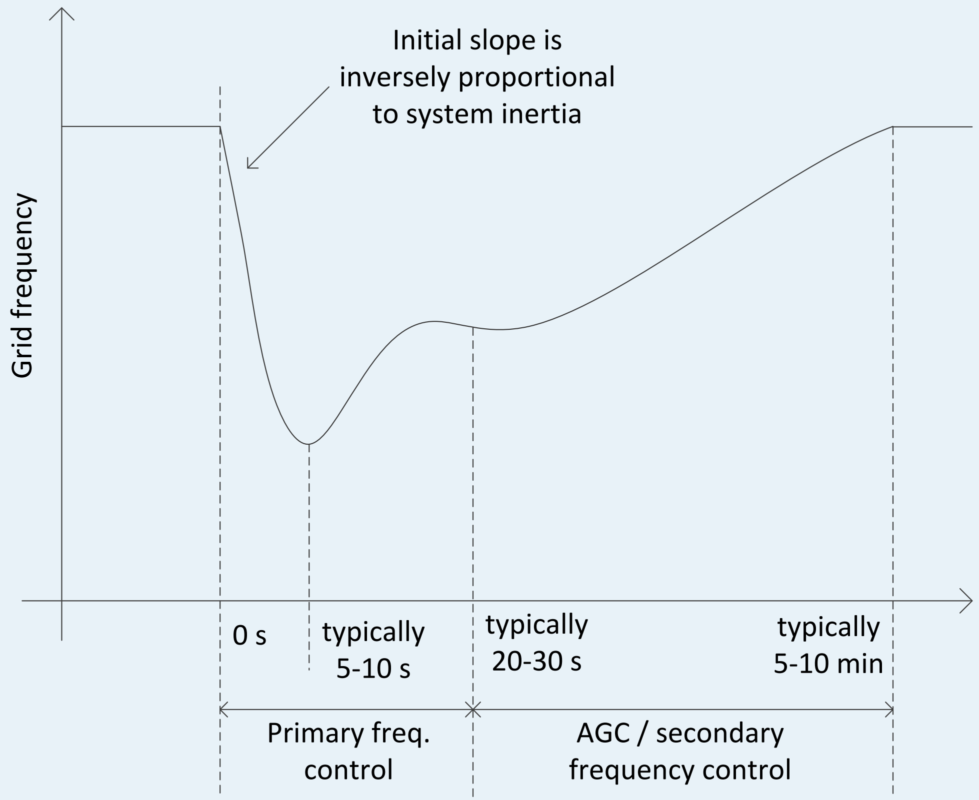


Figure adapted from J. Aho, et al., "Tutorial of Wind Turbine Control for Supporting Grid Frequency through Active Power Control," *2012 American Control Conference*, Montreal, Canada, June 27-29, 2012.

Basics of frequency regulation

Inverters can provide virtual inertial and **primary** frequency response by following a power-frequency droop characteristic (below)

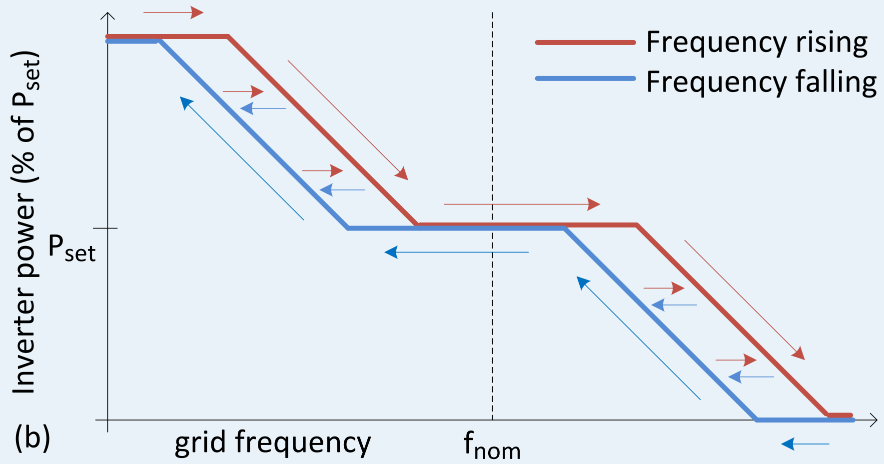
- This is not mechanical inertia; rather the control is fast enough that the output characteristic mimics that of a rotating generator

Digital control allows inverters have a variety of re-configurable droop characteristics, even dynamic or non-linear ones if desired

Inverters can also provide secondary frequency control through communications

Simple P-f droop characteristic

P-f droop with hysteresis and deadband



Likely applications of PV APC

Three scenarios where APC will make sense, despite opportunity cost of lost output:

1. Remote, island, or islanded microgrid power systems.
   - These non-grid-tied systems need to be self-regulating, so if significant PV is present it may need to participate in regulation.
   - E.g. Puerto Rico is requiring new large PV plants to provide FR. Currently this requires batteries because PV-based FR is not available
2. High PV penetration levels
   - As variable renewable penetration rises, the need for FR rises, and the quantity of conventional generation capable of FR falls.
   - At some penetration level, PV will need to fill this gap
3. Regulation markets
   - In a liberalized electricity market, whenever the value per MW-hour of FR exceeds the value per MWh of PV power it would economic sense for PV plants to bid into the FR market.
   - Value of FR is expected to rise
   - Current values: $18-60/MW-hour (overlaps with commercial *retail* cost of power)
   - May require changes to regulations and contracts

Related work

Storage-based APC / FR

- Much past and present research
- Commercially available, but not widespread due to costs

Wind-based APC / FR

- Much research, several patents at both turbine level and plant level
- Commercially available, not widespread, but becoming more common

Supercapacitors

- Can be integrated into PV systems to provide limited FR and bi-directional ramp-rate control
- In R&D phase, appears feasible

Storage-free PV-based APC / FR

- Handful of papers approach the issue
- One challenge: real-time estimate of MPP without tracking MPP

(See paper for full listing of related works.)

Research directions

Development of control techniques to ensure a given reserve power

Simulated and experimental demonstration of PV-based APC and FR

System-level optimization algorithms to maximize technical and economic benefits

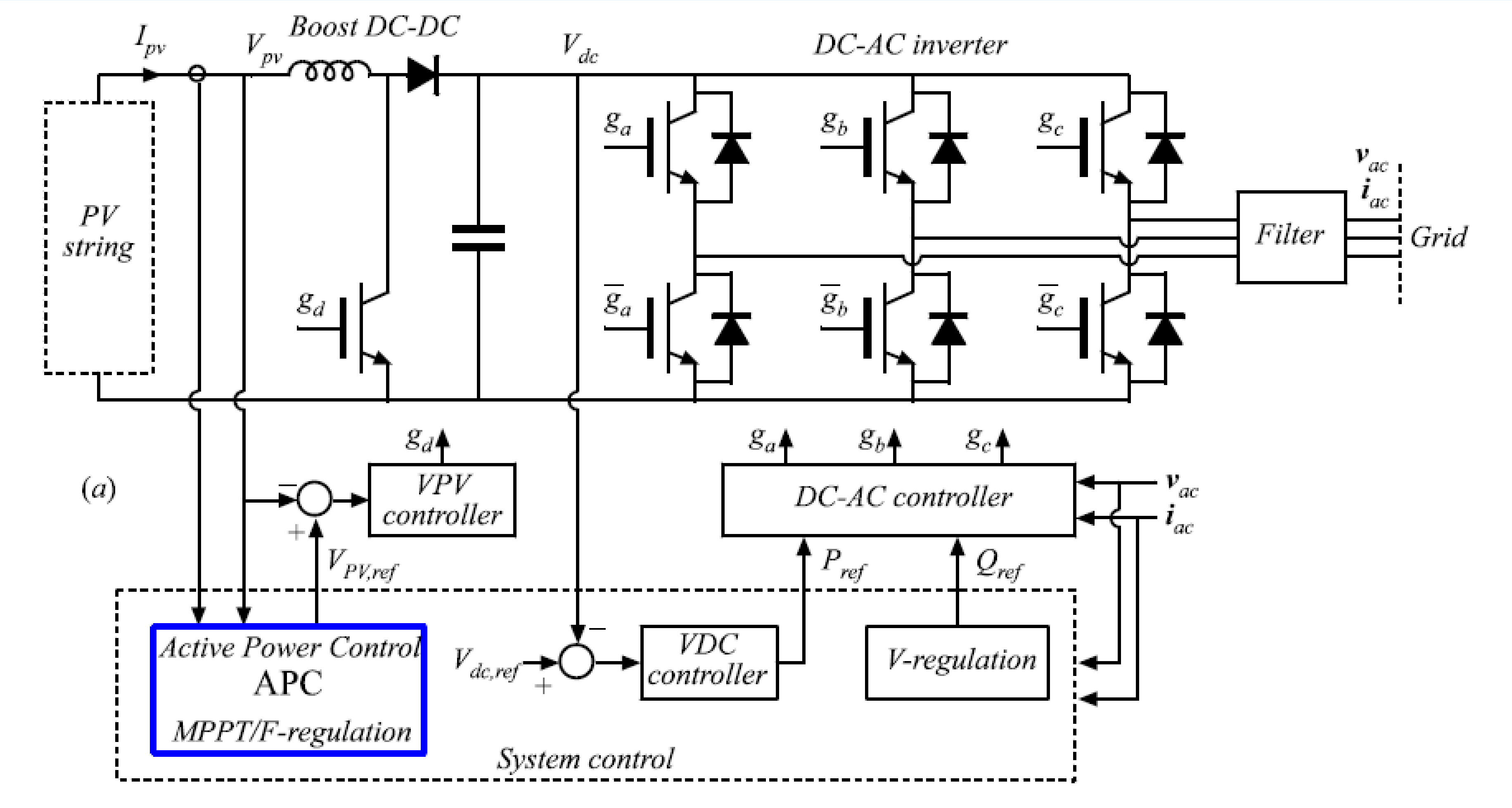
Evaluation of the impact of APC on microgrids and bulk grids

Development of standards and test protocols for APC / FR

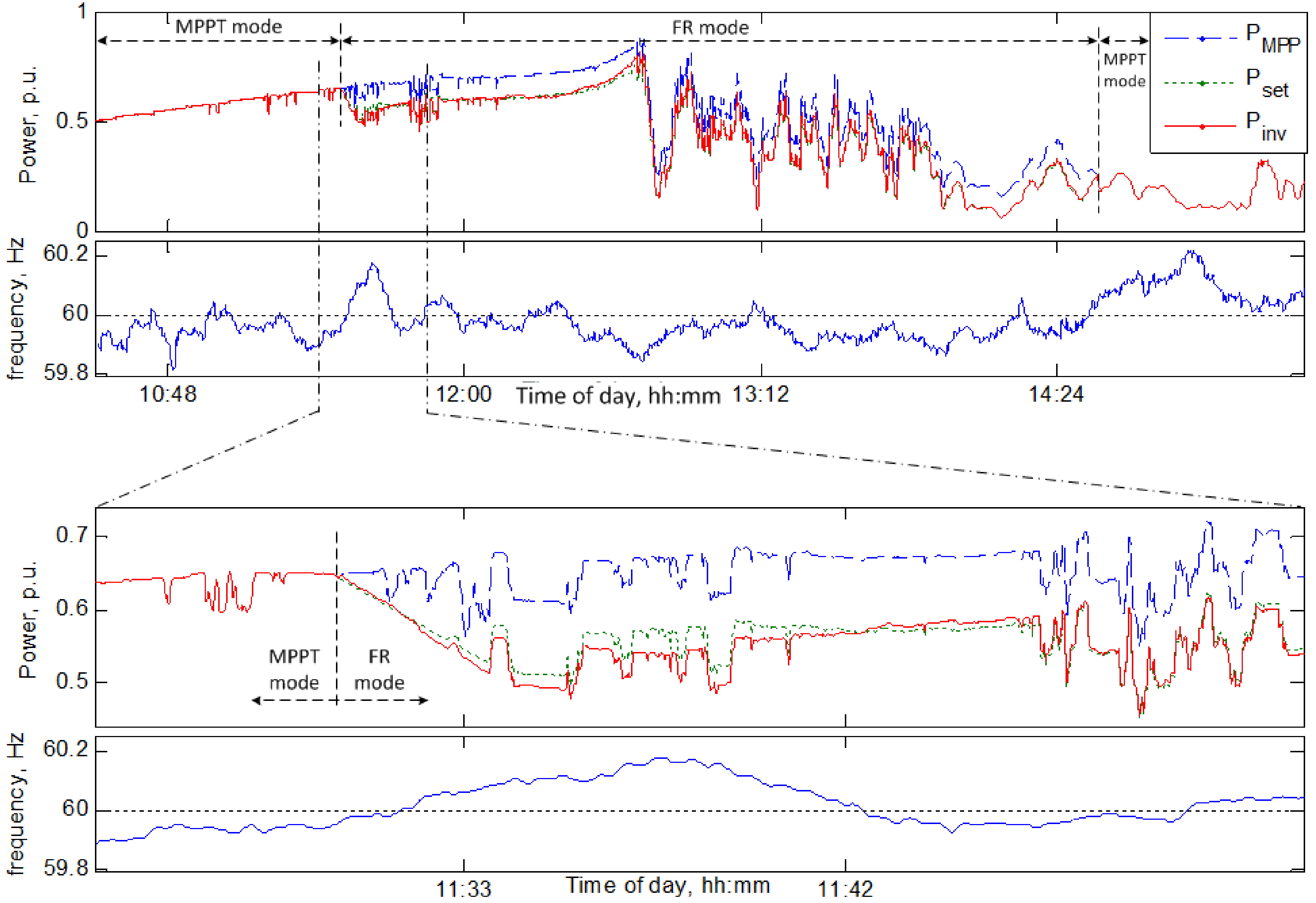
Development of market mechanisms to encourage optimal use of distributed FR

Development of inverter-level and plant-level communication/control techniques

Inverter and control diagram for APC



Simulation of APC for primary FR



Thanks!

Questions?