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HIGH-PENETRATION AUTOMATION AND DER ARCHITECTURE

1. INTRODUCTION

Regulatory, market, and technical drivers

Traditionally, electrical power grids are unidirectional flowed, centralized controlled, vertically integrated and managed with very large remote power plants generating power, transmitting power through high-voltage transmission lines, and distributing to city and load areas through substations and distribution networks. In North America, with the Blackout event in 2003, power industry deregulation has gradually created a structure of distributed generations, bidirectional power flows, horizontally organized and competitive wholesale electricity market. Most state jurisdictions (PUC) have stipulated Renewable Portfolio Standards (RPS) to promote renewable energy given the common belief on global warming and the depletion of fossil fuels in the long run. In the meantime, utilities suffer from aged infrastructure and generation, transmission, distribution resources to manage power flow congestion and to meet increasing electricity consumption. Distributed energy resources and microgrids at the customer sites emerged for local power reliability and correspondingly helped utility T&D infrastructure investment deferment. Utilities have welcomed this change from initial "be-cautious-and-stay-away-from-trouble" attitude (requiring DERs de-energizing grid during grid abnormal and outage) to actively requesting DERs to provide grid services nowadays. This has stimulated many advanced demand response or demand-side management control strategies and market rules.

It may still take decades of years for centralized large power plants and hierarchical transmission/distribution network to disappear. However, with increased penetrations of distributed energy resources (DER) and smart/automated devices, a flatted grid architecture, namely High-Penetration Automation, Energy Storage, and DER Architecture or in short High DER Architecture, is proposed and its key elements, properties, and functionalities are briefly described in this white paper.

Systemic issues and emerging trends

With increasing DER penetration, we have identified several systemic issues in our "Issues and Trends" report [1], including decreasing system inertia and impact on system stability, stochastic generation resources affecting system essential reliability services, protection issues due to conventional design based on unidirectional power flow in distribution feeders, and control and operation challenges with significantly increased control points. While new system integration standards are still under development, e.g. IEEE 1547, IEEE 2800, IEEE 2030, etc., several trends on new control philosophy and control functionalities can be observed, such as emerging smart power electronics converters with integrated system functions [2], changing from generation-follows-load to load-follows-generation strategies at demand side, from centralized control to decentralized controls, from planned and scheduled operation to ad-hoc and real-time operation, from coordinated management to more autonomous and self-optimizing management, and so on.

The purpose of this document

The purpose of this document is to define core principles and specifications to guide high DER grid architecture, control and operation designs, and to create an architectural model or template ("breadboard"), which can be customized for different variety or tailored to certain particularity.

2. ARCHITECTURAL APPROACHES

To cope with the aforementioned issues and trends, grid architecture will need to change accordingly. There are two approaches available, depending on the time horizon to look ahead.

2.1 Evolutionary Approach

The evolutionary approach is more practical and near-term approach, given that the percentage of DERs in generation fuel mix is still low (10%), which is relatively high penetration from the utility perspective of control and operation. The utility is still relying on large power plants providing significant portion of base loading and operation reserves, and the transmission and distribution structures have not changed too much except for the changes at the grid edges, mostly at low-voltage distribution systems owned by the customers and some of medium-voltage distribution grid owned by either utility or independent power producers. The distribution utility operators normally need to conduct studies on feeder hosting capacity and impact analysis with increasing DERs and to impose grid services requirements for DER interconnections. The biggest challenge for the utility is how to coordinate these customer-owned devices or resources with the utility-owned voltage and var control devices (such as distribution substation load tap changers, feeder voltage regulators, fixed or adjustable capacitor banks, and distribution STATCOMs) to guarantee power quality and voltage stability as well as extended device lifetime. The voltage/var optimization (VVO) or DMS-based integrated voltage/var control (IVVC) is typically performed by the DSO in a centralized way, but may not be extended to consider and control all the DERs, especially small-scale DERs, e.g. a 4 kW solar PV inverter at a residential house.

2.2 Revolutionary Approach

The revolutionary approach represents a visionary picture of the future grid with a new grid architecture. Based on our survey, we have read many innovative future grid concepts, such as Japan's digital grid, European supergrid/fractal grid/web-of-cells, energy internet, intergrid, etc. These concepts can be expressed commonly in power electronics based grid or flexible power network. The architecture is highly distributed, flatted (meaning no obvious distinction between transmission and distribution), and networked (among all control devices). Cooperative or collaborative control methodology is applied and system structure can be dynamically reconfigured for fault-tolerance and grid resilience.

3. HIGH DER ARCHITECTURE DESCRIPTIONS

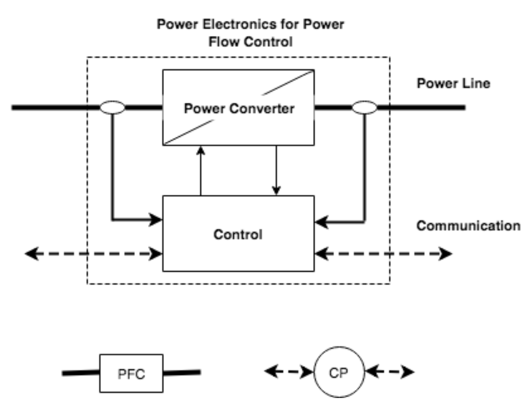
In system engineering, the qualities of a system represent the consumer viewpoint; while the properties of a system represent the provider viewpoint with the system properties support the system qualities. Components, structures, and system properties are elements to construct the system architecture, where the structures and components provide system properties defined by intrinsic characteristics and functional capabilities. In the case of High Automation/DER Architecture, consumers and providers can be interchangeable and hence the term of prosumers can be used.

3.1 Specific architectural elements (components and structures)

Major components:

- Power electronics based power flow controller (PFC)

  A power flow controller is defined as a functional block here, which comprises power electronic converter(s) and its embedded control hardware board (typically with DSP, FPGA, ADC, DAC, RAM, communication ports, etc.), as illustrated in Fig. 1.



The fundamental (external) functions of power electronics include:
1) Change waveform (for dc ←→ ac and meet harmonic requirements)

2) Change magnitude
3) Change frequency (for ac ←→ ac)
4) Control power flow (P and Q, direction and quantity, normal and fault)

The power flow control function exists essentially in all power electronics for grid applications, including HVDC, FACTS, and DER (including solar PV, energy storage, direct-drive wind turbine, microturbine, fuel-cell, small hydro, reactive source, etc.) interconnections. Hereafter, we treat different power electronics converters as a common element in a term of PFC function representing for the physical hardware device and use control point (CP) logically in the cyber layer, as denoted in Fig. 2.

- Distributed computing and control – collaborative control network (CCN)

  CC – area Control Coordinator
  CP – Control Point, inter-area PFC and intra-area PFC

- Distributed intelligence – smart inverters with integrated system functions

- Distributed generations (DER, Energy Storage)

- Responsive loads

- Adaptive protection devices (e.g. FLISR)

- Communications, SCADA, etc.

Structures:

- High DER at grid edges – fitting into existing distribution grid radial architecture High automation for feeder routing.

- logical energy network (LEN) – networked microgrid approach
- Meshed network
- Ultimate distributed architecture – no backbone transmission and bulky generation

3.2 Key grid properties

The grid properties reflect an internal view of grid behavior as seen by the grid designers, operators, and regulators. The key properties associated with High Automation / DER Architecture are as follows:

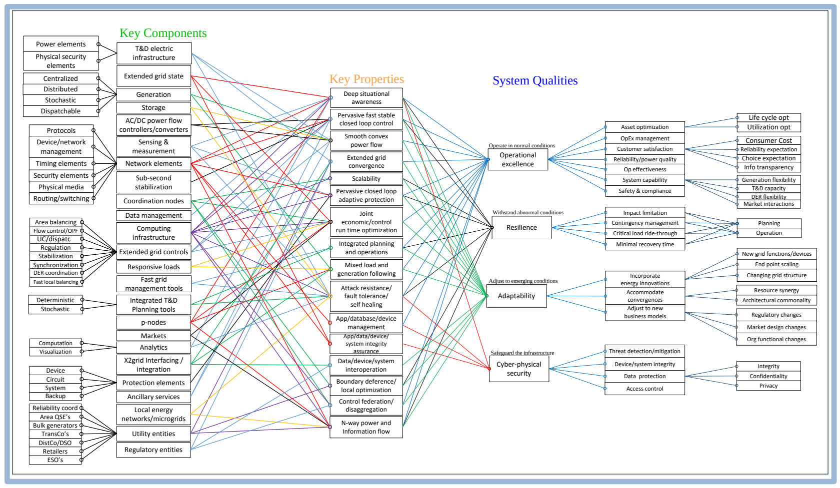
- High reliability
- High availability
- High resiliency
- High flexibility
- High sustainability

3.3 System Qualities

Describe briefly how (much) this architecture contributes to the seven grid qualities:

- Deliver
- Conserve
- Preserve
- Protect
- Adapt
- Enable
- Merit

Fig. 1 links the key elements, properties and functionalities described in this document.



(This is an example: core map + extended nodes)

Fig. x. High DER architecture: a tree-like overview linking components/structures with properties and qualities.

3.4 High DER Architecture View

3.4.1 Physical-layer architecture view

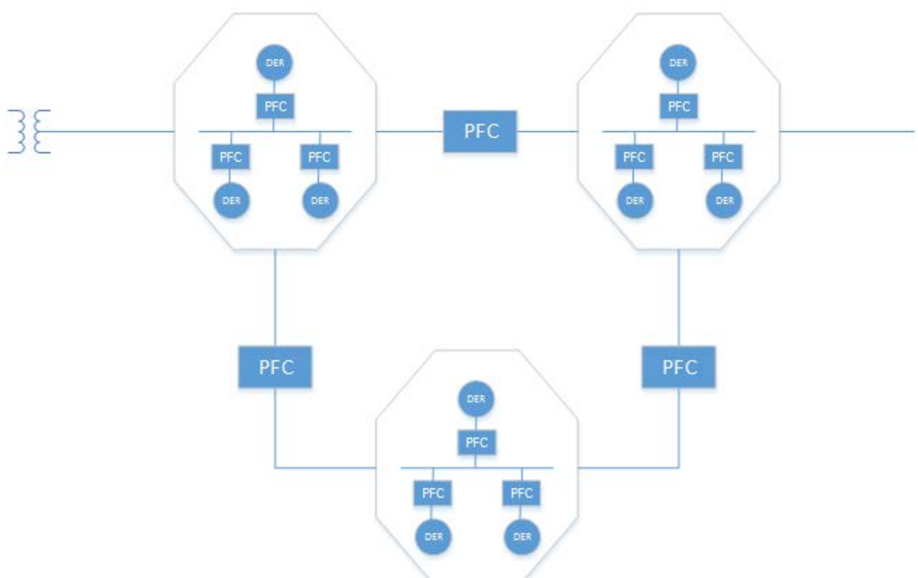


Fig. x. High DER architecture – physical layer.

3.4.2 Control-layer architecture view

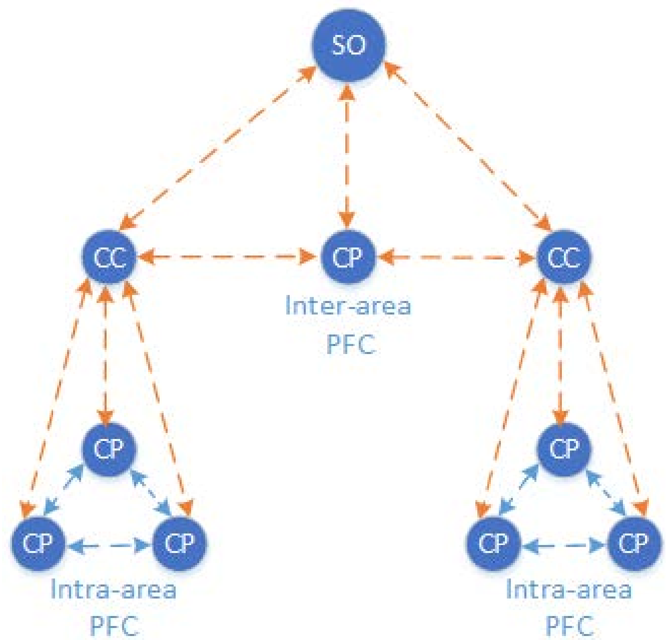
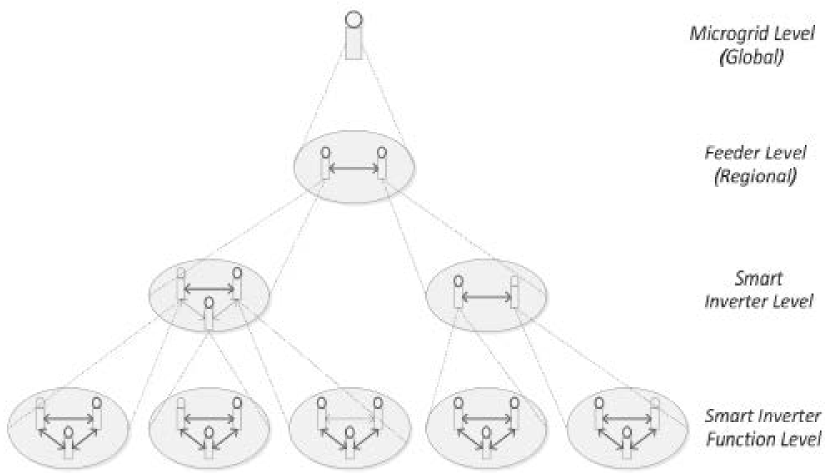


Fig. x. High DER architecture: collaborative controller network.

4. COLLABORATIVE CONTROLLER NETWORK (CCN)

The CCN is the operation brain for high penetration DER/Automation/Energy Storage grid architecture scenario. In this section, we describe its hierarchical control structure, collaborative control mechanism, and advanced control functions beyond the state-of-the-art standard requirements.

4.1 Hierarchical Control Structure



4.2 Collaborative Control and Information Discovery

4.2.1 Collaborative fault-tolerant control

4.2.2 Cooperative control and optimization

4.2.3 Data flow and information discovery schemes

4.3 Distributed Intelligence and Smart Functions

4.3.1 the state-of-the-art - standards and grid codes

Table I. Smart inverter standards and grid codes.

Standard Type	Standards or Activities
Standard control functions	IEEE 1547-2018, EPRI smart inverter initiative, IEC 62109-2
Information & data models	IEC 61850-7-420, SunSpec, OpenADR, OpenFMB, etc.
Communication protocols	IEEE 1815 (DNP3), IEEE 2030.5 (SEP2), etc.
Grid codes	FERC, NERC, CPUC Rule 21, HPUC Rule 14H
Compliance & certification testing	UL 1741 SA, UL 62109-2, IEEE P1547.1

4.3.2 The art of possible – truly smart inverter

Smart Features	Possible Approaches or Control Functions
Plug-and-play	• Standardized communication protocols • Non-formation cooperative controller (distributed frequency control, parallel processing, etc.) • Communication graph (at cyber layer)
Self-awareness	• Fault diagnostics (detection, isolation and classification) • Prognostics & health management (condition monitoring and device lifetime estimation) • Self-expression with communication (alarm, status, etc.)
Adaptability	• Grid parameter estimation • Frequency-adaptive grid synchronization • Distributed anti-islanding detection and adaptive mode transfer • Real-time optimization • Fault tolerance (modular and redundant structure, fault current control, fault ride-through) • Current source/voltage source flexibility
Autonomy	• Active/reactive power flow control • Grid forming/grid following flexibility
Cooperativeness	• Dynamic grid feeding • Dynamic grid supporting • Active/reactive power and harmonic current sharing • Sub- or super-harmonic damping • Ramp rate control • Soft start • Coordinated harmonics compensation • Coordinated unbalance compensation

Fig. 1. A list of control functions and approaches associated with each smart inverter feature.

5. CONCLUSION

A vision statement on high DER structure

High Automation/DER Architecture represents a futuristic grid architecture, which features high reliability, flexibility and scalability, promotes environmental-friendly distributed energy resources, and breaks many bottlenecks and barriers today's power grids are facing, e.g. risk of cascaded failures, large initial capital investment, transmission line power loss, network congestion, slow controls, etc. The control challenges can be approached by the formulation of a collaborative controller network (CCN).

6. REFERENCE

[1]

[2]