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IEEE VISION FOR SMART GRID CONTROLS: 2030 AND BEYOND

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IEEE Vision for Smart Grid Controls: 2030 and Beyond

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Acronyms and Abbreviations

A-AGC	adaptive automatic generation control
AC	alternating current
ACE	area control error
ADC	analog-to-digital converter
ADR	automated demand response
AGC	automatic generation control
AMI	advanced metering infrastructure
APC	active power control
AS	ancillary service
AT&C	aggregate technical and commercial
ATC	available transfer capabilities
CAISO	California Independent System Operator
CAP	switched capacitor
C&I	commercial and industrial
CCS	carbon capture and storage
CCHP	combined cooling, heating and power
CFE	Comisión Federal de Electricidad (English: Federal Electricity Commission)
CHP	combined heat and power
CIN/SI	complex interactive networks/systems initiative
CSP	concentrated solar plant
CT	combustion turbine
DA	distribution automation
DAC	digital-to-analog converter
DAE	differential algebraic equation
DAM	day-ahead market
DC	direct current
DCS	distributed control system
DER	distributed energy resource
DESD	distributed energy storage device
DFIG	doubly fed induction generator

DG	distributed generation
DR	demand response
DRER	distributed renewable energy resource
DSTATCOM	distribution static synchronous compensator
DSM	demand-side management
EMS	energy management system
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
ERP	enterprise resource planning
EU	European Union
EV	electric vehicle
FACTS	flexible alternating current transmission system
FDIR	fault detection isolation and restoration
FERC	Federal Energy Regulatory Commission
FID	fault isolation device
FIDVR	fault induced delayed voltage recovery
GTO	gate turn-off
HESS	hybrid energy storage system
HV	high voltage
HVAC	heating, ventilation and air conditioning
HVDC	high-voltage direct current
ICT	information and communication technology
IED	intelligent electronic device
IGBT	insulated gate bipolar transistor
IGCC	integrated gasification combined cycle
IPP	independent power producer
ISO	independent system operator
LED	light-emitting diode
LMP	locational marginal price
LV	low voltage
MISO	Midwest Independent System Operator
MPC	model predictive control
MPPT	maximum power point tracking

MW	megawatt
MV	medium voltage
NAN	neighborhood-area network
NERC	North American Reliability Corporation
NIST	National Institute of Standards and Technology
OLTC	on-load tap changer
OPGW	optical ground wire
PDC	phasor data concentrator
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PI	proportional-integral
PLC	power line carrier *or* programmable logic controller
PMU	phasor measurement unit *or* phasor management unit
PREPA	Puerto Rico Electric Power Authority
PSS	power system stabilizer
PV	photovoltaic
R&D	research and development
RES	renewable energy source
RPS	Renewable Portfolio Standard
RSR	regulation service reserve
RTM	real-time market
RTO	regional transmission organization
RTU	remote terminal unit
SCADA	supervisory control and data acquisition
SGIP	Smart Grid Interoperability Panel
SOC	sensing, optimization, and control
SQRA	security, quality, reliability, and availability
SSSC	static series synchronous compensator
SST	solid-state transformer
STATCOM	static synchronous compensator
SVC	static VAR compensator *or* static voltage compensator
T&D	transmission and distribution
TOU	time of use

TCSC	thyristor-controlled series compensator
TSO	transmission system operator
UAN	user-area network
UPFC	unified power flow controller
USC	ultra-supercritical
UTE	Usinas y Terminales Eléctricas
VAR	volt-ampere reactive
VMG	virtual microgrid
VSAT	very-small-aperture terminal
VSC	voltage source converter
WAN	wide-area network
WAMS	wide-area measurement system

Glossary

active power control (APC): Control of the real power output of a wind turbine or wind farm in order to assist in balancing total power generated on the grid with total power consumed.

advanced metering infrastructure (AMI): A system for measuring individual customers' electricity consumption at intervals of an hour or less, and communicating that information at frequent intervals to the distribution utility.

automatic generation control (AGC): An automatic system to vary mechanical input to a generator to match small variations in system load.

ancillary services: Services that ensure reliability and support the transmission of electricity from generation sites to customer loads. Such services can include: load regulation, spinning reserve, nonspinning reserve, replacement reserve, and voltage support.

area control error (ACE): A measured signal that is weighted sum of area frequency error and deviations from set point of powers on select transmission lines that carry major power flows in/out of the region of interest.

balancing authority: An entity responsible for balancing generation and load (with specified imports and exports) within a specified geographic region.

congestion: A condition that occurs when insufficient transfer capacity is available to implement all of the preferred schedules for electricity transmission simultaneously. This condition prevents the least-cost set of generators from serving load, causing an increase in the wholesale price of electricity or cost of service at one or more locations in the system.

contingency: An abnormal event in the power system, such as the tripping of a generator or a transmission line.

critical peak pricing: A dynamic pricing plan that combines peak/off-peak time-of-use rates with substantially higher *super-peak* rates that apply only to peak hours on a limited number of critical days during the year. Critical days typically are announced the day before, on the basis of forecast market conditions.

cyber-physical systems: Physical systems whose function is governed by a networked communication and control system.

day-ahead market (DAM): A financial market in which market participants purchase and sell energy at financially binding day-ahead prices for the following day, and calculated every hour.

demand-response (DR): Customer loads that are responsive to conditions in the electric power system, particularly at peak times.

demand-side management (DSM): The amount of consumer load reduction at the time of system peak due to utility programs that reduce consumer load during many hours of the year. Examples include utility rebate and shared savings activities for the installation of energy efficient appliances, lighting and electrical machinery, and weatherization materials. This category also includes all other DSM activities, such as thermal storage, time-of-use rates, fuel substitution, measurement and evaluation, and any other utility-administered DSM activity designed to reduce demand, electricity use, or both.

distributed energy resource: A small, modular, decentralized, grid-connected or off-grid energy system located in or near the place where energy is used.

distributed generation (DG): Small-scale, on-site generation systems owned by entities that are primarily consumers of electricity.

distribution: The delivery of energy to retail customers.

distribution automation: The application of advanced technology to automate the maintenance, control, and operation of the distribution network.

distribution system: The portion of the transmission and facilities of an electric system that is dedicated to delivering electric energy to an end user.

dynamic pricing: A regime in which retail customers face energy prices that vary with the contemporaneous cost of generation or state of supply-and-demand conditions in the electric power system. Prices can be based on day-ahead or hour-ahead forecasts of conditions and can change for as few as 60 *critical peak* hours per year or might change hourly or more often in real-time pricing plans.

economic dispatch: The assignment of generating units' production to minimize overall costs.

electric power grid: A system of synchronized power providers and consumers connected by transmission and distribution lines, and operated by one or more control centers.

electric system reliability: The degree to which the performance of the elements of the electrical system results in power being delivered to consumers within accepted standards and in the amount desired. Reliability encompasses two concepts: adequacy and security. *Adequacy* implies that there are sufficient generation and transmission resources installed and available to meet projected electrical demand plus reserves for contingencies. *Security* implies that the system will remain intact operationally (i.e., will have sufficient available operating capacity) even after outages or other equipment failure. The degree of reliability can be measured by the frequency, duration, and magnitude of adverse effects on consumer service entities, public power districts, public utility districts, municipalities, rural electric cooperatives, and state and federal agencies.

electric vehicle (EV): A vehicle that operates by electric power provided by batteries. EVs include both plug-in hybrid electric vehicles and battery electric vehicles but do not include hybrid electric vehicles, which are self-powered and never connected to the electric grid.

electricity demand: The rate at which energy is delivered to loads and scheduling points by generation, transmission, and distribution facilities.

energy efficiency, electricity: Refers to programs that are aimed at reducing the energy used by specific end-use devices and systems, typically without affecting the services provided. These programs reduce overall electricity consumption (reported in megawatt hours), often without explicit consideration for the timing of program-induced savings. Such savings are generally achieved by substituting technologically more advanced equipment to produce the same level of end-use services (e.g., lighting, heating, motor drive) with less electricity. Examples include high-efficiency appliances, efficient lighting programs, high-efficiency heating, ventilating, and air conditioning (HVAC) systems or control modifications, efficient building design, advanced electric motor drives, and heat recovery systems.

energy management system (EMS): The suite of software and hardware that supports a regional control center in managing the production, purchasing, transmission, distribution, and sale of electrical energy in the power system at a minimal cost with respect to safety and reliability.

flexible alternating current transmission system (FACTS): A set of technologies employing power electronics that enable control of various transmission system operating parameters, including volt-ampere-reactive support and power flow.

generation: The process of producing electric energy by transforming other forms of energy; also, the amount of electric energy produced, expressed in kilowatt-hours.

governor droop control: A feedback loop that measures the individual generator's rotational speed/frequency as output, and modifies prime mover mechanical power in response.

high-voltage direct current (HVDC): Technologies for transmitting bulk power by direct current at transmission-level voltages.

independent power producer: A nonpublic entity that owns facilities to generate electricity for sale to utilities, end users, or both.

independent system operator (ISO): A regulated entity without generation or distribution assets that oversees the wholesale electricity market and operates the bulk power system in a particular region.

intermittent resource: An electric generating plant with output controlled by the natural variability of the energy resource rather than dispatched based on system requirements. Intermittent output usually results from the direct, nonstored conversion of naturally occurring energy fluxes such as solar energy or wind energy.

inverter: A power electronic system whose function is to convert electric power from direct current to alternating current.

islanding: The process by which the power network automatically responds by breaking into self-contained *islands* when major disruptions occur on a power system, according to fixed procedures that have been established well in advance.

load (electric): The amount of electric power delivered or required at any specific point or points on a system. The requirement originates at the energy-consuming equipment of the consumers.

load control program: Demand-response programs that offer customers incentives to reduce their consumption in response to an instruction or signal from the system operator so that the utility can reduce peak demand.

load factor: The ratio between average and peak power.

locational marginal price (LMP): For any economic dispatch, the marginal cost of meeting a small increment of load at a particular location; the spot price of electricity at that location.

losses: The difference between generated power and power delivered to the load, typically caused by resistance in transmission lines and transformers and converted to waste heat.

microgrid: A part of an electric power system consisting of distributed generators, loads, and specialized controls that is capable of operating either in parallel with a utility system or as a stand-alone system.

***N* – 1 contingency analysis:** Evaluation of the transmission line and transformer power flows and bus voltages in case of the loss of a single component, such as a particular generator.

off-peak: Periods of relatively low system demand. These periods often occur in daily, weekly, and seasonal patterns, and differ for each individual electric utility.

on-peak: Periods of relatively high system demand. These periods, which differ for each electric utility, often occur in daily, weekly, and seasonal patterns.

outage: The period during which a generating unit, transmission line, or other facility is out of service.

peak demand *or* **peak load:** The maximum load during a specified period of time.

phase angle: The time, expressed as an angle, by which a voltage and current waveform, or two voltage or two current waveforms, are shifted relative to each other.

phasor measurement unit (PMU): A device used to measure current, voltage, and frequency every 1/30 (one-thirtieth) of a second or faster in synchronicity with other such measurements across a wide area based on a Global Positioning System time signal.

plug-in hybrid electric vehicle (PHEV): A vehicle with an internal combustion engine as well as batteries that can be charged using an external power source.

power electronics: Electronic circuits that employ switching electronic semiconductor devices, whose function is to control electrical energy and convert it from one form to another (e.g., from alternating current to direct current, or alternating current at one frequency to alternating current at another frequency).

power factor: The ratio of real power to apparent power. Reflects the degree to which a given amount of current is producing useful work.

power quality: The extent to which the voltage waveform at a load conforms to the ideal sinusoidal shape and nominal value. Poor power quality is generally the result of loads that draw current that is not sinusoidal (a particular problem with electronically controlled loads) or weak distribution networks producing frequent outages or voltage sags.

power system stabilizer (PSS): An auxiliary feedback loop that modulates field voltage in response to measured frequency, with the objective of improving the damping of the oscillatory frequency modes.

primary governor control: A corrective feedback that incrementally changes a generator's power output in response to locally measured frequency/speed error.

prosumers: A power consumer who can also function as a power producer.

reactance: The property of a conducting device that introduces a phase shift between voltage and current and introduces an impediment to the flow of alternating current.

reactive power: Power that exists in AC power systems when reactance is present. Reactive power charges and discharges the energy stored in reactive elements. It does no time-average work, but its presence still contributes to electrical losses and voltage drops.

real-time market (RTM): Coordinates the dispatch of generation and demand resources to meet the demand for electricity in real time, calculated every 5 minutes to 15 minutes.

real-time pricing: See *dynamic pricing.*

regional transmission organization (RTO): An organization that is responsible for moving electricity over large interstate areas.

regulation service reserve: Reserve used for regulation over a five-minute window to meet the required energy balance and preserving power system stability.

renewable energy resources: Energy resources that are naturally replenishing but flow-limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources include: biomass, hydro, geothermal, solar, wind, ocean thermal, wave action, and tidal action.

regulation: Maintaining voltage and frequency within certain bounds. Also refers to the activity of a government agency charged with controlling the behavior of a public utility or other entity.

renewable Portfolio Standard (RPS): A state-level requirement that a minimum fraction of in-state electricity consumption correspond to generation from specified renewable technologies, such as wind, solar, or geothermal.

reserve capacity microgrids: Microgrids that can be a source of operating reserve for the grid.

secondary control: Control that acts on a slower timescale, over a wider region, by modifying (a subset of) generators' power set points in the region, with the objective of regulating ACE.

static VAR compensator (SVC): A power electronics device belonging to the family of devices known as FACTS used for voltage control by injecting and withdrawing reactive power.

supervisory control and data acquisition (SCADA): Specialized computer systems that monitor and control industrial processes, including the operation of components of the electric grid, by gathering and analyzing sensor data in near real time.

synchronized phasor measurement (synchrophasor): The measurement produced by phasor measurement units; a voltage or current phasor that has been synchronized with other such measurements using a common time signal from the Global Positioning System.

thermal energy storage: The storage of heat energy during utility off-peak times at night, for use during the next day without incurring daytime peak electric rates.

time-of-day pricing: A special electric rate feature under which the price per kilowatt hour depends on the time of day.

time-of-use rates: Rate schedules that establish fixed time periods based on average system load characteristics, across which prices vary. Typical time-of-use tariffs divide weekdays into two or three time periods (peak, off-peak, and perhaps an intermediate block) and assign weekend hours to an off-peak block. Prices increase from off-peak through peak hours, and the entire tariff schedule may change across seasons.

transmission network: The part of the power system that carries electric power over moderate to long distance, usually at high voltage.

unit commitment: The process of scheduling a generator (unit) to provide energy during a specific time period.

virtual microgrid: A cyberspace concept that allows changeable segments of distribution networks to be managed as microgrids.

volt-ampere reactive (VAR): The unit used to measure reactive power, which is present in an AC system when current and voltage are out of phase.

voltage source converter (VSC): A power electronic device for converting a direct current voltage to an alternating current voltage.

wide-area measurement systems (WAMS): A network of devices, usually consisting of phasor measurement units, that measures quantities of interest on the transmission network across a large geographic area in real time.

Chapter 1 Introduction

The Smart Grid is seen as a fundamentally transformative, global imperative for helping the planet deal with its energy and environmental challenges. Environmental stewardship, explosive growth of global energy demand, increasing emphasis on electrified transportation, aging infrastructures, and empowerment of consumers are some of the major drivers that are necessitating this transformation.

On the global canvas, various initiatives are afoot to decrease the carbon footprint. The Renewables Portfolio Standards in the U.S. for example, was established in California in 2002 with a goal of increasing the percentage of renewable energy sources to 20% by 2017 and 33% by 2020 [3]. In Europe, the target is to raise the penetration from current levels of 20% to about 50% by 2050 [4].

World over, electricity demand is projected to double between 2000 and 2030, growing at an annual rate of 2.4%, faster than the projection for any nonrenewable energy source [2]. Electricity's share of total final energy consumption has steadily increased over the years, with the figures in the U.S. starting at 2% at the beginning of the previous century, to 11% in 1940, to 20% in 1960, and to over 40% today [5]. Electricity demand growth is strongest in developing countries, where demand will climb by over 4% per year over the projection period, more than tripling by 2030. Consequently, the developing countries' share of global electricity demand jumps from 27% in 2000 to 43% in 2030 [2]. Growing interest across the globe in electrification of transportation increases these projections further.

There is growing evidence that the U.S. transmission system is in urgent need of modernization. The system has become congested because growth in electricity demand and investment in new generation facilities have not been matched by investment in new transmission facilities. There has been a steady increase in the number of service interruptions on the electricity grid; blackouts result in an estimated $79 billion (approximately 22% of the total revenue for electricity sales) in lost revenue annually. The aging of the electricity infrastructure in the United States exacerbates this problem.

For the purposes of this document, we define a Smart Grid to be an end-to-end cyber-enabled electric power system, from fuel source to generation, transmission, distribution, and end use, that will: 1) enable integration of intermittent renewable energy sources and help decarbonize power systems, 2) allow reliable and secure two-way power and information flows, 3) enable energy efficiency, effective demand management, and customer choice, 4) provide self-healing from power disturbance events, and 5) operate resiliently against physical and cyber attacks.

The path for realizing the Smart Grid is fraught with several formidable challenges. Increased penetration of renewables implies that the transmission systems have to be expanded by a significant amount to support these renewables in dispersed areas. It also introduces operational challenges in terms of requiring significantly higher levels of regulation and ramping capacity. New flow patterns enter the picture at the distribution level and necessitate drastic changes to the protection, distribution automation, and voltage and VAR management. Increased renewable generation also implies limited dispatchability and increased intermittencies, which are concomitant with increased ancillary services. Increased demand the world over, including the anticipated rapid increase in electrification of transportation, will lead to significant new loads on distribution networks, many of which are woefully inadequate when it comes to monitoring and automation.

Control is poised to rise to the occasion and counter a significant number of these challenges. This rise is possible because advances in sensing technologies are making new information available about various aspects of the grid, and progress in communication technologies are making them available at pertinent locations. Decision making, in an automated manner, is therefore becoming feasible, from seconds to seasons, at desired, new, and distributed locations, thereby facilitating a variety of opportunities for control—for reducing consumption, for better exploiting renewable sources, and for increasing the reliability and performance of the transmission and distribution networks. Emerging paradigms of demand response are dramatically altering the picture of loads, allowing them to not simply be followed but shaped. Plug-in electrical vehicles can be viewed not as loads, but as dispatchable assets coming to the aid of the distribution system. Spurred by large-scale experimental and commercial projects, energy storage technologies are rapidly becoming viable alternatives to conventional fossil fuel-based spinning reserves. Each of these factors is making available the use of such information, at pertinent locations, to the relevant decision maker in the grid, thereby bringing control and automation to center stage.

The increased deployment of feedback and communication implies that loops are being closed where they have never been closed before, across multiple temporal and spatial scales, thereby creating a gold mine of opportunities for control. Control systems are needed to facilitate decision making under myriad uncertainties, across broad temporal, geographical, and industry scales—from devices to power system–wide, from fuel sources to consumers, and from utility pricing to demand response. The various challenges introduced can be posed as a system-of-systems problem, necessitating new control themes, architectures, and algorithms. These architectures and algorithms need to be designed so that they embrace the resident complexity in the grid: large-scale, distributed, hierarchical, stochastic, and uncertain. With information and communication technologies and advanced power electronics providing the infrastructure, these architectures and algorithms will need to provide the smarts and use all advances in communications and computation such as 4G networks, cloud computing, and multiple-core processors.

This document highlights the role of control systems in the evolution of the Smart Grid. It includes an overview of research investigations that are needed for renewable integration, reliability, self-healing, energy efficiency, and resilience to physical and cyber attacks. These investigations are encapsulated in several loci of control including: new methodologies for transmission, distribution, and renewable energy, and storage; new roles in emerging topics such as electricity markets, demand response, microgrids, and virtual power plants; and new solutions for efficiency, heating and cooling, and security. Together, they usher in new horizons for control, such as architecting a system of distributed systems, building interfaces to social sciences such as economics, sociology, and psychology, and providing a blueprint for critical infrastructure systems. Although the emerging role of control and its implication on grid architectures have been articulated in papers [1, 6], a comprehensive discourse on the evolution of Smart Grid and the opportunities and challenges that it presents for control, ranging from generators to consumers, from planning to real-time operation, from current practice to scenarios in 2050 in the grid and all of its subsystems, has not been undertaken hitherto and is the purpose of this document.

We begin with current practices in Chapter 2, which illustrate the roles of control in power systems such as power balance, frequency regulation, and reactive power control. Chapter 3 discusses drivers for change that pave the way for a paradigm shift in the electric grid. Chapter 4 presents different scenarios of the Smart Grid that might emerge three decades from now. Chapter 5 delineates research challenges across the entire grid and the emerging control themes. Conclusions are found in Chapter 6.

1.1 Citations

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